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References

1 *PADI Enriched air diver manual.* ISBN 1-878663-21-6. Santa Ana, California: PADI International, 1995
2 *CMAS Mixed gas diving standards*, CMAS, Viale Tiziano 74, 00196 Rome, Italy, 1995
3 U*S Navy Diving Manual. Rev 3 Vol 2 Mixed gas diving.* ISBN 0-941332-22-5. Flagstaff, Arizona: Best Publishing Company, 1991
4 *NPD Guidelines for evaluation of breathing apparatus for use in manned underwater operations in the activities.* ISBN 82-7257-308-3. Stavanger, Norway: Norwegian Petroleum Directorate, 1991
5 *Dykeriarbete. Arbetarskyddsstyrelsens Författningssamling, AFS 1993:57.* ISBN 91-7930-231-9. Solna, Sweden: Publikationsservice, 1993
6 *Dykeritjänstreglemente. DykR:Säk. M7744-390002. Försvarets Bok och Blankettförråd.* Solna Sweden. 1989.
7 Örnhagen H and Hamilton RW. *Oxygen enriched air - "Nitrox"- in surface oriented diving. FOA Report C 50068-5.1*. ISSN 0347-7665. 1989
8 Wright WB. *Use of the University of Pennsylvania, Institute for Environmental Medicine, procedure for calculation of cumulative pulmonary oxygen toxicity. Report 2-72.* Washington, DC: US Navy Experimental Diving Unit, 1972
9 Hamilton RW, Kenyon DJ, Peterson RE, Butler GJ and Beers DM. *Repex: Development of repetitive excursions, surface techniques, and oxygen procedures for habitat diving. Technical report 88-1A*. Rockville, Maryland: NOAA Office of Undersea Research, May 1988
10 Arntzen AJ and Eidsvik S. *Nordisk Standardtabell.* Farsta, Sweden: Svenska Sportdykarförbundet, 1995
11 Lanphier EH and Camporesi EM. Respiration and exertion. In *The Physiology and Medicine of Diving. 4th Ed.* Bennett PB and Elliott DH. Eds. ISBN 0-7020-1589-X. London: WB Saunders Company Ltd, 1993
12 Morrison JB and Reimers SD. Design principles of underwater breathing apparatus. In *The Physiology and Medicine of Diving. 3rd Ed.* ISBN 0 941332 02 0. Bennet PB and Elliott DH. Eds. San Pedro California: Best Publishing Company, 1982.
13 Lundgren CEG. Applying physiology in the design of breathing gear for divers. In *Hyperbaric Physiology and Medicine,* Lin Y-C and Niu AKC. Eds. San Pedro California: Best Publishing Company, 1988; 155-170
14 Loncar M, Larsson Å and H Örnhagen. Oxygen consuming unit for tests of breathing apparatus. In *EUBS-93 Proceedings*. Eidsmo R, Brubakk AD and Bolstad G. Eds. Trondheim, Norway: SINTEF UNIMED, 1993; 99-103
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REBREATHER PHYSIOLOGY

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Key Words

Equipment, mixed gas, oxygen, physiology, rebreathing.

A diver breathing on open-circuit apparatus "throws away" a great deal of perfectly good gas and this "waste" increases with increasing depth. A rebreather recovers and reuses much of this inert gas that would otherwise be lost; it removes the CO_2 and replaces the oxygen consumed.

The basic characteristics of rebreathers in general, a bit about their history and the problems of semi-closed rebreathers have been discussed by Dr Elliott.[1,2]

Rebreather essentials

Only a small amount of the air a person inhales on each breath is actually used by the body. Virtually all of the nitrogen and most of the oxygen is exhaled with a little CO_2. A rebreather enables most of this exhaled breath to be reused and must have a few essential components. These are a breathing loop with valves to control the flow direction, a counterlung or breathing bag, a canister to absorb CO_2 and some way to add gas when the volume in the breathing bag decreases. Valves maintain the flow in a constant direction and breathing pushes the gas through the canister.

