David Sawatzky, Canada

OXYGEN AND DIVING – PHYSICS AND PHYSIOLOGY

Oxygen (O2) is of critical importance in life, and in diving. It is of major importance in recreational nitrox diving and is a common cause of death in technical and rebreather divers. Therefore, a thorough understanding of O2 and oxygen toxicity is important for all divers. In this column I will review the basic physics and physiology of oxygen from the perspective of diving. In future columns I will review the problems a diver encounters when they do not have enough O2 (anoxia/hypoxia) and when they have too much O2 (oxygen toxicity).

Oxygen is an absolute necessity to maintain life for most living things on our planet (a few bacteria do not need oxygen to survive) and the lack of O2 can result in significant problems and or death in humans. Anoxia is the absolute lack of O2 (no oxygen) while hypoxia is the relative lack of O2 (not enough oxygen). At the same time, too much O2 can result in the signs and symptoms of oxygen toxicity. While diving, these signs and symptoms can be fatal and even on the surface, if we are exposed to too much O2 for too long, we will die.

Oxygen Physics

Oxygen has atomic number 8, which means the nucleus is composed of 8 protons and 8 neutrons. It is a colourless, odourless, tasteless gas and by volume, air is composed of 21% O2. Therefore, the partial pressure of O2 (pO2) on the surface at sea level is 0.21 atmospheres (atm), or approximately 160mm Hg (760mm Hg x 21% = 160mm Hg). When we are diving breathing air, the partial pressure of O2 equals the total pressure at depth times 21%. Therefore, at a depth of 10 metres (33fsw) the pO2 will be 0.42atm (21% of 2 atmospheres). At 30 metres (100fsw) the pO2 will be 0.84atm and at 40metres (130fsw) it will be 1.05atm. Therefore, diving at a depth of 40metres (130fsw) while breathing air will expose our bodies to the same amount of O2 as if we were breathing 105% O2 on the surface! This is called the 'surface equivalent'.

Biologically, we are designed to breathe O2 at a partial pressure of 0.21atm but there is some 'flex' in the system. We can function with no significant problems while exercising hard with an inspired pO2 as low as 0.16atm or 16% O2 on the surface. At rest we can function at even lower pO2s.

As we ascend above sea level, atmospheric pressure drops and even though the air we are breathing is 21% O2, the pO2 is less. At an altitude of approximately 2,300 metres (7,500ft), atmospheric pressure is only 76% of the pressure at sea level and the pO2 is only 0.16atm (21% of 0.76atm). But, people live and work at higher altitudes. How is this possible?

With prolonged exposure (days to weeks) our bodies make some biochemical changes so that we can function at lower partial pressures of O2. This is why high altitude climbers must spend weeks at base camp adapting to altitude before going higher. There are limits on how much we can adapt however and no one functions well when the pO2 is less than 0.105atm (10.5%, about 5,500 metres or 18,000 feet above sea level). For divers who are normally adapted to near sea level, the minimum safe pO2 is 0.16atm.

It would seem reasonable to assume that if O2 is good, more O2 is better. But, as with many things in life, more is NOT better. Oxygen normally exists as a molecule made up of two oxygen atoms with the same number of electrons as protons so that the molecule is electrically neutral. In a gas, the molecules are flying around very quickly and they frequently collide with each other and with other molecules. In air there are O2 molecules, nitrogen molecules, water molecules, carbon-dioxide molecules and traces of many other molecules. If O2 collides with another molecule and simply bounces off, life is good. However, sometimes an electron will transfer from one molecule to the other, sometimes the molecule will be broken into atoms, and sometimes the molecules will stick together. This process produces a number of VERY reactive substances called 'free radicals'. The number of free radicals produced is directly related to the pO2. Free radicals are ALWAYS present in O2.

Oxygen free radicals cause damage in our cells. Our cells are well designed to tolerate and even to repair the damage caused by the number of free radicals in O2 at a pO2 of 0.21atm. There is even some reserve. However, at a pO2 greater than 0.5atm our lungs will eventually suffer permanent damage and at a pO2 greater than 1.3atm we can suffer a seizure. I will save the detailed discussion of this problem for the column on oxygen toxicity, but in general recreational divers doing relatively short dives are safe as long as the pO2 is less than 1.6atm. With air the pO2 does not reach 1.6atm until 66 metres (218fsw). However, Nitrox36 has a pO2 of 1.6atm at only 35 metres (114fsw). Technical divers should limit their pO2 to less than 1.6atm and CCR divers should never breathe more than 1.3atm of O2.

Oxygen Physiology

In our bodies, O2 combines with food through a complex series of reactions to produce the energy we need to live. Carbon dioxide (CO2) is produced as a waste product and we must eliminate it through our lungs. These reactions occur in the mitochondria inside every cell of our bodies. Therefore, we must get the O2 we breathe from our lungs to the mitochondria and the CO2 from the mitochondria to our lungs.

