The duration of two carbon dioxide absorbents in a closed-circuit rebreather diving system

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Abstract

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Introduction: Diving rebreathers use canisters containing sodalime preparations to remove carbon dioxide (CO_2) from the expired gas. These preparations have a limited absorptive capacity and therefore may limit dive duration. The Inspiration™ rebreather is designed for use with Sofnolime 797™ but some divers use Spherasorb™ as an alternative. There are no published data comparing the CO_2-absorbing efficacy of these sodalime preparations in an Inspiration rebreather.

Methods: An Inspiration rebreather was operated in a benchtop circuit under conditions simulating work at 6 metabolic equivalents (MET). Ventilation was maintained at 45 L·min^{-1} (tidal volume 1.5 L; respiratory rate 30 min^{-1}) with CO_2 introduced to the expiratory limb at 2 L·min^{-1}. The P_ICO_2 was continuously monitored in the inspiratory limb. The rebreather canister was packed to full volume with either Sofnolime or Spherasorb and 10 trials were conducted (five using each absorbent), in which the circuit was continuously run until the P_ICO_2 reached 1 kPa ('breakthrough'). Peak inspiratory and expiratory pressures during tidal ventilation of the circuit were also recorded.

Results: The mean operating duration to CO_2 breakthrough was 138 ± 4 (SD) minutes for 2.38 kg Spherasorb and 202 ± minutes for 2.64 kg Sofnolime ($P < 0.0001$). The difference between peak inspiratory and expiratory pressures was 10% less during use of Spherasorb, suggesting lower work of breathing.

Conclusions: Under conditions simulating work at 6 MET during use of an Inspiration rebreather a canister packed with Spherasorb reached CO_2 breakthrough 32% earlier with 10% less mass than Sofnolime packed to similar volume. Divers cannot alternate between these two preparations and expect the same endurance.

Key words

Technical diving; equipment; rebreathing; exercise; risk management; safety

Introduction

Effective removal of carbon dioxide (CO_2) is fundamental to the function of rebreathing systems, such as those widely used in anaesthesia and in semi- or fully closed-circuit rebreathers (CCRs) used in technical diving. This is most commonly achieved by passing exhaled gas through granular 'sodalime'; a mix of sodium hydroxide and calcium hydroxide which reacts with CO_2 to produce calcium carbonate ($CaCO_3$) and water (H_2O). This is a consumptive reaction and a given mass of sodalime therefore has a finite absorptive capacity. If this capacity is exceeded during a dive, exhaled CO_2 will 'break through' the scrubber canister and be rebreathed by the diver.[1] CO_2 rebreathing is hazardous because it may result in hypercapnia which, in turn, can cause debilitating symptoms and increase the risk of cerebral oxygen toxicity.[1]

