RELIABILITY AND SOURCE OF ERRORS IN END-TIDAL GAS CONCENTRATION EVALUATION ALGORITHMS DURING AVALANCHE SNOW AND REBREATHING EXPERIMENTS

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Abstract

During breathing experiments in avalanche snow, measurement of CO_2 is often conducted in order to monitor the volunteers or as an endpoint of the trial. From the measured CO_2 signal, monitors calculate end-tidal CO_2 concentrations ($EtCO_2$). The aim of the study was to investigate several related points: to determine if the Datex-Ohmeda S/5 anesthesia monitor evaluates $EtCO_2$ and other parameters of breathing gas correctly, to characterize the frequency and magnitude of error and to determine the possible cause of the error. Data from a previous experiment aimed at investigation of work of breathing into snow in the presence and absence of an artificial air pocket were used to study accuracy of the monitor. The analysis found that an error of $EtCO_2$ occurred in 39% and in 30% of the total experimental time of breathing, with and without the air pocket respectively (range from 13% to 93% of time). Breathing experiments with simulated snow were conducted in order to find the cause of the error. We determined the error occurs immediately after a significant increase of CO_2 in the breathing circuit as a consequence of expired gas rebreathing and is independent of other breathing parameters. The study confirmed that a newer model monitor (CARESCAPE B650) is prone to this error as well. The last experiment conducted with a standard anesthesia machine confirmed, that the error occurs even in a standard clinical setup in the presence of rebreathing. This problem might result in improper actions and could potentially result in harm to a volunteer or a patient.

Keywords

hypercapnia, $EtCO_2$, avalanche, snow burial, device error, Datex S/5, CARESCAPE B650

Introduction

As avalanche burials represent one of the most dangerous risks associated with winter activities in the mountains, research of survival circumstances and possibilities how to improve the survival rate represent topical research questions. The probability of survival rapidly decreases with time [1, 2]. When a victim repetitively inspires previously expired gas, the inhaled gas gradually contains less oxygen and higher concentration of carbon dioxide. This condition leads to asphyxiation as the dominant cause of avalanche-related deaths [3–5].

Recently published experiments, trying to describe the dynamics of asphyxiation in the snow, often measure physiological parameters of the volunteers participating in the research. The concentrations of gases in the inspired and expired gas are the primary parameters determining the dynamics of asphyxiation.

Brugger et al. [6] conducted an experiment in 12 volunteers breathing into snow pockets of volume 1 L or 2 L while they measured changes in peripheral oxygen saturation (SpO_2) and end-tidal concentration of carbon dioxide ($EtCO_2$). SpO_2 and $EtCO_2$ were also selected as primary endpoints in this study. Hypercapnia and its effects on hypothermia during snow burial were studied by Grissom et al. [7]. Hypercapnia increased a cooling rate of the body. $EtCO_2$, fraction of CO_2 in inspired gas ($FiCO_2$) and other parameters were measured in studies characterizing a benefit of AvaLung, a device that removes expired gas from the point of inhalation [8, 9], thus preventing rebreathing of previously expired gas.

During conducting their experiment, Roubik et al. [10] studied, how work of breathing was associated with $EtCO_2$, $FiCO_2$, end-tidal concentration of oxygen (EtO_2) and fraction of O_2 in inspired gas (FiO_2) and what was the effect of a snow pocket on these parameters. Furthermore, a threshold $EtCO_2$ level was

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used as a primary safety measure for terminating the experimental breathing trial of each volunteer. The authors observed several times, that the value of $EtCO_2$ on the screen of the monitor changed suddenly and stepwise and that the displayed $EtCO_2$ value did not correspond to the displayed CO_2 concentration curve. The displayed $EtCO_2$ value was lower than the expected value according to the measured CO_2 concentration curve. This unexpected behavior of Datex-Ohmeda S/5 life function monitor (Datex-Ohmeda, Madison, WI, USA) has not been documented, to our knowledge.

The aim of the study was to investigate possible errors and their frequency in evaluation of gas parameters ($EtCO_2$, $FiCO_2$, EtO_2 and FiO_2) during breathing experiments in the avalanche snow when using Datex-Ohmeda S/5 monitor.

Methods

Study design

The data used in this study were recorded during a prospective randomized double-blind crossover breathing experiment [10]. The study was approved by the Institutional Review Board and registered in the ClinicalTrials.gov registry as NCT02521272. The full protocol of the original study was described in a detail by Roubik et al [10].

