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# Breath-hold Diving

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## Introduction

Breath-hold / apnea diving and underwater swimming have a long history. These have been used in gathering, hunting, warfare, sports – competition, and of course, lifesaving – rescue, search and recovery. Safe breath-hold diving requires an appreciation of the risks and strategies for protection.

## Laws of immersion

The study of several physical laws that explain the occurrence of certain phenomena in the physics and chemistry of the hydrosphere is an essential way to support safe behavior. The law of Archimedes, Boyle and Dalton explain all the effects of immersing a body in water. Not to forget the Blood Shift studies by Karl Shaefer in 1968 and test by Elba Jacques Mayol in 1974 to belie the theory of Cabarrou – "*Après, il s'ècrase*".

## Physiology with immersion

Physiological alterations begin with water immersion. The blood volume in the chest is increased while vital capacity is decreased. Facial immersion in cool water initiates the classic reflex – heart rate and cardiac output are decreased, peripheral vasoconstriction and blood pressure are increased, and the spleen contracts to release more oxygen-carrying red blood cells into the bloodstream.

## Hyperventilation

The most well-known manipulative practice used to increase breath-hold time is hyperventilation. The primary risk of pre-breath-hold hyperventilation is cerebral hypoxia and loss of consciousness. While the hazards of hyperventilation were well described almost 50 years ago [1], imprudent use remains a factor in many fatal incidents.

Weak / tired and anxious / nervous swimmers may sometimes hyperventilate unintentionally, due to the release of Epinephrine; exposing themselves to the same degree of risk.

The primary stimulus to breathe is the partial pressure of carbon dioxide ($P_PCO2$) in the blood and $P_PCO2$ is controlled by breathing. Therefore, by hyperventilating, one can reduce the level of carbon dioxide in his body so that the $P_PCO2$ can be decreased to 25-30 mmHg from the normal 40 mmHg. If the person then holds his breath, because he started with less carbon dioxide than normal, it will take longer time for the $P_PCO2$ to increase to the level at about 50 mmHg where he must breathe, thus he will be able to hold his breath longer.

Hemoglobin is 97% saturated with oxygen during normal respiration and therefore hyperventilating does not increase the quantity of oxygen in the body. As breath-hold time is increased, the amount of oxygen used is increased. The partial pressure of oxygen ($P_PO2$) in the blood is a very weak stimulus for respiration and easily ignored. Therefore, the $P_PO2$ can fall to a point where the swimmer loses consciousness before the $P_PCO2$ rises to a level that forces the swimmer to surface and breathe.

A swimmer who loses consciousness underwater will usually drown and therefore one should recognize the danger of hyperventilation before doing a breath-hold dive.

### Ascent blackout
Another problem during breath-hold diving is that as the swimmer goes deeper, the $P_PO2$ is increased as a result of compression (Boyle's Law). The $P_PO2$ in the blood is usually around 100 mmHg on the surface. If the swimmer does a breath-hold dive and quickly descends to a depth of 10 meters of sea water (msw), the $P_PO2$ will be almost 200 mmHg (total pressure of 1 Atmospheres absolute (ATA) on the surface and 2 ATA at 10 msw). The swimmer therefore has a higher $P_PO2$ at the bottom.

If the swimmer has hyperventilated before diving and stays at 10 msw until the desire to breathe becomes very strong, he will have used up most of the oxygen in his body, even though the $P_PO2$ might still be quite high at 60 mmHg. As he ascends, the $P_PO2$ will drop precipitously and he might lose consciousness before reaching the surface.

Usually, the swimmer will involuntarily breathe out while ascending due to the increased $P_PCO2$. This action will further reduce the $P_PO2$ in the body, therefore escalating the probability of black out.

In this example, the $P_PO2$ would be less than 30 mmHg by the time the swimmer surfaced; which might not be sufficient to sustain consciousness. Diving very deep during a breath-hold dive, especially after hyperventilating, is of elevated probability to blackout.

### Oxygen
Question: When the swimmer is given 100% oxygen for several minutes before the dive, will he be able to reduce his carbon dioxide level and probably be able to hold his breath longer without the concern of black out?

Answer: Yes, by diving with their lungs full of oxygen, one will not risk passing out. Great idea, only as long as he stays at less than 6 msw depth. If he dives deep with lungs full of 100% oxygen, he risks having a convulsion, due to oxygen toxicity to the central nervous system! No matter how we look at it, breath-hold diving can be quite a dangerous activity.

### Restricted hyperventilation
A balance between prolonging breath-hold and reducing the risk of loss of consciousness is possible by restricting the amount of pre-breath-hold hyperventilation. Limiting hyperventilation to two or three maximal ventilatory exchanges immediately before the breath-hold will increase breath-hold time but it is probably also safe for most leisure circumstances. An alternative approach is to arbitrarily restrict breath-hold time.

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A proposal in 2006 called for breath-hold by recreational freedivers to be voluntarily limited to 60 seconds [2]. This would allow for varying patterns of hyperventilation and physical activity with a minimal risk of loss of consciousness.

## Conclusion

Appropriate safety protocols are required for all breath-hold divers. Continued development of appropriate and accessible training programs and the regular communication of incident case reports are important strategies to increase awareness of both risks and appropriate practices.

## Appendix

1 Atmospheric Pressure (ATM) = 1 kg / 1 $cm^2$ = 1.013 Bar = 760 mmHg.

### Boyle's Law:

For a fixed amount of an ideal gas kept at a fixed temperature, pressure and volume are inversely proportional (while one increases, the other decreases).

$$P_1 \times V_1 = P_2 \times V_2$$

Where P = pressure, V = volume.

### Dalton's Law:

The total pressure exerted by a gaseous mixture is equal to the sum of the partial pressures of each individual component in a gas mixture.

$$P_{total} = \sum_{i=1}^{n} Pi \quad \text{or} \quad P_{total} = P_1 + P_2 + \ldots + P_n$$

where $P_1$, $P_2$, $P_n$ represent the partial pressure of each component.

$$P\ air = P_PO_2 + P_PN_2 + P_PCO_2$$

1 ATM = 0.21 ATM + 0.786 ATM + 0.0004 ATM

Where ATM = standard atmosphere

## References

1. Craig AB Jr. Underwater swimming and loss of consciousness. The Journal of the American Medical Association. 1961; 176:255-8.
2. Butler FK. A proposed 60 second limit for breath-hold diving. In: Lindholm P, Pollock NW, Lundgren CEG, eds. Breath-hold diving. Proceedings of the Undersea Hyperbaric Medical Society / Divers Alert Network 2006 June 20-21 Workshop. Durham, NC: Divers Alert Network; 2006: 64-74.