Technical reports

Storage of partly used closed-circuit rebreather carbon dioxide absorbent canisters

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Abstract
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Introduction: Diving rebreathers use "*scrubber*" canisters containing soda lime to remove carbon dioxide (CO_2) from the expired gas. Soda lime has a finite ability to absorb CO_2. We undertook an experiment to determine whether the manner of storage of a partly used scrubber affected subsequent CO_2 absorption.
Methods: An Evolution Plus™ rebreather was mechanically ventilated in a benchtop circuit. Respiratory minute volume was 45 L·min^{-1} and CO_2 was introduced to the expiratory limb at 2 L·min^{-1}. The scrubber canister was packed with 2.64 kg of Sofnolime 797™. Scrubbers were run in this circuit for 90 minutes then removed from the rebreather and stored in packed form under one of three conditions: "*open*" (unsealed) for 28 days ($n = 4$); vacuum "*sealed*" in an airtight plastic bag for 28 days ($n = 5$); or open overnight ($n = 5$). Following storage the scrubber canisters were placed back in the rebreather and run as above until the PCO_2 in the inspired gas exceeded 1 kPa. The total duration of operation to reach this end-point in each storage condition was compared.
Results: The mean run times to reach an inspired CO_2 of 1 kPa were 188, 241, and 239 minutes in the open-28-day, the sealed-28-day and the open-overnight storage conditions, respectively.
Conclusion: Rebreather divers should consider placing partially used soda lime scrubber canisters in vacuum-sealed plastic bags if storing them for longer periods than overnight. If a partially used scrubber canister is to be used again the next day then the storage modality is unlikely to influence scrubber efficacy.

Introduction

Rebreather devices have dramatically enhanced the exploration capabilities of recreational technical divers and scientific divers.[1] Configurations vary, but fundamentally, rebreathers incorporate a circle circuit in which expired gas passes into a counterlung, and is then re-inhaled from the counterlung. Since the diver is metabolising oxygen (O_2) and producing carbon dioxide (CO_2) the O_2 must be replaced, and the CO_2 removed from the circuit. Thus, there is a system (which varies between rebreather designs) of gas addition designed to maintain a safe level of inspired oxygen partial pressure (PO_2) at all times, and the expired gas is passed through a canister containing a CO_2 absorbent material. There are several CO_2 absorbents that may be used in rebreathers, but the most common is soda lime.

Soda lime is a compound substance containing sodium hydroxide, calcium hydroxide and water. It absorbs CO_2 in a three-step chemical reaction in which the sodium hydroxide is recycled and the calcium hydroxide is irreversibly converted to calcium carbonate.[2] Once all the calcium hydroxide is consumed the compound can no longer absorb CO_2 and the canister assembly (typically referred to as a "*scrubber*") is exhausted. This is clearly an important limitation on the duration for which a rebreather can be safely used underwater. If the scrubber is exhausted (or near to it) during a dive, then CO_2 will 'break through' to be re-inspired, and the diver may develop dangerous levels of hypercapnia as a result.[2]

The safe duration of a CO_2 scrubber is determined by many factors including the scrubber design, ambient temperature, the depth of use, the mass of soda lime it contains, and the physical activity level (and, therefore, the CO_2 production and respiratory minute volume) of the diver. Rebreather manufacturers typically promulgate maximum recommended durations based on 'worst case scenario' testing in which the rebreather is operated mechanically at moderate depth in cold water with ventilation parameters chosen to simulate moderate to heavy exercise. These limits are recognised as being conservative, and their interpretation is further complicated by other factors which might affect duration.

One such factor is the manner in which a partially used scrubber canister is stored between dives. It is common for a rebreather dive to be of substantially shorter duration than the manufacturer's recommended scrubber life. Under these circumstances divers will frequently keep a record of the duration of use, then store the scrubber canister for further use on the next dive without changing the soda lime material. This practice has given rise to a debate on the best practice for storage of a partly used scrubber canister. In particular, it is not known whether sealing a partially used scrubber canister from the environment will confer any advantage in terms of its subsequent CO_2 absorbing performance in comparison to simply storing it unprotected.