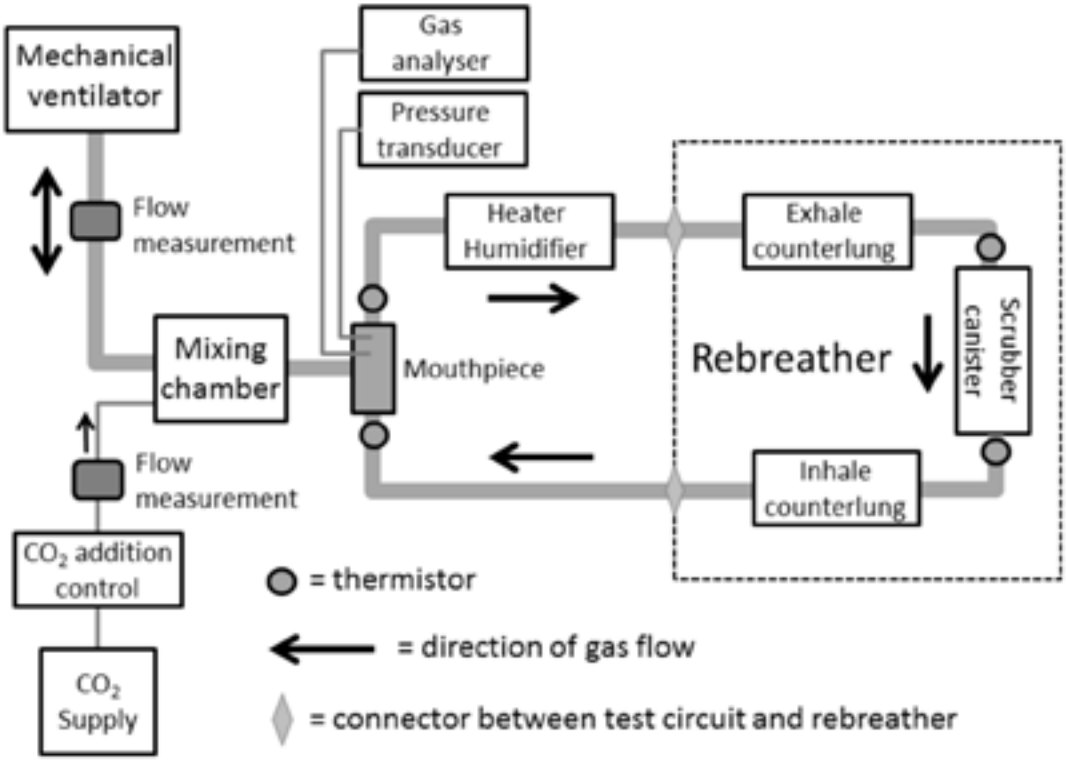
CCRs are usually tested for use with specific sodalime preparations. However, divers may use alternative preparations for reasons that include cost, availability, and/or for perceived advantages in endurance or work of breathing. For example, the Inspiration Rebreather™ (AP Diving, Helston, Cornwall, UK) is designed and tested to use Sofnolime 797™ (Molecular Products, Essex, UK), but divers often report using Spherasorb™ (Intersurgical, Berkshire, UK), a product commonly used in anaesthetic circle circuits in operating rooms.[2] There is controversy regarding the performance of these different sodalime preparations. For instance, an unpublished clinical study (which is nevertheless used in promotion of Spherasorb) concluded that Spherasorb has a 30% longer useful duration than Sofnolime 797,[3] and yet a recent diving fatality during use of an Inspiration rebreather was speculatively attributed to breakthrough with the use of Spherasorb.[2]

There is a conspicuous absence of available data from independent sources describing the relative CO_2 absorbing performance of these two sodalime preparations, particularly in the context of their use in CCRs. We undertook a laboratory study in which the primary outcome was comparison of their respective durations to significant CO_2 breakthrough when used in a CCR under conditions simulating moderate but sustainable underwater work. The null hypothesis was that there would be no difference in duration of use to reach a breakthrough PCO_2 of 1 kPa (7.5 mmHg). A secondary outcome was comparison of the difference between peak inspiratory and expiratory pressures generated when moving a tidal volume of 1.5 L around the rebreather loop during use of the two absorbents.

Methods

Although primarily a bench test study, development of the protocol required human participation and the study was approved by the University of Auckland Human Participation Ethics Committee (Reference 015280).

Figure 1
Schematic layout of the test circuit and monitoring equipment. See text for explanations



CHOICE OF EXPERIMENTAL PARAMETERS

For the purpose of our bench tests we aimed to reproduce conditions of moderate sustainable exertion in respect of ventilation (V_E), tidal volume (T_V), respiratory rate (RR), oxygen consumption ($\dot{V}O_2$) and CO_2 production ($\dot{V}CO_2$). It has previously been agreed that a sustained exercise intensity of 6 metabolic equivalents (MET; one MET equals an assumed resting metabolic rate oxygen consumption of 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$) is a plausible functional capacity standard for divers.[4] Therefore, a well-trained male diver (57 years, height 186 cm, weight 89 kg) exercised on an electronically-braked bicycle ergometer (Velotron, Racermate, Seattle, WA) at 6 MET whilst breathing on an Inspiration Evolution+ CCR (AP Diving, Helston, Cornwall) with a CO_2 scrubber canister packed with Sofnolime 797. The rebreather diluent gas was air, and the PO_2 set-point was 71 kPa (representing an inspired oxygen fraction of 70% at atmospheric pressure).

