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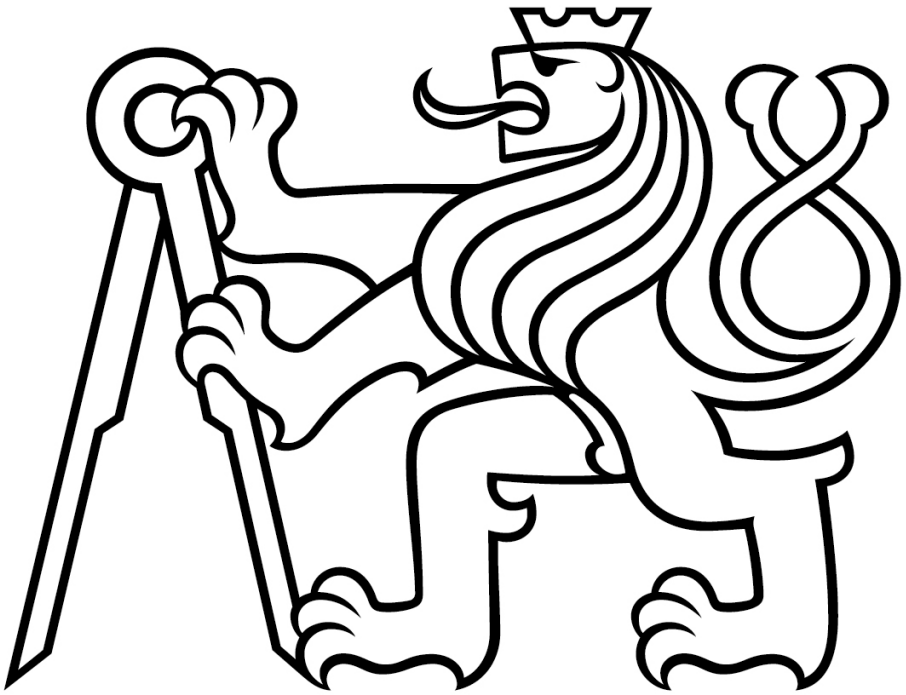

TEZE K DISERTAČNÍ PRÁCI

České vysoké učení technické v Praze
Fakulta biomedicínského inženýrství
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Specifics of medical equipment during field breathing experiments

Specifika použití lékařské přístrojové techniky během terénních dýchacích experimentů

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Oponenti: .....

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Teze byly rozeslány dne: .....

Obhajoba disertace se koná dne ..... v …… hod. před komisí pro obhajobu disertační práce ve studijním oboru (název) v místnosti č ..... Fakulty biomedicínského inženýrství ČVUT v Praze.

Bližší informace o obhajobě disertační práce jsou k dispozici na sekretariátu děkana Fakulty biomedicínského inženýrství, ČVUT v Praze, nám. Sítná 3105, 27201 Kladno.

Content

1. Introduction and the state of the art

Avalanche burials represent one of the most dangerous risks associated with winter activities in the mountains with around a hundred fatalities per year in the European Alps [1]. The survival chances depend on multiple factors: trauma sustained during the accident, the length and depth of the snow burial, and the presence of an air pocket [2-4]. The most common cause of death in avalanche victims is asphyxia [3,5-7]. This occurs as a consequence of blocked airways or due to severe hypoxia and hypercapnia resulting from rebreathing previously exhaled gas. The mechanism of gas exchange in a snow-buried avalanche victim has not yet been fully elucidated and is a subject of worldwide research.

A number of field breathing trials with healthy volunteers have been conducted in order to investigate the gas exchange limitations and work of breathing effects on the probability of survival under avalanche snow. It is a topical subject due to constantly evolving guidelines for the rescue and resuscitation of avalanche victims [8-12]. This research has also affected the development of safety equipment for people in danger of avalanche snow burial [13-15]. Numerous questions remained unanswered by the already published studies. The few already conducted studies have different methodologies, with specific medical and technical aspects, and some of the conclusions are very challenging to compare. Moreover, volunteers are monitored with medical equipment in order to obtain research data and ensure the safety of the subjects. However, the monitoring equipment is challenged by the outdoor environment and physiological changes that are different from what could be seen in critically ill patients, and potential errors have already been identified [16].

The main research focus is on the gas exchange occurring in the air contained within the snow and the role of an ‘air pocket’ in front of the victim’s airways. The air pocket is standardly defined as any space surrounding the avalanche victim’s nose and mouth, no matter how small, in the presence of the victim’s patent airway. No air pocket has a victim whose mouth and nose are sealed with snow or debris [8]. Especially the question of the size of the air pocket has drawn a lot of scientific attention since the 1990s [17]. Initially, the presence and size of the air pocket appeared to be critical for survival [18]; however, Roubík *et al.* proved that breathing into snow is possible even without a formed air pocket in front of patent airways [19]. Still, significant hypercapnia and hypoxemia have been observed in many of the simulated avalanche experiments, no matter how big the artificial air pocket in the snow was [19-21].

The principal identified medical risks of field breathing experiments are associated with rebreathing—hypoxia and hypercapnia; the risk of arrhythmias is also important. This necessitates a meticulous monitoring of the subjects—for their safety, as study endpoints, but also in order to obtain data for further analysis. In some of the already conducted trials, the end-tidal O_2 (EtO_2 in kPa, mmHg, %) and end-tidal CO_2 ($EtCO_2$ in kPa, mmHg, %) reached values that would be considered critical in an intensive care unit (ICU) setting but were also documented in some elite athletes [22].

Also technical aspects must be taken into account during these field experiments; namely the properties of the study material (simulated avalanche snow, whose properties can vary from day to day and within one day), the breathing apparatus used and its tightness, and other environmental conditions (hypobaric hypoxia,

ambient temperature, etc.) that can interfere with the subject's physiology. Moreover, some issues with vital sign monitoring and limitations of standardly used medical equipment have been reported during these experiments [16,23].

For monitoring of the subjects throughout these experiments, various vital sign monitors have been used. Frequently used monitors are originally designed for anaesthesia or critical care units [24-28]; however, even these monitors are, according to the manufacturer, suitable to operate under a wide range of environmental conditions (Table 1). In some studies [29-32], monitors for emergency care have been used [33-35].

Table 1 Environmental requirements of examples of vital sign monitors [24-28,33-35].

Vital sign monitor	Operating temperature (°C)	Storage temperature (°C)	Atmospheric pressure (kPa) (altitude)	Humidity (%)
Datex-Ohmeda S/5[1]	10–35	(-10)–50	66–106	10–90 non-condensing
GE CareScape B650[1]	10–35	(-20)–60	not specified	10–90 non-condensing
Masimo Radical-7[1]	0–50	(-40)–70	50–106 (-304 m to 5486 m)	10–95 non-condensing
Nonin PalmSAT[1]	(-20)–50	(-40)–70	above 19 (up to 12000 m)	10–95 non-condensing
Edan M3B[1]	5–40	not specified	not specified	not specified
Philips HeartStart MRx[2]	0–45	(-20)–70	57–101 (0 m to 4500 m)	up to 95
LIFEPAK 15[3]	0–45	(-20)–65	57–106 (-382 m to 4572 m)	5–95 non-condensing
ZOLL X Series[4]	0–50	(-30)–70	57–103 (-170 m to 4572 m)	15–95 non-condensing

[1]Vital sign monitor used in the presented in this thesis, [2]vital sign monitor used in [29,31], [3]vital sign monitor used in [32], [4]vital sign monitor used in [30].

Vital sign monitors are then used for measuring parameters like oxygen saturation (SpO_2) [18], end-tidal CO_2 ($EtCO_2$), and inspired fraction of CO_2 ($FiCO_2$) and these parameters often serve as study endpoints [19-21,29-32,36]. The limits are set at different values; for pulse oximetry, SpO_2 75% [21,29,31], 80% [32], 85% [20,36], or even 88% [30] and for $EtCO_2$ at 8% [19,31], or 60 mmHg (8 kPa) [32].

However, the reliability of the monitoring during breathing experiments with considerable rebreathing has been questioned. During their laboratory experiments, Roubík and Filip [16] observed a certain discrepancy between the value of $EtCO_2$ displayed numerically on the screen and the value presented via the capnographic curve. The error in $EtCO_2$ was evaluated by the monitor incorrectly in 30–50% of the total

experimental breathing time, but in one subject, this time reached up to 93%, despite regular calibrations of the system. This may be caused by imperfect software dealing with rapid changes in the exhaled gases, which are unexpected in a critical patient for whom these monitors are originally designed.

As the reliability of the other frequent vital sign parameter used as a study endpoint—SpO_2—has not been further studied, this thesis concentrates mainly on this parameter and the associated perfusion index.

Although pulse oximetry is challenged by numerous well-known limitations [37-39], it has been successfully used even in outdoor environments for the assessment of the acclimatisation process at high altitudes or the development of acute mountain sickness [40]. Factors affecting the accuracy of SpO_2 relevant in outdoor environment during monitoring of healthy volunteers are mainly low perfusion state, motion artefacts, and poor probe positioning. The ambient light effect has also been identified, but the clinical relevance seems not to be significant [41] and in field trials in the cold environments, this effect is usually suppressed by the hand placement into a glove.

Perfusion index (*PI*) derived from pulse oximetry is a parameter for the assessment of perfusion changes in peripheral tissues. *PI* is calculated as the ratio of the pulsatile to the non-pulsatile signal amplitude of the infrared signal of the plethysmography waveform [42]. The *PI* can reach values 0.02–20; the higher the *PI*, the better the perfusion. The parameter *PI* is calculated as a ratio of 3–5 s pulse amplitude to the non-pulsatile 30 s average [43], so this averaging could mask the very rapid changes in perfusion.

Overall, the perfusion index is mainly used as a trend parameter. The values differ among individual subjects, the site of probe placement and the clinical situation [44]. Lima *et al.* [45] observed *PI* 1.4 [0.7–3.0] (expressed as median [*IQR*]) in healthy volunteers. Chu *et al*. [46] assessed the perfusion index before and after administration of analgesics. Before the administration, the *PI* was 1.3 ± 1.2; following the administration, the index raised to 1.7 ± 1.6. Another study [47] in urology patients observed baseline *PI* from 1.6 ± 1.1 to 2.0 ± 1.2, depending on the grade of the patient's hydronephrosis. Slightly higher values at rest were measured in patients in the post-operative unit, 2.2 (0.97–3.6), but this value dropped to 1.0 [0.5–1.9] (expressed as median [*IQR*]) after positioning [48]. However, in some studies, the perfusion index values at rest were much higher. In a Japanese study in a laboratory environment in men, the baseline value was 4.99 ± 0.45 (mean ± *SEM*), and after painful stimuli, 3.20 ± 0.37 [49]. Attempts to categorise the *PI* values have been made, for instance, by Thijssen *et al.* [50], who sorted out the *PI* values in critically ill patients into three bins: low *PI* ($PI < 1.0$), intermediate *PI* ($1.0 \leq PI \leq 2.5$), and high *PI* ($PI > 2.5$).

The changes of *PI* during hypoperfusion due to low ambient temperature in combination with motion artefacts, were assessed in a study [51] in a laboratory tempered to 16 °C–18 °C. The resulting median perfusion index was 0.95 (0.63 at the first quartile) in the control hand and 1.16 (0.873 at the first quartile) in the motion hand during non-motion conditions. Under these conditions, the SpO_2 failure rate (proportion of time when the device failed to display SpO_2 value to total test time) was 0% for Masimo Radical, 1.3% Datex-Ohmeda TruSat, and 9.3% for Nellcor N-600.

Attempts to assess the finger perfusion in order to estimate the reliability of the pulse oximetry have already been made, but only in a few studies. In critically ill patients, the higher *PI* was not associated with an improved correlation between SpO_2 and SaO_2 [50]. However, in a study [52] on rabbits with induced sepsis, a bias between SpO_2 and SaO_2 exceeding the declared 3% limit when the perfusion index was below 0.5 was observed.