For diving a rebreather must have a compliant volume, a space that can expand by the same volume that the diver exhales and inhales on a breath. As a result the total gas volume does not change appreciably, so buoyancy does not change during breathing. Usually it is the diver's breathing which moves the gas around the circuit. Valves direct the flow in all but the to-fro types.

A rebreather should have low breathing resistance and protect against excessive heat loss. It should have high reliability, and perhaps redundancy, appropriate size and weight, a manageable degree of complexity in both use and maintenance (i.e. be "diver proof"), reasonable cost, upkeep and maintenance.

For military purposes it might be silent, bubble free and non-magnetic. The lack of bubbles can also be important to photographers and naturalists studying marine wildlife. Oxygen and oxygen-controlled rebreathers produce no bubbles during use at a constant depth, but all rebreathers must vent some gas on ascent. Semi-closed rebreathers make few bubbles, perhaps 15 to 25% of the equivalent open-circuit scuba diver; the bubbles usually come out of the backpack instead of the mouthpiece, so are less noticeable and not so noisy.

Oxygen rebreathers

The simplest category of rebreather for divers is the pure oxygen rebreather. This unit is filled only with oxygen; it adds oxygen when the gas volume in the bag is reduced below a selected volume. Oxygen rebreathers are depth-limited because oxygen becomes more toxic as pressure (depth) increases. Because they are fully closed and do not release any bubbles during level swimming they are popular for military use.

An older British oxygen rebreather uses to-and-fro or pendulum gas flow where the diver breaths directly through the canister; this design is still in use. The diver rebreathes the dead space so these units tend to cause CO_2 build up and unconsciousness. The to-and-fro design does help conserve breathing gas heat, which can be an advantage, and they are less costly, simpler to operate, and in that sense more reliable.

Fully closed rebreathers with oxygen control

The most sophisticated and effective rebreathers are fully closed units with oxygen control. The oxygen level is controlled electronically and usually several sensors are used for redundancy. These units carry both oxygen and diluent gas (an inert gas with a small amount of oxygen), and add whichever gas is needed. The more modern ones have computers and do sophisticated control and logging of many things in addition to adding gas.

A fraction of oxygen should be added to the inert diluent gas to make it breathable or at least survivable in case the diver breathes the diluent gas only. These units allow oxygen to be set at a given PO_2 and held throughout the dive. US Navy (USN) rebreathers (Mark 15 and 16) are "hard wired" to maintain a PO_2 of 0.7 atm (acceptable range 0.6 to 0.9 atm), but other more modern units allow the PO_2 level to be selected. Oxygen-controlled rebreathers usually make no bubbles except during ascents. Considerable experience has been accumulated in military use of this type of rebreather.

Semi-closed rebreathers

Dr Elliott has dealt with these rebreathers and their problems on pages 48-50.[2]

Physiological aspects of rebreathers

There are physiological consequences of breathing on a rebreather that are different from diving with air. Some of these are due to the nature of the gas mixture, others due to the mechanical aspects of the rebreather itself. There can be major physiological concerns to the diver if the rebreather is used beyond its design limits or in the event that it does not function properly. It is advisable for rebreather divers to be acquainted with these factors.

Respiratory exchange and lung ventilation

Exhaled gas (when breathing air) is mostly oxygen and nitrogen but it has less oxygen and also contains some carbon dioxide. About 0.8 as much carbon dioxide is exhaled as oxygen consumed. This difference, the ratio of CO_2 produced to O_2 consumed, is called the respiratory exchange ratio. A volume of gas, with low or no CO_2, much greater than that needed for metabolism has to be breathed to ventilate the lungs sufficiently to remove CO_2. At increased pressures the number of molecules of oxygen in a breath is proportionally more, but the amount of gas required to meet the body's metabolic needs does not change significantly with depth.

