statistically derived, highly informed, but unconfirmed, estimates of the risks associated with decompression from an air saturation. The tables provide several alternative schedules for decompression on air from various depths. The most lengthy (conservative) schedule for each depth is associated with a 1% or less predicted bends incidence. Other schedules have faster overall decompression times at a cost of a higher incidence of DCI, in some cases nearly 80%.

USN Treatment table 7 is an oxygen/air table usually reserved for cases of unresolved or life threatening DCI. It involves a minimum stay of 12 hours at 18 m (2.8 bar) and then a slow decompression back to the surface. The probability of DCI occurring in an individual breathing air throughout a Table 7 has been estimated at 0.2 %; an important consideration for both the medical attendants and the survivors.

In the absence of tested decompression schedules it is planned that survivors from depths between 18-40 m (2.8-5 bar) will commence decompression at a rate of 1 m/hour and continue in accordance with table 7 from 18 m to the surface. The chamber atmosphere will initially be air. It is planned to let the survivors breathe down the oxygen content to maintain a partial pressure of oxygen no greater than 0.5 bar. Oxygen will be added as necessary to maintain this level.

Patients will begin breathing oxygen as soon as possible after reaching 18 m. Oxygen breathing will be limited by pulmonary oxygen toxicity and the medical officer will be required to assess each patient's clinical condition individually. The medical attendants will breathe chamber atmosphere throughout. This decompression schedule will take over 60 hours from 5 bar, the maximum working pressure for the ASRV. Any cases of DCI which occur during these decompressions will be treated with the usual saturation practices.

It is estimated a minimum of five ASRV cycles will be required to bring out half the crew of the disabled submarine. If the internal pressure in the submarine remains constant, once the first 3 compartment complex is full decompression can begin. If however the internal pressure is rising, it is planned to hold each group of survivors in a separate compartment until the maximum pressure is known. Then it will be decided whether earlier rescuees will perform a downward excursion to the depth of the later survivors, or the later rescuees perform an upward excursion based on predicted safe limits.[1] The upward excursion limits are based on limited testing, so, for safety reasons, we will aim to restrict any upward excursion to 50% of the predicted safe limit for that depth. Decompression will then begin. The transfer under pressure (TUP) section will be used for the supply of food and sanitation purposes.

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NORMOBARIC OXYGENATION IN DIVE ACCIDENTS: A CHALLENGE FOR THE DEVELOPERS OF OXYGEN DELIVERY SYSTEMS

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Key Words

Accident, equipment, oxygen, rescue, transport, treatment.

Introduction

The value of immediate normobaric oxygenation (NBO) in the treatment of diving accidents is clear. The main treatment for decompression illness (DCI) is hyperbaric oxygen therapy (HBO). DAN Europe statistics[1] showed that 85% of the DCI cases treated with HBO had complete relief of symptoms. The two main factors influencing the final outcome are immediate treatment with NBO and liquids and the delay before recompression therapy.

In the US DAN statistics[2] about 70% of the patients with minor neurological symptoms or pain as pre-recompression symptoms were still symptomatic after treatment when the delay was more than 12 hours, while the percentage of residual symptoms was only 20% for a delay between 4 and 12 hours and about 10% for a delay less than 4 hours. The median delay before HBO treatment was 7 hours for AGE, 26 hours for DCS I and 20 hours for DCS II. Only 33% of DCI cases were given oxygen as first aid therapy during transport and only 6% of DCI cases got oxygen and fluids. In transit oxygen treatment increased the symptom relief rate before recompression by a factor of 2 to 8.

From the DAN Europe statistics we see an even more striking effect. While 99% of the no-oxygen group remained symptomatic, 55% of the oxygen group showed improvement and 12% had complete relief of symptoms by the time they arrived at a hyperbaric facility. The relief rate after HBO treatment was 70% for the no-oxygen and 96% for the oxygen group. These figures show that oxygen first aid therapy is not just an additive to the overall treatment, but an important contribution with a significant effect on the final outcome. Considering that the majority of divers who got oxygen did not really breathe 100%, because of inappropriate oxygen administration devices, and that many of them did not get oxygen during the whole transport time, the difference in outcome could even be greater.

Oxygen delivery systems

Why is the use of the NBO in first aid treatment still very uncommon in the diving population? Many divers are not aware of the first aid possibilities and do not know the techniques of oxygen therapy.