Study group

Data recorded in 12 male volunteers were evaluated in this study. The basic characteristics of the group of participants, presented as mean ± standard deviation and range (minimum–maximum), are: age 28.8 ± 3.4 (20–30) years, weight 77.7 ± 7.1 (64–90) kg, height 180.0 ± 5.5 (173–192) cm, BMI—Body Mass Index 24.0 ± 1.7 (20–27) $kg \cdot m^{-2}$, FEV1—Forced Expiratory Volume in 1 second 4.5 ± 0.4 (4.0–5.1) L, and FVC—Forced Vital Capacity 5.2 ± 0.5 (4.5–6.1) L.

Experimental protocol and measurements

Each volunteer underwent two phases of the experiment using a breathing circuit presented in Fig. 1: phase "AP"—breathing in snow with a one-liter air pocket, and phase "NP"—breathing in snow with no air pocket. At least a 20-hour recovery interval was inserted between the two phases in each subject.

The breathing circuit was designed in order to minimize its dead space; therefore, the circuit comprised separate inspiratory and expiratory limbs equipped with one-way valves in order to assure the unidirectional gas flow during inspiration and expiration. The dead space volume of the bidirectionally ventilated parts of the tubes was 49 mL.

Before the breathing trial, each subject was connected to a mouthpiece allowing measurement of respiratory gasses and ventilatory parameters. A stabilization period (approx. 5 minutes) for reaching stable ventilatory parameters (steady tidal volume and breathing frequency) was introduced. Then, the subject was connected to the breathing circuit (described above) ending with NP or AP and the breathing trial was initiated. Another stabilization procedure (approx. 5 minutes) followed. This next phase lasted until steady readouts, similar to those recorded before the breathing trial during the stabilization phase, were reached.

Physiological parameters of the subject were recorded by a Datex-Ohmeda S/5 anesthesia monitor

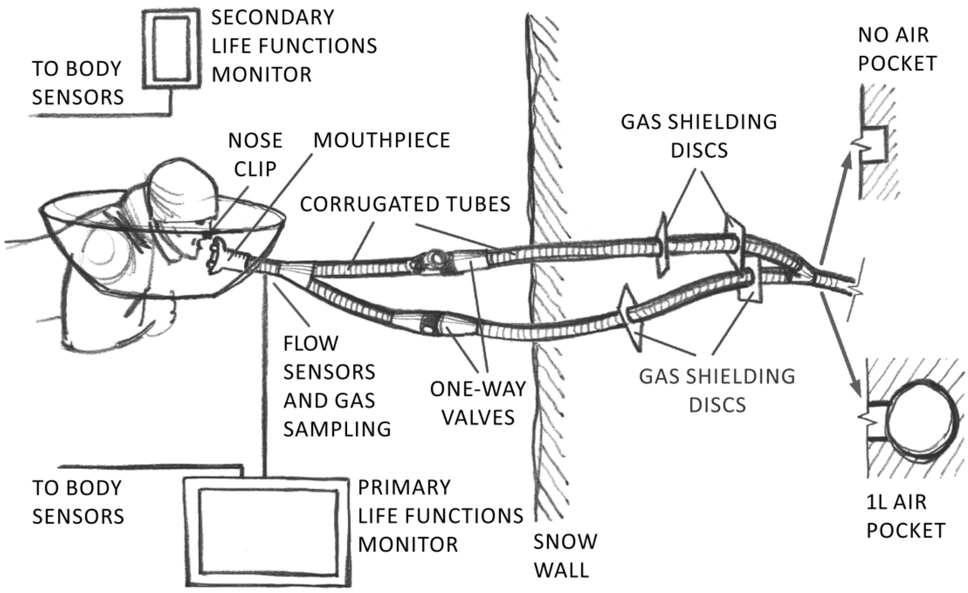

Fig. 1: Scheme of the breathing circuit and its installation in the snow with NP and AP. Reprinted from [10] under CC BY license (Illustration: B. Kracmar).

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(Datex-Ohmeda, Madison, WI, USA) with anesthesia gas module E-CAiOVX (Datex-Ohmeda, Madison, WI, USA) using S/5 Collect software (Datex-Ohmeda, Madison, WI, USA). In this study, a group of parameters were evaluated from the whole set of the recorded parameters. These were all measured at the airway opening and included inspiratory and expiratory curves of O_2 and CO_2 concentrations recorded continuously with a sampling frequency of 25 Hz, inspiratory and end-tidal fractions of oxygen (FiO_2, EtO_2), inspiratory and end-tidal fractions of carbon dioxide ($FiCO_2$, $EtCO_2$), tidal volume (V_T), curves of airway pressure (Paw) and airflow (Qaw).

The Datex-Ohmeda S/5 anesthesia monitor, connected to a laptop computer for data collection, was placed in a heated tent and thermally stabilized using electric heating foils. The gas sampling lines of the monitor were supplemented with a heated wire and a polyurethane insulation in order to prevent condensation and freezing of water in the hoses. The accuracy of the gas analysis module of the Datex-Ohmeda S/5 monitor was checked directly on the site before the first breathing experiment every day using a calibrating gas (5% CO_2, 15% O_2, balanced by N_2) from a high-pressure cylinder.

