Mike Follows

Life below the surface

The science of diving

Key words
diving
pressure
upthrust
Boyle's law

A pressure of 230 bar is 230 times atmospheric pressure.

*Diving is exciting but it can be dangerous. **Mike Follows** explains how understanding a little physics can help divers get out of trouble.*

Scuba diving is the closest any of us will come to a career as an astronaut. Indeed, scuba diving is an important part of astronaut training. Both NASA and ESA (the US and European space agencies) have a Neutral Buoyancy Laboratory (NBL) where they train astronauts. The neutral buoyancy achieved underwater is like the apparent weightlessness of Earth orbit or deep space.

Canadian astronaut David St Jacques undergoes training in a neutral buoyancy tank.

SCUBA is short for Self-Contained Underwater Breathing Apparatus. A 12-litre cylinder charged to a pressure of 230 bar provides enough breathing gas for a dive time of around one hour to a maximum depth of around 30 metres. The cylinder is attached to a buoyancy compensator that is worn like a jacket and the diver is able to breathe quite normally from a demand valve (sometimes called a second stage).

By the time British-born NASA astronaut Nick Patrick had flown his last mission aboard the Shuttle his 'dive-log' totalled 430 hours – 100 dives in the NBL and 100 in open water in preparation for his three spacewalks. He sums up the significant difference between the scuba diving and spacewalking environments like this: "One is blue and wet, and the other is black and a vacuum." Actually, the underwater world is much more beautiful, with weird and wonderful sea creatures to see and wrecks to explore.

Some people are afraid to take up scuba diving because they fret about the extremely remote possibility that they may be mistaken for dinner by a predatory shark. Yet according to the Shark Attack File (www.sharkattackfile.net) there has been an average of about half a dozen fatal shark attacks per year over the last decade while, for every human killed by a shark, our species slaughters over 70 million sharks. Actually, divers need look no further than the nearest mirror to see their biggest potential hazard – themselves. Part of the allure of

'Blue water' diving – more colourful than space

scuba diving is that the underwater world is an alien environment. This means that diving is classed as a hazardous sport yet it is actually very safe, courtesy of the comprehensive training available from scuba diving organisations like BSAC and PADI and the reliable life-support equipment available.

Although scuba divers often become over-reliant on the dive computers they wear on their wrists, they need to learn some basic physics in order to pass their theory exams. In fact, an understanding of Archimedes' Principle, Boyle's Law, heat transfer and Snell's Law helps keep scuba divers safe. Reflecting on the physics helps divers become more skilled.

Buoyancy

Even though divers can ascend and descend diagonally, fins attached to the feet are used for propulsion in the horizontal direction. Vertical motion is achieved by controlling buoyancy and this is the most important skill to be mastered by a scuba diver – ascending too rapidly can lead to a burst lung or DCI (decompression illness).

According to the Archimedes Principle, any object immersed in a fluid receives an upthrust equal to the weight of the fluid it displaces. This can be applied to diving: a diver will descend if her weight exceeds that of the water displaced and rise if her weight is less. A diver achieves neutral buoyancy if her weight exactly equals the weight of water displaced and this mimics the apparent weightlessness experienced by astronauts (see Box on right).

Divers carry several kilograms of lead to ensure that they can sink. However, they control their buoyancy (and hence whether they go and up or down) by varying how much water they displace. They achieve this by controlling how much gas they put into their buoyancy compensator (BC). The BC acts like a lifejacket when the diver is on the surface and provides a convenient place to mount the cylinder that carries the breathing air for the diver.

A diver's buoyancy compensator, used to control the speed of ascent and descent

Floating up, sinking down

Whether a diver will float upwards or sink depends on his density relative to the density of the water around him. Here's why:

The downward force (weight) acting on a diver of volume V depends on his mean density D and the gravitational field strength g:

$$\text{weight} = V \times D \times g$$

Under water, the diver displaces his own volume of fluid, and he experiences an upward force (upthrust) that depends on the density of water D_w:

$$\text{upthrust} = V \times D_w \times g$$

The resultant force is the difference of these:

$$\text{resultant force} = \text{weight} - \text{upthrust} = V \times (D - D_w) \times g$$

A positive value means that the diver will sink – his density is greater than that of water. A negative value means that he will rise, while a zero value means that weight and upthrust are equal and opposite. The forces on the diver are balanced and he will be neutrally buoyant.

