# Technical report

## The performance of 'temperature stick' carbon dioxide absorbent monitors in diving rebreathers

Mårten Silvanius[1,4], Simon J Mitchell[2], Neal W Pollock[3], Oskar Frånberg[4], Mikael Gennser[5], Jerry Lindén[1], Peter Mesley[6], Nicholas Gant[7]

[1] *Swedish Armed Forces Diving and Naval Medicine Centre, Karlskrona, Sweden*
[2] *Department of Anaesthesiology, University of Auckland, Auckland, New Zealand*
[3] *Department of Kinesiology, Université Laval Québec, QC, Canada*
[4] *Blekinge Institute of Technology, Karlskrona, Sweden*
[5] *School of Technology and Health, KTH Royal Institute of Technology, Stockholm, Sweden*
[6] *Lust for Rust Diving Expeditions, Auckland*
[7] *Department of Exercise Sciences, University of Auckland*

***Corresponding author:*** *Nicholas Gant, Department of Exercise Sciences, Centre for Brain Research, University of Auckland, Auckland 1142, New Zealand*
*n.gant@auckland.ac.nz*

**Key words**
Hypercapnia; Monitoring; Technical diving; Soda lime; Equipment

**Abstract**
(Silvanius M, Mitchell SJ, Pollock NW, Frånberg O, Gennser M, Lindén J, Mesley P, Gant N. The performance of 'temperature stick' carbon dioxide absorbent monitors in diving rebreathers. Diving and Hyperbaric Medicine. 2019 March 31;49(1):48–56. doi: 10.28920/dhm49.1.48-56. PMID: 30856667.)
**Introduction:** Diving rebreathers use canisters containing soda lime to remove carbon dioxide ($CO_2$) from expired gas. Soda lime has a finite ability to absorb $CO_2$. Temperature sticks monitor the exothermic reaction between $CO_2$ and soda lime to predict remaining absorptive capacity. The accuracy of these predictions was investigated in two rebreathers that utilise temperature sticks.
**Methods:** Inspiration and rEvo rebreathers filled with new soda lime were immersed in water at 19°C and operated on mechanical circuits whose ventilation and $CO_2$-addition parameters simulated dives involving either moderate exercise (6 MET) throughout (mod-ex), or 90 minutes of 6 MET exercise followed by 2 MET exercise (low-ex) until breakthrough (inspired $PCO_2$ [$P_iCO_2$] = 1 kPa). Simulated dives were conducted at surface pressure (sea-level) (low-ex: Inspiration, *n* = 5; rEvo, *n* = 5; mod-ex: Inspiration, *n* = 7, rEvo, *n* = 5) and at 3–6 metres' sea water (msw) depth (mod-ex protocol only: Inspiration, *n* = 8; rEvo, *n* = 5).
**Results:** Operated at surface pressure, both rebreathers warned appropriately in four o five low-ex tests but failed to do so in the 12 mod-ex tests. At 3–6 msw depth, warnings preceded breakthrough in 11 of 13 mod-ex tests. The rEvo warned conservatively in all five tests (approximately 60 minutes prior). Inspiration warnings immediately preceded breakthrough in six of eight tests, but were marginally late in one test and 13 minutes late in another.
**Conclusion:** When operated at even shallow depth, temperature sticks provided timely warning of significant $CO_2$ breakthrough in the scenarios examined. They are much less accurate during simulated exercise at surface pressure.

## Introduction

A closed circuit rebreather is a type of underwater breathing apparatus that recycles expired gas through a carbon dioxide ($CO_2$) absorbent and incorporates a gas addition system designed to maintain both a safe inspired pressure of oxygen ($P_iO_2$) and an appropriate mix of diluent gases. They are popular with so-called 'technical divers' and scientific divers performing deep and/or long dives because the recycling of expired breath markedly reduces use of expensive gases such as helium, and maintenance of a constant optimal $P_iO_2$ increases decompression efficiency.[1]

There are several forms of $CO_2$ absorbent, but the most commonly used is soda lime; a granular compound containing calcium hydroxide, water and sodium hydroxide. This is packed in a canister (often referred to as a 'scrubber') through which the exhaled gas is passed. Soda lime has a finite capacity for absorbing $CO_2$ and, if this capacity is exceeded, $CO_2$ will 'break through' the scrubber and its re-inhalation by the diver may lead to dangerous hypercapnia. Therefore, the soda lime must be replaced in a timely fashion. Rebreather manufacturers provide guidelines on scrubber canister duration, based on tests conducted under demanding conditions with high simulated $CO_2$ production and low water temperature, which divers may consider to be conservative. Anecdotally, this often results in divers using soda lime for longer than recommended based on their previous experience and best guesses on expected duration.

In an attempt to bring some objectivity to determining safe duration of use of soda lime, several manufacturers have incorporated so-called 'temperature sticks' into the scrubber canister to monitor the exothermic reaction between $CO_2$ and soda lime. These devices are comprised of an array of thermistors that pass through the soda lime bed, and they apply proprietary algorithms to interpret the distal movement of the reaction as it progresses through the canister while proximal exhausted soda lime cools. Proximal in this context refers to the end of the scrubber canister where the exhaled gas enters. Two very popular rebreathers utilising temperature sticks are the Inspiration™ rebreather (Ambient Pressure Diving, Helston, Cornwall, UK), and the rEvo™ rebreather (rEvo Rebreathers, Brussels, Belgium).

