Investigation of a Halcyon RB80 semi-closed rebreather in connection with a diving accident.

Oskar Frånberg[1,2], Mikael Ericsson[3,4], Agneta Larsson[5,6], Peter Lindholm[5]

1: Department of Environmental Physiology, School of Technology and Health, Royal Institute of Technology, Stockholm, Sweden
2: Department of Defence Medicine, Swedish Defence Research Agency, Stockholm, Sweden
3: Submarine Systems Office, Naval Procurement Command, Swedish Defence Material Administration, Stockholm, Sweden
4: Diving and Naval Medicine Centre, Swedish Armed Forces, Karlskrona, Sweden
5: Department of Physiology and Pharmacology, Karolinska Institutet, Stockholm, Sweden
6: Department of Anaesthesiology and Intensive Care, hyperbaric medicine, Karolinska University Hospital, Stockholm, Sweden

ROYAL INSTITUTE OF TECHNOLOGY

The accident and Investigation

The dive was 105 minutes at 28 meters average depth, during which the rebreather was supplied with trimix gas containing 31% oxygen (the diver thought he had a 32% mixture). After this there was a 19-minute oxygen decompression stop at 6 meters. Upon surfacing the diver experienced seizures and signs of severe neurological deficits.

Among other things the oxygen fraction inhaled by the diver (F_iO_2) was investigated.

We suggest that during the dive, the actual F_iO_2% was 17.9-25.3 %, which is considerably lower than the 30 % used for the decompression calculation.

The overestimation of F_iO_2 resulted in too short and/or too few decompression stops during ascent.

CONTACT INFORMATION

Oskar Frånberg, M.sc
Royal Institute of Technology
Oskar.franberg@sth.kth.se

For decompression calculations the diver used table 1. At the time of the accident table 1 could be found on the manufacturer's webpage (1,2) as well as published in the book Mastering rebreathers (3).

Apart from this there are two published algorithms for calculating the oxygen fraction in this type of system, Morrison and Reimers (4) and Nuckols et.al (5)

The gas dosage of the RB80 depends on the ventilation equivalent i.e., the ratio of the respiratory minute ventilation to the rate of oxygen consumption. Ventilation equivalents are generally considered to range in the interval of 15≤ K ≤ 30 (4). Divers as a group tend to have a lower ventilation equivalent (6) and ventilation equivalents as low as 10 have been recorded (4)

When comparing the values suggested in accordance with Table 1 and those obtained in accordance with the algorithms proposed earlier and our measurements (see Figure 1) the fractions are found to deviate considerably.

In table 1 the suggested oxygen fraction drop at 26 msw or greater was 2%-units. In our measurements it was found to be 4 - 10%-units. The gas mixture in the breathing circuit would then have contained between 17.9 - 25.3 % of oxygen during the dive (see Table 2).

As can be seen from the calculations in table 2 there is also an apparent risk of hypoxia at shallow depth. This is further corroborated by another incident on the 31 of March 2007, where a diver lost consciousness in shallow waters at Wakulla Springs, Florida, USA, using the RB80 apparatus (personal communication).

The risk of a hypoxic breathing mixture at shallow depths is further accentuated during ascent since the expanding gas in the breathing loop will reduce the fresh gas dosage.

Hypoxia at shallow depth does not only introduce a risk of syncope it will also affect the inert gas washout rate, by lowering the inert gas gradient.

We want to direct attention to the fact that table 1 is published as Table E-1 in appendix D in 'Mastering rebreathers' (3) and we strongly advise against using this table for decompression calculations.

Depth Feet (meters)	Inspired F_iO_2% Drop
20 (6)	7 %
30 (10)	6 %
40 (13)	5 %
50 (16)	4 %
60 (20)	4 %
70 (23)	3 %
80 (26)	2 %

Table 1: The oxygen fraction vs. depth table as published in Mastering Rebreathers. "Common reduction in oxygen percentage from supply cylinder to inhaled gas supply." (5). Note the strange conversion between feet and msw and also, note our warning about this table