There are two systems for oxygen administration, open and closed. With open systems the exhausted gas is extruded to atmosphere. With the next inspiration the patient again fills his lungs with gas from the system. Open systems can be constant flow or on-demand. Most of the available oxygen systems do not assure 100% inspired oxygen concentration and in many cases the small cylinders only allow short times on oxygen.[3] The great disadvantage of open systems is that they consume large amounts of oxygen, 600 to 900 litres per hour. For a transport time of 2 hours one needs a 10 litre oxygen cylinder (Australian D size cylinders are 9.5 l water capacity).

The most commonly used constant flow oxygen delivery system has a loose fitting mask, designed to allow entrainment of air with each breath. The expired air mixes with the oxygen in the mask, dilutes it and then escapes between the mask and the patient's face. The flow rate is usually between 2 and 10 litres per minute (lpm). It was designed to raise inspired oxygen to around 40%, which is too low for diving casualties but useful to prevent hypoxia.

For a constant flow system to deliver 100% inspired oxygen a close fitting mask, to prevent air entrainment, and a reservoir bag, larger than the inspired volume to store the oxygen delivered during expiration, must be provided. A non-return valve must be used between the reservoir and the patient so that the oxygen in the reservoir is not diluted with expired nitrogen. The oxygen supply must be equal to, or more than, the minute volume, which is 10 to 20 lpm if the patient is to receive 100% oxygen. The Laerdal resuscitation mask, self-inflating bag and reservoir bag with a flow of about 15 lpm is an example.

On-demand systems are similar to a scuba regulator. Oxygen only flows when the patient breathes in so 100% oxygen can be achieved, but is used at the patient's minute volume.

In 1989 we assessed the frequently used oxygen delivery systems for their ability to assure inspiratory 100% oxygen, the maximum duration of the oxygen supply and acceptance of the systems by divers for long term use, which means comfort of the mouthpiece or mask etc. We found that none of the available systems met the optimum conditions for NBO and we therefore proposed the use of closed systems but there was nothing on the market at that time.[4]

Closed systems

With the help of a Siemens engineer I assembled a new device (Fig 1). Soon after the first experiments, this rebreather system, with a closed circuit, was tested.[5] As this type of gas supply is widely used in anaesthesia, the question was not whether it would work but whether such a sophisticated apparatus could be used by divers. When oxygen inflow is higher than uptake excess gas will escape through the relief valve. With an inflow that is too low, the rebreather bag will lose its volume and finally collapse (Fig 2). There is absolutely no danger for the diver, because, as he or she is awake, he can take off the mask and breathe air if the bag collapses.

The danger of CO_2 intoxication was also checked. Even if the colour change in the absorber is not noticed by the diver, the spontaneous increase in tidal volume will alert