When we take a breath, the air we inhale is mixed with the air that remained in the mouth, airways and lungs at the end of the last breath. On the surface our bodies absorb about 4% O2 and produce 4% CO2. Therefore, the air we breathe out and the air left in our mouth, airways and lungs will contain approximately 17% O2 and 4% CO2. In addition, our lungs add water vapour to the inspired air until it is 100% saturated at body temperature (water vapour pressure of 47mm Hg at 37C). The net effect of these factors is that the gas in the alveoli has a partial pressure of O2 of around 105mm Hg.

It takes a small difference in pO2 to drive the O2 across the alveolar walls into the blood, and some blood passes through the lungs without completely equilibrating with the air in the alveoli so that arterial blood leaving the lungs and being pumped by the heart to the body has a pO2 of 100mm Hg in a normal, healthy person.

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However, pO2 is only part of the story. What we really care about is the amount of O2 the blood is carrying to the tissues. At a pO2 of 100mm Hg, approximately 0.3ml of O2 will dissolve in every 100ml of blood. This is a trivial amount of O2 and not nearly enough to sustain life. The secret of life is hemoglobin (Hb). Hemoglobin is a complex protein that is designed to carry 4 molecules of O2. It is contained inside Red Blood Cells (RBC) and gives blood its' red colour. The amount of Hb in blood varies from approximately 12 to 18 grams per 100ml with 15 grams being a normal value in males (slightly lower in females). One gram of Hb can carry 1.36ml of O2 and at sea level in a normal healthy person, Hb is approximately 97% saturated with O2 when it leaves the lungs. Therefore, the Hb in every 100ml of blood can carry 15 x 1.36 x 0.97 = 19.8ml of O2! When we add the 0.3ml of O2 dissolved in the plasma, each 100ml of blood can carry roughly 20ml of O2. How much O2 is off loaded in the tissues depends primarily on blood flow and how much O2 the tissues are using. In most tissues, the blood leaving the tissues has a pO2 of 40mm Hg. When the O2 requirement of a tissue increases (a muscle starts to work), the tissue has some capacity to off load more O2 from the blood, but the primary mechanism used to increase delivery of O2 is to increase the amount of blood going to the tissue. For example, a muscle working at maximum capacity will have a blood flow approximately 100 times greater than the same muscle at rest.

Approximate O2 stores in a person breathing air at sea level:
450ml = O2 in the lungs
850ml = O2 in the blood
50ml = O2 dissolved in body fluids
200ml = O2 bound to myoglobin

It is important to understand that tissues cannot 'store' a significant amount of O2. Muscle contains a small amount of myoglobin. Myoglobin is a protein like Hb, but it can only bind one molecule of O2. Oxygen is used to generate Adenosine Triphosphate (ATP). ATP is the molecule that actually 'makes things happen', like causing muscles to contract. A small amount of energy is also stored as creatine phosphate (CP) but the combined energy stores of ATP and CP will only supply a hard working muscle for a few seconds. The bottom line is that tissues need a continuous supply of O2 to continue functioning.

When asleep (totally at rest), a 70kg (150 pound) person uses about 250ml of O2 per minute. When that same person is exercising at their maximum capacity, they will use up to 4,000ml of O2 per minute (if they are a highly trained athlete). An average, reasonably fit diver will require 3,000 to 3,500ml of O2 per minute at maximum exercise.

From the preceding information it should be apparent that blood leaving the lungs is pretty well saturated with O2 all the time. Therefore, breathing more does NOT increase the amount of O2 in the blood (it does reduce the amount of CO2). Blood leaving the lungs is also saturated with nitrogen and again, breathing more does NOT increase the amount of nitrogen being delivered to the tissues. Nitrogen uptake by the tissues depends on blood flow, not gas consumption. Admittedly, there is a very rough correlation between breathing rate and cardiac output.

In the next column I will discuss anoxia and hypoxia in diving.

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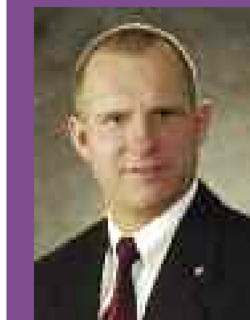

DAVID SAWATZKY, S.C., C.D., B.Med.Sc., M.D., M.Sc., is a diving medical specialist who was on contract at Defence Research and Development Toronto from 1998 to 2005. Previously he was the Canadian Forces Staff Officer in Hyperbaric Medicine at DCIEM (1986-1993) and later the Senior Medical Officer at Garrison Support Unit Toronto (1993-1998). He's written a monthly column on diving medicine in Canada's *Diver* Magazine since 1993, has been on the Board of Advisors for the International Association of Nitrox and Technical Divers (IANTD) since 2000, and is an active cave, trimix and closed circuit rebreather diver/instructor/instructor trainer. David's first love is cave diving exploration and he's been exploring and surveying underwater passages in Canada since 1985. David was responsible for the exploration and mapping of almost 11 kilometres of underwater passages in the Ottawa River Cave System. In 1995, he executed the first successful rescue of a missing trained cave diver. David received the Canadian Star of Courage for this rescue which took place in the chilly Canadian waters of Tobermory, Ontario. He still dives as much as possible, but admits his six year old son Lukas, five year old daughter Emeline and wife (Dr Debbie Pestell) are currently higher priorities than diving!