Walzel, in his study [53], measured *PI* under laboratory conditions during breathing of a hypoxic (12% O_2, 88% N_2) and hypoxic-hypercapnic (5% CO_2, 12% O_2, 83% N_2) gas mixture that imitated rebreathing. The highest PI was measured in the thumb, and the median baseline *PI* was 3.5. No correlation between changes in SpO_2 and *PI* was found.

A study by Louie and colleagues [54] compared the performance of four types of pulse oximeters during motion and used *PI* as one of the assessing parameters. They concluded that PI < 2 is associated with a decreased precision of SpO_2 readings. They also found significant differences in *PI* between male and female volunteers. Female subjects tended to have baseline much lower, usually *PI* below 2.0.

2. Aims of the thesis

The aim of this thesis is to analyse the medical and technical issues in outdoor breathing experiments, especially in simulated avalanche snow, which can potentially affect the results of the studies and pose safety hazards to study subjects.

As documented in the State of the art, there are some errors in displaying data by monitoring medical equipment. The aim is to assess the performance of one of the main monitoring means in field breathing experiments—pulse oximetry. Pulse oximetry is used in these experiments frequently as a study endpoint with a great degree of variability among studies and also as a safety limit for monitoring the subjects.

The perfusion index has been used to assess pulse oximetry performance under a low perfusion state.
Another aim is to assess the dynamic changes in the perfusion index during outdoor breathing experiments with concurrent worsening hypercapnia and hypoxemia due to rebreathing.

The final aim is to assess the possible implications of these findings for clinical practice, including emergency medicine, resuscitation recommendations, and intensive care.

3. Outdoor breathing experiment in simulated avalanche snow: methods

3.1 Study design and equipment

Following approval by the Institutional Review Board of the Faculty of Biomedical Engineering, Czech Technical University (No. A001/018, issued on 22 January 2018) and registration under ClinicalTrials.gov (NCT03413878, last updated: 25 February 2021), the prospective randomised double-blind crossover breathing experiment was conducted between 29 January and 1 February 2018 in Spindleruv Mlyn, Krkonose Mountains, Czech Republic (altitude 762 meters above sea level). Written informed consent was obtained from all volunteers before entering the study.

All recruited volunteers underwent an entrance examination performed by an experienced physician, including assessment of the past medical history, smoking history, physical examination, and spirometry. The exclusion criteria were a Tiffeneau index (*FEV1*/*FVC* ratio) less than 0.70, any acute respiratory infection, and a history of a moderate or severe cardiovascular or respiratory disease. The subjects were continuously monitored throughout the whole experiment. Datex-Ohmeda S/5 (Datex-Ohmeda, Madison, WI, USA) anesthesia monitor [21] served as a primary monitor of physiological and ventilatory parameters, including peripheral saturation of blood with oxygen (SpO_2). Another vital sign monitor, CareScape B650 (GE Healthcare, Helsinki, Finland) [22], provided additional monitoring of SpO_2. Besides those two anesthetic monitors, there were three other monitoring devices in use: Edan M3B (Edan Instruments, Nanshan, Shenzhen, China) [23], Masimo Radical-7 Pulse CO-Oximeter (Masimo, Irvine, CA, USA) [24] and a hand-held pulse oximeter Nonin PalmSAT 2500 (Nonin Medical Inc., Plymouth, MN, USA) [25]. All devices are certified for medical use, had valid periodic safety and technical checks (including validation on a pulse oximeter tester), and are a property of the Faculty of Biomedical Engineering, Czech Technical University in Prague.

Each subject had SpO_2 levels monitored simultaneously by five different finger oxygen saturation probes, placed on right-hand fingers in a standardized manner, presented in Table 2. The position of the finger probe was not randomized. To eliminate possible erroneous readings due to low perfusion or motion artifacts, the volunteer's hand with all probes was placed into a preheated insulated glove and the participants were instructed to minimize hand and finger movements during the experiments. The data from all pulse oximeters and monitors were logged and the screens of the monitors were simultaneously filmed to document the SpO2 values displayed by all oximeters at the same moment. The response times of the individual oximeters were set to minimal possible averaging (in Table 2); this parameter is used in clinical practice to minimize false alarms, but during rapid changes in SpO_2, minimal setting prevents erroneous readings.

Each volunteer underwent three breathing experiments in a random order: 'S'—breathing into the snow, 'PD'—breathing into the dry perlite, and 'PW'—breathing into the wet perlite. Perlite served as a snow model. During each experiment, the study subject was in a prone position, lying on an insulated mat, connected to all sensors of above-mentioned vital sign monitors. At the initiation of the stabilisation phase,

the subject was connected to the mouthpiece with a nose clip, breathing the ambient air; ventilation parameters with the gas analysis results were recorded. After five minutes, the customized tubing was attached to a cone-shaped container [26] filled with the tested material (snow or perlite) and the main part—the breathing phase—was initiated. Throughout the whole experiment, a clinical assessment of consciousness level of the volunteer was performed by a supervising physician: the physician asked the subject to calculate simple mathematical operations and show the result using their fingers which were not attached to the pulse oximeter probes. The breathing into the test material was terminated by a subject's request, by the supervising physician's command, when the study safety limit was reached—$EtCO_2$ 62.5 mmHg (8,3 kPa)—or when a gas leak from the tubing was detected using a tracing gas (nitrous oxide). The participant was then disconnected from the test material and allowed to breathe ambient air through the mouthpiece with the respiratory sensor still attached (recovery phase). When all parameters stabilized and returned close to the baseline values, the subject was detached from the mouthpiece and the experiment was ceased.

The complete detailed material and methodology description is in chapter 4.1 of the doctoral thesis.

Table 2 A list of used pulse oximetry devices, their standardized placement on subjects' right-hand fingers, the manufacturer guaranteed accuracy in the defined measurement intervals of peripheral saturation and the minimal response time set [24-28].

Pulse oximeter	Finger	Interval of SpO_2 measurement	Accuracy in adults (no motion)	Response Time (minimal)
Datex-Ohmeda S/5	V.	40–100 %	80–100 % ± 2 % 50–80 % ± 3 %	beat-to-beat
Masimo Radical-7	IV.	0–100 %	70–100 % ± 2%	2 to 4 s
CareScape B650	III.	40–100 %	80–100 % ± 2 % 50–80 % ± 3 %	3 s
Edan M3B	II.	0–100 %	70–100 % ± 2 % 0–69 % undefined	not adjustable
Nonin PalmSAT 2500	I.	0–100 %	70–100 % ± 2%	not adjustable

3.2 Data processing and statistics

This thesis analyses the performance of five pulse oximeters and the behaviour of the perfusion index derived from pulse oximetry during the experiment of breathing into materials simulating avalanche snow.

The data from pulse oximetry measurements were obtained from simultaneous video recordings of the screens of all the pulse oximeters in 10-s intervals. Data were processed in MATLAB R2019a (MathWorks, Natick, MA, USA) and R (R Project for Statistical Computing, Lucent Technologies, Murray Hill, NJ, USA). Data from all breathing experiments (S, PD, PW) were analysed together because the differences among the tested materials were not the subject of this analysis.

For the analysis, firstly, graphs for all five pulse oximeters measurements in all breathing experiments of all subjects were constructed. Secondly, the graphs were complemented with the interval of accuracy [96,126] stated by the individual manufacturers (as summarised in Table 1). Then, the agreement among the pulse oximeters, including their declared accuracy intervals, was assessed using an algorithm programmed in MATLAB software.

The algorithm divided each graph into congruent and incongruent parts. The SpO_2 signals were evaluated as congruent only when the signals of all five pulse oximeters were present, and the SpO_2 values displayed by all five pulse oximeters lay within the accuracy intervals of all pulse oximeters. If the measured SpO_2 value was out of the interval for which the manufacturer stated the accuracy, the algorithm used the accuracy stated for the previous interval of peripheral oxygen saturation values. For example, if the accuracy ±2% was declared for the interval of SpO_2 70% to 100%, but there was no declared accuracy for values below 70%, the same accuracy was used for these lower values as no other figure was available.

Finally, all five pulse oximeters were assessed together. Every 60 s, starting at the point when the subject was connected to the breathing circuit (time 0 s), the average value from all SpO_2 measurements from all five pulse oximeters in all subjects was calculated and formed the baseline value. Afterwards, the average for each pulse oximeter for all subjects in all experiments was calculated every 60 s and depicted in the graph with error bars representing standard deviation.

For the analysis of the behaviour of perfusion index during the experiment, the synchronised data of end-tidal carbon dioxide and peripheral oxygen saturation with perfusion index values were used.

For the analysis of *PI*, each phase (stabilisation, breathing and recovery phase) was divided into one-minute intervals in order to analyse also the changes in PI within the phases. The stabilisation and breathing phases were divided into four one-minute segments (A1–A4, B1–B4, respectively), and the final recovery phase was divided only into three phases (C1–C3), as in most of the subjects, the physiological parameters returned to the pre-test baseline values within 2.5 to 3 min and hence the subjects were disconnected from the breathing apparatus. In the breathing phase, only the first 240 s were included in the analysis as most subjects completed this period.

The changes of *PI* with time were assessed. The statistical significance of the difference was tested by the ANOVA for repeated measures with Fisher's post-hoc test; the normality was tested using the Shapiro-Wilk test. $P < 0.05$ was considered as statistically significant.

Data are presented as mean ± standard deviation (*SD*) and medians with the 25th and 75th percentiles unless otherwise indicated.

4. Results

The results section presents data from pulse oximetry and perfusion index analysis. A complete evaluation of the clinical trial has been published in [55] and is not a subject of this thesis. The results were published in [56-58].

4.1 Performance of pulse oximeters during field breathing experiments

All 13 recruited subjects completed all breathing experiments (S, PD, PW) and were included in the data analysis; in total, 39 breathing experiments were analysed. The predominant reason for termination of the breathing experiment was the subject's request (n = 24). Identically, in five cases, the breathing experiment was terminated due to accidental disconnection of the breathing circuit due to a detection of the 'tracing gas'—nitrous oxide in the breathing gas—and in the same number of cases, the experiment was ceased upon the physician's decision. No harm occurred to any of the subjects of the experiment. The length of the breathing experiment differed among subjects and materials; the total length of recorded data in one breathing experiment was 419.5 ± 92.4 (230–620) s.

The individual oxygen saturation readings displayed by the five different pulse oximeter devices used in this experiment were found to be variable. They varied at the time of onset of desaturation, in the lowest SpO_2 value, and in the duration of the recovery phase, i.e., the period after the subject was disconnected from the test material, breathing ambient air and the oxygen saturation values were returning to baseline.

An example of changes in SpO_2 over time in one subject during breathing into simulated avalanche snow is presented in Figure 1. The time difference between the moment when the first (Nonin PalmSAT 2500) and the last pulse oximeter (CareScape B650) showed the SpO_2 value of 85% was 90 s. A similar situation occurred at SpO_2 75%, where the difference was 50 s. The lowest recorded values varied from 69% (CareScape B650) to 43% (Edan M3B), and the screen of Edan M3B displayed the lowest value constantly for 70 s.

In the whole dataset of all breathing experiments, the time difference between the moment when the first and the last pulse oximeter showed the theoretical study endpoint value of SpO_2 85% or 75% was 32.1 ± 23.6 s and 24.7 ± 19.3 s, respectively. Moreover, the pulse oximeter embedded in the Edan M3B vital sign monitor had a tendency to show the lowest detected SpO_2 value for a prolonged period of time, despite the fact that four other devices were already displaying normal SpO_2 values (as shown in Figure 5.6). This behaviour was observed in 16 out of 39 breathing experiments (in 41% of cases).

When the declared accuracy of the individual pulse oximeter devices was considered (values for each device are in Table 2), in none of the experimental phases did the pulse oximeters show identical values throughout the entirety of the recorded time. Eleven experiments (28.2%) showed no time period when signals from all five pulse oximeters were congruent. Only in one case did the devices agree in 86.7% of the recorded time.