The Inspiration rebreather control display notionally depicts the temperature profile in the soda lime bed as a bar that turns from clear to black as the scrubber heats up early in the dive, and then progressively (in six steps from proximal to distal) turns from black to clear as the reaction decreases. When the display has only one black step left, which has been designed to occur prior to a $P_iCO_2$ of 0.5 kPa, the diver receives a warning. The display bar is designed to become completely clear prior to a $P_iCO_2$ of 1 kPa, at which point the diver is advised to 'bail-out' off the rebreather and onto an open-circuit gas supply.

Soda lime in the rEvo is divided into two smaller separate canisters connected in series by a short conduit. Each canister has its own temperature stick. This configuration facilitates a cycling regimen between shorter dives whereby the proximal heavily used canister is discarded, the less consumed distal canister is moved into the proximal position and a new canister is placed in the distal position. The idea is to avoid discarding an entire canister containing a lot of unconsumed soda lime after a short dive. The temperature stick algorithm counts down a time (in minutes) to the point beyond which cycling (as above) is no longer considered appropriate. If the dive duration exceeds this cycling time threshold, then the two scrubbers are treated as one and the algorithm counts down a "*remaining scrubber time*" in minutes.

This presentation of information that is analogous to a $CO_2$ scrubber 'fuel gauge' inevitably invites the diver to interpret the data literally, and to base important decisions about conduct of the dive on the temperature stick. This requires that the temperature stick predictions of remaining scrubber life are reasonably accurate in the majority of plausible scenarios. Other than a reference to "*experimentally determined calibration*" in the patent describing the rEvo temperature stick[2] and an abstract alleging successful development of the same device,[3] no data could be found in the public domain describing the accuracy of these devices. Therefore, the ability of these rebreathers to predict $CO_2$ breakthrough was tested. The question in respect of both the Inspiration and rEvo devices was: would the temperature stick warn the diver prior to significant $CO_2$ breakthrough during simulated dives?

**Methods**

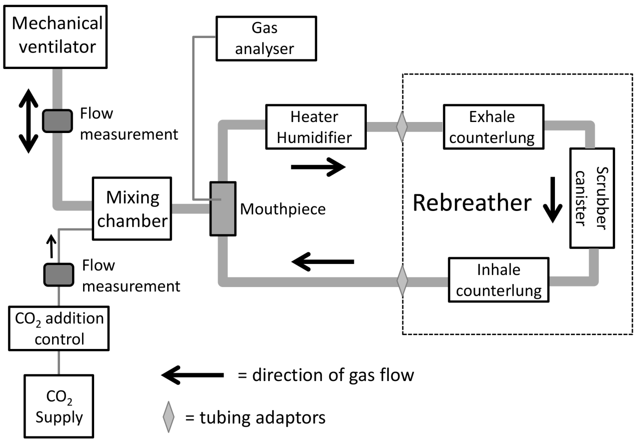
Those aspects of the protocol requiring human participation were approved by the University of Auckland Human Participation Ethics Committee (Reference 015280). This was a laboratory study in which an Evolution Plus™ (a rebreather model in the Inspiration range, henceforth referred to simply as the Inspiration) and a rEvo (standard model) rebreather were operated in a test circuit designed to simulate resting and exercising dives. Thus, in a preliminary phase of this study (described in more detail previously[4]) indicative values for respiratory minute ventilation ($V_E$), tidal volume ($T_V$), respiratory rate (RR), oxygen consumption ($VO_2$), and $CO_2$ production ($VCO_2$) were established in a working subject at the chosen exercise intensity.

A recent consensus on functional capacity for diving activity identified continuous exercise at 6 MET as a desirable and plausible target for sustained exercise output in a diver.[5] One MET [the approximate metabolic rate of an individual at rest] equals an assumed oxygen consumption of 3.5 $mL \cdot kg^{-1}$ body $weight \cdot minute^{-1}$ (min). Therefore, to establish the ventilation and $CO_2$ addition parameters for the benchtop tests our human participant exercised at 6 MET on an electronically braked cycle ergometer whilst breathing on the Inspiration rebreather in dry conditions. At steady state $V_E$ was 44 $L \cdot min^{-1}$ ($T_V$ = 2.0L, RR = 22 $breaths \cdot min^{-1}$) and $VCO_2$ was 2.0 $L \cdot min^{-1}$, actual temperature and pressure dry (ATPD).

SURFACE PRESSURE MECHANICAL TEST CIRCUIT

The initial studies were conducted at the University of Auckland, New Zealand. The ambient pressure for all New Zealand trials was at sea level (surface pressure), chosen of necessity because no pressure testing facility was available. In these studies, the inspiratory and expiratory hoses of the rebreather were attached to a test circuit (Figure 1). The test circuit 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 Rudolph, Shawnee, KS, USA) which simulated the rebreather mouthpiece. A port in the valve allowed continuous sampling of the inspired and expired gas for infrared analysis of inspired and end-tidal $PCO_2$ (ML206 Gas Analyser, AD Instruments, Dunedin, New Zealand). A clinical heater-humidifier (Fisher and Paykell Medical, Auckland, New Zealand) was incorporated into the exhale hose 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 for all experiments.

