Physiology of deep sea diving

Deep sea diving has been around since ancient times; the Greeks initially used deep sea diving for commercial purposes to accumulate lost goods before becoming a very popular recreational activity as it is today. The definition of the term "deep dive" varies across the different classifications of diving. The general limit for recreational divers is considered to be 130 feet (~40 metres) - anything further than this delves into the ranges of technical and professional diving.[1] Specialist training and conditioning programmes are required to deal with the more demanding physiological constraints placed on the body when diving professionally.

Contents

1 Physiological Effects on the body
  1.1 Short term effects
    • 1.1.1 Fatigue
    • 1.1.2 Skeletal muscle cramps
    • 1.1.3 Decompression sickness
    • 1.1.4 Pressure differences in the ears and sinuses
    • 1.1.5 Oxygen toxicity
    • 1.1.6 Hypothermia
    • 1.1.7 Dehydration
  1.2 Long term effects

2 Equipment to cope with physiological demands underwater
  2.1 Body protection
    • 2.1.1 Dry and wet suits
    • 2.1.2 Hot water suit
    • 2.1.3 Atmospheric diving suit
  2.2 Body movement
    • 2.2.1 Weight belt
    • 2.2.2 Buoyancy compensator
    • 2.2.3 Fins and mask
  2.3 Breathing
    • 2.3.1 Oxygen sources
      • 2.3.1.1 Air
      • 2.3.1.2 Nitrox
      • 2.3.1.3 Heliox
      • 2.3.1.4 Trimix
    • 2.3.2 Scuba
      • 2.3.2.1 Open-circuit
      • 2.3.2.2 Rebreathing apparatus
      • 2.3.2.3 Octopus regulator
    • 2.3.3 Surface-supplied diving
      • 2.3.3.1 Helmet diving
      • 2.3.3.2 Hookah diving

Future solutions

References

Physiological Effects on the body

As with any form of physical activity, the body undergoes a series of physical pains that places strain on the individual. The scale of the effects varies in seriousness according to the physical conditioning of the person, as well as the individual’s ability to counter any adverse conditions during physical activity.
**Short term effects**

Before diving, it is important for all new divers to be aware of the dangers they may face when immersed underwater for long periods of time. Whilst the effects range in severity, they all pose a danger to a diver that is not trained with coping with the physiological stresses that their body endures. Short term effects induced by diving are easier to treat compared to long term effects. However, it is important to recognise the symptoms of these effects; when left untreated, the consequences can be fatal.

**Fatigue**

Physical fatigue occurs whenever an individual over exerts themselves beyond their body’s physical limits. Feelings of extreme tiredness and sometimes bouts of fainting can ensue, with recovery periods varying from person to person. Being completely immersed in water can cause a great deal of stress on the body. An increase in hydrostatic pressure within the body due to immersion causes a large amount of blood from veins in the legs to travel towards the chest. The heart is made to work harder in order to pump more blood back to the rest of the body. With less oxygen reaching the muscles, the diver feels more lethargic as the muscles work anaerobically. This creates a build up of lactic acid which causes discomfort.

**Skeletal muscle cramps**

Muscles can be categorized into three sections: skeletal, cardiac and smooth. Skeletal has the largest mass, with the most common problems including muscle fatigue and cramp. If the skeletal muscles experience cramp, the diver could find their motion to be very restricted, which can be very dangerous when several feet underwater. The pressure from the water on the body can cause a constricted blood flow, leading to less oxygen reaching the muscles. This abnormality causes the muscles to work anaerobically, creating lactic acid which in turn triggers muscle spasms.

The most common areas affected by cramp are the calf muscles and hamstrings. Fortunately, cramp is very easily corrected, so is not considered to be severe. It is still considered good practice to always dive in pairs in the event that one of you experiences cramp and cannot correct it by yourself.

**Decompression sickness**

Decompression sickness, also known as “The bends”, can occur when using scuba equipment. It can be described through *Henry’s Law*, which states that “At a constant temperature, the amount of a given gas that dissolves in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid.”

In relation to scuba diving, the gas from the air supply dissolves in to the tissues due to the increasing pressure of that gas underwater. For nitrogen based tanks, excess nitrogen builds up in the body as it is not used. As the diver returns to the surface, the pressure of the gas decreases. However, if the diver resurfaces too quickly, the excess gas shoots out in the form of gas bubbles, creating feelings of sickness wherever the gas had previously been building up.

