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CARBON DIOXIDE – A SILENT KILLER (PART 1)

I have recently been involved as an expert witness in a few diving medico-legal cases where carbon dioxide (CO_2) could have been a major factor in the fatality. Carbon dioxide can be a silent killer in both open circuit and rebreather divers. In addition, CO_2 is an excellent example of how a thorough understanding of diving physiology can have a major impact on how you dive and your dive safety

Where Does Carbon Dioxide Come From? There are two possible sources of CO_2 in diving. First, as we 'burn' food inside our bodies, we produce CO_2, in addition to energy, water, and other waste products. There is a basic amount of CO_2 we produce all the time, but we produce a lot more CO_2 when we are working hard. The amount of CO_2 we produce is directly related to how much oxygen (O_2) our bodies are using. We produce approximately 0.8 liters of CO_2 for every 1.0 liter of O_2 we consume (the ratio depends on the type of food that is being burned).

The other possible source of CO_2 in diving is in the gas we inhale. This CO_2 can originate in the gas that is compressed into our dive tanks, or it can be CO_2 that originated in our bodies that we exhaled, but then breathed back in. Carbon dioxide can be pumped into dive tanks if the intake of the compressor is too close to a fire or any internal combustion engine. When anything is 'burned' (wood, paper, oil, gas, propane, etc.) O_2 is used up and CO_2 is produced. In this situation, the gas we inhale may be contaminated with CO_2, but an even greater hazard is that it will most likely also be contaminated with carbon monoxide (CO). Carbon monoxide is deadly in far smaller concentrations than CO_2 and therefore CO_2 from these sources is not usually the primary problem.

There are many ways in which CO_2 that originated in our bodies can be exhaled, and then inhaled again, returning the CO_2 to our bodies. For this to make sense, we need to discuss the physiology of CO_2.

Carbon dioxide is continuously being produced by our cells (as long as we are alive) and therefore, we always have a certain amount of CO_2 in our bodies. It is produced in the mitochondria inside each cell. From there it diffuses into the cell and then into the blood in the capillaries. In the blood, CO_2 is transported in three forms. A small amount is dissolved in the plasma, a small amount is attached to hemoglobin and other proteins, but the majority of CO_2 is combined with water to form bicarbonate which dissolves in plasma.

The formation of bicarbonate releases hydrogen ions and this results in a small rise in the acidity of the blood. Therefore, the acidity of the blood is directly related to the partial pressure of CO_2 (pCO_2) in the blood, which is related to the total amount of CO_2 in the blood. The acidity of the blood is measured by special receptors in the brain and the results are used to control breathing.

In our lungs, CO_2 diffuses out of the blood and into the gas in the alveolar spaces until the pCO_2 in the gas is equal to the pCO_2 in the blood. The pCO_2 in the blood is in equilibrium with the bicarbonate and if the pCO_2 declines it is rapidly replaced by bicarbonate turning back in to CO_2 and water. When we exhale the gas in our alveoli, CO_2 is removed from our bodies. Therefore, if we increase the amount of clean air we move in and out of our lungs, we will increase the amount of CO_2 that is removed from our bodies and reduce the amount of CO_2 in the blood.

This concept is critical. Our brains use the measurement of the acidity of our blood to control how often we breathe and how deeply we breathe (the ventilation of the alveoli) so that the pCO_2 in our blood is maintained at a constant level.

What Factors Determine the Level of CO_2 in Our Bodies When We Are Diving? There are a large number of ways in which the amount of CO_2 in our bodies can be increased while we are diving. When we are diving we are often working quite hard (the average recreational dive is equivalent to playing basketball). This increases the amount of CO_2 being produced by our cells. To eliminate this CO_2 we have to breathe faster and deeper, but the stimulation for this increased work of breathing requires an elevated pCO_2. Therefore, the pCO_2 in our blood is almost always slightly increased when we are exercising because an increased pCO_2 is required to stimulate the increased respiration. We can voluntarily breathe more or less than required to maintain a normal pCO_2 (breath holding or hyperventilation) for short periods of time but in this discussion we will assume the diver is not consciously adjusting their breathing.