**Figure 1**
Schematic layout of the test circuit and monitoring equipment; (see text for explanation)




Breathing was simulated using a sinusoidal mechanical ventilator (17050-2 Lung Simulator, VacuMed, Ventura, CA, USA) with an inspiratory-expiratory ratio of 1:1. The $T_V$ was set at 1.5 L and the RR at 30 breaths·min$^{-1}$ for the 6 MET experiments. These parameters differed slightly from the derived human values described above ($T_V$ 2.0 L, RR 22 breaths·min$^{-1}$) because the ventilator struggled with the work of moving gas around this circuit with a $T_V$ of 2.0 L. Accurate ventilation was ensured through independent monitoring with a pneumotachograph (800 L, Hans Rudolph, Shawnee, KS, USA).

The ventilator was connected to the circuit one-way valve via a 4 L mixing chamber where the inspired and expired gas mixed with instrument grade $CO_2$ introduced at 2 L·min$^{-1}$ ATPD using a precision flow pump (R-2 Flow Controller, AEI Technologies, Pittsburgh PA, USA) drawing from a Douglas bag reservoir. The $CO_2$ flow was also independently monitored to ensure accuracy using a flow transducer (MLT10L, AD Instruments, Dunedin, New Zealand).

Sofnolime 797™ (Molecular Products, Essex, UK) was used in both rebreathers for all experiments. All Sofnolime was newly purchased, in date, and stored in the manufacturer-supplied sealed containers before use. The Sofnolime was precisely weighed (2.64 kg for the Inspiration scrubber, and 1.35 kg for each of the two rEvo canisters) (GM-11, Wedderburn Scales, Auckland, New Zealand) prior to canister packing. Each new scrubber canister was packed approximately 15 min before the start of an experiment.

In all tests the rebreathers were immersed in water at room temperature (19°C), chosen as a matter of convenience. Although water temperature is known to affect scrubber duration, there are no data on how it may affect temperature stick performance, and any water temperature within the range frequented by divers is operationally relevant.

SURFACE PRESSURE TEST PROTOCOL

The circuit was tested for leaks by holding a positive pressure. The rebreather was switched on and the default surface $PO_2$ set point of 0.7 atmospheres (atm) was chosen for the Inspiration. The rEvo was operated with the oxygen addition system switched off because this unit has a constant mass flow oxygen addition system and with no actual oxygen consumption occurring this resulted in gas accumulation and over-pressure of the circuit. An easily exceeded surface $PO_2$ set point of 0.19 atm (19 kPa) was used to avoid constant hypoxia alarms. The diluent gas was air for all experiments. Ventilation of the circuit was initiated and, after appropriate operation was confirmed, a timed trial started with the continuous addition of $CO_2$ at 2.0 L·min$^{-1}$ ATPD. Every 30 min the ventilation and $CO_2$ addition were briefly paused (approximately one min) to recalibrate the $CO_2$ flow and infrared sensors and to remove any excess moisture from the circuit hoses. These pauses did not elicit any alarms or obvious changes in the temperature stick display (Inspiration) or remaining scrubber time (rEvo).

For each rebreather we ran tests on two protocols. The first was designed to emulate the exercise and ventilation pattern of typical long dives where there would usually be moderate exercise initially followed by a long period of low exercise during decompression. Thus, the rebreathers (*n* = 5 for each model), each containing a newly packed soda lime scrubber, were run on 6 MET parameters (described above) for 90 min (half the Inspiration's expected scrubber life before breakthrough when operated at 6 MET),[4] followed by 2 MET parameters (ventilation 16.5 L·min$^{-1}$ [Tv 1.5 L;, RR = 11 breasths·min$^{-1}$], $VCO_2$ = 0.67 L·min$^{-1}$) until the $P_iCO_2$ rose to 1 kPa; a $P_iCO_2$ that is considered dangerous,[6] and after which the rise in $CO_2$ is generally extremely rapid.

The second protocol was designed to emulate the less plausible scenario of continuous moderate exercise throughout a dive. Thus the rebreathers (*n* = 6 for the Inspiration and *n* = 5 for the rEvo) were run on the 6 MET parameters continuously until the $P_iCO_2$ rose to 1 kPa. Throughout the tests, the decay was noted of the six segments on the Inspiration temperature stick display and recorded the remaining scrubber time (at 10 min intervals) displayed by the rEvo. The primary endpoint in each test was whether the rebreather warned the diver (decay to one segment on the Inspiration and counting down to zero time remaining on the rEvo) prior to reaching breakthrough at 1 kPa.

