Technical report

Performance of cartridge and granular carbon dioxide absorbents in a closed-circuit diving rebreather

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Key words
Technical diving; Closed-circuit rebreather; Carbon dioxide; Soda lime; Scrubber; Hypercapnia

Abstract
(Gant N, van Waart H, Ashworth ET, Mesley P, Mitchell SJ. Performance of cartridge and granular carbon dioxide absorbents in a closed-circuit diving rebreather. Diving and Hyperbaric Medicine. 2019 December 20;49(4):298–303. doi: 10.28920/dhm49.4.298-303. PMID: 31828749.)
Introduction: Scrubbers in closed-circuit rebreather systems remove carbon dioxide (CO_2) from the exhaled gas. In an attempt to be more user-friendly and efficient, the ExtendAir® non-granular, pre-formed scrubber cartridge has been developed. The cartridge manufacturer claims twice the absorptive capacity of granular CO_2 absorbent, with less variability, lower work of breathing, and reduced exposure to caustic chemicals after a flood. To our knowledge there are no published data that support these claims.
Methods: Cartridge (ExtendAir®) and granular (Sofnolime® 797) scrubbers of equal volume and mass were tested five times in an immersed and mechanically ventilated O_2ptima rebreather. Exercise protocols involving staged (90 minutes 6 MET, followed by 2 MET) and continuous (6 MET) activity were simulated. We compared: duration until breakthrough, and variability in duration, to endpoints of 1.0 kPa and 0.5 kPa inspired partial pressure of CO_2; inspiratory–expiratory pressure difference in the breathing loop; and pH of eluted water after a 5 minute flood.
Results: Mean difference in scrubber endurance was 0–20 % in favour of the ExtendAir® cartridge, depending on exercise protocol and chosen CO_2 endpoint. There were no meaningful differences in endpoint variability, inspiratory–expiratory pressure in the loop, or pH in the eluted water after a flood.
Conclusions: Cartridge and granular scrubbers were very similar in duration, variability, ventilation pressures, and causticity after a flood. Our findings were not consistent with claims of substantial superiority for the ExtendAir® cartridge.

Introduction

In closed-circuit rebreather (CCR) diving, divers rebreathe recycled expired gas. Since humans consume oxygen and produce carbon dioxide (CO_2), these gases need to be added to and removed from the breathing 'loop' respectively. CO_2 is removed by a chemical reaction with a 'scrubber' material; typically 'soda lime', which is a granular compound mix of sodium hydroxide (NaOH), calcium hydroxide ($Ca(OH)_2$) and water. This reaction produces calcium carbonate ($CaCO_3$) and water. When there is reduced $Ca(OH)_2$ remaining in the scrubber material, expired CO_2 can 'break through' and be rebreathed by the diver. Breakthrough can also occur if soda lime is improperly packed in the scrubber canister such that CO_2 can pass through without reacting (often referred to as 'channelling'), or if the canister is improperly installed thus allowing 'bypass'. Rebreathing CO_2 reduces the efficacy of ventilation in elimination of CO_2 from the body and can lead to hypercapnia. This may produce hazardous symptoms such as dyspnoea and anxiety and can ultimately result in the diver losing consciousness.[1]

With the above in mind, there is a strong focus among rebreather divers on not exceeding effective scrubber absorptive capacity, and on proper packing and installation of scrubber canisters. An alternative to packing scrubbers with loose granular soda lime preparations are so-called scrubber cartridges (ExtendAir® 801C, Micropore, Newark DE, USA). These single-use products are intended to optimise absorptive capacity, eliminate packing and simplify installation. The cartridge is manufactured by wrapping sheets of absorbent compound around a core in a spiral arrangement, with pre-formed linear channels allowing axial gas flow through the cartridge (Figure 1). ExtendAir® cartridges are putatively claimed to: 1) Out last a granular system (presumably of similar mass or volume) by two times

Figure 1
Micropore ExtendAir® 801C CO_2 scrubber cartridges

or more; 2) Exhibit less variation in duration at any test condition (± 5 % versus ± 30 % using granules); 3) Exhibit 8.5 % lower work of breathing; 4) Produce 70 % less caustic contamination after a 5 minute flood of a rebreather.[2–5] This latter claim relates to the known propensity for soda lime to produce an extremely alkaline liquid when in contact with water. If a soda lime scrubber canister becomes partially flooded and if the contaminated water reaches the diver in the breathing loop, it can cause chemical burns to the mouth and airway.