To our knowledge there has been only one other relevant study. The Canadian Navy investigated the effect of storing new or partially used soda lime in a rebreather for seven days and found no difference in total duration of effective CO_2 removal compared to soda lime that was not removed from its usual storage container until just prior to use.[3] However, all of these storage modes were effectively sealed, and this study therefore did not address the issue of whether a partly used scrubber canister needs to be sealed for storage. Resolution of this question was identified as a research priority at the recent *Rebreathers in scientific diving Workshop*.[4] Moreover, although this issue could be viewed as 'technological' rather than 'medical', the performance expectations of CO_2 scrubbers are of direct relevance to the prevention of an important gas toxicity (hypercapnia), and any significant effect of scrubber storage conditions could be of relevance to forensic investigations of rebreather accidents where hypercapnia appeared to be a plausible cause.

We undertook a study to determine whether airtight sealing of a partially used CO_2 scrubber canister for storage purposes improved subsequent CO_2 absorbing performance. The null hypothesis was that the manner in which a partially used CO_2 scrubber is stored (sealed vs. open) makes no difference to its CO_2 absorbing capacity during subsequent use.

Methods

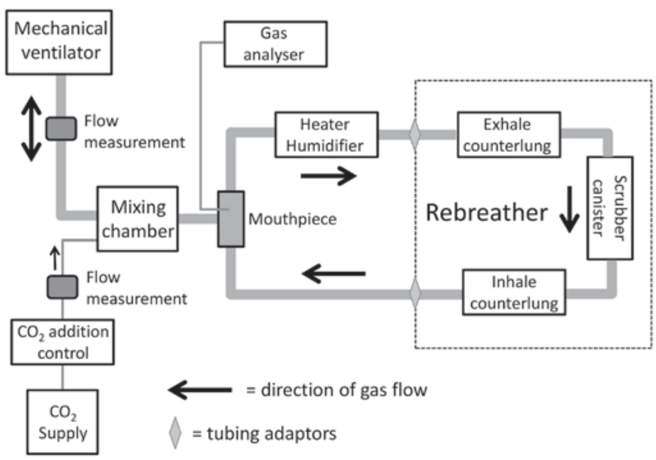
Those aspects of the protocol requiring human participation were approved by the University of Auckland Human Participation Ethics Committee (Reference 015280).

This was a bench-test laboratory study in which an Evolution Plus™ rebreather (Ambient Pressure Diving, Helston, Cornwall) was operated in a test circuit designed to emulate use by an exercising diver. Thus, in a preliminary phase of this study which is described in more detail elsewhere,[5] we established indicative values for respiratory minute (min) ventilation (V_E), tidal volume (T_V), respiratory rate (RR), oxygen consumption (VO_2), and CO_2 production (VCO_2) in a working subject at our chosen exercise intensity. A recent consensus on functional capacity for diving activity identified continuous exercise at 6 MET (one MET equals 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$, the assumed oxygen consumption of an individual at rest) as a desirable and plausible target for sustained exercise output in a diver.[6] Therefore, our human participant exercised at 6 MET on an electronically braked cycle ergometer whilst breathing on the Evolution Plus rebreather in dry conditions. At steady state V_E was 44 $L \cdot min^{-1}$ (T_V = 2.0 L, RR = 22 $breaths \cdot min^{-1}$) and VCO_2 was 2.0 $L \cdot min^{-1}$.

BENCH TEST CIRCUIT DESIGN AND OPERATION

For the subsequent bench test study, the inspiratory and expiratory hoses of the Evolution Plus rebreather were attached to a test circuit (Figure 1) using tubing adaptors (MLA304, AD Instruments, Dunedin, New Zealand). 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. This valve was ported to allow 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 limb of the circuit to reproduce the heating and

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



humidification of expired gas that would occur with a human breathing on the loop. The heating function was set to 34ºC for all experiments.