The inspiratory and expiratory hoses of the rebreather were modified to incorporate a low resistance one-way respiratory valve (5710, Hans Rudolf, Shawnee, KS, USA), which was ported to allow for continuous measurement of mouthpiece dead space gas composition, temperature, and pressure. A heated respiratory flow head (GAK-801 Hans Rudolph, Shawnee, KS, USA) was interposed in the exhale hose to measure ventilation. Gas composition was analysed using an infrared CO_2 sensor and optical O_2 detector (ML206 Gas Analyser, AD Instruments, Dunedin, New Zealand). All data were captured at 1 kHz using a Powerlab 16/35 and the LabChart 7 data acquisition and analysis system (AD Instruments, Dunedin, New Zealand), which was configured to provide real-time breath-by-breath analysis of all physiological variables. Exercise was performed for several hours ensuring stability of the data, with the diver resting for three minutes after every 30 minutes of exercise. During each rest period a gas flow calibration (3-L Calibration Syringe, Hans Rudolph, Shawnee, KS, USA) and gas concentration calibrations were performed, using a three-point calibration for O_2 and CO_2 with reference gases spanning the measurement range.

Using this method with the diver exercising at 6 MET we recorded a mean steady-state ventilation rate of 44 $L \cdot min^{-1}$ (T_V = 2.0 L, RR = 22 $breaths \cdot min^{-1}$) and CO_2 production of 2.0 $L \cdot min^{-1}$. The experimental parameters above, including rest periods every 30 minutes, were replicated for all subsequent bench test trials.

BENCH TEST CIRCUIT DESIGN

The inspiratory and expiratory hoses of an Inspiration Evo+™ rebreather were attached to a test circuit (Figure 1) using tubing adaptors (MLA304, AD Instruments, Dunedin, New Zealand) modified to include Tuohy-Borst instrument seals which provided ports for the introduction of respiratory

temperature probes (MLT415/DL, AD Instruments, Dunedin, New Zealand) routed to lie in the gas flow path just proximal and distal to the CO_2 scrubber canister. The scrubber canister was packed as described below with either Spherasorb or Sofnolime 797. As in the preliminary human study (above) the rebreather diluent gas was air, and the PO_2 set-point was 71 kPa (representing a circuit oxygen fraction of 70% at atmospheric pressure).

The test circuit conduit was composed of 35 mm (internal diameter) smooth bore respiratory tubing (MLA1015, AD Instruments, Dunedin, New Zealand) connected to a one-way respiratory valve (5710, Hans Rudolf, Shawnee, KS, USA). The valve assembly included ports within the mouthpiece dead space for sampling gas concentration and pressure. Sealed instrument adaptors were positioned proximal and distal to the inhale and exhale one-way valves, to measure inspired and expired gas temperatures. A clinical heater-humidifier (Fisher and Paykel Medical, Auckland, New Zealand) was incorporated into the exhale limb of the circuit to reproduce the heating and humidification of expired gas that would occur with a human breathing on the loop. The heating function was set to 34°C in all experiments.

Breathing (inspiratory/expiratory ratio 1:1) was simulated using a sinusoidal mechanical ventilator (17050-2 Lung Simulator, VacuMed, Ventura, CA, USA) with the T_V set at 1.5 L and the RR at 30 breaths·min^{-1} for all unmanned experiments. Ventilation was monitored via a pneumotachograph (800 L, Hans Rudolf, Shawnee, KS, USA) and these apparatuses were connected to a 4-L chamber where the inspired and expired gas mixed with instrument grade CO_2 introduced at 2 L·min^{-1} from a Douglas bag reservoir using a precision flow pump (R-2 Flow Controller, AEI Technologies, Pittsburgh, PA, USA). CO_2 flow was monitored and recorded using an independent flow transducer (MLT10L, AD Instruments, Dunedin, New Zealand). Operated in this mode with a functional CO_2 scrubber, the circuit consistently produced a physiologically authentic end-tidal CO_2 of 5–6 kPa at the mouthpiece dead space. Gas analysis and data acquisition for all parameters were performed as described for the human trial. Barometric pressure, environmental temperature and humidity were measured continuously via instruments (EE10 series monitor, E+E Elektronik, Engerwitzdorf, Austria) positioned adjacent to the test circuit.

