The effect of over- or underfilling the soda lime canister on CO₂ absorption in two closed-circuit oxygen rebreathers.

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Arieli R. The effect of over- or underfilling the soda lime canister on CO₂ absorption in two closed-circuit oxygen rebreathers Undersea Hyperb Med 2008; 35(3):213-218. O₂ diving incidents investigated by our laboratory were related to improper filling of the soda lime canister in closed-circuit oxygen rebreathers. We studied the effect of overfilling or underfilling the canister on CO₂ absorption using a continuous flow of 5% CO₂. With a full canister in the Oxyger 57, CO₂ began to rise at 130-160 min, reaching 1% at 240 min and 1.5% at 270 min. Similar results were obtained after a reduction of 100 g in the quantity of soda lime packed into the canister. After reductions of 200, 300 and 400 g, the rise in CO₂ concentration occurred earlier as a function of the amount of the reduction. The level of CO₂ in the OxyNG 2 began to rise after 250 min with a full canister, reaching 1% at 340 min and 1.5% at 370 min. After a reduction of 100 g there was a delay in the rise of CO₂, which reached 1.5% at 390 min. However, when the reduction was 200, 300 and 400 g, the rise in CO₂ concentration tended to occur earlier as a function of the amount of the reduction. For both rebreathers, when the quantity of soda lime was reduced by 200 g or more, there was a considerable difference in timing between the two test measurements for each weight reduction, due to variations in channeling. For an excess of soda lime, moderate pressure was applied manually to achieve a full canister plus 300 g in the OxyNG 2. The initial rise in CO₂ concentration started early, at 60 min with a full canister plus 300 g compared to 150 min with a full canister; 1% CO₂ was reached at 120 min, compared to 210 min with a full canister. As the use of rebreathers becomes increasingly widespread in diving, close attention should be paid to proper filling of the soda lime canister.

INTRODUCTION

We found that some of the oxygen toxicity incidents reported to us by closed-circuit oxygen divers were related to CO₂ accumulation (1). Testing of the soda lime content in the canisters proved that these had not been completely filled. Slight elevation of the inspired CO₂ can increase the risk of CNS oxygen toxicity. Even as little as a 1 kPa increase in PCO₂ can result in a tremendous increase in the risk of CNS oxygen toxicity in the rat (2). After we issued advice regarding proper filling of the canisters, a subsequent series of diving incidents revealed improper pressure packing of the soda lime. Sometimes this overfilling of the canister resulted in intense breathing resistance, with a pressure greater than 25 cm H₂O on inspiration. This led us to evaluate the effect of over- and underfilling the canister on CO₂ absorption.

Effective absorption by the soda lime is related to breathing pattern. CO₂ absorption
is therefore usually tested using a breathing simulator, which can achieve close similarity to diving with a rebreather and simulate the production of carbon dioxide as measured on expiration (4, 5, 6). A comparison of continuous and cyclic flow for the same CO₂ output found earlier elevation of inspiratory CO₂ in cyclic flow when the gas was dry, and the contrary when the gas was humid (5). For the sake of greater accuracy in CO₂ delivery, and to avoid the variability induced by the breathing cycle pattern, continuous flow was chosen for the present investigation.

**METHODS**

Factors that can reduce the scrubbing efficiency of soda lime are low temperature, high pressure, the water content of the soda lime, and dryness of the gas mixture containing the CO₂. These were not problems which affected our experimental system. The canisters of two closed-circuit rebreathers, the Oxyger 57 and the OxyNG 2 (Aqualung/Spirotechnique, France), were filled with soda lime (SODASORB 4-8 REG HP, Grace, Atlanta, GA, USA), carefully shaking and tapping them all the time to ensure compact and even settling of the granules. The canisters were emptied and the soda lime was weighed. This procedure was repeated six times for both canisters, and the mean weight was 1802 ± 25 and 2056 ± 18 g for the Oxyger 57 and the OxyNG 2, respectively. These figures were rounded to the nearest 10 g, giving 1800 and 2060 g, and were further defined as the values for a full canister. A sample of about 100 g from both batches of soda lime used for the test was desiccated in an oven (110°C) until its weight had stabilized. This yielded 16.0 and 14.5% humidity for the material used in the Oxyger 57 and the OxyNG 2, respectively. Both values are within the limits established by Grace (3) for high-moisture soda lime.