There are no publicly available data to support these claims. Therefore, we undertook a laboratory study in which we compared ExtendAir® cartridges to a matched canister volume of granular soda lime preparation in respect of scrubber duration; variability in duration; resistance to ventilation; and caustic potential. Our primary aim was to establish whether (or not) there was indicative support for the various claims of superiority for ExtendAir® cartridges in relation to these parameters when compared under a limited set of conditions.

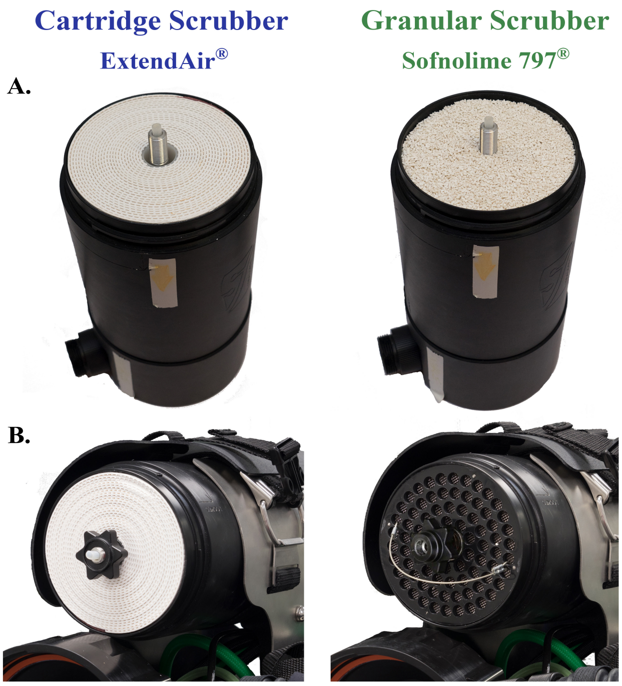
Methods

SCRUBBERS

In this bench test we compared ExtendAir® 801C CO_2 absorbent cartridges (Micropore, Newark, USA) to canisters containing Sofnolime® 797 granular soda lime (Molecular Products, Harlow, UK). The ExtendAir® cartridge absorbent material contains $Ca(OH)_2$ (> 85%), NaOH (3%) and potassium hydroxide (KOH, 2%),[5] whereas the Sofnolime® 797 granules contain $Ca(OH)_2$ (> 75%), NaOH (< 4%).[6]

To ensure a meaningful comparison, we utilised an O$_2$ptima closed-circuit rebreather (Dive Rite, Lake City, USA) which is designed to accept either an ExtendAir® cartridge or equivalent volume of granular soda lime in the same scrubber canister (Figure 2). All scrubber products

Figure 2
A) Scrubber canisters shown with ExtendAir® cartridge installed (left) and packed with Sofnolime® 797 granular absorbent (right). B) Assembled scrubbers installed in the Dive Rite O$_2$ptima closed-circuit rebreather. Granular absorbent is retained with a stainless-steel scrim (right)



had been recently purchased, were in date and had been appropriately stored within the supplied sealed packaging prior to use. The ExtendAir® cartridges weighed 2.15 kg and Sofnolime® 797 granular scrubbers, packed by an experienced rebreather instructor, weighed 2.08 kg for all trials. Granular absorbent was measured by mass (GM-11 laboratory balance, Wedderburn Scales, Auckland, New Zealand) and packed to equivalent volume, then assembled within 5 minutes, and trials commenced within 15 minutes. The timings for cartridge scrubber assembly were aligned with the granular scrubber packing.