CO_2 SCRUBBER CANISTER PACKING

All sodalime material was newly purchased, in date, and stored before use within the supplied sealed containers. The initial packing of the scrubber canister with both types of sodalime was supervised by an experienced instructor on the Inspiration rebreather. Usual practices designed to ensure proper distribution of material within the canister were employed. Emphasis was placed on ensuring an evenly distributed tight pack to eliminate the possibility of settling of material and channelling of gas flow which might cause inaccurate results. After the first supervised pack with each type, the sodalime was precisely weighed (before exposure to CO_2) using a laboratory balance (GM-11, Wedderburn Scales, Auckland, New Zealand) and precisely the same weight of the two materials was used for all subsequent experimental repetitions. The respective weights of the material after this standardised approach to packing were 2.64 kg for Sofnolime and 2.38 kg for Spherasorb. The presence of a greater mass of sodalime in a properly packed canister of Sofnolime resulted from the smaller granule size and implied an advantage in capacity for CO_2 removal (see later). However, since the aim of the study was to predict relative performance of the two materials in the 'real world' of rebreather diving and, since our packing weights reflected canisters packed appropriately for volume as would be done in normal use, it would have been inappropriate to balance the masses of the two materials in the study.

EXPERIMENTAL PROTOCOL

All trials were conducted in the Exercise Physiology Laboratory at the University of Auckland in air temperature and relative humidity of 19.4 ± 0.4°C, 54 ± 6.2%, respectively. The laboratory is effectively at sea level and mean ambient pressure was 101.9 ± 0.5 kPa. The rebreather was not immersed in water.

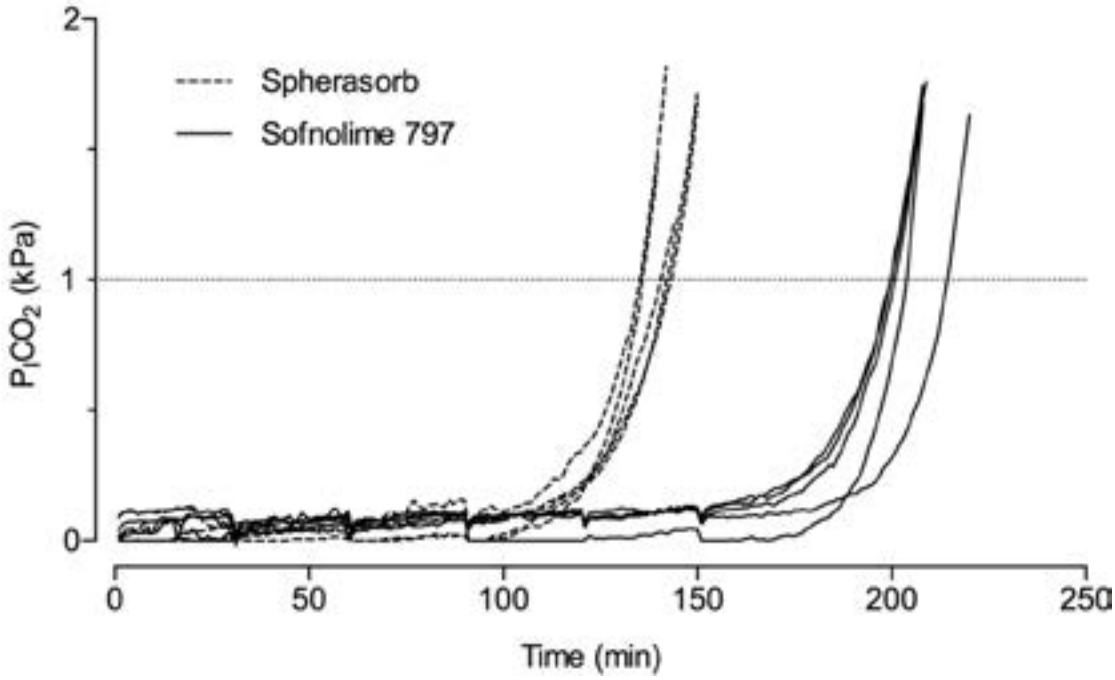
Packing of the scrubber was always conducted within 15 minutes of the start of the experiment. After assembly and positive pressure testing of the circuit, the rebreather was switched on and configured as described above. The heater-humidifier was switched on and the circuit was ventilated as previous described. After verification that circuit ventilation was taking place normally and that monitoring systems were working, the CO_2 flow (2 L·min^{-1}) was opened to the circuit at Time zero. Every 30 minutes thereafter the CO_2 flow and circuit ventilation were suspended as for the human trial (with elapsed time paused). During these rest periods any pooling condensate was removed from the circuit whilst gas flow and gas concentration sensors were recalibrated to external standards. The recalibration was considered necessary because of the potential for even a small error in inward CO_2 flow to confound the results.