All details about the preparation of the breathing circuit and snow conditions, safety measures and other details not essential for conducting the current study are presented in the original paper [10].

In order to identify a probable cause of the error, a post hoc bench test was conducted in a lab under better controlled conditions using a model of the snow allowing expired gas rebreathing as depicted in Fig. 2. The model of the snow consisted of a barrel filled with 40 L of moist perlite.

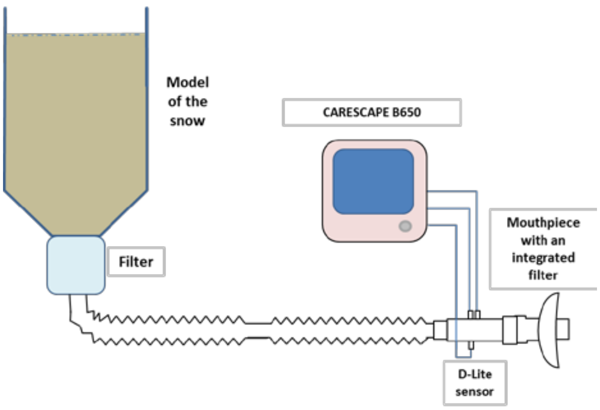

Fig. 2: Model of the snow and experimental setup of the laboratory breathing experiment.

During the post hoc bench test a different patient monitor was used (CareScape B650 GE Healthcare, Helsinki, Finland), which is a successor of Datex-Ohmeda S/5 and uses essentially the same gas measurement technology.

Data processing and statistics

Two sets of data were analyzed and compared: (i) the curves of O_2 and CO_2 and (ii) values of $EtCO_2$, EtO_2, $FiCO_2$ and FiO_2 evaluated by the monitor from the curves of O_2 and CO_2. The curves were recorded with a sampling frequency of 25 Hz and the derived parameters were recorded with a sampling rate of 1 Hz. The respective curves and the derived parameters were synchronized and processed in Matlab R2013b software (MathWorks Natick, Massachusetts, USA).

In the recorded signals, segments corresponding to the breathing trial in snow were selected first (a segment between points ‘B’ and ‘E’ in Fig. 3). The ‘B’ and ‘E’ points were identified as points where rapid changes of gas concentrations occurred as a consequence of connecting and disconnecting of the breathing circuit to the volunteer. This segment, expressed in seconds, represents the total duration of the breathing trial referred to as T_{Tot}. Then, portions of the signal were the evaluated parameters did not correspond with the respective measured curves, were identified. These erroneous segments are marked with red horizontal abscissas in Fig. 3. Tolerance intervals of ±0.1% CO_2 (abs.) for $EtCO_2$ and $FiCO_2$, and ±0.2% O_2 (abs.) for FiO_2 and $EtCO_2$ were applied around the evaluated trend data during the error detection. The summary duration of all the erroneous segments during the entire breathing trial expressed in seconds is referred to as T_{Err}. In addition, the total duration of dropouts in the concentration signal were calculated and referred to as T_{Drop}. These can be seen in Fig. 3. There are 5 dropouts of the signal, where the recorded concentration of both the gases provided by the monitor contains a value of −32 767.

From the determined times T_{Tot}, T_{Err} and T_{Drop}, the percentage of total time when the evaluated parameters are incorrect (Error) and the percentage of time when dropout of the signal is present (Dropout) are calculated according to the following equations:

$$\text{Error}\ (\%) = \frac{T_{Err}\,(s)}{T_{Tot}\,(s)} \cdot 100$$

$$\text{Dropout}\ (\%) = \frac{T_{Drop}\,(s)}{T_{Tot}\,(s)} \cdot 100$$

For statistical evaluation of the results, normality of the data was tested using Kolmogorov-Smirnov test. As the normality of data was violated, non-parametric Mann-Whitney U-test was used for evaluation of statistical significance of the differences between the measured parameters. Statistica 7.1 (StatSoft, Tulsa, OK, USA) was used for statistical calculations and presentation of final data in the form of graphs. $P<0.05$ was considered as statistically significant.