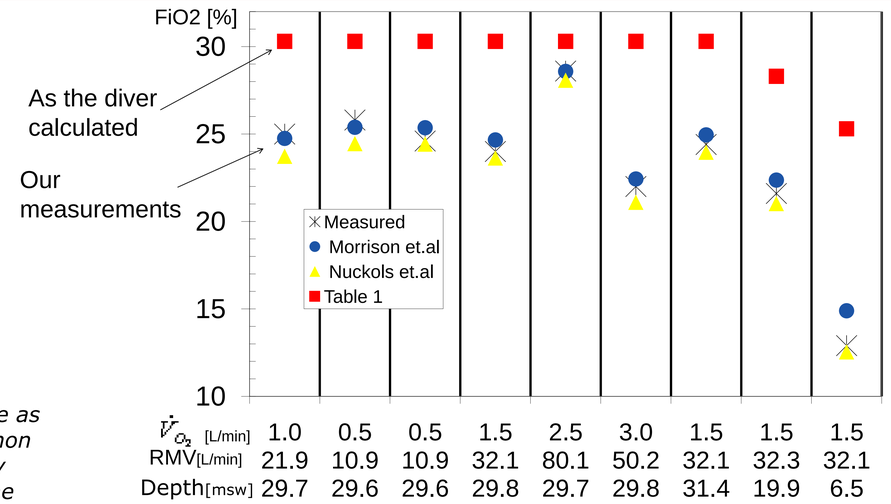

Figure 1: Oxygen fraction measurements and calculations. Supply gas fraction was 32,3% oxygen. An analysis flow 0.5 SL/min has been added to the fresh gas dosage for the calculations.

Rebreather Testing

When testing rebreathers, it is important to test to all relevant morphologic and physiologic variances and not just to an average or best case scenario.

In the U.S.-Navy unmanned testing methods and performance goals (7) as well as during previous unmanned testing of demand controlled rebreathers (8, 9) the tests were conducted with a range of RMV of 22.5 to 62.5 L/min (8,9) and 22.5 to 90.0 L/min (7) but all with a constant ventilation equivalent, K, of 25. A similar situation is apparent in the current European rebreather standard (10) where a range of RMV from 10 to 75 l/min are tested but all with a ventilation equivalent, K, of 22.5. To test a demand controlled semi closed rebreather the ventilation equivalent has to be varied, as shown in table 2. We propose this to be changed.

Ventilation equivalent K	Oxygen fraction 30 msw Nuckols et.al. (12)	Oxygen fraction 30 msw Morrison et.al. (8)	Oxygen fraction 6 msw Nuckols et.al. (12)	Oxygen fraction 6 msw Morrison et.al. (8)
15	17.9	19.5	-	2.3
22.5	22.3	23.3	9.2	11.8
30	24.5	25.3	14.7	16.6

Table 2: Calculated oxygen fractions as % for different relationships between ventilation and oxygen consumption. Calculated with supply gas fraction 31% oxygen at 30 and 6 msw depth.

1) http://www.halcyon.net/rebreather/rb80_configure.shtml on the 16th April 2007. The webpage have been changed since the accident, to see the webpage with the original content the web archive address is listed in ref 4.
2) http://web.archive.org/web/20070419020926/www.halcyon.net/rebreather/rb80_configure.shtml
3) Bozanic J. E. Mastering Rebreathers 2002 ISBN 0-941332-96-9, Best publishing company Flagstaff AZ USA
4) Morrison J. B. Reimers S. D, Bennett and Elliott's Physiology and Medicine of Diving, 3rd ed., Best Publishing Company, 1982. ISBN 0-941332-02-0,
5) Nuckols, M.L. Clarke, J.R. Marr, W.J. Assessment of oxygen levels in alternative designs of semiclosed underwater breathing apparatus, Life support and biosphere science, 1999 vol 6 239-249.
6) Florio J.T. Morrison J.B. Butt W.S. Breathing patterns and ventilatory response to carbon dioxide in divers. Journal of Applied Physiology, 1979, 46 1076-1080.
7) NEDU TM 01-94 U. S. Navy unmanned test method and performance goals for under water breathing apparatus, Navy experimental diving unit, Panama city, Florida, USA 1994.
8) Nuckols, M.L. Gavin Jr, W.A. Finlayson, W.S. Unmanned Testing of a Modified US Divers Oxymix Semi-Closed UBA with Variable Exhaust Volume Ratios, U.S. Naval Academy Report USNA-EW-13-00, 2000
9) Nuckols ML, Finlayson WS, Newville B, Gavin, Jr WA. Comparison of predicted and measured oxygen levels in a semi-closed underwater breathing apparatus. OCEANS, 2001. MTS/IEEE Conference and Exhibition. 5-8 Nov. 2001 pages 1725 - 1730 vol.3
10) European Standard EN14143:2003, Respiratory equipment – Self-contained re-breathing diving apparatus. Publication date 6 October 2005