Effects of breathing gas disturbances

ASPHYXIA

If a person breathes air in and out of a closed bag the bag will accumulate CO_2 and will become depleted of oxygen. In a short time, which depends on the size of the bag and how hard the person is working, the CO_2 will become excessive, causing shortness of breath (dyspnoea), and the oxygen deficient, causing unconsciousness, and if this continues will inevitably lead to death.

With an 8 litre bag, as in some rebreathers, a constant oxygen consumption of 0.5 l/min and constant CO_2 production of 0.4 l/m, in 2 minutes the PO_2 will be down to

0.09 bar (9%) and the PCO_2 will be about 10%. This would be extremely stressful but most people would probably still be conscious. In 3 minutes the PO_2 will be down to 0.02 bar, low enough to cause unconsciousness and very soon death. The PCO_2 will be about 16%, enough to be extremely distressing and narcotic. Although some people might become unconscious from this level of CO_2 it is not life-threatening. Low oxygen is the dominant and dangerous factor in "closed bag" asphyxia. The principle is valid here, but this is a simplification of what would happen.

HYPOXIA

If the bag has a device that will remove CO_2 repeated breaths would deplete the oxygen, but no CO_2 would accumulate. The person would be unlikely to experience severe dyspnoea, and might not be aware of the shortage of oxygen until too late (unconsciousness occurs), but the respiratory minute volume (RMV) would begin to increase due to hypoxia. In about the same time he would become unconscious and eventually die from hypoxia. There would be very little discomfort and he might feel rather euphoric and unconcerned about the situation; euphoria is a typical and characteristically dangerous aspect of hypoxia.

The symptoms of hypoxia with rapid onset (a few minutes) are dizziness, dimness of vision or "tunnel vision," paraesthesia and tingling, numb lips, difficult speech, breathlessness, followed soon by collapse and unconsciousness. These symptoms can be loosely related to decreasing inspired partial pressures or sea level percentages; these are quite variable with individuals and circumstances. In general oxygen levels above 0.16 bar or 16%, have no noticeable effects except loss of night vision; 14 to 12% or 0.14 to 0.12 bar causes tingling, numb lips, tunnel vision and slight increase in RMV; 10 to 9% or 0.1 to 0.09 bar produces difficult speech, dizziness and for some collapse is imminent; leads to unconsciousness and death.

HYPERCAPNIA

A person breathing from a bag filled with oxygen, which has the oxygen replenished as needed but which allows the CO_2 to accumulate would experience mild dyspnoea which would become more severe with each succeeding breath. Eventually the person would become unconscious. As the CO_2 level increased the person would feel considerable circulatory changes, would feel a flush over the body, would begin to have a headache, and might have a convulsion. There is no shortage of oxygen, it is hypercapnia, a build-up of CO_2. A level of up to 30-40% CO_2 is survivable, but well before this level the individual would become unconscious; beyond this level the individual would have serious problems.

HYPERVENTILATION LEADING TO HYPOCAPNIA

Another disturbance is hypocapnia, a reduction of the CO_2 level in the body. CO_2 controls ventilation, which is the only way it can be reduced. Excessive ventilation can wash enough CO_2 out to have physiological effects. These resemble those of hypoxia which can make immediate diagnosis quite difficult. The symptoms are dizziness, paraesthesias and tingling, numb lips, difficult speech, and confusion; in addition there may be a "tetany" or muscle tension and twitching, especially of the hands. Hyperventilation can be triggered by low oxygen (which stimulates breathing), but anxiety is a commoner cause in diving.

HYPERVENTILATION LEADING TO HYPERCAPNIA

Divers are often known to "hyperventilate." The term hyperventilation is used to describe rapid breathing, but in some cases it is not an excess ventilation of the lungs, as the name implies, but rather an excessive ventilation of the dead space, snorkel or rebreather, with inadequate ventilation of the lungs. If the person is exercising this can lead to a rapid CO_2 build-up. Apparent hyperventilation that is in fact inadequate can happen if the breathing rate increases while the effective depth of each breath decreases. This is a natural response when breathing against a resistance and stimulated to breathe (e.g. by exercise). The diver may make a great effort to ventilate, but because the breaths are too shallow the result is ineffective. This is most likely to happen when the diver is distracted and only aware that more ventilation is needed. It is more likely to occur in a to-and-fro type rebreather which adds some dead space. This and other things that can cause a build-up of CO_2 that can lead to loss of consciousness.