The primary endpoint was the elapsed time for the PCO_2 in the inspired gas to reach 1 kPa (7.5 mmHg). To generate more complete CO_2 breakthrough curves the experiment was maintained until 10 minutes after the inspired CO_2 first reached 1 kPa. Ten trials were conducted in total; five using Spherasorb and five using Sofnolime, performed in no specific order.

STATISTICAL ANALYSIS

Times are shown as mean ± standard deviation (SD). A two-tailed Student's *t*-test was used to compare the mean

Figure 2
Breakthrough curves (P_ICO_2 versus time) for 10 trials in which scrubber canisters containing Spherasorb (5 trials) or Sofnolime (5 trials) were ventilated at 45 L·min^{-1} with introduction of CO_2 at 2 L·min^{-1}



elapsed time for the PCO_2 in the inspired gas to reach 1 kPa (7.5 mmHg) for the two sodalime preparations. An alpha value < 0.05 was taken to represent statistical significance.

Results

The elapsed times to reach an inspired PCO_2 of 1 kPa in each of the five trials for Spherasorb and Sofnolime are given in Table 1. The mean duration for Spherasorb was 68% that of a similar packed volume of Sofnolime, and the difference was both statistically significant ($P < 0.0001$) and practically important (being approximately one hour). Therefore, the null hypothesis was rejected. There was a 10% greater mass of Sofnolime in the volume, but the time to breakthrough was 46% longer. 'Breakthrough' curves for these trials are shown in Figure 2. It is clear that at this level of ventilation and CO_2 exposure the deterioration in scrubber canister function was precipitous once breakthrough began, irrespective of the sodalime preparation used.

The peak-to-peak inspiratory/expiratory pressure difference measured at the mouthpiece and averaged across all trials was 8.94 ± 0.29 mmHg for Spherasorb and 10.07 ± 0.63 mmHg for Sofnolime. Thus, in our experimental equipment configuration just over 10% more pressure was required to drive the same tidal volume around the loop when Sofnolime was used. This difference was statistically significant ($P < 0.003$). The temperature of gas entering the CO_2 canister typically was 30.5 ± 2.2°C. The temperature of gas immediately downstream of the CO_2 canister was considerably hotter (47.6 ± 10.7°C) due to the exothermic reaction between sodalime and CO_2.