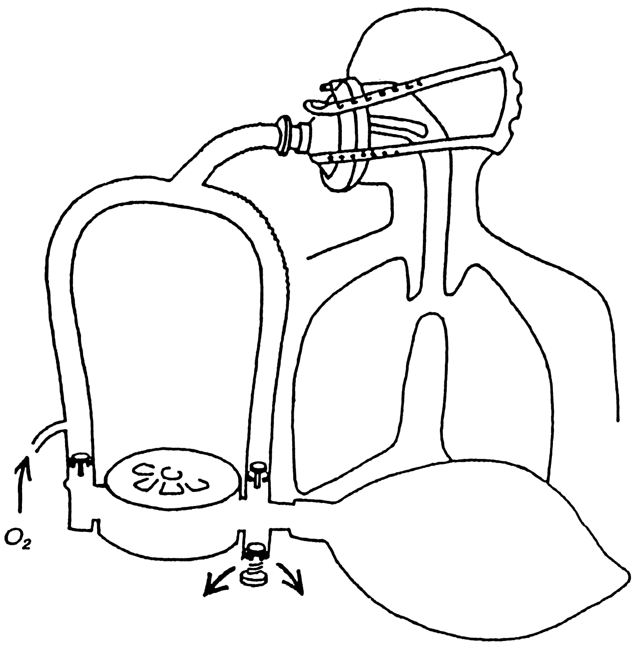
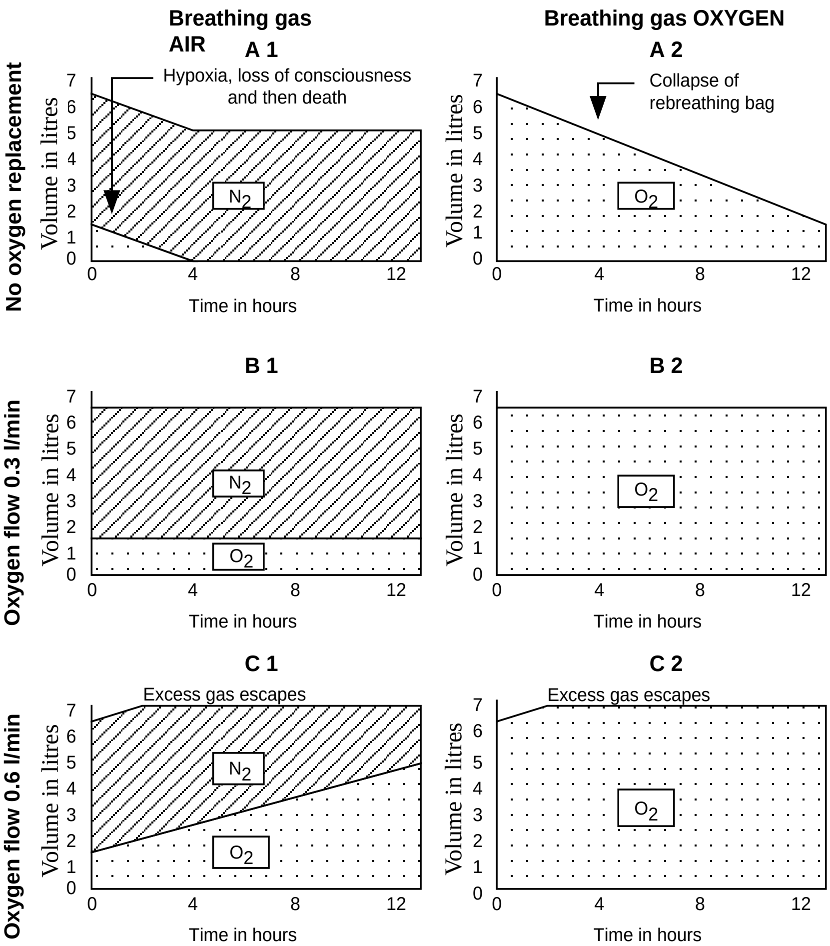


Figure 1. Diagram of closed circuit oxygen system for field first aid (Wenoll system).



A 1 Air closed circuit without oxygen substitution After 2 minutes the gas is hypoxic and will induce unconsciousness and death. Note that there is no ventilatory stimulation due to CO_2 absorption.

A 2 Oxygen closed circuit without O_2 subsitution. The total volume of the system will diminish gradually, so that the rebreathing bag will collaps after a few minutes. There is no danger to life as the gas remains 100 % O_2.

B 1 and B 2
Closed circuit systems with replacement of O_2. Both maintain volume and constant O_2 concentration.

C 1 Air closed circuit system with abundant O_2 supply. O_2 concentration increases while part of the gas mixture escapes to atmosphere.

C 2 Oxygen closed circuit system with abundant O_2 supply. Excess O_2 escapes to atmosphere.

Figure 2. Changes in total volume and oxygen concentration in closed systems with various oxygen inflows. Comparison of a closed circuit air system (left) and pure oxygen circuit (right).

him, or her, and induce interruption of the circuit a long time before the dangerous state of CO_2 intoxication can develop.

Elimination of nitrogen is the main goal of NBO therapy. When a closed oxygen system full of oxygen is attached to the patient who has breathed right out (full expiration) the system still contains some 30% of nitrogen after the first few breaths. This must be washed out in order to get a pure oxygen atmosphere. This can be achieved by a flushing phase, using an inflow of oxygen of 2 lpm for about 10 minutes. After about 10 minutes the N_2 is less than 3% (Table 1). Then the system is closed by reducing oxygen inflow to about 0.5 lpm. Fig 3 shows the Wenoll system in use.

Is a closed oxygen system safe for normal divers?

After six years of experience, carefully testing and improving some details, we can answer the question.[6] Closed systems are now widely used by divers in middle Europe, by Swiss police divers and soon by the Dutch Navy.