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 all experiments. These parameters differed slightly from the derived human values described above (T_V 2.0 L, RR 22 breaths·min^{-1}) because we found that 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} 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). Operated in this mode with a functional CO_2 scrubber canister in the rebreather, the circuit consistently produced a physiologically authentic inspired CO_2 partial pressure (PCO_2) of close to zero and an end-tidal PCO_2 of 5–6 kPa at the simulated mouthpiece.

CO_2 SCRUBBER CANISTER PACKING

Sofnolime 797™ (Molecular Products, Essex, UK) is the recommended CO_2 absorbent for the Evolution Plus rebreather and was used for all experiments. All Sofnolime was newly purchased from the same batch, in date, and stored before use in the manufacturer-supplied sealed containers. The initial packing of the scrubber canister was supervised by an experienced instructor (PM) on this rebreather. Emphasis was placed on ensuring an evenly distributed tight pack to eliminate the possibility of settling of absorbent material and channelling of gas flow which might cause inaccurate results. After the first supervised pack the Sofnolime was precisely weighed (2.64 kg) before exposure to CO_2 using a laboratory balance (GM-11, Wedderburn Scales, Auckland, New Zealand), and exactly the same weight of material was used for all subsequent trial repetitions. Each new scrubber canister was packed approximately 15 min before the start of an experiment.

TRIAL PROTOCOL

After scrubber canister installation, the rebreather was incorporated into the circuit as described above. The circuit was tested for leaks by holding a positive pressure. The rebreather was switched on and its default surface PO_2 set point of 0.7 atm was chosen. 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}. Every 30 min the ventilation and CO_2 addition were briefly paused to recheck the CO_2 flow sensor calibration and to remove any excess moisture from the circuit hoses. The addition of this step to the protocol reflected the criticality of consistently accurate CO_2 addition to the circuit.

Previous experiments had shown that when packed and operated in the test circuit as described above, it took approximately 200 min for the scrubber to fail (defined as a rise in the inspired PCO_2 to 1 kPa (7.5 mmHg).[5] To evaluate the effect of different storage modalities after partial use, we operated each new scrubber in the rebreather for exactly 90 min after which the scrubber canister was removed intact from the rebreather and immediately stored; either unprotected ("*open*") on a shelf in the laboratory, or in a vacuum-sealed plastic bag ("*sealed*") on the same shelf. The airtight bags were commercially available 0.8 m x 0.8 m household double zip vacuum seal clothing storage bags made from polyethylene (wall thickness 70 micron) with a polyamide valve (All Set Brand, China). Residual air was evacuated through the one-way screw cap valve using a household vacuum cleaner.

We investigated two periods of storage. The principle set of experiments evaluated one month of storage (exactly 28 days in all cases) which was considered to represent a typical interval between dives for recreational divers. We subsequently added another series involving overnight storage because this is a relevant storage interval for divers on live-aboard or scientific diving trips. The laboratory conditions were kept constant throughout the period of storage with a mean (± SD) temperature of 19.7 ± 3.1°C and a relative humidity of 53 ± 9%. After the storage period, the scrubber was re-installed in the rebreather and operated under the same conditions until the scrubber failed; that is, until an inspired PCO_2 of 1 kPa was recorded. We had four scrubber canisters available for the study. For each complete cycle of the 28-day storage study two canisters were allocated to open and two to sealed storage so that in any storage period two canisters were stored open and two were stored sealed. For the next cycle of the study each canister would be stored in the opposite condition.