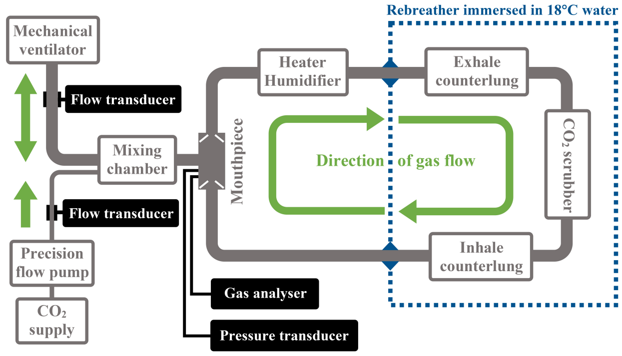
EXPERIMENTAL SET-UP

The study was conducted in the Exercise Physiology Laboratory at the University of Auckland. All experiments were conducted with the rebreather submerged in an upright position at surface pressure (approximately 1 atmosphere or 101.3 kPa). The air and water temperature were maintained throughout the experiment at 18°C.

Details of the bench test apparatus have been published previously.[7] Briefly, the inspiratory and expiratory hoses of the submerged O$_2$ptima rebreather were attached to a test circuit (Figure 3) using tubing adaptors (MLA304, AD Instruments, Dunedin, New Zealand). The test circuit conduit was composed of 35 mm 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 mouthpiece

Figure 3

A schematic layout of the experimental test circuit (grey) and monitoring equipment (black). See text for explanation



included a port for sampling deadspace gas for analysis of CO_2 during inspiration and a port for measuring pressure in the mouthpiece throughout the respiratory cycle. A clinical heater humidifier (Fisher and Paykel Medical, Auckland, New Zealand) reproduced heating (set to 34°C) and humidification of expired gas that would occur with a human breathing on the loop.

Breathing was simulated using a sinusoidal mechanical ventilator (17050-2 Lung Simulator, VacuMed, Ventura, USA) with an inspiratory/expiratory ratio of 1:1. Mixing of gases within the lungs was simulated using a 4 L chamber where CO_2 was added from a Douglas bag reservoir using a precision flow pump (R-2 Flow Controller, AEI Technologies, Pittsburgh, USA) to the inspired gas from the rebreather loop.

Every 30 minutes the trial (and endurance time) was paused, to remove condensation from the loop and to recalibrate gas flow and gas analysers. This recalibration ensured accurate CO_2 addition, for consistent trials. All data were sampled at 1 kHz using Powerlab 16/35 and LabChart 7 data acquisition and analysis system (AD Instruments, Dunedin, New Zealand).

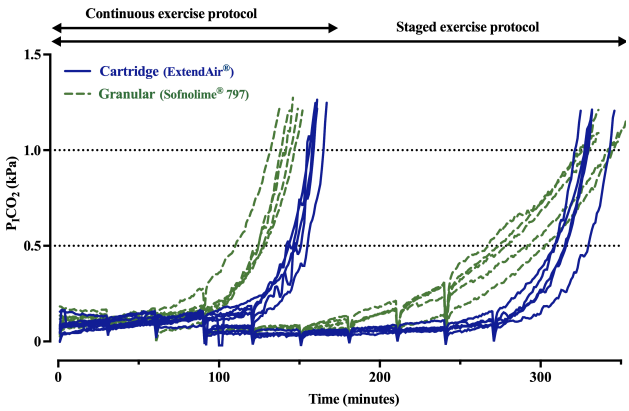
The diluent gas was air, and the rebreather oxygen set point was 0.7 atmospheres (71 kPa), representing a circuit oxygen fraction of ~70 % at atmospheric pressure).