HYPEROXIA

Oxygen is essential in breathing gas for body metabolism, but too much of it can cause oxygen poisoning. The physiological effect of oxygen is a function of its partial pressure (the product of oxygen fraction and pressure), so the ideal fraction of oxygen in a diver's breathing mixture depends on the depth. The remaining space has to be filled with an inert gas usually called the diluent gas. Almost any rebreather that has an oxygen supply component is capable of delivering excess oxygen and the important danger is CNS oxygen toxicity. There are various algorithms for avoiding this, but a good rule of thumb is not to allow the PO_2 to exceed 1.4 bar, or even better, 1.3 bar.

Dealing with breathing gas disturbances

For almost all situations the prescribed action is to abort the dive, switching to the open-circuit backup breathing system if possible. In almost all cases it will be beneficial to reduce the work load. It is good practice in being prepared to deal with emergencies to think about the different things that can go wrong before they happen.

Decompression disadvantages and advantages of rebreathers

Accepting that higher oxygen levels are beneficial to decompression, rebreathers can work both ways with regard to the efficiency of decompression.

Semi-closed rebreathers have two problems. First, they can have a variable level of oxygen which makes predicting the optimal decompression quite difficult. Decompression may have to follow "worst case" presumptions with a significant loss of efficiency.[3] The more important effect is increased diver activity causes the oxygen levels to go down. Activity tends to accelerate the circulation and causes the diver to take on more gas, resulting in a greater decompression obligation. Just when the diver needs the better decompression, which would result from a higher PO_2, the oxygen is lower.

On the other hand, oxygen-controlled rebreathers can be efficient. Decompression can be almost as efficient as it gets with a constant, optimal PO_2 level (a useful setting is 1.3 to 1.4 bar). By maintaining this level throughout the dive the maximum advantage of oxygen is achieved .[4,5] Special decompression tables or a computer are needed. Some state-of-the-art computer-controlled rebreathers also include a decompression computer. This can add to decompression efficiency since it can know the PO_2 continuously as well as the time and pressure profile.

Design factors

Several aspects of rebreathers that are an inherent part of the design can have physiological impact. Among these are breathing resistance, the relative location of the counterlung, and the scrubber. Morrison and Reimers provide a good review of the mechanics and physiology of rebreathers.[6]

References and additional reading

1 Elliott DH. Rebreathers: an introduction. *SPUMS J* 1997; 27 (1): 39-42

2 Elliott DH. Some limitations of semi-closed rebreathers. *SPUMS J* 1997; 27 (1): 48-50

3 Nishi RY and Eaton DJ. Current developments in Canada regarding nitrox and semi-closed diving systems. In: *Harbor Branch Workshop on enriched air nitrox diving. Report 89-1*. Hamilton RW, Hulbert AW and Crosson DJ. Eds. Rockville, Maryland: NOAA National Undersea Research Program, 1989

4 Vann RD. *Mk XV UBA decompression trials at Duke. Summary report to the Office of Naval Research*. Durham, North Carolina: Duke University Medical Center, FG Hall Laboratory, 1982

5 Hamilton RW, Kenyon DJ and Clough SJ. Decompression advantages of a constant oxygen rebreather. In: *Proceedings of the 9th US-Japan Co-operative Program in Natural Resources (UJNR) panel on Diving Physiology and Technology.* Mayama T. Ed. Yokosuka: Japan Marine Science and Technology Centre, 1987

6 Morrison JB and Reimers SD. Design principles of underwater breathing apparatus. In: *The physiology and medicine of diving. Third Edition*. Bennett PB and Elliott DH. Eds. San Pedro, California: Best Publishing Co, 1982

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