TABLE 1

ELIMINATION OF LUNG NITROGEN FROM A CLOSED CIRCUIT (SYSTEM FILLED WITH OXYGEN) USING AN OXYGEN FLOW OF 2 lpm

Time in minutes	Added oxygen	Expired gas Vol	Expired gas Nitrogen %	Expired gas Nitrogen Vol	Nitrogen in circuit %	Nitrogen in circuit Vol
Start					31%	2.00 l
1	+2.00 l	-1.5 l	31%	0.46 l	24%	1.54 l
2	+2.00 l	-1.5 l	24%	0.36 l	18%	1.18 l
3	+2.00 l	-1.5 l	18%	0.27 l	14%	0.91 l
4	+2.00 l	-1.5 l	14%	0.21 l	11%	0.70 l
5	+2.00 l	-1.5 l	11%	0.16 l	8%	0.54 l
6	+2.00 l	-1.5 l	8%	0.12 l	6%	0.41 l
7	+2.00 l	-1.5 l	6%	0.10 l	5%	0.32 l
8	+2.00 l	-1.5 l	5%	0.07 l	4%	0.25 l
9	+2.00 l	-1.5 l	4%	0.06 l	3%	0.19 l
10	+2.00 l	-1.5 l	3%	0.04 l	2%	0.15 l

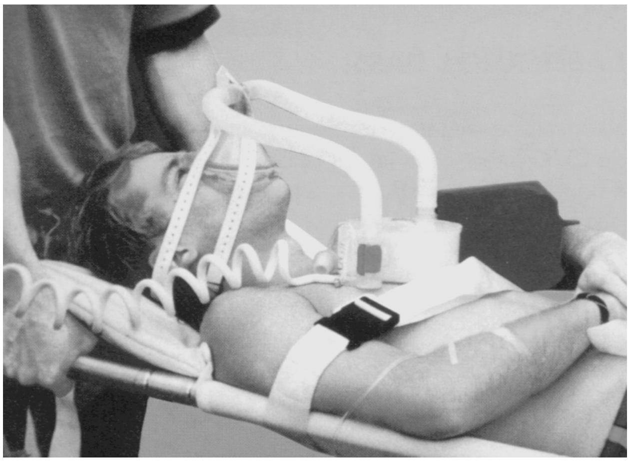


Figure 3. Closed circuit oxygen system (Wenoll system) for normobaric oxygen for divers in use .

For a treatment of less than 5 hours, the system can be turned on with a flow of about 1.3 litres and nitrogen elimination, high oxygen concentrations in the circuit and normal CO_2 levels will be maintained.

If transport will take longer, the system must be used as a closed circuit with flushing at intervals. The oxygen flow is set to 2 lpm for the first 10 minutes, then reduced to 0.5 lpm for 20 minutes. At the end of the 20 minutes another 10 minutes at 2 lpm is followed by another 20 minutes at 0.5 lpm. After these two cycles a 10 minute flush is followed by 50 minutes at 0.5 lpm three times, taking the patient to the 4 hour mark when the absorber has to be changed. With these settings a 2 litre oxygen cylinder at 200 bar will allow the whole five flush cycle to be repeated as the oxygen supply will be sufficient for up to 8 hours (Australian C size cylinders are 2.84 l water capacity and pressurised to 163 bar).

If CPR is needed, the system can easily be connected to a tracheal tube or a resuscitation mask and controlled ventilation with 100% oxygen performed. Another special use is closed circuit therapy in hypothermia, used by coastal life guards or alpine rescue teams, which however requires some adaptations to the equipment.

Conclusion

Although some open systems can be very useful for NBO they all have the disadvantage of a limited capacity due to high oxygen consumption (600-900 litres per hour). Closed-circuit rebreather systems are a new approach to the problem. They use less than 50 litres of oxygen per hour, which allows continuous NBO treatment for many hours using small oxygen cylinders. This argument might not be very important in my home country (Switzerland). However in the world's most favoured diving places transport time is so significant that the use of closed oxygen systems should be promoted as the standard procedure in first aid treatment of diving accidents in order to reduce residual symptoms and invalidity.

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The closed circuit oxygen rebreathing system presented in the article is produced by EMS Elektromechanische Systeme GmbH, Waldstrasse 2, D - 91096 Möhrendorf, Germany. Phone + 49 9131 440 420. Fax +49 9131 47468

The Wenoll system sells for DM 350. A complete set with light weight box, 2 l oxygen cylinder, reduction valve with flowmeter is DM 1,100. Highly resistant special boxes (Pelikan type) with more space for first aid equipment are also available.