In addition to exercise, there are other reasons our pCO_2 can be elevated. When we are stressed, some people breath more rapidly, but less deeply (we move less gas in and out of our lungs with each breath). This can result in a dramatically elevated pCO_2 in our bodies. When we exhale, some gas is left in the alveoli, in the airways in our lungs (including the trachea) our throat and our mouth. This volume of gas is typically around two liters but the most important part of it is the approximately 250 mls of gas in the airways, throat and mouth (called the "dead space"). When we are breathing normally, we typically move about 500 mls of gas per breath. Therefore, when we inhale the first thing that happens is that the 250 mls of gas in dead space moves back into the alveoli. This gas just came from the alveoli and therefore is already saturated with CO_2. The next 250 mls of gas is 'fresh' and should contain very little CO_2. As a result, in normal respiration only 50% of the gas moving past our lips is getting into the alveoli.

WHEN WE ARE BREATHING NORMALLY, WE TYPICALLY MOVE ABOUT 500 MLS OF GAS PER BREATH.

Now imagine what happens if we were to 'pant like a dog' and only move 250 mls of gas with each breath. When we exhale, 250 mls of gas would move from the alveoli into the dead space. When we inhale the same 250 mls would move back into the alveoli. NO FRESH GAS would be entering the alveoli and NO CO2 WOULD BE LEAVING THE BODY (no oxygen would be getting in either). As a result the level of CO_2 in the body would rapidly rise. Try it! After much less than a minute you will be forced to take deeper breaths to eliminate the CO_2 that has built up in your body.

This leads to the first critical response to elevated CO_2. You should take slow deep breaths to increase the amount of CO_2 you are eliminating. Stress/panic often results in shallow breathing and this is one reason divers (and others) are advised to take slow deep breaths when they are feeling anxious.

Now, let's look at ventilatory dead space and diving. The gas volume in a standard scuba regulator second stage is dead space (the gas we exhale into it is breathed back into our lungs on the next breath). Therefore this volume must be added to the physiologic dead space in our mouth, throat and lungs. Many of us have dived with a 'mouth mask' that has a much larger 'dead space' so that we can talk more easily while diving. With these masks it is very important to take deeper breaths than normal.

Full face masks are becoming more common in diving but they too can have significant CO_2 retention problems due to dead space. Most full face masks have a special section that seals around the mouth to reduce the dead space, but if this seal is not working properly, the entire volume of the mask can become dead space and CO_2 is likely to accumulate in the body.

Another mechanism by which CO_2 is frequently elevated while we are diving is related to the 'work of breathing'. It takes a certain amount of effort to breathe. On the surface, our brains stimulate our breathing enough to maintain a normal pCO_2 in our blood. However, if we make the 'work of breathing' harder, it will take a stronger stimulus for us to breathe and therefore we will have a higher pCO_2 in our bodies.

When we are diving, there are MANY things that make the work of breathing harder. All regulators increase the work of breathing because we have to 'activate' the regulator and all regulators provide some obstruction to the flow of gas. A 'good' regulator will have a lower work of breathing than a 'poor' regulator.

This problem gets even worse when we go deeper. As we descend, the gas we are breathing is compressed and increases in density. At 30 meters there are four times as many molecules in every breath we take compared to when we are on the surface. This increased density can dramatically increase the work of breathing. This is why a regulator with a moderate work of breathing can be perfectly acceptable on a shallow dive but almost unusable on a deep dive. I have several old regulators that I use on decompression bottles. On one dive I mistakenly used one on a bottle that I was going to be breathing deep. When I

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diving medicine

switched to that regulator at approximately 75 meters depth, it was like trying to suck soup through a small straw! Fortunately, I was ascending rapidly and the work of breathing quickly became tolerable.

This problem is so serious that on deep dives the work of breathing actually limits the amount of work the diver can do, and the work of breathing itself becomes a significant source of CO2! Helium is a much smaller and lighter atom than nitrogen and therefore the work of breathing is reduced when nitrogen is replaced with helium.

When we are diving, we often wear equipment that increases the work of breathing. All wetsuits and most drysuits make it more difficult to contract our diaphragm (pushing our stomach out) and expand our ribcage so that we can suck gas into our lungs. If the wetsuit or drysuit is too small, the problem is much worse.

The weight belt, harness, buoyancy compensator, cummerbund, etc. can all restrict the movement of our stomach and chest and make breathing more difficult. As a result of these many factors, every diver, on every dive will have an elevated pCO2 in their blood during the dive. Normally, this small elevation of the pCO2 does not cause the diver any difficulties. However, if anything causes the pCO2 to rise even further, the diver can quickly experience CO2 toxicity and that can be rapidly fatal.

In the next column I will review the signs and symptoms of CO2 toxicity and look at how the problem of CO2 can be much worse when you are diving a rebreather.

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