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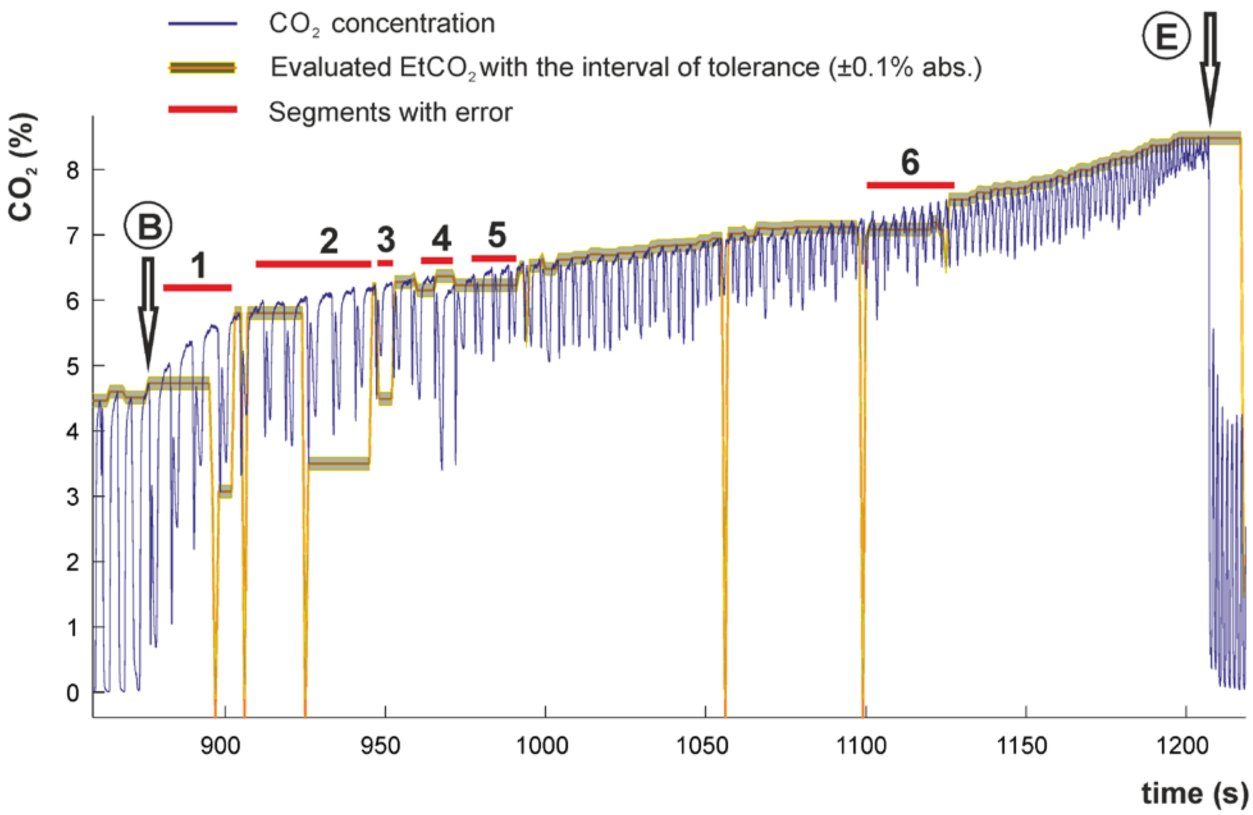

Fig. 3: Example of a curve of measured CO_2 concentration (blue line) and the values of $EtCO_2$ (yellow line) evaluated by the monitor. Segments where $EtCO_2$ does not correspond to the CO_2 concentration curve are marked with red horizontal lines. B—beginning of breathing trial in the snow after the initial stabilization period; E—end of the breathing trial.

Results

There were differences in the average durations of erroneous evaluation among $EtCO_2$, $FiCO_2$, EtO_2 and FiO_2. These parameters differ also depending on the breathing circuit configuration, i.e. with one-liter air pocket (AP) and without air pocket (NP). These results are summarized graphically in Fig. 4 for oxygen related parameters and in Fig. 5 for carbon dioxide related parameters.

The data presented also demonstrates a significant inter individual variability. As an example, $EtCO_2$ was evaluated incorrectly in 13% of the total breathing time with AP in one volunteer and in 71% of time in another one. In one volunteer, the error in evaluation of EtO_2 was detected in 93% of the entire breathing trial time with AP. There was not a statically significant difference between the same parameters recorded with AP and NP.

The duration of the dropout in the gas concentration signal was much less in all the conditions ($p<0.001$), as depicted in Fig. 6. When present, the dropout occurred in both O_2 and CO_2 signals at the same time. The average percentage of the dropout in O_2 and CO_2 measurement during the entire breathing trial was 3.9% for breathing with AP and 3.5% with NP. In several subjects no dropout occurred. The maximum duration of dropout was 10%.