EXERCISE PROTOCOLS

Each scrubber type was subjected to ventilation and CO_2 addition parameters simulating two exercise protocols: 1) staged exercise; 2) continuous moderate exercise. The staged exercise protocol was intended to resemble a typical dive, with a 90 minute period notionally representing the descent and bottom phase with moderate exercise intensity (6 MET ~ oxygen uptake 21 ml·kg^{-1}·min^{-1}), followed by a lower intensity period (2 MET ~ oxygen uptake 7 ml·kg^{-1}·min^{-1}) notionally representing the resting decompression phase. This low intensity phase continued until the inspired partial pressure of CO_2 (P_ICO_2) rose to 1.0 kPa (breakthrough).

Figure 4

Breakthrough curves for granular (green dashed lines; Sofnolime® 797) and cartridge (blue lines; ExtendAir®) scrubbers. Inspired partial pressure of CO_2 (P_ICO_2) is plotted for two exercise protocols; continuous exercise (6 MET, left side); and staged exercise (6 MET for 90 minutes followed by 2 MET until breakthrough, right side). Horizontal dotted lines highlight CO_2 breakthrough endpoints of P_ICO_2 0.5 and 1.0 kPa



The continuous exercise protocol has been used previously,[7] and utilises ventilation and CO_2 addition parameters simulating continuous 6 MET exercise from the beginning of the experiment until breakthrough. During the 6 MET exercise the minute ventilation was set to 45 L·min^{-1}, with a tidal volume of 1.5 L and a respiratory rate of 30 breaths per minute; CO_2 was added at a rate of 2 L·min^{-1}. During the 2 MET exercise minute ventilation was reduced to 17 L·min^{-1} (tidal volume of 1.0 L and 17 breaths per minute), and CO_2 was added at a rate of 0.67 L·min^{-1}. The respiratory volumes and CO_2 flows were independently verified using a pneumotachograph (800 L, Hans Rudolf, Shawnee, USA) and an independent flow transducer (MLTJOL, AD Instruments, Dunedin, New Zealand) respectively.

SCRUBBER FLOODING

We exposed five unused scrubber canisters packed with both types of scrubber material to a simulated flood by completely flooding the rebreather scrubber compartment with fresh water with the scrubber canister in situ. After 5 minutes of immersion, the scrubber cartridge or granules were removed and the pH of residual water within in the scrubber canister was measured (pH meter 9532000, Hach, Loveland, USA).

OUTCOME MEASURES

1) Scrubber duration. We compared the mean time to breakthrough of 1.0 kPa P_ICO_2 in the two scrubber types for both the staged and continuous exercise protocols. A secondary endpoint of breakthrough to P_ICO_2 0.5 kPa was retrospectively analysed.
2) Duration variability. We compared variability within scrubber types by calculating a coefficient of variation (%) for both exercise protocols.
3) Ventilation pressures. The mean peak-to-nadir expiratory/

Table 1
Scrubber duration (minutes) to breakthrough, variation in duration (%), peak-to-nadir expiratory/inspiratory loop pressures (kPa) during ventilation, and pH of water eluted from flooded granular (Sofnolime® 797) and cartridge (ExtendAir®) scrubbers. Breakthrough endpoints of 0.5 and 1.0 kPa inspired partial pressure of CO_2 (P_ICO_2) are shown for staged exercise (6 MET for 90 minutes followed by 2 MET to breakthrough) and continuous exercise (6 MET) protocols; standard deviation (SD); coefficient of variation (CV); mean difference (MD) with 95% confidence interval [95% CI]