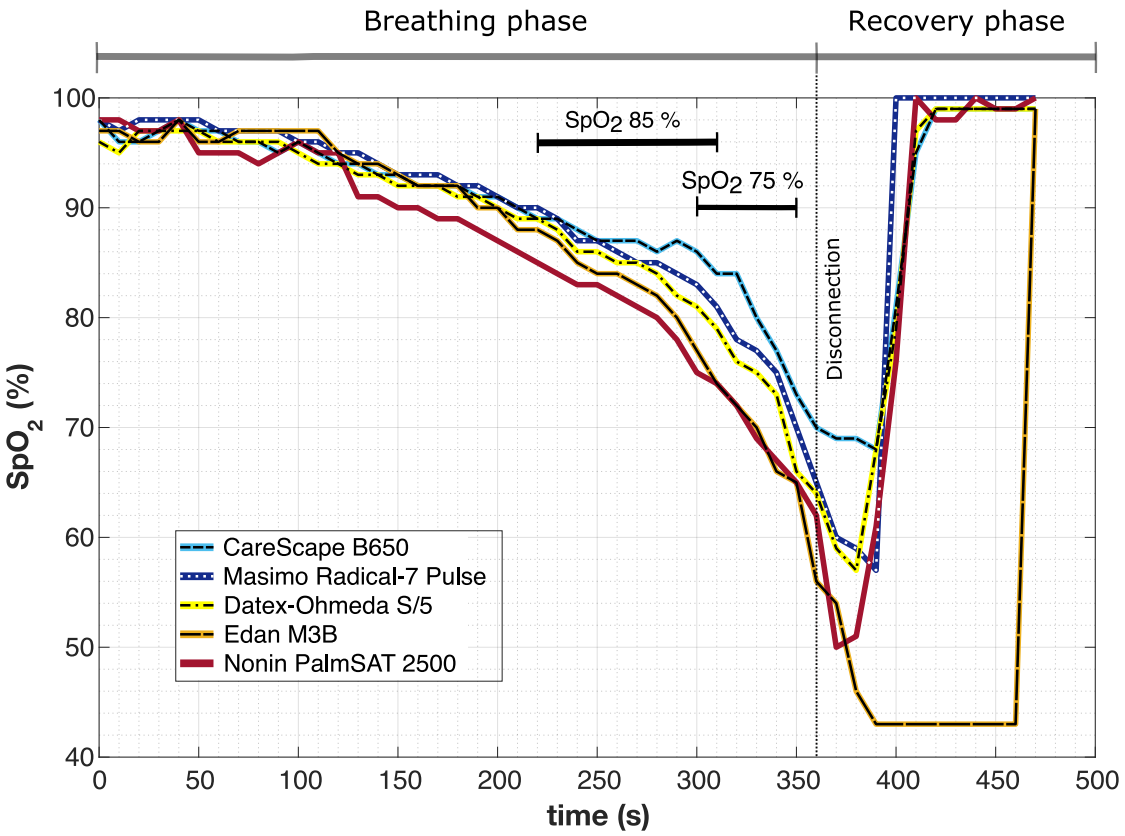

Figure 1: An example of SpO_2 waveforms simultaneously presented by five different pulse oximeters. The time difference between the point when the first and the last pulse oximeter showed the typical study endpoints SpO_2 85% and 75% is depicted as the black horizontal line. The pulse oximeter Edan M3B showed a stereotypical value of 43% for 70 s after the end of the breathing phase even though other devices presented values within the physiological range already.

However, on average, the congruent periods formed 30.5 ± 26.4 (5.5–86.7) per cent of the recorded time. The total duration of the congruent signals was 115.6 ± 94.0 (30–290) s, with the length of individual segments lasting from 10 s to 260 s. The signal often had two or three separated congruent segments (both n = 8); seven signals had only one of these segments. The maximum number of observed congruent segments was four in four cases. The duration of incongruent segments was 303.9 ± 152.8 (40–620) s.

Three examples of evaluation of the congruent segments using an automated algorithm are shown in Figure 2. In Figure 2a, the signals are incongruent most of the time; however, there are three short congruent segments (depicted as bright green lines)—two segments at the beginning of the breathing phase and one at the end of the resaturation. The graph in Figure 2b shows the longest uninterrupted congruent segment lasting 260 s with an additional 30 s segment at the end of the recovery phase, which forms nearly three-quarters of the total recorded time (74.4%). The graph in Figure 2c shows another breathing experiment, where the signals seem congruent; however, following the analysis, only two congruent segments, lasting only 50% of the time, were identified. Moreover, these congruent segments were present outside periods of rapid changes in SpO_2.

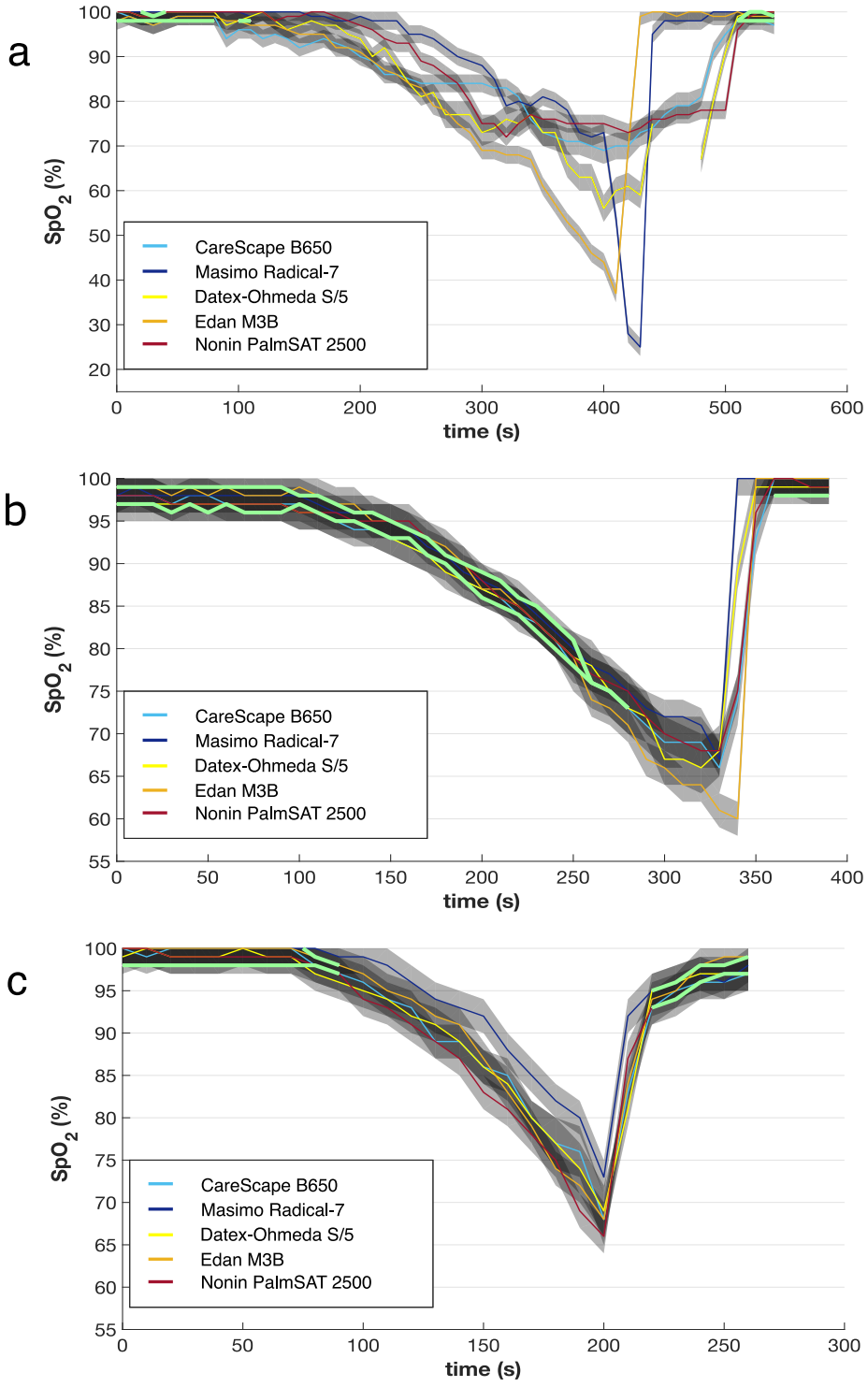

Figure 2: Examples of three individual breathing experiments underwent by three different subjects. The SpO_2 values measured by five different pulse oximeters are presented by colour lines. A grey stripe around each line represents the accuracy range of the respective oximeter guaranteed by the manufacturer. Green thick lines represent periods when all five grey stripes overlap, that means all five pulse oximeters showed a value consistent with the others when respecting the accuracies guaranteed by the manufacturer. (**a**) Very short congruent periods; (**b**) long congruent periods lasting 74.4% of experimental time; (**c**) ostensibly long congruent periods were proved to be congruent only in 50% of time; moreover, the congruent segments were present outside the period of rapid changes of SpO_2.

When all breathing phases were analysed together, the difference between the average value displayed by the particular device in all breathing phases and the average value across all the devices is shown. This graph shows that with the time course of desaturation, the variance among the devices increased.

4.2 Perfusion index derived from pulse oximetry during the breathing experiments

Although all thirteen volunteers completed the three breathing experiments from the protocol (39 breathing experiments in total), due to technical issues with data recording, only 33 complete sets of perfusion index data were eligible for analysis; the other 6 data sets were excluded due to long periods of corrupted or missing data. A minimal duration of the breathing phase was set at 240 s, and for insufficiently short experimental breathing, all three breathing experiments of one subject and two of another subject were excluded. In total, 29 breathing experiments of 12 subjects were included in the final analysis of *PI*.

The baseline perfusion index value of all 33 experimental breathings during the stabilisation phase of the experimental protocol was, on average, 1.54 ± 1.01 (mean ± *SD*). The perfusion indices of the 29 experimental breathings included in the final analysis during all three experimental phases are presented in Table 3.

Table 3: The perfusion index of all subjects during the experimental breathings included in the analysis.

Perfusion index	**Experimental phase**		
	Stabilisation phase	***Breathing phase***	***Recovery phase***
Mean ± SD	1.58 ± 1.34	1.25 ± 0.71	3.92 ± 3.36
Median (IQR)	1.20 (0.85–1.80)	1.1 (0.78 – 1.50)	3.00 (1.50 – 6.20)

Figure 3 shows an example of experimental breathing with its phases and corresponding changes in perfusion index, peripheral saturation of blood with oxygen, and end-tidal concentration of carbon dioxide. The slow onset of hypoxemia and hypercapnia due to re-breathing of the exhaled gas is apparent. When the breathing phase is ceased, the rapid increase of SpO_2 back to the pre-test values is accompanied by a slower restoration of the concentration of carbon dioxide in the organism.

Figure 4 presents box plots of the individuals' *PI* values to document the variability of perfusion indices among the tested subjects. Even in the stabilisation phase, the subjects reached different baseline perfusion index values. The recovery phase is characterised by a surge in *PI* values and an increase in *PI* value variability.

The changes in *PI* values assessed over one-minute intervals for all subjects are presented in Figure 5. A statistically significant difference exists between the recovery phase and all segments of the stabilisation and breathing phases. Within the stabilisation and breathing phases, the segments are not significantly different, so there is no detectable change in the perfusion index prior to disconnection of the subject from the tested material when hypoxemia and hypercapnia develop. However, in the second minute of the recovery phase, the subjects reached higher *PI* values compared to the other two segments of this phase.