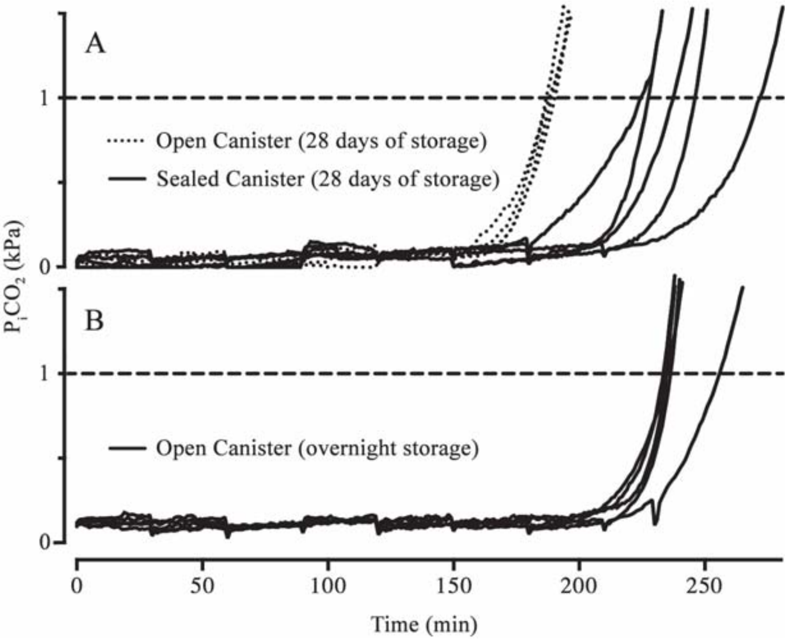
We aimed to investigate five scrubbers in each of three storage conditions: 28-day-sealed; 28-day-open; and overnight-open. The primary outcome was a comparison of the mean total scrubber duration (the sum of pre- and post-storage operating time before failure) in each of the three conditions. Where necessary, statistical comparison between two conditions was made using a two-tailed *t*-test. A *P*-value less than 0.05 was taken to indicate statistical significance.

Results

We completed five trials in each of the 28-day-sealed and overnight-open conditions, and four experiments in the 28-day-open condition. Unfortunately, we exhausted our

Figure 2

Breakthrough curves for the individual scrubber trials in three storage conditions subdivided into the 28-day storage duration (Panel A) and the overnight storage duration (Panel B). The small periodic downward spikes in the curves correspond to the short half-hourly pauses for recalibration of the CO_2 flow sensor and removal of moisture from the circuit hoses (see Methods)



same-batch supply of Sofnolime 797 with one trial in the 28-day-open condition remaining to be done. We attempted to run the trial with Sofnolime from another batch and obtained an aberrant result. Given the confluence of the results obtained in the trials performed using Sofnolime from the common batch (see below) we considered it reasonable to stop the study one trial short in the 28-day-open condition, rather than repeat the entire study with a new batch of Sofnolime.

The elapsed times to reach the failure end-point in each scrubber trial arranged by storage condition, and the mean times to failure for each condition are shown in Table 1. The breakthrough curves for each scrubber trial are shown in Figure 2. There was a substantial (> 50 min) difference in mean duration to failure between scrubbers stored for 28 days in the sealed condition (longer) compared to the open condition (shorter; $P = 0.003$). Scrubbers stored 'open' for the much shorter overnight period showed no difference in mean duration to failure when compared to the canisters sealed for 28 days.

The volumes of CO_2 introduced prior to reaching the failure end point in each scrubber trial arranged by storage condition and the mean volumes for each condition are shown in Table 2. Since some CO_2 was accumulating in the circuit (as opposed from being removed by the scrubber) prior to reaching the 1 kPa inspired CO_2 endpoint, it is not strictly correct to view these data as representing the volume of CO_2 absorbed. Nevertheless, it is a good approximation for the latter. On that basis, on average, the scrubber canisters stored

Table 1

Elapsed time (min) to reach the predefined failure point (an inspired PCO_2 of 1 kPa) in trials in which scrubber canisters were ventilated at 45 L·min^{-1} with introduction of CO_2 at 2 L·min^{-1} to simulate 6 MET exercise. All scrubber canisters were stored in the condition indicated after an initial 90 minutes of operation, and then run to failure after storage