**PROCEDURES**

**A. Underfilling with soda lime**

A predetermined weight of soda lime (full, full minus 100g, full minus 200g, full minus 300g, full minus 400g) was poured into the canister. The closed-circuit scuba was immersed in a water tank at a temperature of 24.7 ± 0.7°C and placed in the prone position. Using two flowmeters, compressed air, and a tank of pure carbon dioxide, we prepared a mixture containing 5% CO₂ to simulate the production of 0.95 liter STPD CO₂/min (a value measured in underwater scooter divers (7)). The flow of the mixture was checked using a turbine-type spirometer (Spirometer, K L Engineering, Northridge, CA). The gas mixture was bubbled through a water column for humidification, and was driven into the expiratory hose of the rebreather. Carbon dioxide was measured alternately in the expiratory and inspiratory hoses using a mass spectrometer (CaSE, 9000T/BG, Biggin Hill, UK). Each of the chosen weights of soda lime was tested twice. The test was terminated when the concentration of CO₂ in the inspiratory hose was above 1.5%. The canister was emptied, and its contents were weighed, desiccated in an oven until no further decline in weight was noted, and weighed again.

**B. Overfilling with soda lime**

Soda lime was packed into the canister of the OxyNG 2 using moderate manual pressure to achieve a full canister plus 300g. Otherwise the procedure was as described in section A. CO₂ production was 1.12 liter STPD CO₂/min, as measured in fin diving (7). This level was selected because the reported incidents occurred during fin dives. The same mixture containing 5% CO₂ was used, with a slight increase in flow to produce the desired output. The test was terminated when the concentration of CO₂ in the inspiratory hose was close to 1%.
Calculation of absorbed CO₂

The water content of fresh soda lime was used to calculate the initial dry weight (IW). The final dry weight (FW) was the weight measured after desiccation of all the used soda lime from the canister. Assuming the end product to be mostly CaCO₃, the mass of the absorbed CO₂ will be given by (FW - IW) × 44/26, where 44/26 = 1.692 is the molecular weight ratio of absorbed CO₂ to gained dry weight, which is affected by the loss of one water molecule for each absorbed CO₂ molecule.

RESULTS

A. Underfilling with soda lime

The level of CO₂ in the inspiratory hose of the Oxyger 57 is shown in Fig. 1. (Figs 1, 2, 3 can be found on page 216). With a full canister, CO₂ began to rise at 130-160 min, reaching 1% at 240 min and 1.5% at 270 min. Similar results were obtained after a reduction of 100 g in the quantity of soda lime packed into the canister. After a reduction of 200, 300 and 400 g, the rise in CO₂ concentration tended to occur earlier as a function of the amount of the reduction (Table 1). When the quantity of soda lime was reduced by 200 or 300 g, there was a considerable difference in timing between the two measurements. The level of CO₂ in the OxyNG 2 (shown in Fig. 2) began to rise after 250 min with a full canister, reaching 1% at 340 min and 1.5% at 270 min. After a reduction of 100 g there was a delay in the rise of CO₂, which reached 1.5% after 390 min. However, when the reduction was 200, 300 and 400 g, the rise in CO₂ concentration occurred earlier as a function of the amount of the reduction (Table 1). When the quantity of soda lime was reduced by 300 g, there was a considerable difference in timing between the two measurements. With a reduction of 400 g CO₂ began to rise at the outset, and so only one test was conducted. The slope of the rise in CO₂ concentration for the two rebreathers was similar, despite the difference in the mass of soda lime in the canisters (0.55 ± 0.08 %/min and 0.64 ± 0.13 %/min for the Oxyger57 and the OxyNG 2, respectively). The volume of absorbed carbon dioxide in the two rebreathers and the time to 0.3% CO₂ in the inspiratory hose are given in Table 1. The volume of absorbed CO₂ was similar for a full canister and full minus 100 g for both rebreathers (Table 1), and declined as the mass of soda lime in the canister was reduced. However, the weight percentage of absorbed CO₂ was between 20 and 30% of the soda lime dry weight, and seems to be little affected, if at all, by the mass of the soda lime. The time to 0.3% CO₂ in the inspiratory hose, which is related to breakthrough time, tends to decrease when the weight of the soda lime was reduced.

Table 1. Absorbed CO₂ in liters STPD, weight percentage of CO₂ to dry weight of the soda lime, and time to 0.3% CO₂ in the inspiratory hose, for a full canister and for a canister underfilled by four different amounts.

<table>
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<tr>
<th>Measure -ment</th>
<th>Absorbed CO₂ in liters STPD (Oxyger 57)</th>
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<th>Full minus 300 g</th>
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Fig. 1. CO₂ measured in the inspiratory hose of a closed-circuit rebreather (Oxyger 57) while a mixture containing 5% CO₂, simulating CO₂ production of 0.95 l/min, was driven through the expiratory hose. Results from a full soda lime canister are compared with four reductions in the amount of soda lime in the canister. The full and empty symbols represent the test and the repeat test for the same condition.

Fig. 2. CO₂ measured in the inspiratory hose of a closed-circuit rebreather (OxyNG 2) while a mixture containing 5% CO₂, simulating CO₂ production of 0.95 l/min, was driven through the expiratory hose. Results from a full soda lime canister are compared with four reductions in the amount of soda lime in the canister. The full and empty symbols represent the test and the repeat test for the same condition.