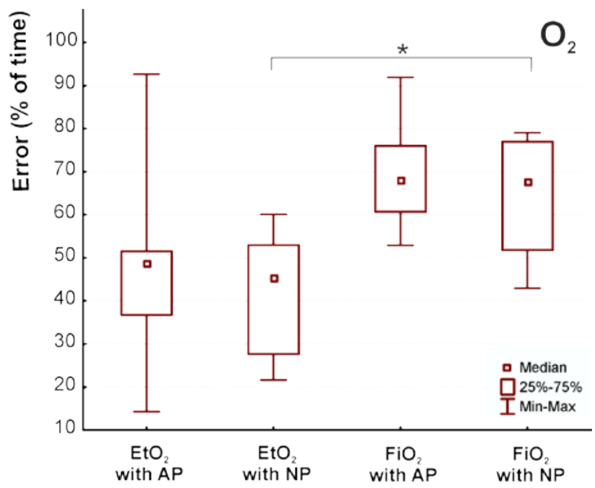

Fig. 4: Duration of erroneous evaluation of oxygen parameters during breathing trials in the snow. AP—breathing with a one-liter air pocket in the snow, NP—breathing in the snow without an air pocket. Symbol "" denotes $p < 0.05$.*

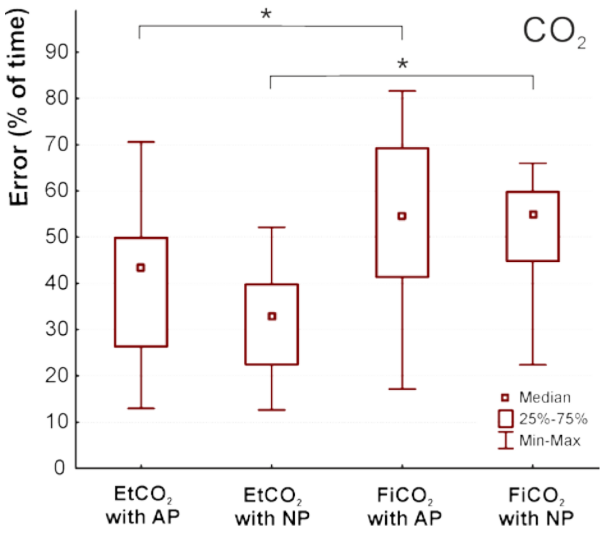

Fig. 5: Duration of erroneous evaluation of carbon dioxide parameters during breathing trial in the snow. AP—breathing with a one-liter air pocket in the snow, NP—breathing in the snow without an air pocket. Symbol "" denotes $p < 0.05$.*

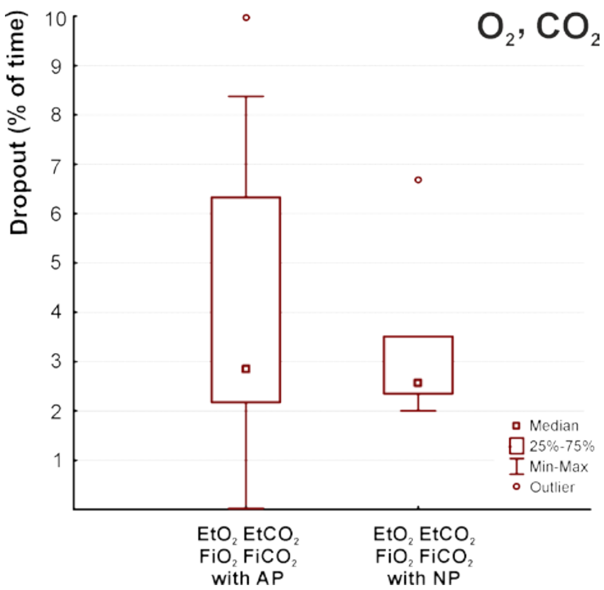

Fig. 6: Duration of dropouts in evaluation of oxygen and carbon dioxide parameters during breathing trial in the snow. AP—breathing with a one-liter air pocket in the snow, NP—breathing in the snow without an air pocket.

Discussion

The main finding of the study is that Datex-Ohmeda S/5 monitor fails to provide correct values of $EtCO_2$, $FiCO_2$, EtO_2 and FiO_2 during experimental breathing in avalanche snow. The error occurs in 30–50% of the entire breathing trial time, but may reach up to 93% in an individual breathing volunteer.

During these breathing experiments, the calibration gas (5% CO_2, 15% O_2, balanced by N_2) was regularly used for verification of the precision of gas concentration measurement. During these calibration procedures, no error in measurement of gas concentrations was identified. The measured values always corresponded to the composition of the calibration gas, even though the verification was conducted in the outside environment as during the breathing experiments.

There was a frequent lack of agreement between concentrations correctly measured by the gas analyzer module of Datex-Ohmeda S/5 and the consequent algorithm calculating $EtCO_2$, $FiCO_2$, EtO_2 and FiO_2 values. The algorithm often failed to provide correct values corresponding to the measured O_2 and CO_2 concentrations. Therefore, the cause of the problem may rest in imperfect software.