**Pressure differences in the ears and sinuses**

When immersed underwater, the body is subjected to numerous changes in pressure. *Barotrauma* refers to the harm caused to the body due to the changing pressures in air or water. For the ear, pain occurs when there are pressure differences between the inside and outside of the eardrum. Water pressure increases with depth, and the ears and the sinuses must be able to equalize the changing pressure. If the ears and/or the sinuses are unable to do so, then the diver may experience discomfort in these areas.

There are many symptoms associated with barotrauma which indicate the severity of the damage. Aside from the obvious experiences of pain and discomfort, other symptoms for divers can include ringing sounds and muffled hearing. If too much fluid gathers in the middle ear, damage can occur to the inner ear.

These effects can be countered by using equalizing techniques that work best for the individual.

**Oxygen toxicity**

Air consists of 21% oxygen. However, oxygen toxicity does not occur due to breathing higher percentages of O₂, but rather due to the inhalation of oxygen at increased partial pressures. This results in an excessive amount of oxygen in the tissues of the body, which can cause *hyperoxia*. Depending on which tissues are affected, the consequences can vary.
Partial pressures of oxygen and nitrogen within Air and Nitrox at various depths below sea water[8]

<table>
<thead>
<tr>
<th>Depth (fsw)</th>
<th>Depth (msw)</th>
<th>Pressure (ATA)</th>
<th>pO₂ (ATA)</th>
<th>pN₂ (ATA)</th>
<th>pO₂ (ATA)</th>
<th>pN₂ (ATA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>Surface</td>
<td>1.0</td>
<td>0.21</td>
<td>0.79</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>33</td>
<td>10</td>
<td>2.0</td>
<td>0.42</td>
<td>1.58</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>66</td>
<td>20</td>
<td>3.0</td>
<td>0.63</td>
<td>2.37</td>
<td>1.2</td>
<td>1.8</td>
</tr>
<tr>
<td>99</td>
<td>30</td>
<td>4.0</td>
<td>0.84</td>
<td>3.16</td>
<td>1.6</td>
<td>2.4</td>
</tr>
<tr>
<td>132</td>
<td>40</td>
<td>5.0</td>
<td>1.05</td>
<td>3.95</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>218</td>
<td>66</td>
<td>7.61</td>
<td>1.60</td>
<td>6.01</td>
<td>3.0</td>
<td>4.6</td>
</tr>
<tr>
<td>297</td>
<td>90</td>
<td>10.0</td>
<td>2.10</td>
<td>7.90</td>
<td>4.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

When breathing Nitrox, oxygen toxicity occurs at shallower depths of feet/metres of sea water. This is due to the increased partial pressures of oxygen compared to that of air's composition.[8] Nitrogen narcosis can occur in recreational divers breathing air at depths greater than 40 msw. The increased partial pressures of oxygen and nitrogen induces states similar to those experienced under the influence of alcohol.

The main forms of oxygen toxicity are pulmonary and ocular toxicity and central nervous system toxicity (CNS).[9] Pulmonary toxicity manifests due to the increased partial pressures in the lungs. This can cause irritation in the trachea, leading to minor coughing. If left untreated, the diver will experience severe difficulties when breathing and can feel very disoriented. A continuous exposure to these high levels of partial pressures of oxygen can even have fatal consequences.[9] It is important when diving to know the thresholds at which increased partial pressures become dangerous.

Damage to the CNS can result in the sensory neurons becoming dysfunctional. Depending on the type of air supply being used, CNS toxicity can occur at varying depths beyond the recreational limit. If the CNS is exposed to higher levels of partial pressure of oxygen, seizures can occur, which are more dangerous when underwater.

**Hypothermia**

Hypothermia is the outcome of losing too much body heat, resulting in the core temperature dropping below 35°C. Symptoms can vary from shivering, pale skin and feelings of distress or disorientation. If not treated properly and promptly, hypothermia can be extremely uncomfortable and result in death.

Heat can be transferred in four different ways: convection, conduction, evaporation and radiation. Convection is the transfer of heat energy between a solid object and a fluid. When underwater, it is estimated that a person loses heat approximately 25 times faster than a person on dry land would.[10] It is therefore vitally important to have a wetsuit that retains as much heat as possible, without making you lose too much heat through sweat.