Under pressure

Fluids – liquids and gases – are substances that flow. Pressure falls as one ascends in a fluid (e.g. gaining altitude in an aircraft). Descending through a fluid leads to an increase in pressure, as a result of the increasing weight of fluid pressing down on you. The change in pressure is more obvious in water than air because its density is roughly 1000 times as great. Even if you just hold your breath and duck dive to the bottom of a deep swimming pool, you may feel a pain in your ears as the pressure on the outer ear increases while the air trapped in the middle ear is compressed. Divers need to learn how to 'equalise' so that the pressure is the same on both sides of the eardrum.

Equalising is easy for a novice to remember, because it hurts when they don't. However, just as gases are compressed on descent, they expand on ascent according to Boyle's Law. The air in your lungs will be at the same pressure as the surrounding water. Panicking divers will sometimes bolt for the apparent sanctuary of the surface. If they also hold their breath as people are apt to do when alarmed, they put themselves in acute danger of bursting a lung or inducing decompression illness (known as 'the bends'). Scuba trainees are taught to never hold their breath.

The more time that is spent breathing air at higher pressure, the more gas is dissolved in the blood and body tissues. As a diver ascends, pressure is reduced. But, if this takes place too quickly, the gas forms bubbles as it comes out of solution. In the most extreme case, it is like opening a bottle of fizzy drink. These bubbles often form in joints and the accompanying pain is so intense that the victim can be 'bent' double. Depending on the severity of the bend, other symptoms range from a skin rash, paralysis and even death. Divers are taught to use decompression tables that tell them how long they can spend at different depths to reduce the risk of reducing a bend, though they often delegate this task to their wrist computers. The tables used by BSAC are based on the research started in 1905 by Dr John Scott Haldane, whose experiments decompressing goats reduced the incidence of decompression illness (DCI) in Royal Navy divers.

Air consumption

It is important for all divers to be able to estimate how long their air supply will last. A miscalculation could leave you with choosing between drowning and making a dash for the surface, risking a burst lung or DCI in the process. Boyle's law tells us that, as we dive to greater depths, the same air will occupy a smaller volume. Since the volume of your lungs does not change as you dive, filling your lungs when at a depth of 30 m, where the pressure is four times atmospheric pressure, requires four times as many air molecules. So, as you dive deeper you use more air. A cylinder of air that would last for one hour at the surface may last for only 15 minutes at 30 m.

Racks of diving gas cylinders

Heat transfer

For most people the mental image of scuba diving involves wetsuits and warm tropical waters, referred to by British divers as 'blue-water' diving. But how does a wetsuit work? Wetsuits are made of synthetic rubber (usually neoprene) that has been foamed to create gas bubbles. These bubbles are isolated from each other so that the suit does not absorb water as a sponge might.

In warm water, a diver may risk wearing just a swimsuit.

A layer of water becomes trapped between the diver's skin and the wetsuit. Warmed by heat from the diver, the trapped water soon reaches body temperature. A tight-fitting suit makes it less likely that cold water will flush out this layer of warm water and, because the material stretches, it can be very close fitting.

The neoprene fabric is a poor thermal conductor and the tiny air pockets make it like cavity-wall insulation, reducing conduction still further. But donning a wetsuit simply reduces the heat leaked by the diver to the surrounding water. It does not stop it altogether. Colder water demands a thicker wetsuit. However, when diving in temperate waters, like those around the British coast, the temperature gradient becomes so steep that a wetsuit has to be so thick that it becomes impractical. Apart from a few diehards, divers normally switch to a drysuit, which traps air between the diver and the water. This makes sense because air is a much poorer conductor: air conducts heat 25 times more slowly than water. Water leaking into a drysuit essentially turns it into a 'wetsuit' and is usually the cue for a diver to 'call' (i.e. end) the dive and get back on terra firma.

