The Underlying Physics and Applied Physiology

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A detailed knowledge of the physics and physiology of diving is not needed by those concerned with the prevention and management of drowning. What is necessary to know is that increased environmental pressure is a unique physiological variable that affects all those who descend below the surface of the water. By definition man is exposed to 1 atm of pressure (1 bar) at sea level. The pressure increases while descending through the water, such that each additional 10 m (33 ft) of water increases the environmental pressure by one additional atmosphere. Some knowledge of the natural laws that relate to the hyperbaric environment is needed in order to understand the hazards to which divers are uniquely exposed. A full account of the relevant aspects of environmental physiology is available elsewhere and so a summary can suffice.

Barometric pressure is transmitted throughout the body just as it is through a fluid, and so the diver should not usually sense its direct effects. The barometric pressure:

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- Acts at the molecular and cellular level in a complex manner.
- Acts directly on the gas-containing spaces of the body, such as ears, sinuses and lungs, in accordance with Boyle's Law.
- Causes the pulmonary gases at increased pressure to be dissolved into the tissues of the body until equilibrium, also called saturation, is achieved. Beyond a brief threshold duration, the diver needs to surface by following a predetermined slow ascent in order to assist the safe elimination of the gases.
- Causes an increase in the partial pressure of the respiratory gases to the extent that some significant effects, such as seizures due to toxicity, can occur that endanger the individual.

166.1 Gas Pressure and Volume

The ideal gas law, also known as the Boyle's Law, is $PV = nRT$ where P is the absolute pressure, V is the volume of gas, n is the number of moles of gas, R is the universal gas constant and T is the absolute temperature. In other words, Boyle's Law states that the volume of a given mass of gas is inversely proportional to the pressure. Thus 1 l of gas at sea level (100 kPa) decreases to 0.25 l at 30 m (400 kPa; 100 ft). Of equal importance to the pathogenesis of dysbaric illnesses is the converse of this that 1 l of compressed gas at 30 m (400 kPa; 100 ft) will expand on ascent to 4 l at the surface.

166.2 Compression Barotrauma

During descent, the reduction in volume of gas contained in the body needs to be compensated by the addition of an appropriate supplementary volume of compressed gas. Thus the respiratory gases must have easy access to compensate the gas-filled spaces of the sinuses and middle ear, otherwise the diminishing volumes of their gas may cause pain and possibly vertigo. This can be the start of a cascade of events that may lead to death by drowning but is not a primary concern during treatment if that happens.

166.3 Partial Pressures

The application of Dalton's law that the partial pressure of a gas in a mixture is equal to the product of its fractional concentration and the absolute pressure has a special importance in the hyperbaric environment. Thus at 50 m (600 kPa; 165 ft) the partial pressure of oxygen in compressed air is 126 kPa which is equivalent to breathing a hypothetical 126 % oxygen at the surface.

166.4 Gas Solubility and Uptake

Henry's law determines how much gas dissolves in a particular liquid with which it is in contact. In accordance with Henry's Law, the quantity of gas dissolved in a liquid is proportional at constant temperature to the partial pressure of that gas.

Some gases are more soluble than others, and their solubility in the watery and the fatty tissues of the body is not the same. Also, the uptake of the inert components of the respiratory gases into solution in the body depends upon the characteristics of the circulation during the transient dynamic phase until the steady state of tissue gas equilibrium, or saturation, has been achieved.

166.5 Lack of Oxygen

Hypoxia is a particular hazard of some types of diving in which errors can be made in the content of the respiratory gas supplied to the diver or when there is a failure of complex breathing apparatus. With persons breathing compressed air, hypoxia should not be a hazard. A hazard arises when divers are required to breathe a gas mixture which is meant to be in the partial pressure range of 20–150 kPa and either the wrong oxygen percentage is provided, or the oxygen make-up system of a closed-circuit or semi-closed-circuit breathing apparatus fails. With a scrubber in the circuit, there is no concurrent accumulation of carbon dioxide then, unlike hypoxia from most other causes, its onset may not be noticed by the subject who gently passes through unconsciousness towards an anoxic death.

166.6 Oxygen Toxicity

The toxic effects of oxygen on the lungs and the central nervous system are especially important in diving where not only is partial pressure of oxygen in the air increased by descent, but also because pure oxygen and oxygen-enriched mixtures are used as respiratory gases. Pulmonary oxygen toxicity is not likely to arise in diving of the type associated with the commoner causes of drowning. Most compressed-air divers are exposed only briefly to such moderate pressures that oxygen neurotoxicity does not usually occur in that category of diving. However, it does occur among working divers and more advanced types of recreational diving and so, for practical purposes, the important aspects are those of recognition.

Neurotoxicity, however, is important. The partial pressure threshold for the neurological effects of oxygen is in excess of 150 kPa and can easily be exceeded by divers. This form of oxygen toxicity is relatively quick in onset. Nitrogen narcosis, heavy exercise and carbon dioxide build-up are considered to be synergistic with oxygen in causing this toxicity. The classic presentation is that of a sudden seizure. If this occurs in the water, it may have a fatal outcome.

166.7 Carbon Dioxide Effects

To prolong breath-hold duration, hyperventilation may be intentional for the purposes of reducing CO_2 levels. It may be unintentional, in association with near panic. The latter is likely to be concurrent with other factors contributing towards a perceived in-water emergency and may contribute to an unfavourable outcome.

Excess CO_2 may be due to extrinsic causes such as the failure of carbon dioxide scrubbing in closed-circuit breathing apparatus or intrinsic, such as voluntary hypoventilation to conserve breathing gas. This hypercapnia alone can account for dyspnoea and headaches, even seizures and unconsciousness, but it is perhaps more significant as just one of several synergistic factors in cases of unexpected loss of consciousness underwater.

166.8 Nitrogen Narcosis

At increased partial pressures, nitrogen behaves as a narcotic agent, the mechanism of its action being analogous to that of alcohol and volatile anaesthetics. Euphoric irresponsibility is not compatible with the safe use of complex procedures and equipment, and for this reason commercial compressed-air diving in the North Sea is limited to 50 m (165 ft). In other places slightly deeper limits may be in force. In general, at deeper depths nitrogen is replaced by helium as the necessary oxygen diluent. Compressed air in the past has been used successfully by experienced divers to 90 m. Much beyond that, there is the probability of narcosis leading to unconsciousness. Helium has no significant narcotic properties at depths down to around 700 m (2,300 ft).

166.9 Decompression Illnesses

A few diving deaths are precipitated by decompression illness, but drowning is rare in these circumstances.

The pathology of burst lung during ascent, called pulmonary barotrauma, may lead to the passage of air bubbles in the blood to the brain (arterial gas embolism). Characteristically this can lead to unconsciousness on arriving at the surface, and the victim may sink. If then found and recovered, the diagnosis of drowning may hide the need to treat underlying cerebral arterial gas embolism.

The pathology of decompression sickness arising from bubbles formed from dissolved gases means that its onset is usually after the dive. Thus it is a concern only when a drowning diver with an inert gas load is recovered to the surface with no opportunity to off-gas by completing the appropriate decompression protocol. There is then a risk of the onset of neurological deficits during the next 24 h.

166.10 Children

Children are not merely small adults. Children and adolescents differ in their mental, physical and emotional capacities. Ability of children to understand the basic physics of diving on compressed gas, to comprehend the biology and physiology of diving and to judge the conditions during open water excursions may be significantly less than the abilities of adults. Children also cannot legally or morally agree to assume the risks inherent in diving. Children are more susceptible to cold stress, exhaustion and fatigue in some circumstances.