	P_ICO_2	**Cartridge** (ExtendAir®)		**Granular** (Sofnolime®)		**Cartridge** (ExtendAir®) **versus Granular** (Sofnolime®)	
		Mean (SD)	CV	Mean (SD)	CV	MD [95% CI]	*P*-value
Scrubber duration (min)							
Staged exercise	**1 kPa**	329 (8)	2.4%	330 (10)	3.1%	-1 [-14 to 12]	0.89
	0.5 kPa	314 (9)	2.9%	278 (14)	5.2%	36 [19 to 54]	0.001
Continuous exercise	**1 kPa**	158 (4)	2.5%	139 (6)	4.2%	19 [11 to 26]	< 0.001
	0.5 kPa	144 (6)	5.8%	120 (7)	5.9%	24 [14 to 33]	< 0.001
Ventilation pressures (kPa)							
Staged exercise		0.57 (0.04)		0.63 (0.04)		-0.06 [-0.11 to 0.00]	0.053
Continuous exercise		1.23 (0.27)		1.18 (0.11)		0.04 [-0.25 to 0.34]	0.75
Causticity							
pH (flooded scrubber)		12.8 (0.0)		12.7 (0.1)		0.2 [0.1 to 0.3]	0.009

inspiratory pressure difference measured at the mouthpiece was taken as a surrogate index of breathing performance. This measure was calculated for both scrubber types during the two exercise protocols.
4) Causticity. We compared the mean pH of water eluted from the five flooded scrubbers of each type in order to estimate the causticity of a contaminated solution that might be inhaled or ingested by the diver.

SAMPLE SIZE AND STATISTICAL ANALYSES

In accordance with testing protocols recommended by the Navy Experimental Diving Unit (NEDU)[8] we used a sample size of 5 for each scrubber type and exercise protocol. Therefore, in total twenty trials were conducted in no specific order; five ExtendAir® cartridges, and five Sofnolime® granule scrubber canisters in both exercise protocols.

Mean and standard deviation (SD) are provided for scrubber duration, ventilation pressures and pH. Independent samples *t*-tests, with α set at 5%, were used to compare the mean differences in scrubber duration, ventilation pressures and pH alongside 95% confidence intervals (CI).

Results

In the staged exercise protocol, cartridge and granular scrubbers exhibited equal duration (0% difference) at the P_ICO_2 endpoint of 1.0 kPa P_ICO_2. The gradient of breakthrough was steeper for cartridges compared to granular absorbent, as highlighted by the mean difference of 36 minutes (13%) at the P_ICO_2 endpoint of 0.5 kPa (Table 1 and Figure 4). Not surprisingly, the continuous exercise protocol resulted in much shorter breakthrough times compared to the staged exercise protocol. In this protocol the cartridges outperformed the granules by 14% (mean difference of 19 minutes) and 20% (mean difference of 24 minutes) at the P_ICO_2 endpoints of 1.0 kPa and 0.5 kPa, respectively (Table 1 and Figure 4).

The between-trial variability in scrubber duration was similar for both types of scrubbers in all conditions (Table 1), with granular scrubbers exhibiting slightly more variability than cartridges in every condition. The absolute deviation for both scrubber types was low, being always less than 6 % of total duration.

There was no difference between the cartridge and granular scrubbers in mean peak-to-nadir expiratory/inspiratory pressure difference measured at the mouthpiece in either the 6 MET or 6 then 2 MET simulated exercise conditions (Table 1).

After flooding both scrubbers for 5 minutes, the eluted water became extremely alkaline; slightly more so for the cartridge (ExtendAir® cartridge pH = 12.85 (SD 0.04) vs. pH = 12.66 (0.12) for the Sofnolime® granules, Table 1).

Discussion

This comparison of a cartridge and a granular scrubber of identical volume and similar mass in the O_2ptima closed-circuit rebreather revealed few practically important differences.

DURATION

Scrubber duration is similar between the two types, though there are differences depending on the exercise protocol and chosen endpoint.

We tested two exercise protocols; a staged exercise protocol and a continuous exercise protocol. Because of the reduced exercise intensity (with proportionally decreased CO_2

addition and minute volumes), endurance time (for either scrubber type) was more than twice as long in the staged compared to the continuous exercise protocol. Although continuous moderate exercise is commonly simulated in endurance testing, staged exercise arguably has a higher relevance to actual diving, with a higher intensity for 90 minutes simulating the descent and bottom phase, followed by a lower intensity period simulating the decompression phase.