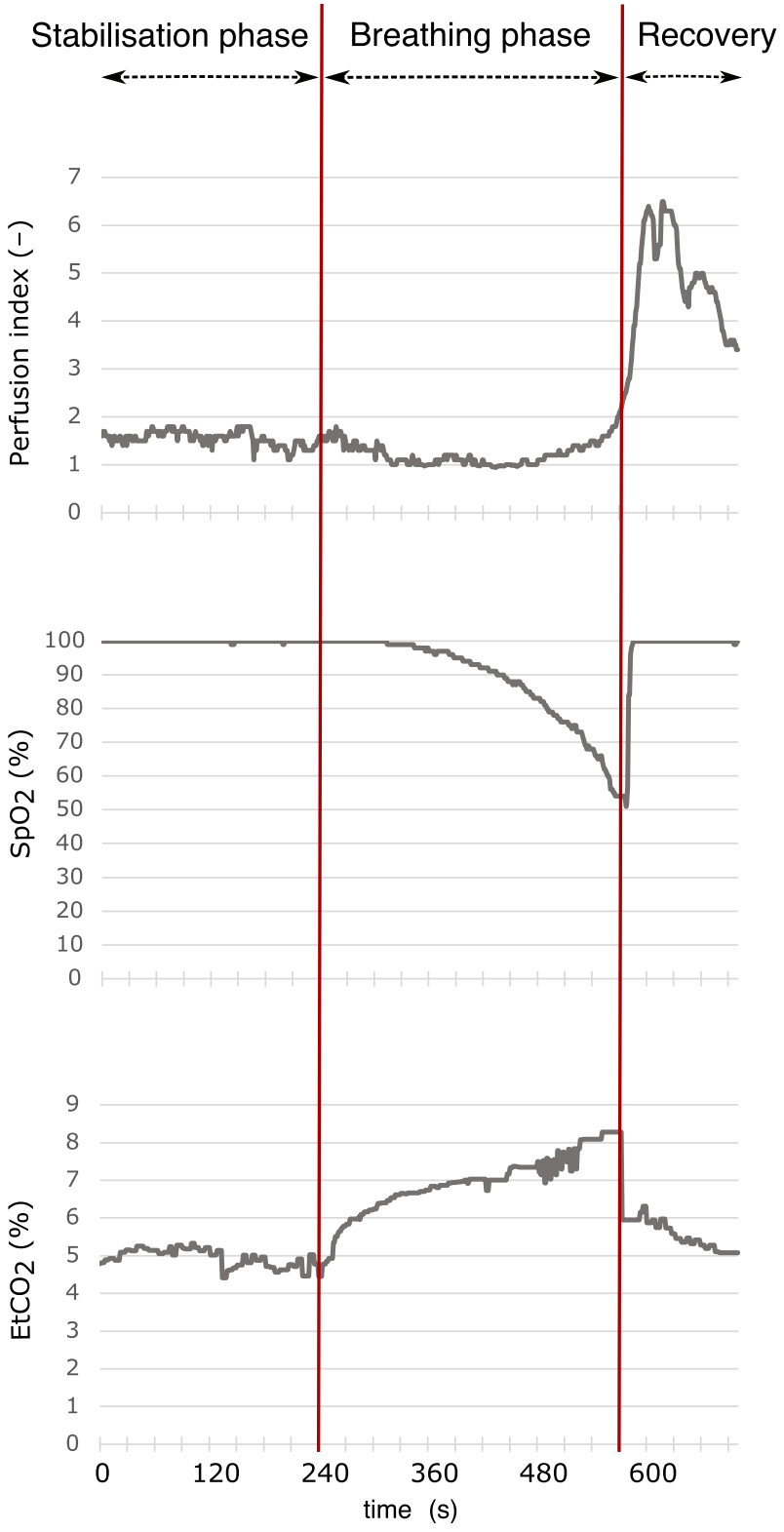

Figure 3: An example of recorded physiological parameters during experimental breathing of one of the subjects. The graphs show simultaneous measurements of perfusion index (*PI*), peripheral saturation of blood with oxygen (SpO_2) and end-tidal carbon dioxide concentrations ($EtCO_2$). The experimental phases are labeled: stabilisation, breathing and recovery phase.

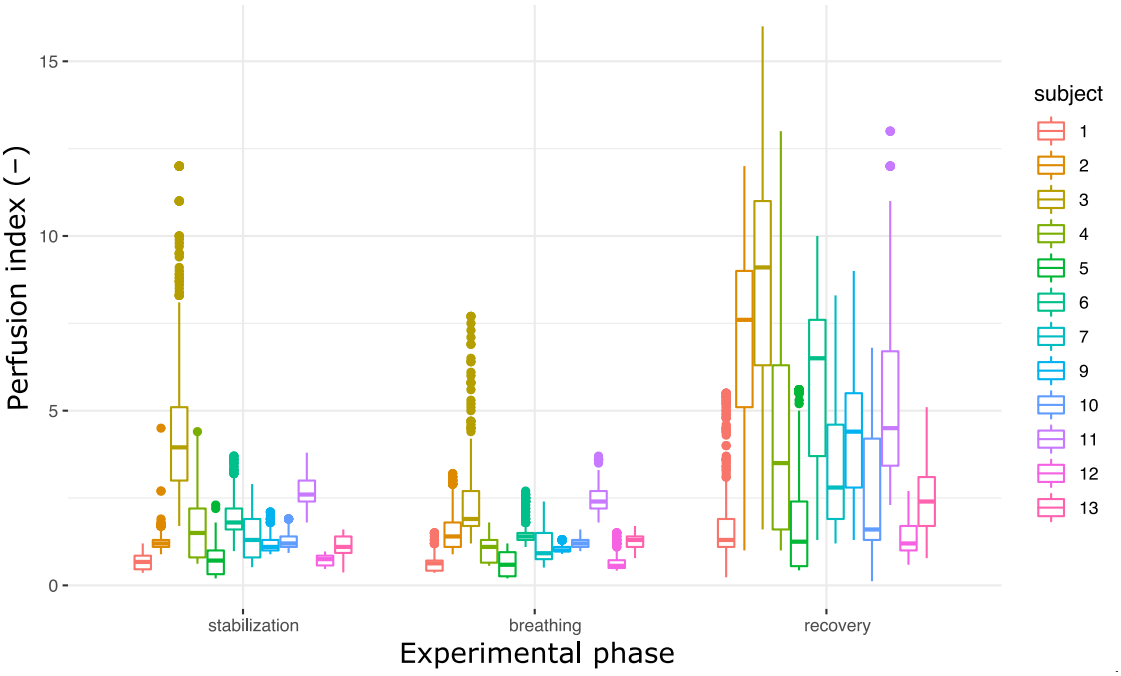

Figure 4: The *PI* values of individual subjects 1–13 (subject number 8 excluded) in the experimental phases. The box plots are made from the one-second raw data, the dots represent outlying values.

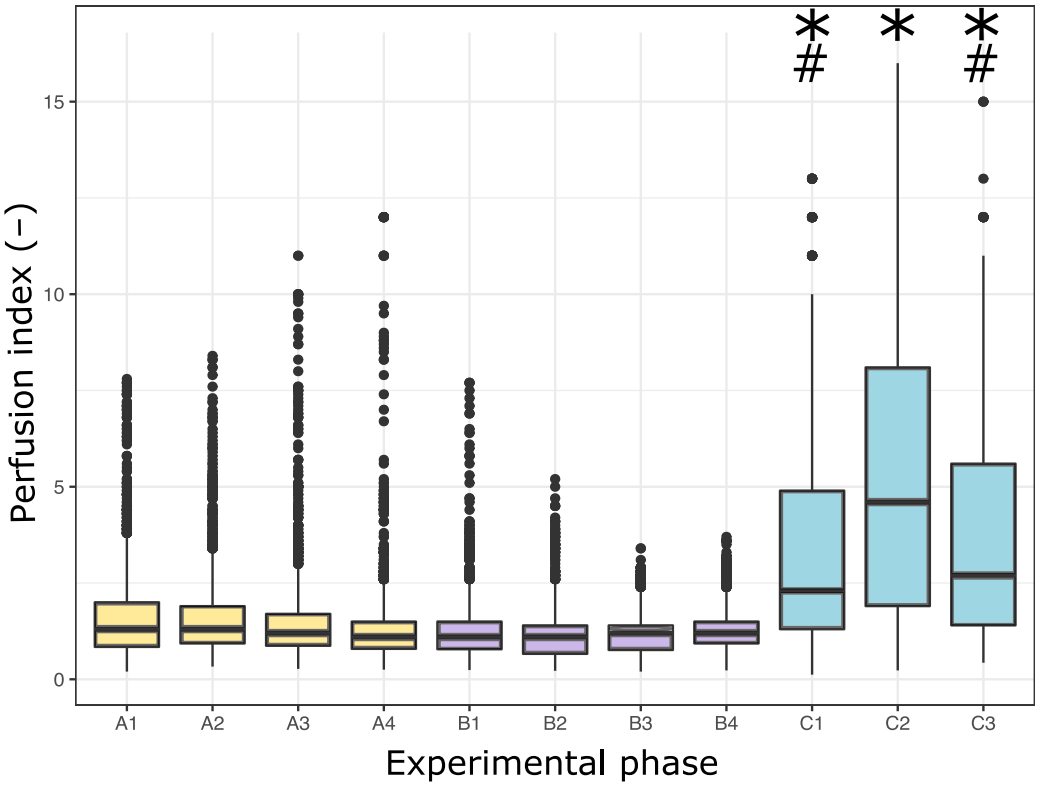

Figure 5 The changes in *PI* values in the experimental phases. The phases are divided in one-minute segments: four segments of stabilisation phase (A1–A4), four segments of breathing phase (B1–B4) and three segments of recovery phase (C1–C3). In the breathing phase, only the first 4 minutes are included in the analysis. The symbol * represents statistically significant difference of the segment from all segments of the stabilisation and breathing phases, the symbol # represents statistically significant difference from the segment C2.

Finally, in Figure 6, the relationship between the mean perfusion index and the proportion of the congruent segments of SpO_2 values from the total length of recorded data during the stabilisation and breathing phase is presented. The linear regression model was insignificant in both phases, with p = 0.62 for the stabilisation phase and p = 0.35 for the breathing phase.

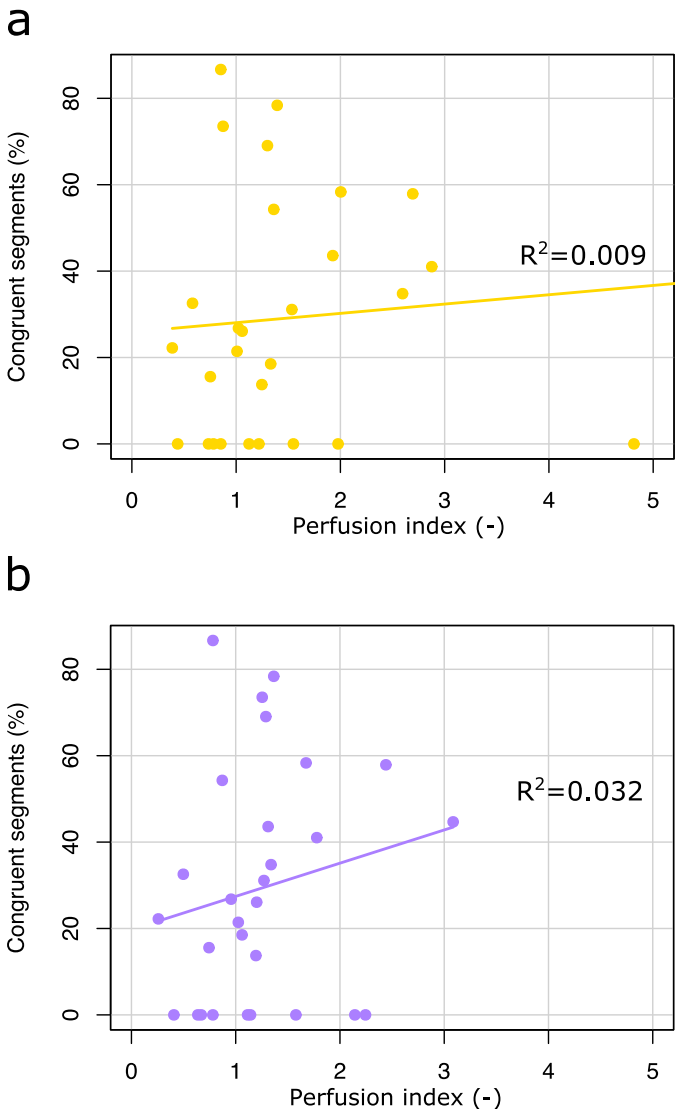

Figure 6: The relationship between the mean perfusion index and the proportion of congruent segments of SpO_2 values from the total length of recorded data during stabilisation (a) and breathing (b) phase of the experiment in all analysed subjects. R^2 – coefficient of determination of the linear regression model.