It is important to properly insulate and support divers once they have emerged from the water. Conductive heat losses involve the transfer of heat between two solid mediums. This is why it is important to remove a wetsuit as soon as possible from the moment the diver re-emerges; the colder wetsuit absorbs the heat from your body, lowering your body temperature.

Evaporative heat losses occur when liquid on the skin evaporates, taking heat away from the body. This does not contribute towards hypothermia as much as conduction or convection as the rate of heat transfer through evaporation is less.

Radiative heat transfer happens when a body emits heat into the surroundings.

**Dehydration**

Dehydration happens when the body takes in less fluid compared to how much it is losing. This can lead to many other adverse effects such as fatigue, nausea and muscle cramps. Left unresolved, dehydration can also be a large contributing factor towards decompression sickness. It is imperative that divers remain hydrated throughout their activity as failure to do so can result in severe consequences. Dehydration when diving can occur due to the copious amounts of sweat lost. It is important to hydrate at regular intervals rather than consuming large portions of water in one go. This is because your urine production will swiftly increase instead of the body’s tissues becoming hydrated.[11]

**Long term effects**
There are many serious long term damages caused to the human body through prolonged and frequent deep sea diving. It is difficult to say whether deep sea diving specifically contributes to long term health issues as there are other variables involved that affect the physiology of divers. Limited sample sizes also prevent us from making definitive statements about the long term effects of diving.

Whilst not considered to be a direct outcome from regular diving, cases of dysbaric osteonecrosis (DON) in divers have begun to surface more frequently.[12] DON can occur without the increased pressures that act on the body when diving, but is commonly thought to happen due to the disruption of the circulatory system.[12] Divers who suffer from DON can experience severe pain should damage occur to any joints, and sometimes the only option is corrective surgery. It is thought that DON is more likely to occur in those who partake in deep and long dives (dives greater than 115-130 feet), those with circulatory problems and those who have suffered previously from decompression sickness.[12]

Barotrauma can also lead to permanent hearing loss if symptoms are not recognised promptly. Symptoms can be worsened if the individual continues to dive. If the diver also has poor equalizing techniques, then this could also contribute towards permanent hearing damage.

Equipment to cope with physiological demands underwater

People are not naturally equipped to stay under water for long periods of time. The atmospheric pressure in water, increasing by around 14.5 psi (1 atm~14.7 psi) every 33 feet (~10 meters) from the initial 1 atm at the surface,[13] affects the way divers control their movements and breathe at different depths. Additionally, divers are affected by the surrounding water temperature. Special equipment is necessary to ensure divers are safe, in control of their bodies and their physiological functions are sustained.

Body protection

Dry and wet suits

Dry and wet suits are commonly used by recreational and professional divers. Both suits are often made out of neoprene or rubber[14],[15] and serve as a protection from the outside (e.g. low temperatures or potential mechanical damage to the tissue), but their structure and uses differ a lot.

Dry suits are thick and keep the body dry and warm by trapping air inside them, which acts as an insulation layer. For this reason, they can be used all year round. By controlling the amount of air inside the suit (supplied by a gas cylinder)[14], divers can control their buoyancy.[16] However, they are quite expensive, heavy and not as easy to put on and move around in as wet suits.[17]

Wet suits are comparatively thin, comfortable and cheap.[17] The tiny air bubbles impregnated into their material give wet suits great buoyancy in shallow waters, which initially needs to be overcome with a heavy weight belt. As the diver goes deeper, these air bubbles are compressed due to increase in pressure (Boyle’s law) and buoyancy of the diver decreases. This change needs to be offset by a controllable buoyancy compensator.[18] The air bubbles also provide thermal insulation once water inside the suit warms up from the body.[16] Because water gets inside the suit, the insulation is dependent on the temperature outside and wet suits should not be used in cold environments (risk of hypothermia).