The European standard EN 14143 for rebreather testing,[9] recommends that manufactures should report their CO_2 scrubber endurance time at the lower breakthrough threshold of 0.5 kPa. We report both 0.5 kPa and 1.0 kPa but chose 1.0 kPa as our primary breakthrough endpoint as this level of inspired CO_2 is an indisputable physiological hazard.

During the staged exercise protocol both scrubber types had virtually identical CO_2 breakthrough duration at the 1.0 kPa endpoint. The striking difference was that breakthrough in the granular scrubbers was more gradual (Figure 4) meaning that the P_ICO_2 for Sofnolime® reached the 0.5 kPa secondary breakthrough endpoint on average 36 minutes earlier than the ExtendAir® cartridges (Table 1). It is possible to speculate that either pattern of breakthrough is an advantage or disadvantage. For example, if a diver is symptomatically sensitive to an increase in CO_2, the more gradual breakthrough in the granular scrubber could provide an earlier warning signal. However, it has been shown that divers are particularly bad in detecting high CO_2 levels, and can retain CO_2, sometimes even without obvious symptoms or major adjustments in ventilation.[10] On that basis, the longer period with lower inspired CO_2 (and less danger of CO_2 retention) associated with the ExtendAir® cartridge could therefore be considered advantageous. During the continuous exercise protocol both canisters exhibited a similar exponentially increasing pattern of CO_2 accumulation (Figure 4), and the ExtendAir® canister exhibited a longer duration to breakthrough using either endpoint criteria (Table 1). However, longer durations for cartridges in our study (24 minutes for 0.5 kPa breakthrough and 19 minutes for 1.0 kPa breakthrough) were considerably less than the claimed doubling of duration published in the ExtendAir® cartridge manufacturer's promotional material,[2] despite the fact that the comparison was made with a granular canister of equal volume and almost identical weight.

In the latter regard, the ExtendAir® scrubbers were slightly heavier (3%) than those packed with granular scrubber material. In theory more scrubber material could account for higher endurance times. However, the ExtendAir® canister also included structural plastic material that does not contribute to the chemical reaction which suggests that it is more efficient. This higher efficiency could be explained by a different amount of catalyst in the ExtendAir® canister (5%) versus the granular soda lime (< 4%) and/or the type of catalyst (respectively, KOH + NaOH versus only NaOH). The cartridge also potentially has a higher amount of active absorbent $Ca(OH)_2$, although the datasheets of both scrubbers are ambiguous on the exact amount in both (respectively, > 85% and > 75%). One related point which is obvious but needs to be made, is that the present comparison was made between cartridge and granular absorbents of near identical volume and weight in a rebreather canister designed to take both types. This seemed a pragmatic and ecologically valid approach to the comparison. However, most rebreathers utilising granular soda lime incorporate canisters of greater volume which contain a greater mass of soda lime. These higher capacity systems will last longer. For example, in a recent study in which a different rebreather with a scrubber canister containing 2.64 kg of soda lime (Sofnolime® 797) was operated in the identical continuous exercise protocol as used in the present study, the mean duration to breakthrough at P_ICO_2 of 1.0 kPa was 202 min.[7] There is no equivalent option of increasing the size of ExtendAir® cartridges.

VARIABILITY IN DURATION

Both canister types exhibited similar between-trial variation in breakthrough endpoint (less than 6% in either exercise protocol). This casts some doubt on the ExtendAir® cartridge manufacturer's marketing claim that granular scrubbers have a much higher variability. Also, we must acknowledge that our test granular canisters were packed by an experienced operator using precisely weighed masses of soda lime, and thus with a superior degree of consistency that is unlikely to be replicated in the real world. To properly pack a granular scrubber, some training and practice is necessary, whereas ExtendAir® canisters require no packing prior to assembly. The evidential basis for the claim that granular canisters exhibit much greater variability in duration is not specified,[2] but the possibility that variability is greater during real world use than found in the present study cannot be excluded.