HYPERBARIC TEST CIRCUIT

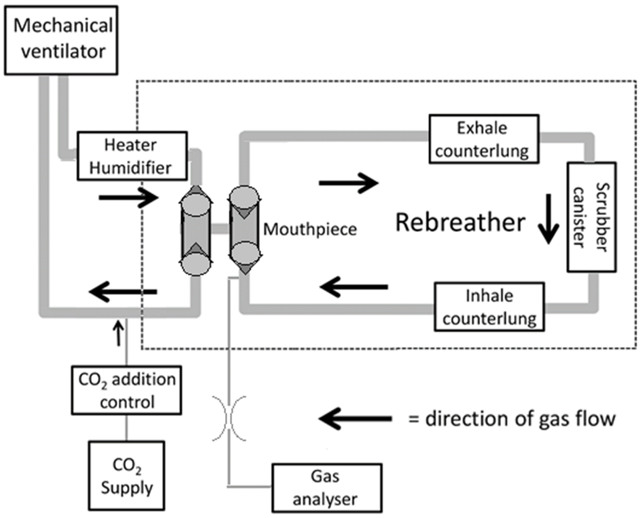
After some results of the surface pressure tests were found to be discordant with manufacturer tests conducted under pressure (Martin Parker, personal communication, December 2016), we elected to repeat the continuous moderate exercise tests in both rebreathers at elevated ambient pressure at the

**Figure 2**

The ANSTI underwater breathing apparatus test system. The pressure vessel is in the centre. The pressure control, ventilation and heater/cooler systems are on the right of the pressure vessel, and the monitoring system is on the left

**Figure 3**

Schematic layout of the ANSTI breathing test circuit and monitoring equipment; (see text for explanation)




Swedish Armed Forces Diving and Naval Medicine Centre at Karlskrona. The same scrubber and temperature stick units used in the surface pressure experiments (both rebreathers) were employed here. In these studies, the rebreather was connected to an ANSTI machine test circuit.[7] The ANSTI machine is a purpose-built underwater breathing apparatus test station (Figure 2) that allows mechanical ventilation with heated and humidified gas, and precise $CO_2$ addition to an immersed rebreather under pressure.

The laboratory environment was maintained at 20°C and 35–45% relative humidity. As in the surface pressure circuit, $CO_2$ was precisely introduced to the ANSTI machine ventilation system at 1.86 L·min$^{-1}$ standard temperature and pressure dry (STPD) giving a volume of 2 L·min$^{-1}$ at ATPD via a mass flow controller (Brooks Instrument 0-5 L·min$^{-1}$ $CO_2$, Hatfield PA, USA) such that it entered the exhale hose of the rebreather loop as it would during use by a diver (Figure 3). Gas from the rebreather inhale hose was sampled at 250 mL·min$^{-1}$ for continuous analysis in an infrared $CO_2$ analyser (Servomex 1440 D, Crowborough, UK). This sampled gas was replaced, and rebreather loop volume preserved during compression to elevated pressures, by allowing the rebreathers' automatic diluent addition valves to add air into the rebreather circuit.

The experiments were identical to the surface pressure tests with respect to rebreather configuration, ventilation parameters, expired gas heating and humidification, water temperature and soda lime management (see above). As in the surface pressure experiments throughout each test there was periodic two-point calibration of the inspired $CO_2$ analyser using reference gases, and independent calibration of the $CO_2$ inflow rate (DryCal Definer 220, Butler NJ, USA).

HYPERBARIC TEST PROTOCOL

The set up and oxygen management in each rebreather was as described for the surface pressure studies, except that the rEvo would not accept a $PO_2$ set point of 0.19 atm at depth and the 0.7 atm (71 kPa) set point for the Inspiration was unacceptably high for safe operation of the ANSTI circuit. Therefore, a set point of 0.5 atm (50.6 kPa) was used for both rebreathers. The rEvo was run with the oxygen addition system switched off so that the constant oxygen flow would not disturb the measurements, and the hypoxia alarm was cancelled when it was active.

For each experiment the rebreather was secured in the ANSTI test chamber and immersed while being ventilated to check for leaks. The test chamber lid was then closed and the chamber pressurised to the chosen depth. Because the hyperbaric studies were being performed in response to the finding of suboptimal temperature stick performance at the surface (Figures 5 and 6), we ran the hyperbaric experiments at the shallowest depths that are nevertheless of undisputed relevance to divers during decompression (3 or 6 metres' sea water (msw)). Similarly, because the temperature sticks had performed well on the low exercise protocol but failed on the moderate exercise protocol at surface pressure, we only performed the hyperbaric studies in Sweden on the moderate exercise protocol.

Two Inspiration scrubber canisters were available (thus two different temperature sticks: stick A that had been used in the surface pressure experiments, and stick B, not previously used in our work). Two tests were run using each stick at 3 and 6 msw; a total of eight Inspiration tests. Five tests were run with the rEvo; three at 3 msw and two at 6 msw. Finally, in order to corroborate our previous finding of temperature stick failure during moderate exercise at surface pressure (sea level) one test was run with the Inspiration (stick A as previously used at surface pressure) immersed in the ANSTI machine but without pressurising the test chamber.