Hot water suit

A hot water suits consist of a dry suit and a special type of underwear. Water is heated up in a heater and sent through special loops placed in the underwear, thus warming up a diver, and therefore the suit can be used in very cold environment. A diver is dry and even warmer than in a traditional dry suit, but the underwear can significantly restrict diver’s movement.[19]

Atmospheric diving suit

Atmospheric diving suit (ADS) is "a merger between the commercial diver and a single-person submersible"[20], a specialist type of suit, which can be made of materials such as aluminium and reinforced-glass plastic.[21] Pressure inside ADS is kept constant at 1 atm (surface atmospheric pressure), which enables divers to reach depths up to 2,000 feet and its solid structure protects its user from many potential physiological harms. For these reasons, it has, since its very beginning, been used in the offshore industry and naval submarine rescue missions.[22]

Body movement

In order to control movement when immersed deep below the water surface, divers need to equip themselves, especially when wearing a wet suit, with additional articles. These need to compensate
for changes in buoyancy at different depths and enable divers to move in whichever direction they choose.

**Weight belt**

Weight belt is usually worn by divers to achieve neutral buoyancy. A belt of up to 2.3 kg is most commonly heavy enough when not wearing an exposure suit. The need to compensate for buoyancy is higher when wearing a wet suit and the weight of 4.5 to 13.5 kg is then necessary.[19]

Additionally, weight belts are used as a safety feature during accidents and should be immediately released in the event of emergency.[15] This allows for the quick resurfacing and obtaining medical help as soon as possible.

**Buoyancy compensator**

A buoyancy compensator (BC) is used when wearing a wet suit to compensate for changes in buoyancy as diver moves deeper. Air needs to be added to the compensator to offset the increasing density of the suit when descending and removed to offset the decreasing density when ascending. This can be easily controlled by a diver using a BC device, allowing them to change their depth immediately.[23]

**Fins and mask**

Another standard parts of diving equipment are fins and mask. Fins significantly increase divers' efficiency when moving in water and let them control direction of their swim. Masks, on the other hand, enable divers to see the direction of their movement. Because diving mask cover nose, diver can exhale into it and thus it also helps to equalise pressure changes.[15]

**Breathing**

**Oxygen sources**

As in case of any physical exercise, the intake of oxygen is higher when deep diving. This increased oxygen demand results in higher tidal volume (from 500 ml during quiet respiration up to 5 litres during any extreme exercise) and flow of air (from around 30 litres per minute up to 100 litres per minute during maximum scuba swim).[15] The diving equipment needs to supply enough oxygen to ensure a diver not only survives underwater but also that their increased physiology demands are met.

**Air**

Air, usually compressed at around 3000 psi in a portable tank[15], is the most basic oxygen source used in deep diving. It can be easily obtained and it provides enough oxygen support for recreational scuba divers. It limits the depth which divers may safely reach to around 130 feet, although this is not a strict limit.[24] Factors that may contribute to this limit are resistance to breathing (higher pressure increases density of air and hence the resistance of airflow in the equipment and lungs) and endurance of the regulator. For every atmosphere below the sea level, the actual oxygen intake is one times larger due to increase in partial pressures[8]. The lower the diver goes, the more oxygen is supplied by an air supply, which at some point cannot be maintained.[15] Additionally, receiving too much oxygen is dangerous as it may lead to oxygen toxicity.

**Nitrox**

Nitrox, also known as “oxygen-enriched air” (OEA) and “enriched air nitrogen” (EAN), is a mixture of oxygen and nitrogen. Because the mixture contains less nitrogen than air (64% or 68%), it reduces the risk of developing decompression sickness and nitrogen narcosis. It also lengthens the time a diver may stay under water (compared to when using air supply). However, it does not enable the diver to go deeper than when using air.

Nitrox is most commonly used for technical and professional purposes and is usually not recommended for recreational diving due to several reasons. Divers need to be specifically trained to use it and its blending needs to be tightly controlled. Commercial nitrox is notorious for its poor quality control and was linked to higher prevalence of oxygen toxicity (nitrox has higher oxygen content than air: 32% or 36%). Because recreational divers dive below 30 meters only for short periods of time, it can be argued that the benefits of their using nitrox are not worth the associated potential risks.[25]
Heliox

Heliox is a mixture of helium and oxygen. It has smaller density than air and, therefore, smaller resistance to breathing\textsuperscript{[19]}. Heliox enables divers to reach depths below 200 feet and is therefore used for technical and professional purposes. Using heliox does not lead to nitrogen narcosis but may result in developing high pressure nervous syndrome at large depths\textsuperscript{[25]} (syndromes include headache, tremors and electrophysiological changes\textsuperscript{[29]}).