We never identified a similar error of $EtCO_2$, $FiCO_2$, EtO_2 and FiO_2 parameters during preparatory, stabilization or testing phases. The problem occurred during the breathing trial itself and often persisted for a short period of time immediately after the breathing trial (Fig. 3).

The breathing trial phase is characterized by fast changes of the gas concentrations and their trend values, irregular and rapidly changing breathing patterns and breathing parameters outside their normal physiological ranges. Even more, breathing in the snow brings significant accumulation of CO_2 in the snow surrounding the end of the breathing circuit and causes also a decrease of oxygen content in this area. As a consequence, rapidly increasing CO_2 rebreathing and decrease in inspired fraction of oxygen can occur. All these conditions could be related to the failure of the algorithm evaluating $EtCO_2$, $FiCO_2$, EtO_2 and FiO_2.

Another possible cause of the problem could be distorted curves of O_2 and CO_2 concentrations due to the breathing circuit used. The scheme of the breathing circuit from Fig. 1 is presented in Fig. 7.

Two limbs of the circuit (inspiratory and expiratory) equipped with one-way valves in order to minimize the dead space during breathing, acting during inspiration and expiration alternatively, result in the gas present in these limbs from the previous breathing cycle being measured first, before the gas from the snow inhalation reached the sensors. This often resulted in concentration curves with two minima and maxima during a single breathing cycle. Further as the composition of gases when breathing with AP and NP differ, different concentration curves occur, as depicted in Fig. 8 and Fig. 9.

In order to verify behavior or the monitor under different conditions, a bench test with the experimental set up depicted in Fig. 2 was conducted. The following conditions were tested: quiet natural breathing, shallow

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fast breathing, breathing with deep breaths and very irregular breathing. These were all conducted with ambient atmosphere without the model of the snow first. Then the snow model breathing phase was initiated. The resulting concentration curves, evaluated EtO_2, $EtCO_2$ parameters and other measured breathing parameters are presented in Fig. 10.

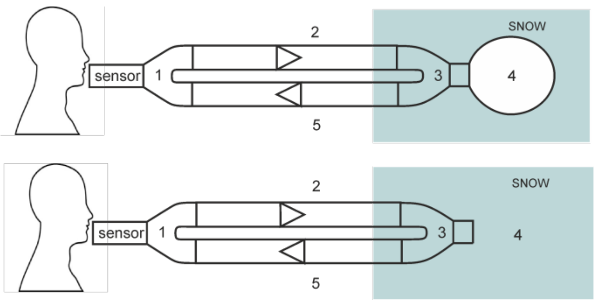

Fig. 7: Scheme of the breathing circuit. 1—Y-piece, 2—expiratory limb with an expiratory one-way valve, 3—Y-piece, 4—snow cavity for AP (top) or plain snow for NP (bottom), 5—inspiratory limb with a one-way valve.

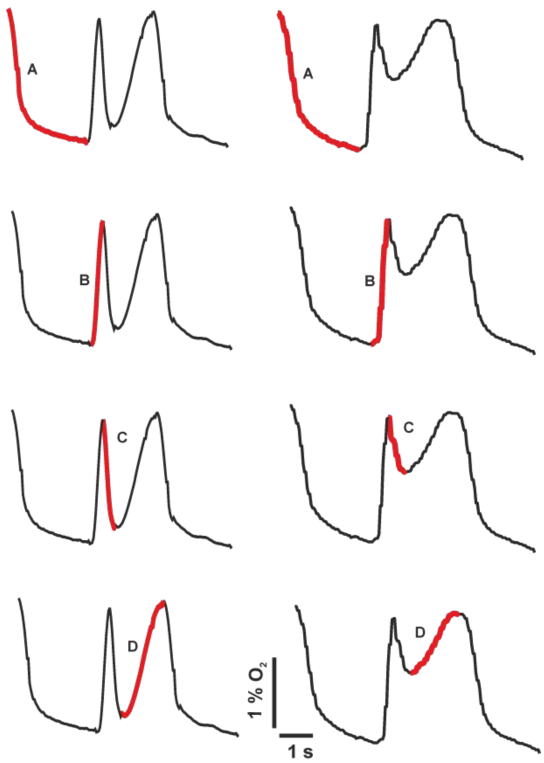

Fig. 8: Pattern of O_2 concentration curves and their phases during breathing trial with NP (left) and AP (right). A—the sensor measures the entire expiratory phase, B—the gas sensor measures concentration of the gas from the inspiratory limb, i.e. gas of the same composition as was at the end phase of the previous inspiration phase, C—gas sensors record gas coming from Y-piece close to snow and early gas from snow cavity for AP, or directly from snow for NP, D—gas concentrations improve because during this late inspiratory phase the gas from rear places in snow enters the sensors.