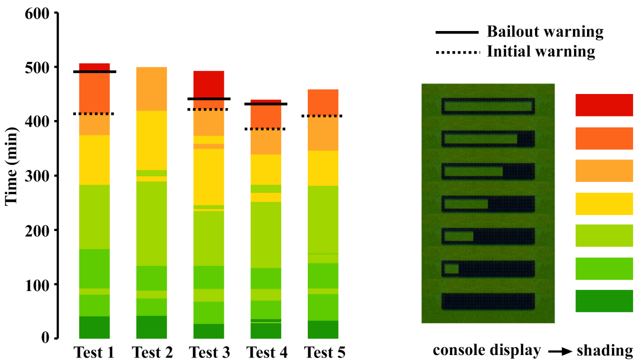
**Table 1**

The remaining scrubber time (RST) (minutes) displayed by the rEvo rebreather at the point of $CO_2$ breakthrough to a $P_iCO_2$ of 1 kPa in the low and high exercise tests conducted at surface pressure; a negative offset is the time elapsed between zero time remaining on the scrubber monitor and the actual time of breakthrough to $P_iCO_2$ = 1 kPa, and represents early warning; a positive offset is the time remaining on the scrubber monitor at the actual time of breakthrough to $P_iCO_2$ = 1 kPa, and represents a late warning; zero offset means that the remaining time on the scrubber monitor at exactly the same time as breakthrough to $P_iCO_2$ = 1 kPa

| Condition | Low exercise tests | | | | | | Moderate exercise tests | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Test number | 1 | 2 | 3 | 4 | 5 | | 1 | 2 | 3 | 4 | 5 |
| RST at $P_iCO_2$ = 1 kPa | 0 | 15 | 0 | 0 | 0 | | 15 | 75 | 4 | 0 | 25 |
| Offset (minutes) | -45 | 15 | -57 | -18 | -63 | | 15 | 75 | 4 | 0 | 25 |

**Figure 4**

Changes in the Inspiration temperature stick display over the course of each low exercise test conducted at surface pressure. Each bar represents a separate test; the top of the bar represents the time (y axis) of breakthrough to a $P_iCO_2$ of 1 kPa; the coloured shading represents the appearance of the temperature stick display according to the key. Note that the dark green segment at the base of each bar represents both the time taken for the stick display to become completely black signifying heat throughout the soda lime bed, and the time it remained completely black. The timing of both alarm conditions is shown (initial warning = dotted line occurring when one black segment remains, and bailout warning = solid line occurring when no black segments remain)




Temperature stick data from both rebreathers were recorded as described for the surface pressure studies.

THERMISTOR EVALUATION

After small but consistent differences were found in the performance of the two Inspiration temperature sticks (Figure 7), the readings obtained from the nine thermistors arrayed in each temperature stick were compared under carefully controlled temperature conditions. The two sticks were placed in a climate chamber (T-70/1000, CTS GmbH Hechingen, Germany), and the temperature reading of each thermistor noted after 30 minutes' stabilisation at 5ºC and 50ºC. Similarly, each stick was placed in a heated water bath and stabilised at a fixed temperature measured with a digital thermometer (Fluke 51, Fluke Corporation Everett, USA). The temperature reading of each thermistor was noted after five minutes' stabilisation.

## Results

SURFACE PRESSURE TESTS

Both rebreather temperature sticks warned prior to significant breakthrough ($P_iCO_2$ = 1 kPa) in four of the five low-exercise tests conducted at surface pressure. The changes in the Inspiration temperature stick display over the course of each test are depicted in Figure 4. The time remaining on the rEvo scrubber monitor at the point of $CO_2$ breakthrough in each test is shown in Table 1.

In contrast, both rebreathers' temperature sticks failed to warn prior to significant $CO_2$ breakthrough in the moderate exercise tests conducted at surface pressure (Table 1 for the rEvo and Figure 5 for the Inspiration results, respectively). In testing of the rEvo, a lack of linearity was noted in the remaining scrubber time estimation which was over-estimated early in the test, then declined faster than real time later (Figure 6).

HYPERBARIC TESTS

Both rebreather temperature sticks performed substantially better on the constant moderate-exercise protocol when operated at pressure. There was no discernible difference in performance between 3 and 6 msw. The changes in the Inspiration temperature stick display over the course of eight tests are depicted in Figure 7.

Whereas the Inspiration temperature stick had failed to warn before breakthrough to $P_iCO_2$ = 1 kPa on any of six continuous moderate-exercise tests at atmospheric pressure, it warned before or soon after breakthrough in all the tests under pressure. However, there was a difference between the two sticks tested. The accuracy of Stick A in precisely predicting and defining breakthrough was remarkable. The $P_iCO_2$ data are not presented here, but in every test Stick A initially warned just prior to breakthrough to $P_iCO_2$

**Figure 5**

Changes in the Inspiration temperature stick display over the course of each moderate exercise test conducted at surface pressure; note the much shorter duration of each test in comparison with the low exercise tests in Figure 4; interpretation of the figure is otherwise as described as for Figure 4; none of the runs reached the alarm condition (1 black segment remaining) prior to $P_iCO_2$ = 1 kPa

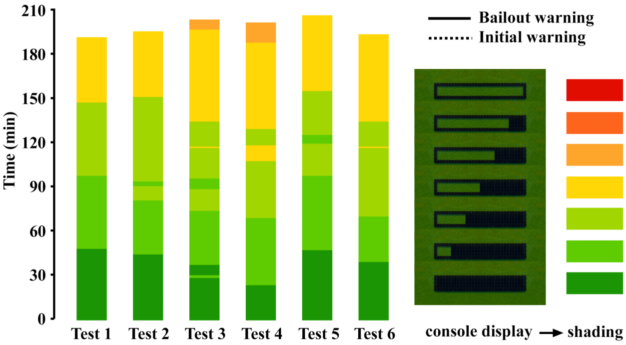



**Figure 6**

Remaining scrubber time (blue lines) and $PiCO_2$ over the course of the five moderate exercise tests at surface pressure using the rEvo rebreather; time remaining predictions are non-linear

