Decompression Theory

As a scuba diver, theoretical knowledge cannot always be immediately recognized as useful. It does, however, come in handy. If you decide to move on to a professional level of certification, theoretical knowledge development is a requirement. It can also provide understanding behind practical decisions, guiding your reasoning in a more educated manner than just following a set of rules. So let’s talk about the biggest theoretical area there is for scuba divers, decompression theory.

The need for decompression theory arises from decompression sickness (DCS). DCS encompasses the illnesses that may occur from the body's exposure to varying pressures. This is not strictly limited to scuba divers, but clearly we have a highly vested interest in the development of sound theory to describe the causes, effects, and preventions of DCS.

I say this, because the discovery of DCS predates recreational scuba diving by about 100 years. There is documentation of DCS symptoms as early as the 1840s, where workers in pressurized French mines fell ill with the now-recognizable effects of "the bends."

It was well over 60 years before enough progress was made for any practical advantage. In 1906, the British Royal Navy commissioned physiologist John Scott Haldane to study DCS. He built on the work of Paul Bert who, years earlier, made progress in identifying the cause of DCS. In particular, it was Bert who named dissolved nitrogen as the culprit in DCS. However, it was Haldane who built the first complete theoretical model.

Haldane and his team experimented with goats in pressure chambers. This research led him to describe a theoretical decompression model and build the first dive tables that could be verified experimentally. Today, over 100 years later, practically all dive tables and dive computers are built upon this original Haldanean decompression model.

Decompression models

A decompression model is some theory you can follow and apply in order to decrease your risk of DCS. A model is only as good as it has been verified to prevent DCS. There are many factors involved to currently guarantee prevention. As they say, the only way to 100%

prevent DCS is to not dive. Aside from that, there are models that have been in use for a very long time (like the Haldanean model) and have been shown to decrease your risk of DCS *drastically*.

Ideally, a model is developed through scientific means---by studying the physics and physiology of the human body. It doesn't *have* to be, though. For example, a model followed by early divers was "the 50 rule." This "model" dictates that the depth (in meters) and time of your profile should add up to no more than 50. A 10 meter dive for 40 minutes, 20 meters for 30 minutes, and so on. This actually wasn't a terrible model, although there is no real theory behind it. You'll notice that it is overly conservative, though. This guides continual research into model development---getting you the maximum dive time in the safest way possible.

Haldanean model

Building on the observation that dissolved nitrogen triggers DCS, the Haldanean model is build around a few principles:

- Nitrogen dissolves into tissues. After enough time, the tissue becomes completely saturated. This is Henry's law.
- The tissue will reach saturation determined by the *ambient pressure*. So a given tissue under higher pressure contains more nitrogen than the same tissue at the earth's surface.
- The difference between the ambient pressure of nitrogen and a tissue's partial pressure of nitrogen is called the *pressure gradient*.
- When ascending, the dissolved nitrogen's partial pressure may be higher than the ambient pressure. The body can tolerate some amount of pressure gradient without DCS.
- If the pressure gradient becomes too high, the dissolved nitrogen cannot be eliminated quickly enough. Nitrogen bubbles form, leading to DCS. Thus, the risk of DCS can be reduced by keeping the body's pressure gradient within acceptable limits.

To understand these ideas better, we need to review a few concepts.

Partial pressure

Recall from our article on enriched air / nitrox the idea of partial pressure. Total ambient pressure at sea level is 1 atm. Therefore, the air we are breathing is also at 1 atm. This air is comprised of mainly two components: 21% oxygen and 79% nitrogen. We can say, then, that the *partial pressure* of oxygen at the surface is 21% of 1 atm, or .21 atm (some people write this as .21 PPO, for partial pressure oxygen).

Likewise, the partial pressure of nitrogen at the surface is .79 atm. This principle is captured by Dalton's law, which states that the 1 atm of pressure at the surface can be written as the sum of the partial pressures, .79 atm nitrogen + .21 atm oxygen = 1 atm total.

This is all at sea level. The deeper we go, the higher the pressure, and the higher the resulting partial pressures. At 10 meters depth, the pressure is 2 atm. By Dalton's law, the partial pressure of nitrogen is 1.58 atm and for oxygen is .42 atm (notice how they both add up to 2 atm).

Mainly what this means is that the deeper you dive, the more nitrogen you absorb with each breath.

Tissue compartments

Haldane's model is built around how the body's tissues absorb and release nitrogen. There's just one problem: the body is incredibly complex, and accurately modeling all its tissues is not a tractable problem, not even now, much less over 100 years ago.

What Haldane could determine was that different parts of the body absorb and release dissolved nitrogen at different rates. Instead of attempting a much larger problem, he simply represented the entire body by a number of theoretical tissue compartments. These are called "theoretical" because they don't correspond to any particular tissue in the body, but rather attempt to capture the idea that the body absorbs nitrogen at different rates. Together, these theoretical tissues are meant to represent the body as a whole and the time scales at which it deals with nitrogen.

Haldane originally used 5 compartments. Later, the US Navy dive tables used 6. Some modern tables use as many as 14. There is no limit to the number of theoretical compartments, but any advantage they may provide rapidly falls off as you add more.