5. Discussion

5.1 Medical and technical aspects of the field breathing experiments

The findings presented in this thesis offer novel insights crucial for the design and conduction of field breathing experiments, particularly experiments in simulated avalanche snow. These findings primarily address the interaction between subjects and medical equipment, as well as the performance of medical equipment during experiments involving physiological parameter changes due to factors such as rebreathing of exhaled gas, progressive hypoxia, hypercapnia, increased work of breathing, and nonstandard environmental conditions. Understanding these medical and technical aspects is paramount not only for effective study designs and accuratel data analysis but also for ensuring the safety of the subjects involved.

Field breathing experiments' technical and medical aspects are directly related to the vital sign monitors and their functionality in specific environmental conditions, as discussed in [23]. While errors in $EtCO_2$ display during simulated avalanche breathing experiments have been reported [16], the performance of pulse oximetry—the commonly monitored parameter and endpoint in such studies—remains unexplored, to the best of my knowledge. Additionally, despite its potential clinical significance, the behaviour of the perfusion index under these specific conditions has not been thoroughly investigated.

Within my thesis, I have focused on examining these two aspects: the performance of pulse oximeters and the behaviour of the perfusion index. The subsequent discussion will explore these topics further.

5.2 Performance of pulse oximeters during field breathing experiments

The main finding is that oxygen saturation readings displayed by the five pulse oximeter devices during short periods of rapid onset hypoxemia and hypercapnia were significantly different. They varied in the time of desaturation onset, in the lowest measured SpO_2 value, and in the duration of the recovery phase, when the subject was already breathing ambient air and the SpO_2 was returning to pre-experimental values.

The results suggest that if SpO_2 is chosen as a study endpoint for a field breathing trial, the selection of a particular device can prolong or shorten the trial by tens of seconds (Figure 1). If we consider that most of the volunteers in this study managed to complete 240 s to 300 s of breathing into the material simulating avalanche snow, the change in the testing period by, e.g., 50 s is a significant intrusion into the course of the clinical trial.

Not only the rate of the SpO_2 changes but also the minimal values reached following the disconnection from the test material can pose a significant drawback. Even when the declared accuracyof the devices was considered (summarised in Table 2), the values from the pulse oximeters were often not comparable (examples in Figure 2). In fact, in 28.2% of the breathing experiments (n = 11), there was no congruent

signal identified, and in the rest of the experiments, the congruent intervals covered, on average, only less than a third of the total recorded time (30.5 ± 26.4%). The intervals of congruent signals were observed mainly at the beginning of the breathing phase and at the end, during the recovery phase. However, in the course of the desaturation, which is the potentially risky experimental phase, the congruity among the devices was infrequent.

The resaturation phase also exhibited considerable differences among the pulse oximeters. Moreover, one device (Edan M3B) had a tendency to show the lowest measured value for a prolonged period of time, whereas the SpO_2 level was within the normal range according to the other devices (as in Figure 1). This behaviour can be potentially dangerous because the displayed low value could spur the physician to undertake unnecessary measures.

As a part of the settings of each device, it is possible to select data averaging and display refreshment time, usually referred to as 'response'. This equates to the speed at which the displayed value appears following the measurement of the parameter. For SpO_2, the monitor can display the values beat-to-beat or present an average of results from the set time period, e.g., 20 s. The latter is a default setting for Datex-Ohmeda S/5 monitors because, in anaesthesia, it helps to eliminate distracting artefacts and false alarms. However, in breathing experiments, we may observe changes in volunteers' physiological parameters within a couple of seconds, and this averaging can give us incorrect information about the subject's state and inaccurate experimental data. In addition, this can present safety risks to the volunteers [23]. In this current study, the 'response' was set to the minimal option available, so it was different for each device (listed in Table 2). The difference in the device response times may have affected the simultaneously displayed SpO_2 values [59].

Although pulse oximetry is a widely used means of monitoring with upgraded algorithms [60], it has well-known limitations [39], and its use outside the hospital environment is challenging [40]. The peripheral low perfusion state, typically associated with cold conditions, can alter the pulse oximetry readings. However, during all breathing experiments, a maximum effort was made to prevent this effect: the subjects had their hand placed in a warmed glove, and the perfusion of the fingers was monitored by perfusion index—*PI* [26]. No significant decrease in the perfusion index was observed throughout the breathing experiments (Fig. 5), and no significant relationship between the low *PI* and an increased proportion of incongruent segments was identified (Fig. 6). We can speculate that the low perfusion state was not a crucial limiting factor for the performance of the pulse oximeters and, hence, an important source of the incongruity in the displayed SpO_2.

Moreover, the popular breathing experiment study endpoints of SpO_2 75% to 88% lie in the interval where the mean error in SaO_2 measured by pulse oximeters is more pronounced [61,62]. Several studies observed the tendency of SpO_2 to underestimate [63,64] or overestimate [65-67] the SaO_2 value. However, to date, no study has examined the bias in adult subjects during field breathing experiments with progressive hypoxia and hypercapnia due to rebreathing, so the tendency of the pulse oximeters in this scenario is unknown.

Also, in general, differences in performance among pulse oximeters under hypoxic conditions have already been demonstrated [53,54,64,68,69], but to my best knowledge, not in field experiments with concomitant

progressive hypoxemia, hypercapnia and increased work of breathing. A complex assessment of different brands of pulse oximeters from different manufacturers during desaturation is not possible as each study uses different devices, and the pace of introduction of new types exceeds the rate of new studies. We can only say that in some studies, the Masimo devices with the SET technology were found to be superior to some other devices under motion and low perfusion conditions [51,68,70].

The limitations of this study include mainly the lack of randomisation of finger probe placement or, alternatively, simultaneous placement of the same saturation probes in different locations. The pulse oximetry probes were placed on fingers in a standardised manner (Table 2). The possible differences among fingers could have affected the displayed values, although the variability between fingers is small [37,53,71-73]. On the other hand, due to the nature of these experiments, a more complex study protocol with randomisation and cross-over design would be very complicated. In the current study, compared to laboratory experiments, the test site preparation was elaborate, and the subjects needed a significant amount of time to recover from each breathing experiment. This is another particularity of the field breathing experiments—some conventional study designs are very challenging to be employed.

An important limitation of this study is also the lack of a gold standard reference for pulse oximeters, like SaO_2 repetitively measured in arterial blood samples during a steady state of hypoxemia [59]. The nature of this experiment does not favour this type of assessment, although arterial blood sampling [32] and mixed capillary blood [31] gas analyses have already been employed in these experiments. Still, the fast changes in subject oxygenation make this test hard to be evaluated.

Additionally, a restricted number of tested devices and the use of only peripherally placed pulse oximetry probes, known to have delayed detection of desaturation compared to centrally placed probes (earlobe, forehead), limited the study. The difference in the response time between the ear probe and the finger probe can be up to 20 s [64]. However, we studied finger probes as they are the most popular, mainly due to their simple use. Based on the experience from the ICU, it can be speculated that earlobe probes might not stay in place during the subjects' head movements, and they may produce even less reliable data. That should be a subject of further research.

Another limitation was the different response time of each device, although it was set to the minimal available value. Finally, the number of study subjects was only thirteen, which could be considered a small trial. However, some studies of pulse oximetry accuracy under hypoxic conditions had ten or fewer subjects [64,69,74]. Furthermore, only male subjects were included, even though there is a known difference in SpO_2 values between men and women [75].

Further studies are needed to compare devices currently used in clinical practice in hospitals and during field experiments. With the fast development of these monitoring means, testing of the devices in in-hospital and out-of-hospital settings can change the perceived reliability in non-standard situations. Additionally, this study documents that monitoring during short-term changes of peripheral saturation with oxygen has several

limitations and clinical assessment by a skilful physician is irreplaceable. Moreover, relying on a single parameter as a study endpoint or a safety limit could not be recommended.

5.3 Perfusion index during field breathing experiments

The main finding is that during hypoxemia and hypercapnia associated with field experiments simulating breathing under avalanche snow, the perfusion index derived from pulse oximetry does not vary significantly from the baseline values. When the breathing experiment is ceased, and the hypoxemia quickly resolves, the *PI* value shoots up. These findings suggest that the subjects of these experiments do not suffer from inadequate perfusion of acral regions. Thus, the values of SpO_2 displayed by the pulse oximeter during the progressive hypoxemia and hypercapnia should not be significantly affected by the low perfusion state. To my knowledge, this is the first analysis of the perfusion index during field experiments in a situation of combined hypoxemia, hypercapnia and increased work of breathing.

Our results suggest (Figures 1 and 2) that discrepancies among SpO_2 values displayed by different pulse oximeters may be an issue during field breathing experiments. The question is whether these incongruent results could have been caused by poor perfusion of the subjects' fingers, a well-known limitation of this method [37,39]. In the field experiments, the low perfusion state due to low ambient temperature can be an issue; however, during the current study, all effort was made to guarantee maximal thermal comfort. The subjects were lying on an insulated mat, well dressed, with the test hand placed in a glove pre-heated by a warmer and before arriving at the outdoor test site, they were waiting in a close heated hut.

Figure 6 shows no systematic relationship between the proportion of incongruent SpO_2 segments from the total experimental time and the perfusion index. It can be seen that 0% congruent segments were observed in subjects with the whole range of *PI* values. The attempted general linear regression model for elucidation of the relationship between the perfusion index and the proportion of the SpO_2 congruent segments yielded statistically insignificant results, suggesting minimal explanatory power of the model. The analysis suggests that the incongruence of the SpO_2 values displayed by the five different pulse oximeters could not be explained only by the finger low perfusion monitored by the perfusion index.

To date, the threshold *PI* value indicating a low perfusion state has not been defined. In an attempt to evaluate finger perfusion using the *PI*, the cutoff value suggesting a low perfusion state for critically ill adult patients was proposed at a *PI* of 1.4 [45]. Hummler *et al.* [52] recommended verifying the SpO_2 value with arterial blood gas analysis in situations when *PI* drops below 0.5.

As discussed above, the accuracy of pulse oximetry is crucial, especially during the breathing phase, when rapid changes of SpO_2 occur, predominantly in case the peripheral saturation of blood serves as a study endpoint [20,21,29,36]. On the other hand, advancing hypoxemia and hypercapnia (as can be seen in Figure 3) may potentially affect the vascular tonus and, thus, the perfusion of the monitored site. The changes in vascular activity are complex, with several synergic and antagonistic processes.

In this study, the perfusion index in some subjects tended to decrease between the stabilisation and the breathing phases (as seen in Figure 4). However, these changes were not statistically significant. The drop in perfusion index could have been caused by prolonged exposure to the cold environment despite all efforts to protect the subjects. The effect of hypoxemia and hypercapnia on the perfusion index is uncertain. In studies, hypoxia increased blood flow into the forearm due to concomitant vasodilation [76,77]. Yet Abramson *et al.* [76] observed that this increased forearm blood flow is associated with vasoconstriction in the hand, which might be an oxygen-sparing mechanism. On the other hand, hypercapnia is a potent vasodilator and promotes increased blood flow through the brachial artery by 10–30% [78]. We can speculate that the vasodilatory and vasoconstrictive effects are in a delicate balance during the breathing phase, and the perfusion of the fingers is preserved. A completely different situation is in the recovery phase: the hypoxia resolves swiftly when the subjects stop re-breathing the exhaled gas, but the elimination of the accumulated carbon dioxide is prolonged and hence its effect on the vascular tone. The unmasked vasodilation due to hypercapnia is represented by the perfusion index of double or triple values compared to the baseline.