Table 1
Elapsed time in minutes to reach a P_ICO_2 of 1 kPa in 10 trials in which scrubber canisters containing Spherasorb (5 trials) or Sofnolime (5 trials) were ventilated at 45 L·min^{-1} with introduction of CO_2 at 2 L·min^{-1}

Trial	Duration (min)	
	Spherasorb	**Sofnolime**
1	135	202
2	139	198
3	142	198
4	141	213
5	134	199
Mean ± SD (min)	138 ± 4	202 ± 6

Discussion

Our experiment exposed a commercially available diving rebreather to ventilation and incoming CO_2 at rates simulating moderate levels of physical exertion. It took, on average, just over an hour longer for CO_2 breakthrough to reach 1 kPa during use of Sofnolime 797 compared to Spherasorb. This outcome was a very consistent, reproducible finding with very small within-material variance.

This result contradicts that of the only other relevant comparison that we can find in the public domain.[3] That

study compared the total anaesthetic time in adult patients undergoing general anaesthesia before 1 kg of Spherasorb or Sofnolime allowed CO_2 breakthrough to 0.2 kPa in the inspiratory limb of the anaesthetic circuit. The author reported that Spherasorb lasted 30% longer than Sofnolime; an opposite finding to our result. However, the exact exposure of the CO_2 scrubber canisters to CO_2 was unknown, and the canisters were stored for unreported periods between cases. This makes the results difficult to interpret. The study was internally published in a Russian institution and has not appeared in the mainstream peer-reviewed medical literature.

One important difference between our methods and the Russian study is that the latter used equal masses of absorbent material (1 kg) whereas we used the mass of each material that achieved an optimal pack in the Inspiration CCR scrubber canister (2.64 kg for Sofnolime and 2.38 kg for Spherasorb). The greater mass (0.26 kg; 11%) of absorbent present in the Sofnolime-filled canister would be expected to result in a greater absorptive capacity. However, it seems implausible that this difference in mass alone accounts for the disparity in duration we recorded. Based on the performance of the Spherasorb canisters in our study, this material was capable of absorbing approximately 12 L $CO_2 \cdot 100\ g^{-1}$ of sodalime (calculated from: mean duration to breakthrough of 138 minutes at 2 L $CO_2 \cdot min^{-1}$ = 276 L ÷ 2.38 kg = 11.6 L·100·g^{-1}). Thus, another 0.26 kg of Spherasorb could be expected to absorb 2.6 x 11.6 L = 30.2 L. This accounts for only 25.2% of the extra 120 L of CO_2 the Sofnolime canisters were exposed to over their extra hour of operation.

We have not attempted to elucidate the explanation for the discrepancy in absorptive capacity between the two materials but it is likely to be due to their respective physical presentations. The Spherasorb granules are roughly spherical in shape and larger (4–8 mesh, 2.5–5 mm diameter) than the Sofnolime 797 granules (8–12 mesh, 1.5–2.5 mm) which are irregular in shape. It follows that Sofnolime absorbent material not only allows packing of a greater mass into a scrubber canister, but also presents a greater surface area to the passing gas. It seems reasonably well appreciated within the industry (even if not among the wider group of end users) that this is likely to result in greater absorptive capacity. Almost certainly for this reason the company that manufactures Spherasorb also produces a 8–12 mesh non-spherical product which (according to in-house testing) has similar absorptive capacity to Sofnolime.[5]

It is also possible that differences in chemical composition of the two products could contribute to different absorptive performance. The amount of calcium hydroxide present is the primary determinant of the amount of CO_2 that can be incorporated into calcium carbonate. The material datasheets for Sofnolime 797 and Spherasorb specify ">75%"[6] and "93.5%"[7] respectively. The preparations also contain sodium hydroxide (a recycling intermediary in the multistage chemical reaction[1]) at "<4%" and "1.5%" respectively. The imprecision in the reported composition of Sofnolime makes direct comparison difficult and detailed analysis of the chemical engineering of these products is not essential to the practical interpretation of our results by divers.