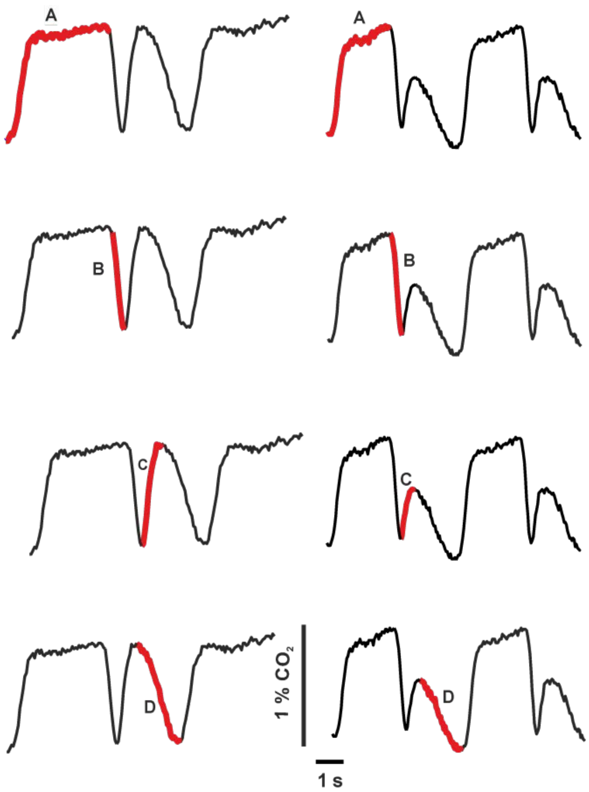

Fig. 9: Pattern of CO_2 concentration curves and their phases during breathing trial with NP (left) and AP (right). A—the sensor measures the entire expiratory phase, B—the gas sensor measures concentration of the gas from the inspiratory limb, i.e. gas of the same composition as was at the end phase of the previous inspiration phase, C—gas sensors record gas coming from Y-piece close to snow and early gas from snow cavity for AP, or directly from snow for NP, D—gas concentrations improve because during this late inspiratory phase the gas from rear places in snow enters the sensors.

Even though the laboratory trial was not conducted with a group of volunteers as a standard study, from the curves presented in Fig. 10 the same behavior of the monitor is apparent as observed during the study during breathing in the real snow. When no rebreathing was present, even with the 2-way breathing circuit, no erroneous evaluations of EtO_2 and $EtCO_2$ were detected and rapid and significant changes in breathing

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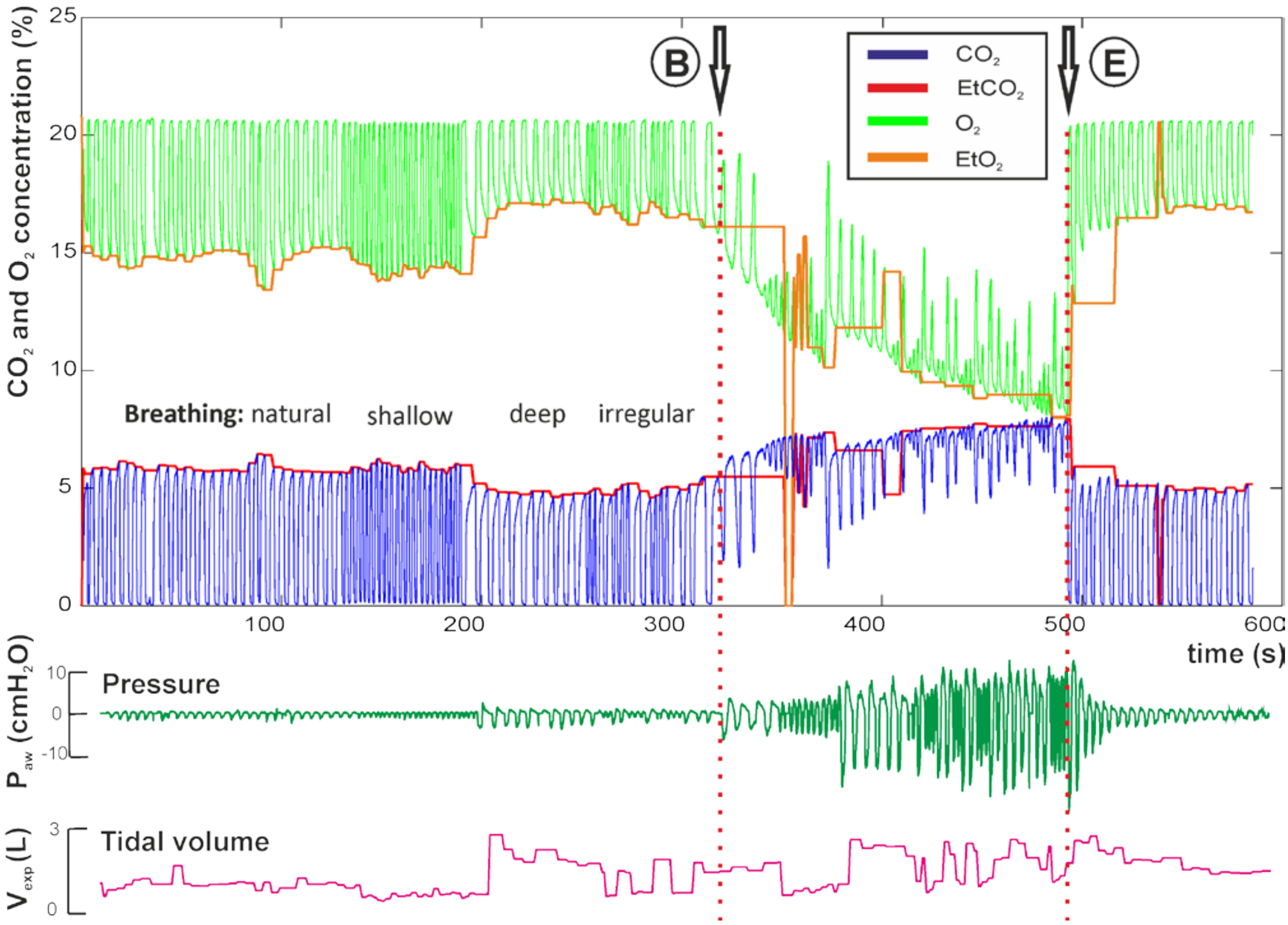