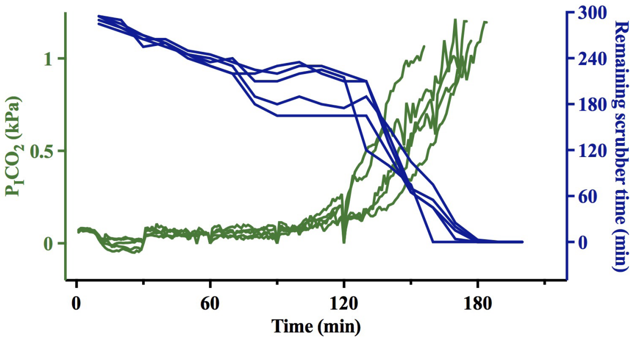
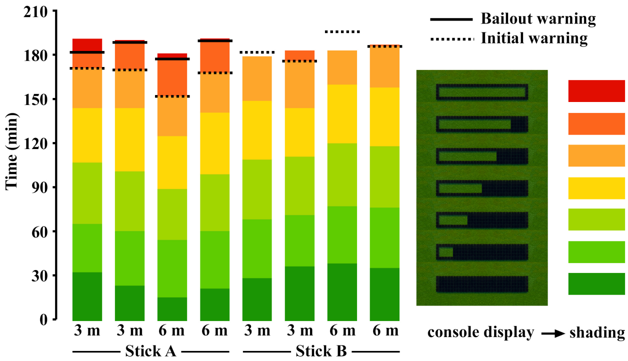



**Figure 7**

Changes in two Inspiration temperature stick displays (designated A and B) over the course of eight moderate exercise tests conducted at 3 and 6 msw as indicated; interpretation of the figure is otherwise as described for Figure 4




= 0.5 kPa, and then recommended bailout just prior to breakthrough to $P_iCO_2$ = 1 kPa. In contrast, Stick B gave warnings just prior to breakthrough to $P_iCO_2$ = 1 kPa in two tests, and 3 min after in one. The warning came 13 min after breakthrough in a fourth test (Figure 7). In contrast to the above results, in the single test performed using the Inspiration rebreather and Stick A in the ANSTI machine at surface pressure (data not shown) we recorded exactly the same failure to provide any warning prior to breakthrough to $P_iCO_2$ = 1 kPa as seen in the previous moderate-exercise tests at surface pressure.

The time remaining on the rEvo scrubber monitor at the point of $CO_2$ breakthrough in each test is shown in Table 2. Toward the end of several rEvo tests problems with moisture from the rebreather circuit entering the gas sampling line were experienced, and it was not possible to run every test through to a breakthrough of $P_iCO_2$ = 1 kPa. We did, however, get to $P_iCO_2$ = 0.5 kPa in all tests. We thus report 0.5 kPa as an alternative endpoint. In fact, our primary question was answered in the absence of continuing to a breakthrough of $P_iCO_2$ = 1 kPa because the remaining scrubber time had declined to zero prior to $P_iCO_2$ = 0.5 kPa in every test (see Table 2). As with the Inspiration, this result contrasted markedly with the rEvo temperature stick's failure to warn of breakthrough in four of five moderate-exercise tests conducted at surface pressure. We also noted that although there remained a minor tendency for the rEvo to report overly-optimistic remaining scrubber time estimations early in the dive, the decline in estimated time to zero was much more linear in the tests conducted under pressure (Figure 8).

The comparison of the temperature readings obtained from the nine thermistors on each of the two Inspiration temperature sticks (designated A and B respectively) in both the climate chamber and water bath evaluations are shown in Tables 3 and 4.

## Discussion

Hypercapnia in diving may arise from either failure by the diver to ventilate adequately or from rebreathing of $CO_2$, or a combination of both.[8] The potential to rebreathe $CO_2$ is important in the use of rebreathers which rely on soda lime to remove $CO_2$ from the expired gas. Soda lime has a finite life and must be replaced in a timely fashion or expired $CO_2$ will break through the soda lime canister and be rebreathed. Temperature sticks represent an attempt to indirectly confirm $CO_2$ removal by measuring reactivity in the soda lime canister during a dive. This study evaluated the reliability of these devices in warning the diver prior to significant $CO_2$ breakthrough as soda lime became exhausted under two test conditions. The first simulated the work rate and respiratory parameters of a notional long decompression dive with moderate exercise early in the dive, followed by less activity during a long decompression when the soda lime would often be nearing the limits of its absorptive capacity. The second protocol involved moderate exercise throughout

**Table 2**
The remaining scrubber time (RST) (minutes) displayed by the rEvo rebreather at the point of $CO_2$ breakthrough in the moderate exercise tests conducted at 3 and 6 msw; a negative offset is the time elapsed between zero time remaining on the scrubber monitor and the actual time of breakthrough to $P_iCO_2$ specified and represents early warning

| Depth (msw) | 3 | | | | 6 | |
|---|---|---|---|---|---|---|
| Test number | 1 | 2 | 3 | | 4 | 5 |
| RST at $P_iCO_2$ = 0.5 kPa | 0 | 0 | 0 | | 0 | 0 |
| Offset (minutes) | -46 | -36 | -22 | | -40 | -22 |
| RST at $P_iCO_2$ = 1 kPa | – | 0 | – | | 0 | – |
| Offset (minutes) | – | -60 | – | | -61 | – |

