SOME LIMITATIONS OF SEMI-CLOSED REBREATHERS

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Key Words

Equipment, mixed gas, nitrogen, oxygen, rebreathing.

A rebreather has several features which make it attractive to the recreational diver but with it come additional hazards which must be understood if they are to be controlled. In most of the semi-closed oxy-nitrogen rebreathers made for the recreational diver, a pre-mixed gas is supplied at a pre-determined flow rate to a counterlung or breathing bag. The fresh gas is mixed there with the gas already present, much of which has just been exhaled and scrubbed of CO_2. Thus the diver breathes in from the counterlung and exhales through the scrubber back to the counterlung from which excess gas is vented at virtually the same rate that fresh gas is being supplied.

Calculation of the oxygen percentage in the counterlung is based on a simple formula which is independent of depth. In the steady state the percentage of oxygen in the breathing bag may be given quite simply by:

$$O_2\,\% = \frac{(O_2 \text{ flow} - O_2 \text{ consumed})}{(\text{Mixture flow} - O_2 \text{ consumed})} \times 100 \qquad (1)$$

As can be seen, this percentage is independent of depth and, once the supply flow rate has been set for a particular pre-mix, the only variable is that of oxygen consumption. The oxygen percentage is also independent of the volume of the breathing bag. The volume of the counterlung, or more strictly that of the whole breathing circuit including the lungs, will affect only the rate of change from one steady state of oxygen consumption to the next. The rate of change of oxygen content in the counterlung when the diver's work level changes can also be calculated[1] but, with a small circuit volume in relation to a respiratory minute volume for divers of around 20 l/min, this transient phase is brief in relation to the ability to sustain hard work.

Unlike open-circuit systems, in which the composition of the supply gas should be constant, and closed-circuit systems, in which the composition of the inspiratory gases is capable of being provided precisely, the semi-closed system is a dynamic system. The breathing bag provides the diver with gas the composition of which changes during the dive. Given a pre-determined flow rate to the breathing bag of premixed gas with a known composition, the formula above can be used in maintaining the oxygen range within predictable upper and lower limits. Thus the dominant variable during the dive is that of oxygen consumption and will be determined by activities ranging from minimal muscular effort (perhaps when composing a photograph) to maximum sustainable breathing capacity (in some life-threatening situation). Before examining the implications that varied activity may have for the gas composition inspired from the counterlung and the potential consequences of this for the diver, some basic assumptions need to be considered.

Minimal oxygen consumption

An oxygen consumption of around only 0.25 l/min is widely accepted as a lower limit. This value is therefore used to determine the highest percentage of oxygen that could be found in the counterlung, a percentage approaching that of the pre-mixed gas. The maximum allowable PO_2 can then be used to calculate the maximum depth permitted for that flow rate and mixture. In open circuit nitrox diving, the upper limits of allowable oxygen partial pressure have been reduced over the years to 1.5 bar for working hose divers in the North Sea and around 1.4 bar for recreational scuba divers. It is therefore disconcerting to calculate, from the data offered on one recreational semi-closed rebreather, a maximum oxygen percentage which, at the depth quoted, could have a partial pressure exceeding 1.7 bar.

High oxygen consumptions

The other extreme, the maximum sustainable oxygen consumption, is more difficult to predict. For a diver of average size and reasonable "fitness'", an O_{2max} of at least 3 l/min can usually be expected and is almost universally accepted.[2] For the elite athlete performing out of the water an oxygen consumption exceeding 7 l/min can be sustained.[3,4] It is also known that maximum voluntary ventilation (MVV) and maximum breathing capacity (MBC) are significantly reduced at raised environmental pressure,[2] and by as much as around 50% at 45 m. Nevertheless, for counterlung calculations the Royal Navy uses O_2 3 l/min and the U.S. Navy and at least one manufacturer use 2.5 l/min. Given also that apparatus for sport diving is not denied to exceptional athletes, the figure of at least 3 l/min for maximum sustainable O_2 should be used as the value appropriate for application to semi-closed apparatus at all depths.

An implication for the diver using apparatus set up in accordance with calculations based on oxygen consumptions lower than these extremes is that, when maximally exercising, the diver could well sustain an oxygen consumption greater than the volume of oxygen provided. One semi-closed rebreather currently available provides the diver with only 5 l/min of 40% oxygen according to its manufacturer.[5] These figures have since been confirmed by that manufacturer. That provides only 2 l/min of oxygen but even less than that is available for the diver's use and, when oxygen consumption exceeds 1.25 l/min, the breathing bag oxygen will become less than 21%. The same apparatus, at a possible oxygen consumption of 1.75 l/min, with a constant mass flow of 5 l/min 40/60, will supply the diver with a PO_2 of 0.3 bar at its advertised maximum depth of 30 m. However, this would be achieved with only around 8% oxygen in the breathing bag which would mean, not only an equivalent air depth of 36 m, but also that it would not be a safe mixture for making the ascent. Although this particular breathing apparatus is claimed to be for only those divers weighing 198 lbs (90 kg) or less, maybe it should also be restricted to macro-photographers diving in swimming pools.

That example of 5 l/min seems particularly extreme because other manufacturers and several training agencies recommend double that flow rate for 40/60. Yet even these higher flows do not solve all the potential problems. In at least one design, an oxygen consumption 2.5 l/min (which is less than that used by the Royal Navy for its evaluation of breathing apparatus) can still be sufficient to bring counterlung oxygen content down below 21% and so reverse the advantages of using an "equivalent air depth" for decompression. Specifically with a 40% oxygen premix at the manufacturer's constant flow setting of 9.2 l/min, the formula (1) provides

$$\frac{(9.2 \times 0.4) - 2.5}{(9.2 - 2.5)} = 17.6\ \%\ \text{oxygen.}$$

The manufacturer's setting for 32% oxygen premix is 11.4 l/min. Perhaps the reader would like to calculate the oxygen percentage from that setting at a O_2 of 2.5 l/min or more. One conclusion might be that macrophotography and gentle swimming may be relatively safe with those settings, but the diver must not to get into a life-threatening situation which needs sustained hard work.