Although its lower absorptive capacity may be a disadvantage, the use of Spherasorb is probably also associated with a lower work of breathing compared to the finer grain Sofnolime material. This may be an advantage in certain circumstances; particularly in Spherasorb's intended medical applications when CO_2 production and respiratory minute volumes are usually much lower. We recorded an approximate 10% reduction in the difference between peak inspiratory and expiratory pressures when using Spherasorb in comparison with Sofnolime. Given the artificial nature of our circuit (which was not immersed and included long hoses and a heater-humidifier) we can draw no quantitative conclusions about the effect of Spherasorb on work of breathing when diving on a rebreather.

It is pertinent to clarify several of the methodological choices we made in this study. Firstly, the studies were conducted with the rebreather not immersed. Testing protocols for establishing the duration of a rebreather scrubber canister typically include immersion of the rebreather in cold water because this is known to reduce scrubber efficiency. We chose not to do this because the goal of our study was to compare the absorptive capacity of two absorbents rather than to generate definitive guidelines on predicted duration. Since both absorbents were operated under identical conditions we believe the comparison of efficiency is valid. We acknowledge it is likely that both materials would have returned shorter durations if the experiment had been conducted in cold water and we cannot exclude the possibility that extreme cold might disproportionately affect performance of the preparations.

Secondly, we chose a P_ICO_2 of 1 kPa as a simple, easily understood, but admittedly arbitrary endpoint for the comparative experiment. We provide the breakthrough curves so that readers can satisfy themselves that changing the inspired CO_2 endpoint would not alter the conclusions. For experiments aiming to establish recommendations for safe duration of CO_2 scrubber canisters in diving we concur with other commentators who advocate conservative (low) limits,[8] and consider a breakthrough P_ICO_2 of 0.5 kPa to be an appropriate choice of endpoint in that setting.

Conclusions

In a simulation of sustained moderate exercise with an Inspiration rebreather, 2.38 kg of Spherasorb CO_2 absorbent allowed CO_2 breakthough (P_ICO_2 = 1 kPa) into the inhaled gas after a significantly shorter period (138 min) than 2.64 kg of Sofnolime 797 (202 min). Thus, the simple but important message for divers using rebreathers is that they cannot alternate between materials and expect the same CO_2-absorbing performance from both.

References

1 Doolette DJ, Mitchell SJ. Hyperbaric conditions. *Compr Physiol*. 2011;1:163-201.

2 CCR Explorers rebreather diving forum. [cited 2016 January 31]. Available at: http://www.ccrexplorers.com/showthread.php?t=18518&highlight=spherasorb.

3 Intersurgical complete respiratory systems [Internet]. Citing: Lihvansev VV. The final report on two brand name sodalimes comparative testing SPHERASORB (Intersurgical, Great Britain) and SOFNOLIME (Molecular Products, Great Britain) [Internet]. Moscow 2000, Moscow Scientific Anaesthetic Society. [cited 2016 May 04]. Available at: http://www.exhausmed.com/docs/Intersurgical/2007/Videos/titlesphera.swf.

4 Mitchell SJ, Bove AA. Medical screening of recreational divers for cardiovascular disease: Consensus discussion at the Divers Alert Network Fatality Workshop. *Undersea Hyperb Med*. 2011;38:289-96.

5 Holder M. *Technical datasheet. Intersorb 8 to 12 mesh indicating and non-indicating comparison with Sofnolime 797*. Berkshire UK, 2010: [cited 2016 February 01]. Available at: http://www.divelong.com/files/test-data1.pdf.

6 Molecular Products, *Sofnolime Safety Datasheet. Revision 1 June 2015*. [cited 2016 April 28]. Available at: http://www.molecularproducts.com/us/products/n1025p40l02/sofnolime-797-non-indicating/details.

7 Intersurgical products. *Spherasorb medical grade soda lime information sheet*. [cited 2016 April 28]. Available at: http://www.intersurgical.com/products/anaesthesia/spherasorb-medical-grade-soda-lime.

8 Shykoff BE, Warkander DE. Exercise carbon dioxide (CO_2) retention with inhaled CO_2 and breathing resistance. *Undersea Hyperb Med.* 2012;39:815-28.

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