The presented results can have implications in clinical practice as well. Not only during the outdoor experiments but also in pre-hospital care and operation theatres, the cold environment can raise questions regarding the perfusion of the peripheral tissues and, hence, the accuracy of the pulse oximetry. The perfusion index can help us assess the perfusion of the fingers where the pulse oximeter probe is placed. Although we are unable to set a distinctive threshold *PI* value for low perfusion state (mainly due to the significant inter-individual variability, as seen in Fig. 4), the perfusion index can serve as a trend marker.

The results also demonstrate that the effect of hypercapnia can be observed on the perfusion index; however, the effect of hypoxemia is uncertain. Clinically, similar dynamic changes of the perfusion index might be observed, for example, in patients suffering from respiratory failure with hypoxemia and hypercapnia. However, the data from these patients are not available, and it is a matter of further research.

This study has several limitations. Firstly, the statistical comparison was difficult as the duration of each breathing phase differed significantly among the subjects. Secondly, all breathing experiments into different materials were analysed together. However, the assessment of the effect of the different snow model materials was not the aim of this study. Finally, the number of study subjects was small and only young fit male volunteers were recruited, although sex differences in *PI* have been reported and female baseline *PI* tends to be below 2.0 [82]. The lack of female participants in these studies, or an imbalance between men and women in the study group [53,54,69,79], can be a weak point in this research. Further research in more groups of subjects is needed.

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5.4 Specifics of medical equipment use in field breathing experiments

Monitoring devices originally designed for anaesthesia or ICU may provide inaccurate or misleading data during field breathing experiments even though they are used according to the operating conditions listed in the manual. A straight use in the outdoor environment, and unquestioning operation in such studies may pose the study participants into threat.

On the other hand, the summary of environmental parameters of the devices used in the recent studies on breathing into simulated avalanche snow (Table 1) revealed that the ambient temperature, humidity, and pressure limits of the ICU and anaesthesia monitors do not differ much from the parameters of the monitors used in emergency medicine. These “emergency monitors” are designed also for transport in a helicopter and for monitoring in outdoor environment [33-35]. Unfortunately, the ambient temperature value is not accessible in the raw data of any of the monitors used in this study; only ambient pressure is recorded, although both these parameters are used by the monitor for calculations, e.g., for ventilatory parameters. The medical device’s ambient temperature should be logged externally in future experiments.

Although the vital sign monitors are constantly improving, the users—in clinical environment, or during field experiments—should bear in mind their limitations. For instance, pulse oximeters have recently obtained an improved algorithm for resistance to motion artefacts and low perfusion states. Both these situations interfere with the original model of SpO_2 measurement and can mimic desaturation [68]. Our current study does not directly support the findings about the superiority of the Masimo Radical-7 with the SET technology (described in [26,60]). However, our aim was not to compare the devices in order to find the best one, and the study lacks a gold standard like SaO_2 measurements.

Not only the choice of the appropriate monitored physiological parameters but also the particular monitoring device can be crucial for the course of the experiment. This study demonstrated that the choice of a specific pulse oximeter can shorten the experiment by up to one-quarter of its length (Fig. 1). In the past, Roubík and Filip [16] showed the discrepancy between the trend data and displayed waveform in capnography during simulated avalanche breathing experiments. Also, Wik *et al.* [32] experienced a limitation in the monitoring device. They placed a gas monitor Dräger, X-AM 5600 (Dräger, Vienna, Austria) into the air pocket. However, this monitor is able to measure the maximal CO_2 concentration at only 5%; higher concentrations are indicated as "over the range". The use of this measuring instrument caused a loss of potentially valuable experimental data when the limiting CO_2 concentration had been exceeded.

Recently, the monitoring of cerebral oxygenation using near-infrared spectroscopy (NIRS) monitors has been introduced to the experimental protocols of field breathing experiments [29,31,32]. Also, this non-invasive optical method has significant limitations [80]. For field experiments, the most relevant limitations might be the unknown effect of extracranial tissues on NIRS signal—including the skin blood flow changes due to, for instance, cold environment—no clear reference values defined, ambient light and movement artefacts, and the lack of standardisation for signal processing, or data analysis [80,81].

5.5 Clinical application of the results

Although the presented study was conducted on subjects during outdoor breathing experiments in simulated avalanche snow, the results and conclusions may be applicable to clinical practice in anaesthesia, intensive care, and emergency medicine.

Fast changes in oxygenation can occur, for instance, during difficult airway management and intubation failure, not only in anaesthesia but also in critical care or emergency medicine settings. The behaviour of the pulse oximeters can directly affect patient management. Delayed display of desaturation or even resaturation can lead to improper treatment.

I myself have had a patient who desaturated during induction to anaesthesia due to a difficult airway situation. The monitor displayed the lowest measured SpO_2 value for a prolonged period of time even though, clinically, the ventilation and oxygenation had already been restored. After a couple of minutes, the displayed SpO_2 suddenly jumped to 100%. This case report is going to be published.

The changes in *PI* during hypoxia and hypercapnia are also potentially relevant to anaesthesia and other medical fields where this parameter is in use. As *PI* is used for pain assessment during anaesthesia, the simultaneous effect of hypercapnia, for instance, during pneumoperitoneum insufflation with carbon dioxide, can be potentially important. However, the parameter has not been examined under these circumstances, and further studies are needed. The combination of hypoxemia and hypercapnia can be seen in hypoventilating patients, for instance, following general anaesthesia or with other reasons for combined respiratory failure. Also, in these cases, the effects on *PI* should be investigated.

6. Conclusions

During field breathing experiments, the use of monitoring medical equipment has notable limitations. The devices are used in conditions substantially different from anaesthesia and intensive care unit settings. Safety limits of physiological parameters must be interpreted in these experiments considering the limiting conditions; otherwise, the data may be falsely interpreted, and the safety of the subjects may be endangered. Along with technical issues, medical precautions must be applied during the breathing experiments. The physiological parameters of the subjects get quickly out of the normal range, which increases the risk of complications.

In the study, the peripheral oxygen saturation (SpO_2) readings displayed by the five pulse oximeter devices during short periods of rapid onset hypoxemia and hypercapnia were significantly different. They varied in the time of desaturation onset, in the lowest measured SpO_2 value, and in the duration of the recovery phase, when the subject was already breathing ambient air and the oxygen saturation was returning to pre-experimental values. The results suggest that peripheral oxygen saturation might not be a reliable parameter as a study endpoint or, more importantly, as a safety limit in field experiments. The choice of a particular pulse oximeter device can significantly affect the duration of the breathing experiment.

The perfusion index (*PI*) derived from pulse oximetry does not decrease significantly during hypoxemia and hypercapnia, which are associated with field experiments simulating breathing under avalanche snow, compared to baseline *PI* values. When the experimental breathing is ceased and the hypoxemia resolves, the perfusion index tends to double or triple its values. This surge of *PI* in the recovery phase is likely due to the effect of carbon dioxide on the vascular tonus. The average baseline *PI* in this study is within the range or just slightly lower compared to values observed in other clinical situations. These findings suggest that the subjects of these experiments do not suffer from insufficient perfusion of acral regions, so a low perfusion state should not be a source of the inaccuracy of pulse oximetry.

The irreplaceable role of clinical assessment by a skilled physician should be considered. More parameters and continuous clinical assessment should be included in the design of future studies.

Author's publications on the topic

A. Journal articles

1. Horakova, L., & Roubik, K. (2022). Pulse Oximeter Performance during Rapid Desaturation. Sensors, 22(11), 4236.

2. Roubik, K., Sykora, K., Sieger, L., Ort, V., Horakova, L., & Walzel, S. (2022). Perlite is a suitable model material for experiments investigating breathing in high density snow. Scientific reports, 12(1), 1-12.

3. Roubik, K., Walzel, S., Horakova, L., Refalo, A., Sykora, K., Ort, V., & Sieger, L. (2020). Materials Suitable to simulate snow during breathing experiments for avalanche survival research. Lékař a technika-Clinician and Technology, 50(1), 32-39.

B. Conference proceedings

4. Horakova, L., Kudrna, P., & Roubik, K. (2021). Dynamic changes of perfusion index during hypoxemia and hypercapnia in outdoor experiments. In: 2021 International Conference on e-Health and Bioengineering (EHB). IEEE, 1-6.

   Awarded: **2nd prize Young Researcher Award** – conference EHB 2021

5. Horakova L., & Roubik, K. (2019). Performance of Different Pulse Oximeters Can Affect the Duration of Field Breathing Experiments. In 2019 E-Health and Bioengineering Conference (EHB) (pp. 1-4). IEEE.

   Awarded: **3rd prize Young Researcher Award** – conference EHB 2019

6. Horakova L., Sykora K., Sieger L., Roubik K. (2018) Monitoring of subjects during avalanche breathing experiments - possible errors. ISSW 2018 Proceedings.

7. Horakova L., Sykora K., Sieger L., Roubik K. (2018) Breathing Experiments into the Simulated Avalanche Snow: Medical and Technical Issues of the Outdoor Breathing Trials. In: Lhotska L., Sukupova L., Lacković I., Ibbott G. (eds) World Congress on Medical Physics and Biomedical Engineering 2018. IFMBE Proceedings, vol 68/1. Springer, Singapore.