Fig. 3. CO₂ measured in the inspiratory hose of a closed-circuit rebreather (OxyNG 2) while a mixture containing 5% CO₂, simulating CO₂ production of 1.12 l/min, was driven through the expiratory hose. Results from a full soda lime canister are compared with those from a canister packed with a surplus of 300 g soda lime.
lime is reduced by more than 200 g. There was a minimal difference (difference divided by the mean in percent) between the two measurements for full minus 100g (2 and 10%), and greater differences of 21, 30, and 58% for full minus 200g and full minus 300g. When we tested the correlation between any two of the three parameters in Table 1, it was significant only for the Oxyger 57 regarding time to 0.3% CO₂ in the inspiratory hose and the volume of absorbed CO₂ ($r^2 = 0.64, p<0.05$).

B. Overfilling with soda lime
With a surplus of 300 g soda lime in the canister, the initial rise in CO₂ concentration started early, at 60 min compared to 150 min with a full canister (Fig. 3); 1% CO₂ was reached at 120 min, compared to 210 min with a full canister.

DISCUSSION
The moisture in the soda lime used for the two rebreathers, 14.7 and 16%, was within the accepted limits of 14-19% (3). The weight percentage of absorbed CO₂ was 22-24% of the soda lime in the full canisters when calculated for wet weight. This does not fall below the minimum value of 22% considered acceptable by Grace (3). It is within the range measured in exercising subjects breathing via closed-circuit oxygen scuba until they reached 1% inspired CO₂ (14-35%) (8), and similar to three other types of soda lime studied using a breathing simulator with comparable CO₂ production, when the CO₂ concentration reached 1.5% (25-28%) (4).

The dispersion of the gas within the soda lime, and therefore its efficacy, would appear to be determined by the configuration of the canister. Thus, although the Oxyger 57’s canister contains only 12.6% less soda lime than that of the OxyNG 2, the time to the initial rise in CO₂ concentration in the Oxyger 57 was 58% shorter than in the OxyNG 2. Due to a difference in canister shape, the result of reducing the quantity of soda lime will not be the same in the two rebreathers, because the same volume of free space will have a different form and thus a different effect.

For the sake of precision, we used constant flow of the gas mixture containing CO₂. However, in previous tests of these two rebreathers in a breathing simulator using tidal flow, the time to the initial rise in CO₂ was the same. We therefore believe that the present report represents a good simulation of real diving.

In both closed-circuit oxygen rebreathers, a full canister and 100 g less than a full canister yielded the longest time until CO₂ began to rise in the inspiratory hose. We found a certain advantage to 100 g less than a full canister. It is possible that even the small amount of pressure applied to close the cover on a full canister will to some extent increase the uneven flow through the grains of soda lime, and thus decreases its scrubbing efficiency. However, unless the soda lime can be weighed exactly, it is too hazardous to advise against filling the canister to the limit.

Absorption tended to deteriorate with further reductions in the amount of soda lime in the canister. The similarity of the CO₂ concentration slopes in the two rebreathers suggests a similar reduction in the CO₂ scrubbing efficiency of the different masses of soda lime. This does not reflect complete utilization of the soda lime, because if that were the case, when the reaction was completed the weight percentage of absorbed CO₂ would be at least 59% of the dry soda lime, compared with the present values of 24-30% (Table 1). In previous tests we conducted on canisters from diving apparatus, as well as transparent canisters, that were incorrectly filled with soda
lime containing an indicator, we observed patches of colored soda lime across the spaces. This was due to channeling of the gas flow. Variability in the CO₂ concentrations obtained for reductions of 200, 300 and 400 g in the amount of soda lime in the canister is related to different channeling, whereby the gas stream flows via pathways of least resistance within the soda lime, forming channels which bypass masses of the absorbent (3). When it is not completely filled with soda lime, tilting or any other movement of the canister can lead to temporary rearrangement of the free spaces, which will result in variations in channeling and considerable differences in CO₂ scrubbing capacity. The greater difference in the time to 0.3% CO₂ in the inspiratory hose for full minus 200 g and full minus 300 g (Table 1) also points to a variation in channeling. Overfilling the canister by pressure packing the soda lime most probably forced channels through the less dense granules and reduced the scrubbing efficiency.

The present report provides what may be a simple and straightforward explanation for some of the oxygen toxicity incidents in divers using closed-circuit oxygen rebreathers, where the presence of CO₂ on inhalation was the precipitating factor (1). In some of the incidents we have investigated, we found an increased level of CO₂ in the rebreather of the diver involved, but not in that of his buddy (unreported data). The author believes this study bears a clear message regarding the importance of proper packing of the canister with soda lime. The canister should be filled to the limit, shaking and tapping it all the time until the granules settle and no free space remains. However, care should be taken not to fill it to excess, so that the cover can be closed without compressing the soda lime inside. As the use of rebreathers becomes increasingly widespread in recreational diving, close attention should be paid to proper filling of the soda lime canister.

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REFERENCES