Fig. 10: Concentration curves of O_2 and CO_2, evaluated EtO_2, $EtCO_2$ parameters and other breathing parameters recorded during the laboratory experiment. Paw—pressure in the airways measured in the airway opening, Vexp—expired tidal volume; 'B'—beginning of breathing trial with the snow model; 'E'—end of the breathing trial with the snow model.

pattern did not affect the correctness of EtO_2 and $EtCO_2$ parameters. The errors occurred during the phase with rebreathing using the model of snow.

The last experiment in the laboratory was conducted using a standard anesthesia machine (Zeus Infinity Empowered, Dräger AG, Lübeck, Germany). A CARESCAPE B650 monitor was used for $EtCO_2$ monitoring and a separate device, a capnograph (Nellcor OxiMax NPB-75 Nellcor Puritan Bennett, Minneapolis, MN, USA), was used as well. When the standard configuration of the patient circuit with a CO_2 absorber was used, both the monitors performed well even during irregular breathing. During this configuration, inspired fraction of CO_2 was always below 1%. Second, the CO_2 absorber in the circuit was emptied, i.e. the absorber did not contain the CO_2 absorbing soda lime. In this configuration, a fast increase in CO_2 concentration in the circuit was recorded similar to breathing in snow or the snow model. Even though the Nellcor OxiMax NPB-75 measured the $EtCO_2$ correctly, evaluation of $EtCO_2$ using the CARESCAPE B650 monitor exhibited the same errors as during the breathing experiments in the real snow or in the snow model.

The behavior of the monitor during both the laboratory experiments was very similar to that of during the breathing experiments in the real snow. Neither different nor changing breathing parameters caused the erroneous evaluation of EtO_2 and $EtCO_2$ when rebreathing of expired gas was not present. The error occurred during the rebreathing and a short period of time immediately after it. But we cannot determine the real cause of the error, as other parameters also varied, with some outside the normal physiological range. For example, airway pressure (Paw) amplitudes were increased markedly due to a high airflow resistance both of the real and simulated snow. On the other hand, the methodology of this article was designed in order to document and quantify the error occurring during the real breathing experiments with human volunteers, not to investigate the exact cause of the problem.

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Conclusion

The study documents that even though both the monitors (Datex Ohmeda S/5 and CARESCAPE B650) measured the concentration of gases correctly, the end tidal parameters ($EtCO_2$, $FiCO_2$, EtO_2 and FiO_2) were derived incorrectly during breathing in the snow. This condition may represent a possible danger when investigators rely extensively on $EtCO_2$ parameter during control of the breathing experiments. $EtCO_2$ is often used for evaluation of safety of the participants, or, as an endpoint of such experiments. Verification of the evaluated parameters, such as $EtCO_2$, with the corresponding gas concentration curve, should be conducted on a regular basis. For design of prospective research studies, we also recommend recording of concentration waveforms for the consequential verification of provided $EtCO_2$, $FiCO_2$, EtO_2 and FiO_2 parameters.

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