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BREATHHOLD DIVING

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Key Words

Breathhold diving, hypoxia, unconscious.

Abstract

Breathhold diving has been practised for millennia. Until the advent of the diving bell and underwater breathing apparatus it was the only way that man could harvest food and valuable items such as sponges and pearls from the sea. Although there are still commercial breathhold divers, breathhold diving has largely changed into a sport. Among these sportsmen there is a cadre of elite divers who devote themselves to diving ever deeper. There are a number of physiological constraints that need to be overcome to undertake very deep dives. It was once thought that thoracic squeeze was the main limitation to how deep a breathhold diver could go. As this theoretical limit was exceeded in the 1960s other parameters have become limiting. This brief review examines breathhold break points and techniques for extending a breathhold dive, possible adaptation to breathhold diving and loss of consciousness during ascent.

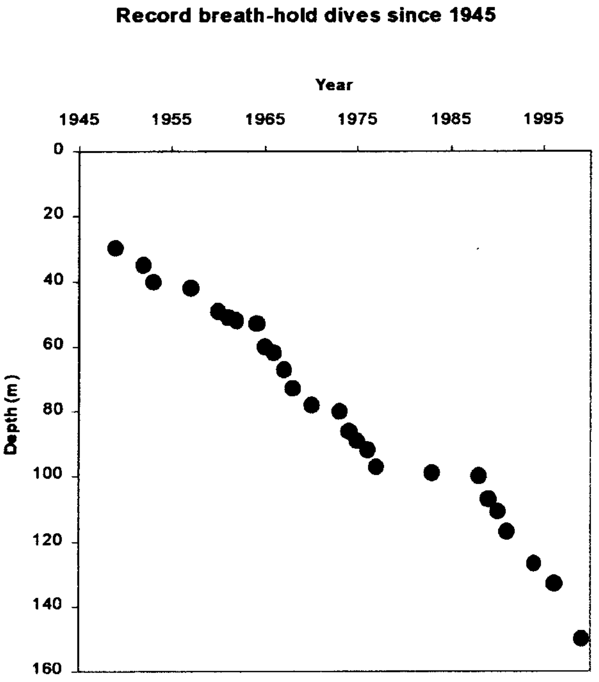

Figure 1. Record breath-hold dives since 1945.

Introduction

The idea of venturing underwater without a supply of breathing gas is increasingly alien to a western world that is more aware than ever of the undersea environment. Through film and television people who have never ventured into water deeper than their knees have become familiar with scuba and other diving apparatus to the point that some find even the idea of free diving frightening.

The fact is that for most of man's evolution, breathhold diving was the only technique available for exploring underwater. For many centuries it was the way in which lost items were recovered and food and valuables, such as pearls and sponges, were harvested from the sea, practices which persist to this day in parts of the Far East.

Today, most free diving is conducted as a sport and its elite practitioners are devoted to diving ever deeper. Figure 1 shows graphically how, since WWII, ever deeper records have been set. Two techniques are used: the first is an "unassisted" dive whereby the diver descends and ascends using their own power, either finning or pulling hand-over-hand up and down the shot line. "Assisted" dives are those where the diver uses a weight or sled to increase the rate of descent and a buoyancy aid to speed their ascent back to the surface. At the time of writing the record, assisted dive was held by Umberto Pelizzari, who dived to 150 m in October 1999. In the same week, he also claimed the unassisted dive record of 80 m.

In the remainder of this paper I will describe some of the physiological factors associated with this kind of diving.

Thoracic squeeze

Gas in the lungs obeys Boyle's Law and consequently, during descent, it will decrease in volume in proportion to the depth achieved. It was once believed that if the volume of gas in the lungs was compressed to less than the residual volume (RV) of the lungs then a relatively negative pressure would develop in the chest and thoracic "squeeze" would occur. This would result in pulmonary oedema, frank haemorrhage into the lungs and, in extremis, death.