Trial	Storage Condition		
	28 days open	28 days sealed	Overnight open
1	188	229	234
2	188	224	235
3	187	237	237
4	190	246	255
5	–	271	235
Mean (SD)	188 (1)	241 (19)	239 (9)

Table 2

Estimated volume (L) of introduced CO_2 required to elicit an inspired PCO_2 of 1 kPa in trials in which scrubber canisters were ventilated at 45 L·min^{-1} with introduction of CO_2 at 2 L·min^{-1} to simulate 6 MET exercise

Trial	Storage Condition		
	28 days open	28 days sealed	Overnight open
1	378.1	458.9	484.3
2	377.5	451.5	484.2
3	375.3	476.8	498.1
4	381.5	493.6	480.7
5	–	544.8	502.3
Mean (SD)	378.1 (2.6)	485.1 (37.1)	489.9 (9.6)

sealed for 28 days were capable of absorbing approximately 100 L more CO_2 than those stored open for the same period. Although these latter data are largely reflective of the durations reported in Table 1, presentation of the outcome as a function of CO_2 absorption has implications for interpretation of the results (see discussion below).

Discussion

We have shown that storage of a partially used CO_2 scrubber for 28 days in a vacuum-sealed bag substantially preserves its ability to absorb CO_2 during subsequent use when compared to a scrubber that has been stored in an open (unprotected) condition. Our null hypothesis was therefore rejected. This result is consistent with the Canadian Navy finding of no apparent degradation in absorbing function when a partially used scrubber was stored in a sealed environment for seven days,[3] but our study is the first to compare sealed versus open conditions. The results support the view of those in the rebreather community who advocate a sealed condition when a scrubber is stored for a protracted period.

However, our results also indicate that open storage for 24 hours or less does not appear to result in significant degradation of scrubber function. Therefore, it is unlikely to be disadvantageous to store a partly used scrubber in an open condition if it is going to be reused the next day. In this regard we acknowledge that we did not test overnight storage in a sealed condition as a direct comparator. We considered it unlikely that this would reveal significant benefit, not least because the scrubbers stored overnight in the open condition were performing as well or even slightly better than scrubbers operated under identical conditions without a storage period in a previous study.[5]

An obvious question that arises is the cause of the degradation in scrubber function during storage in the open condition. An intuitively obvious explanation is the absorption of CO_2 from the surrounding air. However, the data in Table 2 suggest that for this to be the explanation the scrubber would have absorbed over 100 L of CO_2 during storage. This represents the content of approximately 250,000 L of air (the CO_2 content of air = 0.04%). It is clearly implausible that this degree of bulk flow occurred through the scrubber during its storage, but the extent to which an equivalent amount of CO_2 absorption could have occurred by diffusion of CO_2 into the scrubber canister is unknown.

Another possible answer lies in the dependence of soda lime on the presence of water for the reaction with CO_2 to proceed efficiently.[7] Unfortunately much of the relevant literature is old and published in foreign language journals.[8] Nevertheless, it is part of the wisdom of anaesthesia that dry soda lime is inefficient, and one anaesthesia education website states "*dry granules become exhausted quicker than granules with correct water percentage*".[9] It seems plausible that in an air-conditioned environment at a relative humidity of 54% the canisters stored open may have desiccated to some extent, and this may have resulted in reduced absorptive capacity in subsequent use.

It is relevant to briefly discuss our choice of an inspired PCO_2 of 1 kPa as an end point for our experiments. There has been some debate over safe limits for inspired CO_2 during diving, but recent evidence suggests that limits should be low.[10] Indeed, a widely accepted breakthrough end point for the testing of CO_2 scrubber duration is 0.5 kPa. We chose 1 kPa as a level of inspired CO_2 that few (if any) would regard as clinically insignificant in the diving context. However, we provide the breakthrough curves (Figure 2) partly as evidence that our conclusions would not have materially changed whether we chose 0.5, 1.0, or 2.0 kPa of inspired CO_2 as the end point. We also chose to use a simulated workload ($VE = 45\ L{\cdot}min^{-1}$ and $VCO_2 = 2\ L{\cdot}min^{-1}$) that has a published physiological provenance of relevance to diving,[6] rather than the European standard that is often used for scrubber endurance testing ($VE = 40\ L{\cdot}min^{-1}$ and $VCO_2 = 1.6\ L{\cdot}min^{-1}$).[11] These parameters are similar, and in a study comparing the effect of different storage conditions (as opposed to generating guidelines on scrubber durations) this choice is also of no material significance.