References

1. Techel, F.; Jarry, F.; Kronthaler, G.; Mitterer, S.; Nairz, P.; Pavšek, M.; Valt, M.; Darms, G. Avalanche fatalities in the European Alps: long-term trends and statistics. *Geogr. Helv.* **2016**, *71*, 147-159, doi:10.5194/gh-71-147-2016.
2. Stalsberg, H.; Albretsen, C.; Gilbert, M.; Kearney, M.; Moestue, E.; Nordrum, I.; Rostrup, M.; Ørbo, A. Mechanism of death in avalanche victims. *Virchows Archiv A* **1989**, *414*, 415-422, doi:10.1007/BF00718625.
3. Falk, M.; Brugger, H.; Adler-Kastner, L. Avalanche survival chances. *Nature* **1994**, *368*, 21-21.
4. Brugger, H.; Falk, M.; Adler-Kastner, L. Der Lawinennotfall. Eine aktuelle Übersicht. *Wiener Klinische Wochenschrift* **2003**, *9*, 691-701.
5. Grossman, M.D.; Saffle, J.R.; Thomas, F.; Tremper, B. Avalanche Trauma. *Journal of Trauma and Acute Care Surgery* **1989**, *29*, 1705-1709.
6. Logan, N.; Atkins, D. *The Snowy Torrents: Avalanche Accidents in the United States, 1980-86*; Colorado Geological Survey, Department of Natural Resources, State of Colorado: 1996.
7. Hohlrieder, M.; Brugger, H.; Schubert, H.M.; Pavlic, M.; Ellerton, J.; Mair, P. Pattern and severity of injury in avalanche victims. *High altitude medicine & biology* **2007**, *8*, 56-61.
8. Brugger, H.; Durrer, B.; Adler-Kastner, L.; Falk, M.; Tschirky, F. Field management of avalanche victims. *Resuscitation* **2001**, *51*, 7-15, doi:https://doi.org/10.1016/S0300-9572(01)00383-5.
9. Brugger, H.; Durrer, B.; Elsensohn, F.; Paal, P.; Strapazzon, G.; Winterberger, E.; Zafren, K.; Boyd, J. 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*, 539-546.
10. Kottmann, A.; Blancher, M.; Pasquier, M.; Brugger, H. Avalanche Victim Resuscitation Checklist adaption to the 2015 ERC Resuscitation guidelines. *Resuscitation* **2017**, *113*, e3-e4, doi:10.1016/j.resuscitation.2017.01.008.
11. Lott, C.; Truhlář, A.; Alfonzo, A.; Barelli, A.; González-Salvado, V.; Hinkelbein, J.; Nolan, J.P.; Paal, P.; Perkins, G.D.; Thies, K.-C. European Resuscitation Council Guidelines 2021: cardiac arrest in special circumstances. *Resuscitation* **2021**, *161*, 152-219.
12. Pasquier, M.; Strapazzon, G.; Kottmann, A.; Paal, P.; Zafren, K.; Oshiro, K.; Artoni, C.; Van Tilburg, C.; Sheets, A.; Ellerton, J.; et al. On-site treatment of avalanche victims: Scoping review and 2023 recommendations of the international commission for mountain emergency medicine (ICAR MedCom). *Resuscitation* **2023**, *184*, 109708, doi:https://doi.org/10.1016/j.resuscitation.2023.109708.
13. Windsor, J.S.; Hamilton, E.; Grocott, M.P.; O'Dwyer, M.J.; Milledge, J.S. The Snow Snorkel: A Proof of Concept Study. *Wilderness & Environmental Medicine* **2009**, *20*, 61-65, doi:https://doi.org/10.1580/08-WEME-BR-183.1.
14. Haegeli, P.; Falk, M.; Procter, E.; Zweifel, B.; Jarry, F.; Logan, S.; Kronholm, K.; Biskupič, M.; Brugger, H. The effectiveness of avalanche airbags. *Resuscitation* **2014**, *85*, 1197-1203, doi:https://doi.org/10.1016/j.resuscitation.2014.05.025.
15. Ng, P.; Smith, W.R.; Wheeler, A.; McIntosh, S.E. Advanced Avalanche Safety Equipment of Backcountry Users: Current Trends and Perceptions. *Wilderness & Environmental Medicine* **2015**, *26*, 417-421, doi:https://doi.org/10.1016/j.wem.2015.03.029.
16. Roubík, K.; Filip, J. Reliability and source of errors in end-tidal gas concentration evaluation algorithms during avalanche snow and rebreathing experiments. *Lékař a technika-Clinician and Technology* **2017**, *47*, 73-80.
17. Radwin, M.I.; Keyes, L.; Radwin, D.L. Avalanche air space physiology. In Proceedings of the Proceedings International Snow Science Workshop, 1998; p. 296.
18. Grissom, C.K.; McAlpine, J.C.; Harmston, C.H.; Radwin, M.I.; Giesbrecht, G.G.; Scholand, M.B.; Morgan, J.S. Hypercapnia effect on core cooling and shivering threshold during snow burial. *Aviat Space Environ Med* **2008**, *79*, 735-742, doi:10.3357/asem.2261.2008.
19. Roubík, 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*, e0144332.
20. Grissom, C.K.; Radwin, M.I.; Harmston, C.H.; Hirshberg, E.L.; Crowley, T.J. Respiration during snow burial using an artificial air pocket. *Jama* **2000**, *283*, 2266-2271.

21. Brugger, H.; Sumann, G.; Meister, R.; Adler-Kastner, L.; Mair, P.; Gunga, H.; Schobersberger, W.; Falk, M. Hypoxia and hypercapnia during respiration into an artificial air pocket in snow: implications for avalanche survival. *Resuscitation* **2003**, *58*, 81-88.
22. Hansel, J.; Solleder, I.; Gfroerer, W.; Muth, C.M.; Paulat, K.; Simon, P.; Heitkamp, H.-C.; Niess, A.; Tetzlaff, K. Hypoxia and cardiac arrhythmias in breath-hold divers during voluntary immersed breath-holds. *European journal of applied physiology* **2009**, *105*, 673-678.
23. Horáková, L.; Sýkora, K.; Sieger, L.; Roubík, K. Breathing Experiments into the Simulated Avalanche Snow: Medical and Technical Issues of the Outdoor Breathing Trials. In Proceedings of the World Congress on Medical Physics and Biomedical Engineering 2018, 2019; pp. 711-717.
24. Company, G.E. Datex Ohmeda S/5 Compact Anesthesia Monitor. Technical Reference Manual; Madison, MI, USA, 2006.
25. USA, E. M3B Vital Signs Monitor User Manual, version 1.6.; EDAN Instruments: San Diego, CA, USA, 2012.
26. Masimo. Radical-7 Operator's Manual; Masimo: CA, USA, 2012.
27. Healthcare, G. Carescape Monitors B850 and B650 User's Manual; Milwaukee, WI, USA, 2013.
28. Nonin. Model 2500 PalmSAT. Operator's Manual; Nonin Medical Inc.: USA, 2014.
29. Strapazzon, G.; Paal, P.; Schweizer, J.; Falk, M.; Reuter, B.; Schenk, K.; Gatterer, H.; Grasegger, K.; Dal Cappello, T.; Malacrida, S. Effects of snow properties on humans breathing into an artificial air pocket–an experimental field study. *Scientific reports* **2017**, *7*, 1-12.
30. McIntosh, S.E.; Little, C.E.; Seibert, T.D.; Polukoff, N.E.; Grissom, C.K. Avalanche airbag post-burial active deflation — The ability to create an air pocket to delay asphyxiation and prolong survival. *Resuscitation* **2020**, *146*, 155-160, doi:https://doi.org/10.1016/j.resuscitation.2019.11.023.
31. Strapazzon, G.; Gatterer, H.; Falla, M.; Dal Cappello, T.; Malacrida, S.; Turner, R.; Schenk, K.; Paal, P.; Falk, M.; Schweizer, J.; et al. Hypoxia and hypercapnia effects on cerebral oxygen saturation in avalanche burial: A pilot human experimental study. *Resuscitation* **2021**, *158*, 175-182, doi:https://doi.org/10.1016/j.resuscitation.2020.11.023.
32. Wik, L.; Brattebø, G.; Østerås, Ø.; Assmus, J.; Irusta, U.; Aramendi, E.; Mydske, S.; Skaalhegg, T.; Skaiaa, S.C.; Thomassen, Ø. Physiological effects of providing supplemental air for avalanche victims. A randomised trial. *Resuscitation* **2022**, *172*, 38-46, doi:https://doi.org/10.1016/j.resuscitation.2022.01.007.
33. PHILIPS. *HeartStart MRx Instructions For Use*; Philips Medical Systems: Andover, MA, USA, 2009.
34. Physio-Control, I. LIFEPAK 15 monitor/defibrillator Operating Instructions; 2019.
35. ZOLL. *ZOLL X Series Advanced Operator's Guide*; ZOLL Medical Corporation: Chelmsford, MA, USA, 2021.
36. Radwin, M.I.; Grissom, C.K.; Scholand, M.B.; Harmston, C.H. Normal oxygenation and ventilation during snow burial by the exclusion of exhaled carbon dioxide. *Wilderness & Environmental Medicine* **2001**, *12*, 256-262.
37. Jensen, L.A.; Onyskiw, J.E.; Prasad, N. Meta-analysis of arterial oxygen saturation monitoring by pulse oximetry in adults. *Heart & lung* **1998**, *27*, 387-408.
38. Chan, E.D.; Chan, M.M.; Chan, M.M. Pulse oximetry: Understanding its basic principles facilitates appreciation of its limitations. *Respiratory Medicine* **2013**, *107*, 789-799, doi:https://doi.org/10.1016/j.rmed.2013.02.004.
39. Jubran, A. Pulse oximetry. *Crit Care* **2015**, *19*, 272, doi:10.1186/s13054-015-0984-8.
40. Dünnwald, T.; Kienast, R.; Niederseer, D.; Burtscher, M. The Use of Pulse Oximetry in the Assessment of Acclimatization to High Altitude. *Sensors* **2021**, *21*, 1263.
41. Robert R Fluck, Jr.; Christine, S.; Greg, F.; Brad, K.; Brenda, E. Does Ambient Light Affect the Accuracy of Pulse Oximetry? *Respiratory Care* **2003**, *48*, 677.
42. Lima, A.; Bakker, J. Noninvasive monitoring of peripheral perfusion. In *Applied Physiology in Intensive Care Medicine 2: Physiological Reviews and Editorials*, Pinsky, M.R., Brochard, L., Mancebo, J., Antonelli, M., Eds.; Springer Berlin Heidelberg: Berlin, Heidelberg, 2012; pp. 39-49.
43. Shang, A.B.; Kozikowski, R.T.; Winslow, A.W.; Weininger, S. Development of a standardized method for motion testing in pulse oximeters. *Anesthesia & Analgesia* **2007**, *105*, S66-S77.
44. Masimo. Clinical Application of Perfusion Index. **2007**.

45. Pinto Lima, A.; Beelen, P.; Bakker, J. Use of a peripheral perfusion index derived from the pulse oximetry signal as a noninvasive indicator of perfusion. *Critical Care Medicine* **2002**, *30*, 1210-1213.
46. Chu, C.-L.; Huang, Y.-Y.; Chen, Y.-H.; Lai, L.-P.; Yeh, H.-M. An observational study: The utility of perfusion index as a discharge criterion for pain assessment in the postanesthesia care unit. *PLOS ONE* **2018**, *13*, e0197630, doi:10.1371/journal.pone.0197630.
47. Huang, H.-S.; Chu, C.-L.; Tsai, C.-T.; Wu, C.-K.; Lai, L.-P.; Yeh, H.-M. Perfusion Index Derived from a Pulse Oximeter Can Detect Changes in Peripheral Microcirculation during Uretero-Renal-Scopy Stone Manipulation (URS-SM). *PLOS ONE* **2014**, *9*, e115743, doi:10.1371/journal.pone.0115743.
48. Hasanin, A.; Mohamed, S.A.R.; El-adawy, A. Evaluation of perfusion index as a tool for pain assessment in critically ill patients. *Journal of Clinical Monitoring and Computing* **2017**, *31*, 961-965, doi:10.1007/s10877-016-9936-3.
49. Nishimura, T.; Nakae, A.; Shibata, M.; Mashimo, T.; Fujino, Y. Age-related and sex-related changes in perfusion index in response to noxious electrical stimulation in healthy subjects. *Journal of pain research* **2014**, *7*, 91.
50. Thijssen, M.; Janssen, L.; le Noble, J.; Foudraine, N. Facing SpO2 and SaO2 discrepancies in ICU patients: is the perfusion index helpful? *Journal of Clinical Monitoring and Computing* **2020**, *34*, 693-698, doi:10.1007/s10877-019-00371-3.
51. Shah, N.; Ragaswamy, H.B.; Govindugari, K.; Estanol, L. Performance of three new-generation pulse oximeters during motion and low perfusion in volunteers. *Journal of Clinical Anesthesia* **2012**, *24*, 385-391, doi:https://doi.org/10.1016/j.jclinane.2011.10.012.
52. Hummler, H.D.; Engelmann, A.; Pohlandt, F.; Högel, J.; Franz, A.R. Decreased accuracy of pulse oximetry measurements during low perfusion caused by sepsis: is the perfusion index of any value? *Intensive Care Medicine* **2006**, *32*, 1428-1431, doi:10.1007/s00134-006-0254-y.
53. Šimon, W. Variabilita měření SpO2 v závislosti na volbě prstu pro umístění senzoru. České vysoké učení technické v Praze. Vypočetní a informační centrum., 2021.
54. Louie, A.; Feiner, J.R.; Bickler, P.E.; Rhodes, L.; Bernstein, M.; Lucero, J. Four Types of Pulse Oximeters Accurately Detect Hypoxia during Low Perfusion and Motion. *Anesthesiology* **2018**, *128*, 520-530, doi:10.1097/aln.0000000000002002.
55. Roubik Karel, S.K., Sieger Ladislav, Ort Vaclav, Horakova Lenka, Walzel Simon. Perlite is a suitable model material for breathing experiments studying survival of a victim covered with high density avalanche snow. *Scientific reports* **2021**.
56. Horakova, L.; Roubik, K. Performance of Different Pulse Oximeters Can Affect the Duration of Field Breathing Experiments. In Proceedings of the 2019 E-Health and Bioengineering Conference (EHB), 2019; pp. 1-4.
57. Horakova, L.; Kudrna, P.; Roubik, K. Dynamic Changes of Perfusion Index During Hypoxemia and Hypercapnia in Outdoor Experiments. In Proceedings of the 2021 International Conference on e-Health and Bioengineering (EHB), 18-19 Nov. 2021, 2021; pp. 1-6.
58. Horakova, L.; Roubik, K. Pulse Oximeter Performance during Rapid Desaturation. *Sensors (Basel)* **2022**, *22*, doi:10.3390/s22114236.
59. Standardization, I.O.f. Medical electrical equipment – Part 2-61: Particular requirements for basic safety and essential performance of pulse oximeter equipment ISO 80601-2-61:2017. **2019**.
60. Goldman, J.M.; Petterson, M.T.; Kopotic, R.J.; Barker, S.J. Masimo signal extraction pulse oximetry. *Journal of clinical monitoring and computing* **2000**, *16*, 475-483.
61. Louw, A.; Cracco, C.; Cerf, C.; Harf, A.; Duvaldestin, P.; Lemaire, F.; Brochard, L. Accuracy of pulse oximetry in the intensive care unit. *Intensive Care Medicine* **2001**, *27*, 1606-1613, doi:10.1007/s001340101064.
62. Nitzan, M.; Nitzan, I.; Arieli, Y. The Various Oximetric Techniques Used for the Evaluation of Blood Oxygenation. *Sensors* **2020**, *20*, 4844.
63. Taylor, M.; Whitwam, J. The accuracy of pulse oximeters: a comparative clinical evaluation of five pulse oximeters. *Anaesthesia* **1988**, *43*, 229-232.
64. Trivedi, N.S.; Ghouri, A.F.; Shah, N.K.; Lai, E.; Barker, S.J. Pulse oximeter performance during desaturation and resaturation: a comparison of seven models. *Journal of clinical anesthesia* **1997**, *9*, 184-188.
65. Johnston, E.D.; Boyle, B.; Juszczak, E.; King, A.; Brocklehurst, P.; Stenson, B.J. Oxygen targeting in preterm infants using the Masimo SET Radical pulse oximeter. *Archives of Disease in Childhood-Fetal and Neonatal Edition* **2011**, *96*, F429-F433.