In most people, if a full breath is taken at the surface, the lung will reach residual volume at a depth of 30-50 m. In the mid-1960s deeper breathhold dives were being achieved. Schaefer et al. studied Robert Croft, a US Navy diver who had reached a depth of 73 m. His total lung capacity (TLC) was 9.11 litres with an RV of 1.31 l.[1] Theoretically the maximum that he should have been able to dive and avoid lung squeeze was 69.5 m. They found

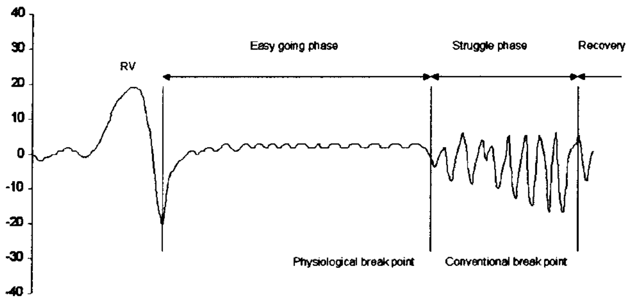

Figure 2. After breathing out to residual volume, a breath is taken and held. During the easy going phase of the breathhold there is little respiratory muscle activity. As the central drive to breathe increases the physiological break point is reached and involuntary respiratory muscle activity starts. This increases until the conventional break point is reached, and a breath is taken. (Adapted from Reference 2).

that, during a breath hold dive, his thoracic blood volume (TBV) increased by between 850 and 1,047 ml. The equivalent figures for Jacques Mayol, another record-breaking free diver, were TLC 7.211, RV 1.881.[2] To achieve his record dive of 70 m, it was calculated that he would have to increase his TBV by 980 ml. Increasing the TBV has the effect of reducing the residual volume and thereby greatly increasing the maximum depth that can be achieved.

Breathhold break points

To undertake a successful breathhold dive, the diver must be capable of holding his or her breath for a considerable period. Even using assisted techniques, deep dives take as long as three minutes or longer to complete. Figure 2 shows a recording of oesophageal pressure during a breathhold at the surface. There are two distinct phases. During the first there is little respiratory muscle activity and this ends at the physiological break-point. During the second phase, respiratory muscle activity gradually increases until the breathhold is broken at the conventional break point.[3] The physiological break point is reached largely involuntarily. It occurs when the alveolar pressure of carbon dioxide (P_ACO_2) reaches about 46 mm Hg. The duration of this phase can be extended by increasing the volume of the lungs at the start of the breathhold or by blunting the hypercapnic respiratory drive by inhaling 100% oxygen prior to the breathhold.[4] The duration of the struggle phase has a substantial voluntary component and is determined by many more factors (Table 1).

TABLE 1

FACTORS AFFECTING THE DURATION OF EACH PHASE OF A BREATHHOLD DIVE

Easy-going phase

Lung volume at start of breath-hold
Oxygen content of the gas breathed
Arterial PCO_2 (and PO_2)

Struggle phase

- Immersion
- Water temperature (if immersed)
- Mechanoreceptor stimulation:
  - Rebreathing
  - Releasing air
  - Valsalva manouvre
- Distracting activity:
  - Physical
  - Mental
- Arterial PCO_2 (and PO_2)
- Tolerance to hypercapnia and hypoxia:
- Training
- O_2 and CO_2 stores:
  - Hyperventilation
  - Oxygen breathing

However, as with the physiological break point, the P_ACO_2 is an important determinant. Consequently, the fundamental physiological determinants of a breathhold duration are the metabolic rate and the capacity of the CO_2 store. Superimposed on this will be individual's tolerance to hypercapnia and hypoxia.

Immersion in water can increase the duration of a breathhold by about 26%, although this effect is highly dependent on the temperature of the water.[5] The maximal effect is seen during immersion in thermoneutral water. The mechanisms involved are unclear. One possibility is an acute increase in carbon dioxide stores.[6] The role of the oxygen conservation and other metabolic consequences of the dive reflex in man is controversial.[7,8] The duration of breathholding can be shortened dramatically by immersion

TABLE 2

HUMAN OXYGEN AND CARBON DIOXIDE STORES[13,14]

