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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 CO2 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 CO2. 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 CO2 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
rebreathe the dead space so these units tend to cause CO2
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 PO2 and held throughout
the dive. US Navy (USN) rebreathers (Mark 15 and 16) are
“hard wired” to maintain a PO2 of 0.7 atm (acceptable range
0.6 to 0.9 atm), but other more modern units allow the PO2
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
CO2 produced to O2 consumed, is called the respiratory
exchange ratio. A volume of gas, with low or no CO2, much
greater than that needed for metabolism has to be breathed
to ventilate the lungs sufficiently to remove CO2. 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 CO2 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 CO2 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 CO2
production of 0.4 l/m, in 2 minutes the PO2 will be down to
0.09 bar (9%) and the PCO\textsubscript{2} will be about 10%. This would be extremely stressful but most people would probably still be conscious. In 3 minutes the PO\textsubscript{2} will be down to 0.02 bar, low enough to cause unconsciousness and very soon death. The PCO\textsubscript{2} will be about 16%, enough to be extremely distressing and narcotic. Although some people might become unconscious from this level of CO\textsubscript{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\textsubscript{2} repeated breaths would deplete the oxygen, but no CO\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{2}. A level of up to 30-40% CO\textsubscript{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**

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\textsubscript{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\textsubscript{2} that can lead to loss of consciousness.

**HYPOXIA**

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\textsubscript{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. 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 PO2, 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 PO2 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. 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 PO2 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.

References and additional reading

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