Trimix

Trimix is a mixture of heliox with nitrogen. It is used for very deep diving (of usually more than 400 feet) during short deep dives and whenever there is a risk of high pressure nervous syndrome\textsuperscript{[27]}. This is due to the fact that nitrogen present in trimix slows down the nerve conduction, thus reducing the risk of developing the syndrome\textsuperscript{[25]}.

Scuba

Self contained underwater breathing apparatus, commonly known as scuba, provides divers with a high degree of freedom underwater and remains the most popular choice of recreational divers\textsuperscript{[19]}.

Open-circuit

An open-circuit system set is a simple and commonly used breathing system when diving. The main elements of the scuba set include an oxygen supply tank, first-stage and second-stage demand regulator, mouthpiece, breathing hoses, and check and exhaust valves.

Demand regulators are used to reduce the pressure from the cylinder (e.g. air is usually compressed to the pressure of around 150-200 atm\textsuperscript{[15]} ) to the ambient pressure in water and to supply the gas on demand. A breathing hose connects the tank to a mouthpiece, thus allowing a diver to breathe. Check valves restrict movement of gas to one direction only and their special type is an exhaust valve. Exhaled air is removed from the breathing system by being pushed through the exhaust valve into the water, where it appears in the form of air bubbles. The exhaust valve ensures no water enters the breathing system, which would be a potentially dangerous situation\textsuperscript{[19]}.

Rebreathing apparatus

Rebreathing apparatuses try to maximise the efficiency of inhaling gas from a tank by reusing some or all of its supply. There are three basic types of rebreathers, known as closed and semi-closed circuits and oxygen rebreathers.

A breathing loop is attached to a mouthpiece and connects it to a breathing bag called “counterlung”. The counterlung is in turn connected to an oxygen supply, and a carbon dioxide absorber (“scrubber”\textsuperscript{[15]}) is located inside it. At the beginning, a diver inhales fresh air provided by the tank. When he or she exhales gas later, it goes back to the counterlung, where the waste CO\textsubscript{2} is absorbed by the scrubber. The remaining gas is later inhaled by a diver again. Fresh portion of oxygen is added whenever needed and there exist different methods of detecting oxygen level and supplying more of it depending on whether a system is an oxygen rebreather, a semi-closed or closed circuit\textsuperscript{[28]}.

Octopus regulator

An octopus regulator is a a second-stage demand valve, which provide divers with an alternative, secondary source of air. It is used in the events of emergency, for example when the main valve in the scuba system stops working\textsuperscript{[15]}.

Surface-supplied diving

Supply of air does not need to be carried by a diver. Surface-supplied diving uses a hose to supply a diver with air from a cylinder – a hookah unit – or a compressor known as SSBA (surface supply breathing apparatus)\textsuperscript{[15]}.
Helmet diving

Helmet or hard-hat diving involves pumping down pressurised air through a hose directly to a diver’s helmet, known as hard hat. Hard hat is a part of standard dress—a traditional diving suit usually consisting of a rigid copper or brass helmet and heavy duty dry suit.[15] Helmet diving is still practiced today in a refined form; however, it has many disadvantages compared to the popular scuba, such as significant reduction in mobility and cost.[29] Helmet diving can also lead to body barotrauma (diver being compressed into helmet), if pressure of the air delivered is not appropriately adjusted according to diver’s depth, or the hose raptures.[15]

Hookah diving

Hookah diving is an alternative surface-supplied diving option. Divers can swim in light and comfortable wet suits and the hose with continuous air supply is connected directly to the mouthpiece. The hookah service providers claim the system is cheaper than scuba[30],[31] and moving around without heavy gas tank may be considered more convenient an option. However, there exist risks associated with hookah diving and these include decompression accidents, carbon monoxide poisoning and barotrauma.[32]

Future solutions

It can be expected than technological progress in many engineering areas will result not only in the improvement of current diving solutions but also in the emergence of completely new ideas and designs. The existing promising concepts under development include exosuits (improved version of atmospheric diving suits)[33], scuba helmets, which extract oxygen directly from the surrounding water[34], and fish-like suits, which supply diver with liquid air thus mimicking the way fish breathe.[35]

References