Oxygen stores (litres)		**Carbon dioxide stores (litres)**	
Haemoglobin			
Venous blood	0.60	Bone	106.5
Arterial blood	0.28	Muscle	9.5
Myoglobin	0.24	Other tissues	7.0
Dissolved in tissues	0.06		
Lung (at FRC)	0.37		
TOTAL	**1.55**	**TOTAL**	**123.0**

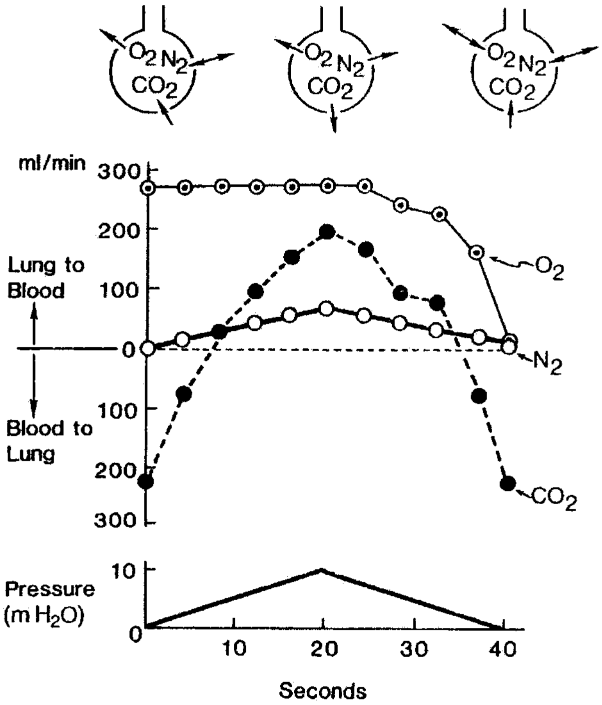

Figure 3. The rate of alveolar O_2, CO_2 and N_2 exchange during a breathhold dive to 10 m. (From Reference 23).

in cold water. Five subjects immersed in water of 20°C could only hold their breath for about 40% of the duration of a control, non-immersed breathhold.[5] This shortening of the breathhold time is probably due to two effects: the direct stimulation of skin cold receptors and the increased metabolic rate caused by immersion in cold water.[3,9]

A breathhold can be extended by rebreathing from a bag. Whitelaw et al. have shown that a higher P_ACO_2 and lower alveolar oxygen pressure (P_AO_2) can be tolerated by stimulation of thoracic mechanoreceptors.[10] This may explain why trained breathhold divers perform Valsalva manoeuvres or release air from the lungs to extend their breathhold time. Distracting physical or mental activity such as squeezing a rubber ball or doing mental arithmetic can also be used to prolong a breathhold.[11,12]

Another means of increasing the duration of a breathhold is by increasing the store of available oxygen in the body and postponing the rise in the arterial carbon dioxide pressure (P_aCO_2) by increasing the capacity of the body's carbon dioxide stores. Table 2 shows the extent of these stores in a 70 kg man. The first and obvious point to make is that the carbon dioxide stores are two orders of magnitude greater than those of oxygen. The oxygen stores can be increased by three strategies: Hyperventilation can increase the alveolar oxygen content by about 0.15 litres and the pulmonary oxygen store can be increased by another 0.5 litres by starting the breathhold at TLC rather than FRC. The biggest effect, however, is achieved by breathing oxygen. If the final breath before the breathhold (from RV to TLC) is taken using 100% oxygen, the pulmonary oxygen store can be increased by between 3.5 and 4.5 litres in a healthy adult male. The carbon dioxide storage capacity can be increased quite simply by blowing off CO_2 through hyperventilation. Taking twenty deep breaths in a minute will blow off about 1.4 litres of CO_2. This exceeds eupneic CO_2 elimination by about 1.1 litres or roughly 4 minutes of CO_2 production. Using a combination of hyperventilation and oxygen breathing an average male can increase his breathhold duration from about 2.5 to 12 minutes.