A manufacturer's response to my queries included the following:

> at the lower limit of technical tolerances a constant flow is guaranteed that creates a minimum O_2 content of 17% at a metabolic rate of up to 2.5 l/min.
>
> it is part of the training that in periods of higher workload and breathing, the diver needs to exhale through the nose in order to *(empty the breathing bag and)* make sure fresh gas is supplied through the bypass valve when inhaling the next time.
>
> for the calculation of EADs ... assume a constant O_2 consumption of 1.5 l/min.
>
> in case the diver encounters higher consumptions than estimated, we suggest the use of air-decompression tables.
>
> our ranges are only suggestions, the settings are the responsibility of the training organisations.

These answers raise yet more questions. Because decompression tables require to be entered at the deepest depth of the dive, how can one estimate the deepest EAD of the dive? Is it valid to estimate an average oxygen consumption? What would be the implications of an EAD which, using the conventions of the diving tables, should be based on 17% oxygen? In particular, as the actual EAD varies during a dive and sometimes, based on the quoted settings, may tend on some dives towards being deeper that the actual depth, how can a safe decompression ever be planned?

But enough has been said already to demonstrate that there are some uncertainties with the use of semi-closed circuit breathing apparatus. These need to be dealt with by the training agencies, perhaps at the price of increasing flow rates even though this reduces cylinder duration.* It is possible that there is sufficient padding in the decompression tables that these questions about unpredictable EADs and decompression are relatively academic, but the data needs to be collected and published. In the meanwhile, the active diver using semi-closed apparatus might prefer to plan on using the air decompression tables for the actual depth dived.

Evaluation of breathing apparatus

Once upon a time all new decompression tables and all new items of breathing apparatus were vigorously evaluated by a naval Experimental Diving Unit before being brought into service for the naval diver and, in due course, being released for public use. No longer is this process routine but rigorous testing of non-military equipment is still available if required. However, the recreational diving industry appears to be sufficiently confident in their designs that some items may never have been tested to their limits. A request to a particular manufacturer for data from manned testing on actual levels of oxygen in the breathing bag during hard work revealed that no such data was available. Wisely perhaps, some of the trainers using one semi-closed set have increased the flows and reduced the maximum depths for some mixtures. It is not known if such decisions are based on measurement or, more probably, intelligent guesswork and it is not known if the same safety factors are introduced worldwide by all training agencies. Also, it is not known, to the author at least, if similar safety considerations have been reviewed for all the versions of semi-closed sets that may appear on the market.

*** Footnote**

Since being sent a prepublication copy of this SPUMS presentation, one manufacturer has incresased their flow rates significantly and has also undertaken some manned testing of oxygen levels. A welcome step towards improved safety.

In contrast to the introduction of new naval equipment, a team of leading training agency officials and recreational instructors was convened some time ago for the first formal training program of a new oxy-nitrogen semi-closed rebreather. One would imagine that this group would comprise instructors who are focussed on diving safety and its evaluation but it is reported[6] that, in their spare time, some of them scuba dived solo on compressed air to 123 metres (400 feet). If this were so would *you* trust as safe a complex new breathing apparatus that is recommended by such an instructor? Validation demands appropriate laboratory evaluations by scientists and/or the military who are, and remain, independent.

Conclusion

More work needs to be done to confirm the safety of semi-closed breathing apparatus for recreational use. Gas samples for both O_2 and CO_2 from breathing bags at the O_2 extremes during shallow manned trials by exceptionally fit divers need to be taken at a laboratory experienced in diving physiology and analysed before settings such as flow rates are decided. A number of the claims made in the sport diving press and by the manufacturers about semi-closed rebreathers appear to be exaggerated, but the diving public is not sufficiently well informed to assess this. Diving doctors need to be aware of these problems and be prepared to educate if and when the agencies and manufacturers provide misleading statements.

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TESTING THE PERFORMANCE OF REBREATHERS

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Key Words
Equipment, mixed gas, oxygen, performance, rebreathing.

Abstract

The growing interest in nitrox- and tech-diving among recreational divers has created the demand for rebreathers. Compared with open systems, this breathing apparatus offers long duration, silent diving and, in some cases, decompression benefits. Some rebreathers are on the market, but many are designed and built by the divers themselves, with a possible increase in the risks for accidents caused by malfunction of the unit.

When rebreathers are approved for use today, only the work of breathing and the scrubbing capacity, using a CO_2-injection technique, are tested. We suggest the use of a respiratory simulator capable of extracting oxygen. The respiratory simulator, using catalytic combustion of propylene, also imitates other aspects of respiration such as CO_2, humidity and heat production. With the respiratory simulator standardised tests can be performed which, together with a limited number of verifying dives with divers, should offer good possibilities of revealing weak spots in rebreather designs.

Introduction

The growing interest in nitrox and so called "technical diving", has created an increasing interest in rebreathers to meet various demands from recreational divers. Sports diving associations such as PADI and CMAS have already issued special procedures for mixed gas or enriched air diving for open circuit breathing equipment.[1,2] It is likely there will soon also be procedures for rebreathers because closed circuits are needed to allow full use of the advantages with nitrox in scuba.