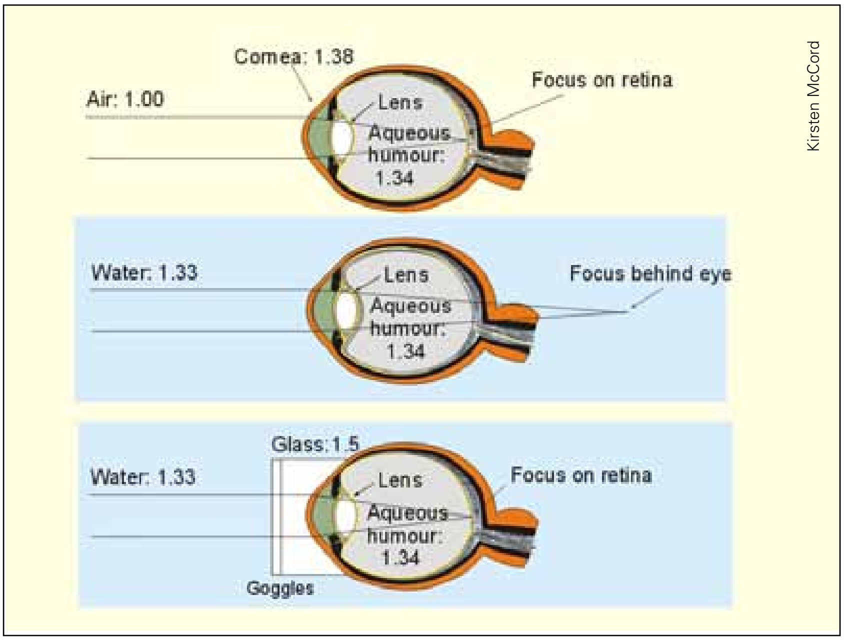
A diver's neoprene drysuit; the latex cuff and neck seal keep water out.

The effectiveness of a drysuit versus wetsuit in British waters was amply illustrated by Hywel Dyer and Jamie Lewis who lost contact with their dive boat on 8 September 2007. Divers are taught to drink plenty of fluid to reduce the risk of DCI so their bladders were probably full when they surfaced from their dive to discover that their boat was nowhere to be seen. They were eventually rescued by helicopter after being adrift for nine hours off the Pembrokeshire coast. However, not long before they were airlifted to safety, Dyer was no longer able to suppress the urge and urinated into his drysuit, providing a liquid path for his body heat to pass into the sea. Heat takes the path of least thermal resistance, just as most electric current flows along the path of least electrical resistance. Dyer had created a 'thermal short-circuit' which made him "very cold, very quickly". Lewis managed to resist the urge and "this eventually meant the difference between him walking off the helicopter (into hospital A&E) while I got stretchered," added Dyer.

The eyes have it

Our eyes have evolved for vision in air. When light enters our eyes it slows down and the curvature of both the cornea (at the front of the eye) and the lens ensures that it is refracted (changes direction) and is brought to a focus on the retina at the back of the eye. When we open our eyes underwater, everything looks blurred because images are no longer brought to a focus on the retina; water has almost the same refractive index as the aqueous and vitreous humours inside the eye so virtually no refraction takes place. This is resolved by donning a mask that covers the eyes and nose. It is 'cleared' by exhaling through the nose and displacing the water, leaving a pocket of air between our eyes and a flat piece of toughened glass.

A diver's mask covers both eyes and nose so that it can be 'cleared'.



How a mask or goggles allows a diver to see clearly under water; the figures show the refractive index of each material.

Colours towards the red end of the visible spectrum are absorbed more by water, so that everything looks bluer the deeper you descend. Particularly if visibility is poor, it can also become quite dark, so divers should carry a torch as a precaution.

Skin protection

Tropical waters can be around 30 °C so snorkelers in particular are often tempted to wear nothing more than a swimsuit. Kept cool by the water, they do not notice that they are being 'burned' by the ultraviolet (UV) radiation. The pigment called melanin cannot be produced quickly enough to screen this radiation, leading to a risk of melanoma or skin cancer. A wetsuit offers good protection against UV.

Mike Follows is a BSAC Dive Leader and Open Water Instructor