Another methodological matter that deserves comment is our use of a benchtop circuit with the rebreather operated in dry conditions at one atmosphere pressure rather than immersed at elevated ambient pressure. It is known, for example, that immersion in cold water negatively affects the efficiency of CO_2 scrubbers, and operation at greater pressure also shortens duration. However, it must be clearly understood that the primary goal of this study was to investigate any effect of storage conditions on subsequent efficacy of a partly used scrubber. For that purpose, provided methodologic consistency was maintained, the mode of use of the rebreather was essentially irrelevant. We can think of no plausible reason why running the experiment at atmospheric pressure would either mask or exaggerate any deterioration in scrubbing capacity arising from non-optimal storage. As a corollary to these comments it must also be clearly understood that we were not attempting to generate data that might be used to guide the duration of use of scrubbers in real world diving, and our data must not be used in this way. For the sake of comparability, duration testing would best be conducted to a more widely used protocol such as the European standard.[11]

There are several observations that we have not elaborated on in detail here. First, we found greater variability in the time to the endpoint in the canisters that were stored sealed for one month. We do not have an explanation for this observation. Though interesting, it does not materially alter our conclusions. Second, as alluded to earlier, we have noted that canisters stored either sealed for 28 days or open overnight actually appear to have a longer total duration than those used from new through to the endpoint without interruption in another study.[5] We have not detailed this observation in this paper because it will be the subject of further work designed to more formally investigate and document the phenomenon. Finally, the aberrant result seen with a change in scrubber batch requires further evaluation.

LIMITATIONS

Firstly, this is a small study, and was one trial smaller than intended because we exhausted our supply of soda lime from the same batch. Nevertheless, we believe the results establish a clear signal that a sealed condition is likely to be the optimal approach for prolonged storage without the need for a larger study. Sealing the scrubber inside the rebreather may confer a similar advantage,[3] but we did not specifically test that.

Secondly, in relation to the above, we have not accurately defined "*prolonged*" in relation to scrubber storage. That is to say, we have not established a threshold storage period beyond which soda lime absorptive efficacy declines. Although it would be possible to undertake such work it would be a substantial effort. Moreover, it may be confounded by factors other than time which affect storage (see below), and we are satisfied that simply identifying an advantage for sealed storage under a limited set of conditions is a valuable observation in itself.

Thirdly, it is possible that different conditions of storage may affect the outcome, particularly in relation to the open storage condition. For example, if desiccation is the explanation for degradation of efficacy in the open condition, then the effect may be less dramatic in a more humid non-air-conditioned environment. Similarly, it is possible that the effect may be more dramatic (and possibly apparent over a shorter storage period, including overnight) in a much drier environment. Our results may not be generalizable to all environments.

Finally, we cannot definitively rule out an advantage from sealing for overnight storage because we did not perform trials in this condition. Nevertheless, any such advantage is likely to be small. Despite being stored open overnight, the scrubbers performed in a virtually identical manner to the scrubbers that were sealed for 28 days and slightly better than scrubbers that were run from new to the end point without storage in an earlier trial.[5]

Conclusions

Rebreather divers should consider placing partially used soda lime scrubber canisters in vacuum-sealed plastic bags if storing them for longer periods than overnight. If a partially used scrubber canister is to be used again the next day then the storage modality is unlikely to influence scrubber efficacy.

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Conflicts of interest: nil

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