**Table 3**
Temperature readings from the nine individual thermistors (designated T0 – T8) on two Inspiration temperature sticks (designated A and B) recorded at 5 and 50ºC in a climate chamber

| Thermistor number | T0 | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 |
|---|---|---|---|---|---|---|---|---|---|
| Stick A @ 5°C | 4.5 | 6.6 | 5.0 | 5.5 | 5.5 | 5.0 | 5.5 | 6.0 | 6.0 |
| Stick B @ 5°C | 4.5 | 4.8 | 4.5 | 4.5 | 4.5 | 4.0 | 4.5 | 5.0 | 5.0 |
| Stick A @ 50°C | 49.0 | 50.9 | 49.0 | 49.0 | 49.0 | 48.0 | 48.5 | 48.5 | 48.0 |
| Stick B @ 50°C | 49.0 | 49.3 | 49.0 | 49.0 | 49.0 | 48.5 | 48.5 | 48.5 | 48.5 |

**Table 4**
Temperature readings from the nine individual thermistors (designated T0–T8) on two Inspiration temperature sticks (designated A and B) recorded at fixed temperatures in a water bath

| Thermistor number | T0 | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 |
|---|---|---|---|---|---|---|---|---|---|
| Stick A @ 32.5°C | 32.5 | 34.4 | 32.5 | 33.0 | 33.0 | 32.5 | 33.0 | 33.0 | 32.5 |
| Stick B @ 33.1°C | 31.5 | 31.9 | 31.5 | 31.5 | 31.5 | 31.0 | 31.5 | 31.5 | 29.5 |

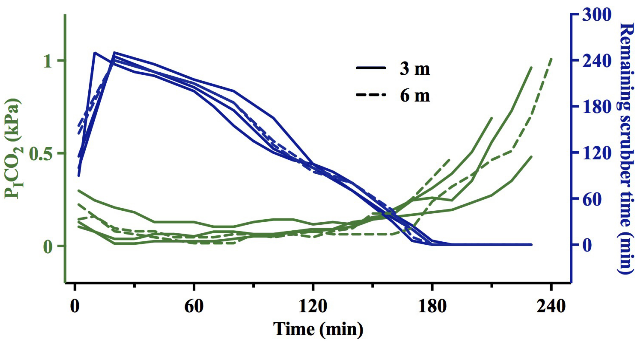
the life of the scrubber. It should be made clear that the latter is a less plausible real-world scenario than the former, but it was purposely chosen as a relevant scenario thought likely to provoke failure in temperature stick predictions. Based on these results, the following observations about temperature sticks are offered.

Firstly, there was a substantial improvement in accuracy when tests were conducted at even shallow depths compared to surface pressure. It is notable that, in the process of following up on the results of the surface pressure tests, the manufacturer of the Inspiration rebreather also found less accuracy when conducting an ANSTI machine test on the moderate-exercise protocol at surface pressure (Martin Parker, personal communication, July 2017). It seems clear that even small elevations of ambient pressure are an important requirement for accurate function of temperature sticks. The basis for this effect of depth was not established. An explanation is both beyond the scope of this work and inconsequential to answering the current research question. It could, however, form the basis for further research.

Secondly, based on the reasonably good performance of both rebreathers' temperature sticks during the low-exercise protocol even at surface pressure (appropriate warnings occurred prior to significant breakthrough in four of five tests in both rebreathers) together with the finding of markedly improved accuracy at shallow depths compared to surface pressure, it is predicted that both rebreathers tested will reliably provide warnings prior to significant $CO_2$ breakthrough in typical long decompression dives where the diver is at rest in shallow, temperate water toward the end of scrubber life. One can feel confident in this prediction for conditions conforming to those of the study tests, but it must be acknowledged that the scrubbers had not been exposed to typical dive depths early in each test and that variations

**Figure 8**

Remaining scrubber time (blue lines) and $P_iCO_2$ over the course of the five moderate exercise tests conducted under pressure using the rEvo rebreather; time remaining predictions are more linear than when the rebreather was operated at surface pressure (Figure 6)




in other conditions such as water temperature could affect temperature stick performance.

Thirdly, both rebreathers performed surprisingly well in the much more provocative continuous moderate-exercise protocol when tests were conducted at depth, though both exhibited different vulnerabilities.

There was a difference in performance between the two Inspiration temperature sticks with one (Stick A) providing precisely timed and accurate warnings before significant breakthrough on all four tests, and the other (Stick B) providing appropriate warnings on two occasions, a marginally late warning on one occasion, and a warning 13 min late on another (Figure 7). The comparison of temperature measurements in the thermistor arrays of the two sticks did reveal some subtle differences in accuracy (Tables 3 and 4) which might explain their different behaviour, but one cannot be certain about this. More detailed investigation, which would include consideration of the dynamic nature of the responses, is beyond the scope of this study.