66. Ross, P.A.; Newth, C.J.; Khemani, R.G. Accuracy of pulse oximetry in children. *Pediatrics* **2014**, *133*, 22-29.
67. Bachman, T.E.; Newth, C.J.; Ross, P.A.; Iyer, N.P.; Khemani, R.G. Characterization of the bias between oxygen saturation measured by pulse oximetry and calculated by an arterial blood gas analyzer in critically ill neonates. *Lékař a technika-Clinician and Technology* **2017**, *47*, 130-134.
68. Barker, S.J. "Motion-resistant" pulse oximetry: a comparison of new and old models. *Anesthesia & Analgesia* **2002**, *95*, 967-972.
69. Hartmut Gehring, M.; ME, H.M.; Schmucker, P. The effects of motion artifact and low perfusion on the performance of a new generation of pulse oximeters in volunteers undergoing hypoxemia. *Respiratory care* **2002**, *47*, 48-60.
70. Kawagishi, T.; Kanaya, N.; Nakayama, M.; Kurosawa, S.; Namiki, A. A Comparison of the Failure Times of Pulse Oximeters During Blood Pressure Cuff-Induced Hypoperfusion in Volunteers. *Anesthesia & Analgesia* **2004**, *99*, 793-796, doi:10.1213/01.Ane.0000130343.66453.37.
71. Mizukoshi, K.; Shibasaki, M.; Amaya, F.; Mizobe, T.; Tanaka, Y. Which finger do you attach pulse oximetry to? Index finger or not. *Eur J Anesthesiol* **2009**, *26*, 3AP1-3AP5.
72. Basaranoglu, G.; Bakan, M.; Umutoglu, T.; Zengin, S.U.; Idin, K.; Salihoglu, Z. Comparison of SpO2 values from different fingers of the hands. *SpringerPlus* **2015**, *4*, 561, doi:10.1186/s40064-015-1360-5.
73. Agrawal, P.; Pursnani, N.; Gautam, A.; Singh, A.P.; Garg, R.; Pandey, A.; Agarwal, A. Assessing the SpO(2) in a random population - Looking for the best among fingers. *J Family Med Prim Care* **2022**, *11*, 5506-5509, doi:10.4103/jfmpc.jfmpc_2596_20.
74. Yamaya, Y.; Bogaard, H.J.; Wagner, P.D.; Niizeki, K.; Hopkins, S.R. Validity of pulse oximetry during maximal exercise in normoxia, hypoxia, and hyperoxia. *Journal of Applied Physiology* **2002**, *92*, 162-168.
75. Ricart, A.; Pages, T.; Viscor, G.; Leal, C.; Ventura, J.L. Sex-linked differences in pulse oxymetry. *British Journal of Sports Medicine* **2008**, *42*, 620-621, doi:10.1136/bjsm.2007.038653.
76. Abramson, D.I.; Landt, H.; Benjamin, J.E. Peripheral Vascular Response to Acute Anoxia. *Archives of Internal Medicine* **1943**, *71*, 583-593, doi:10.1001/archinte.1943.00210050003001.
77. Black, J.; Roddie, I. The mechanism of the changes in forearm vascular resistance during hypoxia. *The Journal of physiology* **1958**, *143*, 226.
78. Vantanajal, J.S.; Ashmead, J.C.; Anderson, T.J.; Hepple, R.T.; Poulin, M.J. Differential sensitivities of cerebral and brachial blood flow to hypercapnia in humans. *Journal of Applied Physiology* **2007**, *102*, 87-93, doi:10.1152/japplphysiol.00772.2006.
79. Lee, S.; Kim, K.-S.; Park, S.-W.; You, A.-H.; Lee, S.-W.; Kim, Y.-J.; Kim, M.; Lee, J.-Y.; Choi, J.-H. Correlation between the Perfusion Index and Intraoperative Hypothermia: A Prospective Observational Pilot Study. *Medicina (Kaunas)* **2021**, *57*, 364, doi:10.3390/medicina57040364.
80. Shaaban-Ali, M.; Momeni, M.; Denault, A. Clinical and Technical Limitations of Cerebral and Somatic Near-Infrared Spectroscopy as an Oxygenation Monitor. *Journal of Cardiothoracic and Vascular Anesthesia* **2021**, *35*, 763-779, doi:10.1053/j.jvca.2020.04.054.
81. Ferrari, M.; Quaresima, V. Near Infrared Brain and Muscle Oximetry: From the Discovery to Current Applications. *Journal of Near Infrared Spectroscopy* **2012**, *20*, 1-14, doi:10.1255/jnirs.973.

RESUMÉ

Terénní dýchací experimenty jsou důležitým podkladem pro vytváření a aktualizování mezinárodních doporučení pro záchranu a resuscitaci obětí zasypaných sněhovou lavinou. U tohoto typu experimentů ovšem byla zaznamenána celá řada medicínských i technických specifik, zvláště v použití lékařské přístrojové techniky původně určené pro monitoraci pacientů v rámci anestezie a intenzivní medicíny. Cílem této disertační práce je analyzovat specifika použití lékařské přístrojové techniky během terénních dýchacích experimentů se zaměřením na pulzní oxymetrii a související parametr – perfuzní index (*PI*).

Analyzovaná data pocházejí ze studie na 13 dobrovolnících, kteří pomocí speciálně upravené aparatury dýchali do simulovaného lavinového sněhu, nebo do materiálu, který měl takový sníh imitovat. Během tohoto dýchání došlo k rozvoji progresivní hypoxémie a hyperkapnie spolu se zvýšenou dechovou prací, což jsou i hlavní identifikovaná patofyziologická rizika těchto experimentů. Každý proband byl simultánně monitorován pomocí pěti různých sond pro pulzní oxymetrii na prstech pravé ruky. V průběhu experimentu byly pozorovány rozdíly v zobrazených hodnotách periferní saturace (SpO_2) a to jak v rychlosti nástupu desaturace, tak i v nejnižší dosažené hodnotě a návratu zpět k normálním hodnotám po ukončení experimentu. Rozdíly mezi jednotlivými pulzními oximetry v čase dosažení teoretické cílového hodnoty experimentu 75 % nebo 85 % SpO_2 byly až 50 s, respektive 90 s, což by znamenalo potenciální zkrácení experimentu až o jednu čtvrtinu času. Jeden pulzní oxymetr navíc ve 41 % případů ukazoval stereotypně nejnižší zobrazenou hodnotu ještě v době, kdy již ostatní čtyři přístroje zaznamenávaly normální saturaci probanda. Perfuzní index probandů během těchto experimentů nenaznačoval, že by problémem ve správnosti zobrazené hodnoty SpO_2 byla limitace této metody v podobě nízké perfuze monitorovaných prstů. Hodnoty *PI* probandů se výrazně nelišily od hodnot v řadě studií mimo outdoorové prostředí a během samotného dýchacího experimentu nedošlo ke statisticky významnému poklesu *PI*, a to ani během úvodní stabilizační fáze. Po odpojení probanda od aparatury ovšem došlo k dvoj- až trojnásobnému nárůstu hodnoty *PI*, což bylo pravděpodobně způsobeno vazodilatačním efektem nashromážděného oxidu uhličitého při progresivní hyperkapnii.

Na základě závěrů z této disertační práce byla vytvořena doporučení pro další podobné studie.

SUMMARY

Field breathing experiments form an important basis for designing and updating international guidelines for the rescue and resuscitation of avalanche snow-buried victims. However, several medical and technical specifics have been identified for these experiments, especially when medical equipment designed for monitoring patients in anaesthesia and critical care is used. The aim of this doctoral thesis is to analyse the specifics of the use of medical equipment during field breathing experiments, specifically pulse oximetry and the associated parameter—perfusion index (*PI*).

The analysed data originate from a clinical trial involving 13 subjects who breathed through a specially designed breathing apparatus into simulated avalanche snow or snow model material. During the experimental breathing, progressive hypoxemia, hypercapnia, and increased work of breathing developed, which are also the main pathophysiological aspects identified in these experiments. Each subject was simultaneously monitored by five different pulse oximeters on the right-hand fingers. The peripheral oxygen saturation (SpO_2) readings differed significantly throughout the experiment. They varied in the time of desaturation onset, in the lowest measured SpO_2 value, and in the duration of the recovery phase, when the subject was already breathing ambient air and the oxygen saturation was returning to pre-experimental values. The differences among individual pulse oximeters in the time of reaching the theoretical study endpoint SpO_2 of 75% or 85% was as much as 50 s, and 90 s, respectively, which could have shortened the experimental breathing by up to one-quarter of the time. Moreover, one pulse oximeter had a tendency to show, in more than 41% of cases, the lowest measured value for a prolonged period of time, whereas the SpO_2 level was within the normal range according to the other devices. The perfusion index values during these experiments did not suggest that the error source in the displayed SpO_2 was caused by the limitation of the method, which is the low perfusion of the monitored fingers. The *PI* values did not differ significantly from the values recorded in many studies outside the outdoor environment. In the breathing experiment, there was no statistically significant decrease in *PI*, not even during the initial stabilisation phase. Following the subject disconnection from the apparatus, a two- to threefold surge in *PI* occurred, very likely due to the vasodilation effect of the accumulated carbon dioxide during progressive hypercapnia.

Based on the conclusions of this doctoral thesis, several recommendations for similar future trials were created.