Halftimes

These theoretical tissue compartments (from now on, just tissues, or compartments) represent the different rates different parts of the body absorb and release dissolved nitrogen. The model must then deliver these rates. It does so, in the form of *tissue halftimes.* A tissue halftime is the length of time it takes for a given compartment to halve the pressure gradient.

For example, if a compartment contains absolutely no dissolved nitrogen, and is exposed to air at 1 atm, its halftime is the amount of time until the partial pressure of nitrogen in the tissue is .395 atm (half of the partial pressure of the nitrogen in the air, .79 atm / 2 = .395 atm).

Saturation is reached when the pressure gradient is 0, or the partial pressure of nitrogen in the air is the same as the partial pressure of nitrogen in the tissue. This means after one halftime a compartment is 50% saturated. It is not 100% saturated after two halftimes, since each time the pressure gradient is halved, so after two halftimes a compartment is 75% saturated. After three, 87.5%. Four, 93.8. For simplicity, we say a compartment is 100% saturated after 6 halftimes (it's actually 98.4%, but that's close enough).

The US Navy model uses 6 compartments with halftimes of 5, 10, 20, 40, 80, and 120 minutes.

Examples

Halftimes can be confusing, so let's look at examples. For further simplicity, we refer to a compartment's saturation level in terms of depth. We definitely wouldn't say 50% saturated, since that gives no indicated of the partial pressure. Similarly, we don't say the tissue has 1.185 atm nitrogen, although you could. Instead, we give the depth corresponding to that partial pressure of nitrogen. In this case, the partial pressure of nitrogen in air is 1.185 at 5 meters. So we say this compartment has a nitrogen loading of 5 meters (this is also written as meters /feet sea water, or msw / fsw).

Imagine a dive to 20 meters for 40 minutes. What do the 6 compartments look like? For the 5-minute compartment, 40 minutes is 8 halftimes. Recall that we consider 6 halftimes as reaching saturation, so the 5-minute compartment is completely saturated, and has a nitrogen loading of 20 meters.

The 10-minute compartment has gone through 4 halftimes. After the first halftime, its loading is 10 meters. After the second, 15 meters. Third, 17.5 meters. Fourth, 18.75 meters.

The 20-minute compartment has completed 2 halftimes, so it is at 75% saturation, or 15 meters. The 40-minute tissue has completed one halftime, so 10 meters. The 80-minute has completed half of a halftime, so 5 meters. The 120-minute compartment is at 3.33 meters.

M-values

Notice something interesting about what we've covered so far. Nowhere has there been any indication on how this model guides your dives. That's because it doesn't! To decrease our risk of DCS when ascending, we have to keep a tissue's pressure gradient below an acceptable threshold. The model so far has not given these thresholds.

These thresholds can only be obtained experimentally. That's what we've done over the years. After thousands of controlled dives and observing symptoms at the surface, scientists obtain values for acceptable pressure gradients for each theoretical tissue. These values are called *M-values*.

There are M-values for each compartment for each decompression stop. In no-decompression diving, however, we only have to be concerned with the values for the pressure at the surface, which are sometimes written as "M~0~-values."

Dive table designers can experiment with different M-values, but they should be consistent with the data. If experiments show that exceeding a certain value for a given compartment usually results in DCS, then the final table should limit dive profiles based on that value.

A complete model

We now have all the tools for a complete model. A set of compartments with their halftimes, as well as an M-value for each compartment. Let's do an example.

Let's use the same compartment halftimes with M~0~-values of 30 meters, 20 meters, 15 meters, 10 meters, 7.5 meters, and 5 meters. This means that the 5-minute compartment should not exceed a nitrogen loading of 30 meters, the 10-minute compartment should not exceed 20 meters, and so on.

With our dive to 20 meters for 40 minutes, our tissue loadings were 20 meters, 18.75 meters, 15 meters, 10 meters, 5 meters, and 3.33 meters. Uh-oh! Our 20-minute and 40-minute compartment have reached their M-values (15 meters and 10 meters). That means it's time to end the dive or ascend to a shallower depth.

If we ascend shallow enough, the 20-minute and 40-minute compartments, even when saturated, can never exceed their M-values. So as long as we ascend shallower than 10 meters, the 40-minute compartment can never exceed its M-value. From this we notice that shallower depths are controlled by slow compartments (high halftimes), while the fast compartments (short halftimes) control deeper dives.

For instance, the 5-minute compartment will reach its M-value very quickly at deep depths. At 40 meters (the recreational limit), one halftime (5 minutes) will load the compartment to 20 meters. Another 5 minutes will have it at 30 meters. Staying at 40 meters any longer will require decompression stops.

Keep in mind that following this model with these M-values does not provide any guarantee that DCS won't occur. It can still happen, although many years of diving with established tables has shown that the chances are minimal. Still, it doesn't hurt to dive conservatively.

Conclusion

Phew! That was a lot of material. Give it a little time to sink in. We'll pick up where we left off in future articles. For example, what about repetitive dives? How do compartments release nitrogen when we are out of the water? At the same rate that they absorb?