Adaptation

There is some evidence that training can increase breathhold duration. Schagatay and Andersson studied nine groups of subjects with varying degrees of experience of breathhold diving.[8] They showed that young, trained breathhold divers could tolerate the longest apneas (and greatest reduction in heart rate and skin blood flow) compared with groups of older and inexperienced divers and non-diving controls. Ferretti et al. found the same in a study of three elite breathhold divers and nine controls.[15] How this adaptation occurs remains unclear. Elite divers are able to tolerate a lower P_AO_2 and arterial oxygen saturation than controls and are more tolerant of CO_2. Reduced sensitivity to CO_2 has been shown in Korean diving women, Japanese Ama and underwater hockey players.[16-19] The question remains whether this finding is an example of adaptation or whether people with low sensitivity to CO_2 self-select for breathhold diving occupations or pastimes.

It is well known that diving using underwater breathing apparatus is associated with an increase in vital capacity.[20-22] The same phenomenon has been found in

TABLE 3

ALVEOLAR GAS COMPOSITION IMMEDIATELY BEFORE DESCENT, ON THE BOTTOM AND IMMEDIATELY AFTER RETURNING TO THE SURFACE AFTER A 10M BREATHHOLD DIVE[23]

	Alveolar Gas Tension (mm Hg)	Alveolar Gas Fraction (%)
Surface		
O_2	120	16.7
CO_2	29	4.0
N_2	567	79.3
10 m		
O_2	149	11.1
CO_2	42	3.2
N_2	1143	85.7
Surface		
O_2	41	5.9
CO_2	42	5.9
N_2	631	88.2

TABLE 4

HYPERVENTILATION AND BREATH-HOLD BREAK POINT[24]

Measurement	Normal breath		Hyperventilation	
	Rest	Exercise	Rest	Exercise
Breath-hold time (second)	87	62	146	85
End Tidal CO_2 (mm Hg)				
Start	40	38	21	22
At break point	51	54	46	49
End Tidal O_2 (mm Hg)				
Start	103	102	131	130
At break point	73	54	58	43

the Japanese and Korean Ama.[16,18] Again, it is unclear whether this is cause or effect, because having a large VC would confer an advantage in terms of the capacity of the pulmonary oxygen store. In addition, a high VC/RV ratio would theoretically reduce the risk of thoracic squeeze although, as we have seen above, this effect is probably of no practical significance.

Loss of consciousness on ascent

Alveolar gas exchange during a breathhold dive is determined by the body's metabolism and the effect of pressure. Figure 3 illustrates the direction and rate of exchange of oxygen, carbon dioxide and nitrogen during a 10 m breathhold dive lasting 40 seconds. It can be seen that, towards the end of the dive, there is virtually no exchange of oxygen from the lung to the blood. Table 3 (page 29) shows the effect of this gas exchange on the gas tensions in the lung. On longer dives the partial pressure of oxygen in the lungs falls sufficiently that the direction of oxygen exchange can reverse and the lungs actually remove oxygen from venous blood.

Table 4 shows the effect of hyperventilation prior to a breathhold on end-tidal gas tensions. It shows the extent to which a resting and exercising breathhold can be extended by hyperventilation. Note that the end tidal oxygen pressure ($P_{ET}O_2$)at the end of breathholds preceded by hyperventilation is significantly lower than in those which were not. As was discussed above, the reason for this is that hyperventilation increases CO_2 storage capacity far more than it increases the body's O_2 stores. We have seen in Table 3 that the alveolar oxygen tension is maintained on the bottom by the effect of pressure. Consequently it is the P_aCO_2 which is the primary determinant of the breathhold break point underwater and, with it, the signal for the diver to return to the surface. It follows that, having extended the time underwater, the alveolar oxygen tension may fall to dangerously low levels during ascent to the point that the diver may lose consciousness. Not only may the diver drown in such circumstances, but it is this effect rather than lung squeeze, which limits how deep man can dive without the use of breathing apparatus.

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SIMULATIONS OF NEAR-DROWNING AND DECOMPRESSION SICKNESS: A PRELIMINARY STUDY

Chris Acott and David J Doolette

Key Words

Decompression illness, near drowning, oxygen, physiology, simulations, treatment.

Abstract

Theoretically near-drowning should decrease inert gas elimination from tissues by a reduction in cardiac output and increased intrapulmonary shunting. A delay in inert gas elimination may prolong tissue supersaturation and so