The rEvo temperature stick provided warnings prior to significant breakthrough on all the moderate exercise tests, but these warnings came an hour before our experimental end-point of 1 kPa of inspired $CO_2$, and could perhaps be interpreted as too conservative. On the other hand, if the goal is to warn before a lower pressure of inspired $CO_2$ (such as 0.5 kPa)[6] then the decline in "*remaining scrubber time*" to zero seems substantially less premature (Figure 8) with negative offsets between 22 and 46 min (Table 2). There was also a small degree of non-linearity in the time remaining predictions, with optimistic predictions early in the simulated dive and a subsequent decline that was faster than real time. These observations on both temperature sticks must be interpreted within the context of the experiment in which they were made; that is, a sustained exercise test scenario that was considered likely to provoke failure and which is relatively less plausible in real-world technical decompression diving.

Fourthly, the failure of both temperature sticks during the moderate exercise protocol tests conducted at surface pressure is potentially relevant to surface swimming at the end of a dive while breathing on the rebreather loop. Although the consequences of a hypercapnic event at the surface are likely to be much less serious than one occurring at depth, divers should nevertheless be aware that a temperature stick may not provide accurate data during a vigorous surface swim conducted near the end of scrubber life.

An obvious limitation of this study is the relatively small number of tests with the various temperature sticks in the different conditions, and the limited range of conditions tested. There are other scenarios such as deeper depths, colder and warmer water temperatures, use of different gases, and different patterns of exercise and rest in which temperature stick performance could be evaluated and might be different. This work was challenging and time consuming, and the effect of any variation in conditions requires multiple confirmatory repetitions. Thirty-five tests are reported in this paper; and each test took four to eight hours to complete depending on whether it addressed moderate or lower exercise, respectively.

It is germane to state that temperature sticks do not actually measure $CO_2$ and are not capable of detecting or predicting $CO_2$ rebreathing that occurs as a result of exhaled gas bypassing the scrubber bed, or abnormally channelling through it for some reason. Therefore, divers should adopt a holistic approach to appraisal of scrubber performance during diving and not consider temperature stick predictions to be immutably correct, especially in the face of symptoms that might suggest hypercapnia.

## Conclusions

These data represent the first publicly reported demonstration that temperature sticks can reliably warn indirectly of $CO_2$ breakthrough before it occurs during simulation of a common rebreather diving scenario (resting decompression in 19°C temperate water). This was usually also true even during moderate exercise at shallow depths; conditions which, based on our tests at surface pressure, we incorrectly predicted would significantly confound temperature stick accuracy. However, despite this positive result, one cannot draw confident conclusions about temperature stick performance in conditions beyond those tested in this study. The possibility cannot be excluded that factors such as colder or warmer water, greater levels of exercise, greater pressures and different gases may change their accuracy.

## References

1 Mitchell SJ, Doolette DJ. Recreational technical diving part 1: an introduction to technical diving methods and activities. Diving Hyperb Med. 2013;43:86–93. PMID: 23813462.

2 Warkander DE. Temperature based estimation of remaining absorptive capacity of a gas absorber. United States Patent No.

US 6,618,687 B2. September 09 2003. [cited 2018 October 12]. Available from: https://patentimages.storage.googleapis.com/fc/63/e6/b5df0bd127bd3c/US6618687.pdf.
3 Warkander DE. Development of a scrubber gauge for closed circuit diving. Undersea Hyperb Med. 2007;24:251. Available from: http://archive.rubicon-foundation.org/5110. [cited 2018 February 14].
4 Harvey D, Pollock NW, Gant N, Hart J, Mesley P, Mitchell SJ. The duration of two carbon dioxide absorbents in a closed-circuit rebreather diving system. Diving Hyperb Med. 2016;46:92–7. PMID: 27334997.
5 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. PMID: 21877558.
6 Shykoff BE, Warkander DE. Exercise carbon dioxide ($CO_2$) retention with inhaled $CO_2$ and breathing resistance. Undersea Hyperb Med. 2012;39:815–28. PMID: 22908838.
7 Life Support Equipment Test Facility. ANSTI Test Systems Ltd. [cited 2018 February 10]. Available from: http://www.ansti.com/.
8 Doolette DJ, Mitchell SJ. Hyperbaric conditions. Compr Physiol. 2011;1:163–201. PMID: 23737169.

**Acknowledgements**

We thank Eng. Ingmar Franzén and Lt(N) Roine Bystedt at the Swedish Armed Forces Diving and Naval Medicine Centre without whose technical expertise and diligence this work could not have been completed. We sincerely thank Martin Parker, Ambient Pressure Diving, UK for the loan of an Evolution Plus rebreather and several scrubber canisters, and Mr Bruce Partridge of Shearwater Research, Vancouver, Canada for the loan of a personal rEvo rebreather and his technical assistance with the experiments.

**Funding**

This work was supported by grants from Shearwater Research, Vancouver Canada, and the Eurotek Advanced Diving Conference Research Fund, Birmingham, UK.

**Conflicts of interest**

Simon Mitchell and Neal Pollock are members of the Editorial Board of *Diving and Hyperbaric Medicine*, but had no input into the peer review or decision-to-publish processes.

**Submitted:** 22 July 2018; revised 19 October 2018
**Accepted:** 09 December 2018