CIRCUIT PRESSURES

Though an imperfect surrogate, the peak-to-nadir expiratory/inspiratory pressure difference in the loop can be regarded as an index of breathing performance. The present tests demonstrated no difference between the two scrubber types tested. However, as with the variability in duration, this result must also be interpreted with some caution. The experiments were conducted at atmospheric pressure, and we cannot exclude the possibility that a relevant advantage or disadvantage for the ExtendAir® cartridges might become apparent when they are operated at greater depth and gas densities.

CAUSTICITY

After a five minute flood, both scrubber canisters eluted water with a pH of almost 13 that would be extremely caustic and result in serious injuries if inhaled or ingested. This result appears to contrast with the manufacturer's claim that the ExtendAir® cartridge would be 70% less caustic than granular absorbent.

We did not evaluate the possibility of caustic inhalation of soda lime dust during the packing phase of a granular scrubber canister. The manufacturers of Sofnolime® expect that the risk of caustic powder inhalation is negligible since the caustic chemicals are contained in a pellet.[6] In contrast to inhalations of caustic water during use of a rebreather, the authors are unaware of clinically significant inhalations of dust during granular scrubber canister packing, so it is probably an extremely rare event. Nevertheless, it is acknowledged that the lack of a requirement to pack loose material containing fine particles is a theoretical advantage of the ExtendAir® cartridge.

LIMITATIONS

This study has some limitations that must be acknowledged.

First, the scrubber canisters were operated at surface pressure and in temperate water. Operation of scrubbers at greater pressures (and with denser gases) and at lower temperatures is known to affect duration (typically adversely). It must therefore be explicitly understood that the purpose of the study was not to define expected durations, but rather to compare two different scrubber types under a set of standardised conditions. These data cannot be used to formulate usage guidelines for either of the scrubber materials tested. Similarly, other granular products (8–12 mesh) may be used in this rebreather and produce differing outcomes.

Second, and in a related vein, these experiments were undertaken in a narrow range of pressure, temperature, and simulated exercise conditions that are limited compared to the myriad of possible combinations encountered in diving. Our experiments examined scrubber endurance under sub-maximal exercise conditions and did not include a maximal capacity breakthrough challenge, such as introducing 3 $L{\cdot}min^{-1}$ CO_2 with ventilation set to 75 $L{\cdot}min^{-1}$ at 6 MFW, as required for European Standard EN 14143.[9] Extrapolation of the comparisons to scenarios with other combinations of these variables must therefore be made with caution. Nevertheless, with the possible exception of the effects of gas density on work of breathing (acknowledged earlier), there is no obvious reason to believe that varying conditions would preferentially advantage or disadvantage one scrubber type over another.

A strength of the bench test design was a rigorously standardised comparison. The use of a rebreather canister explicitly designed to accept either type of scrubber resulted in a comparison that seemed equitable.

Conclusions

In a comparison of CO_2 absorbent cartridges and granular soda lime canisters occupying identical volumes and of comparable mass, no evidence was found to support claims that the cartridge scrubber (ExtendAir®) would exhibit double the duration, less variability in duration, lower work of breathing, or produce a less caustic solution when flooded, than a granular product (Sofnolime®). During submaximal testing, both types of CO_2 scrubbers operated effectively in a closed-circuit rebreather and the preferred scrubber material may depend on other factors such as availability, costs and preference of the diver.

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Acknowledgements

We thank Lamar Hires of Dive Rite, Jacksonville, FL, USA, for the loan of an O_2ptima closed-circuit rebreather.

Conflicts of interest and funding

This work was supported by a grant from Shearwater Research, Vancouver, Canada.

Submitted: 29 April 2019
Accepted after revision: 22 September 2019