Diving Physics and "Fizzyology"

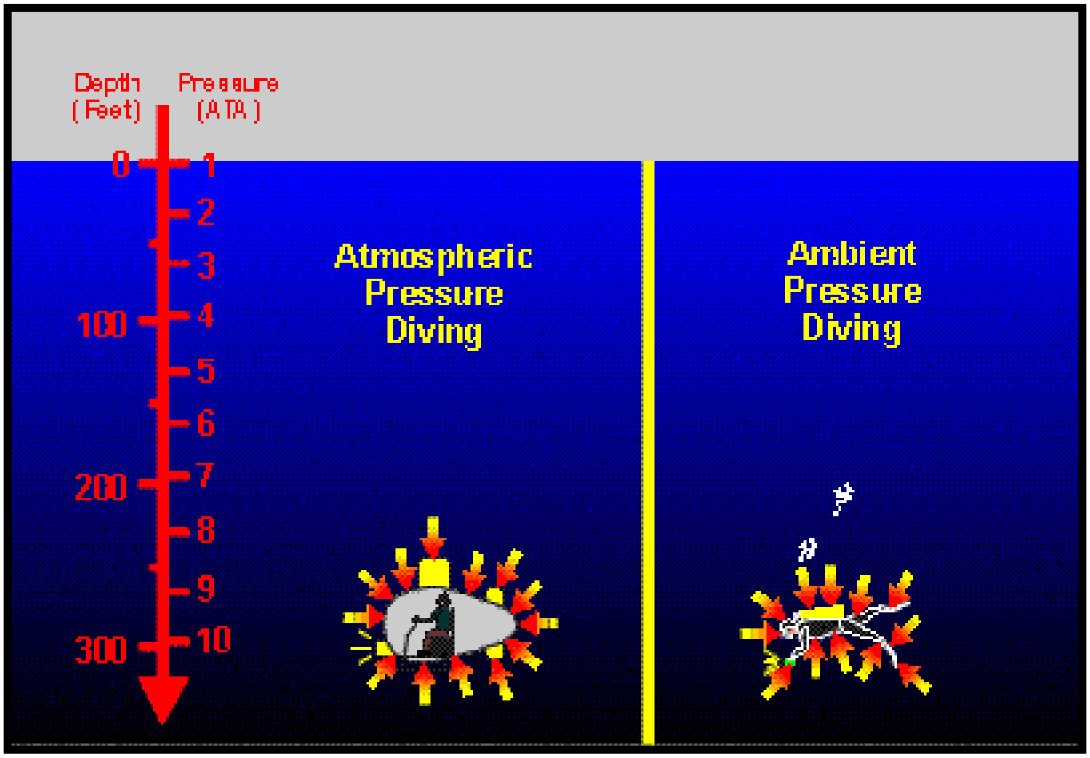
Introduction

Like all animals, human beings need oxygen in order to survive. When we breathe, we extract oxygen from the air, and use that oxygen for *metabolism*, which is how we convert the food we eat into useable energy to do the things that we do. One of the by-products of metabolism is *carbon dioxide*; whenever we exhale, we are getting rid of the carbon dioxide that our bodies produce. The main purpose of breathing, therefore, is to provide our bodies with oxygen, and rid our bodies of carbon dioxide. We humans are terrestrial (land-dwelling) mammals, and as such, our lungs are designed to breathe gas. Unlike fishes, we have no gills, so we cannot breathe water. Therefore, the first problem we must overcome to explore the underwater realm is a means to provide breathing gas. However, if this were the only barrier humans must overcome to enter the sea, we would have long-ago discovered most of the mysteries of the ocean. All we would need to remain underwater indefinitely would be a long tube going to the surface -- a huge snorkel -- through which we could breathe. Unfortunately, there is another problem we must over come when descending to the depths -- a problem with far more complex and difficult consequences. That problem is *pressure*.

Pressure

Have you ever wondered why nobody makes snorkels that are ten, or twenty, or a hundred feet long? The answer becomes obvious as soon as you try to breathe through a snorkel when your body is more than two or three feet (~1 meter) beneath the surface of the water. If you have ever tried this, you will know that it becomes extremely difficult to inhale under those circumstances. That's because the deeper underwater you go, the greater the *pressure* is. Think of pressure as a force pushing on you from all directions. At sea-level, we are exposed to about 14.7 *pounds per square inch* (psi) of pressure. This means that each square inch of our bodies has the equivalent force of about 14.7 pounds pressing on it. The source of this pressure is actually a result of the *weight* of the air in Earth's atmosphere. Like all gases, the air around us is composed of *molecules* of different gases; in this case, about 21% of these molecules are oxygen, about 78% are nitrogen, and the rest is composed of assorted trace gases. These gas molecules have weight, which means that gravity is pulling them toward Earth. As it turns out, if you took a column of air, one square inch in cross-section, extending from sea-level all the way to the edge of the atmosphere, all the gas molecules in that column of air would have a combined weight of about 14.7 pounds -- which leads to 14.7 psi of pressure at sea level. For convenience, physicists have defined the "atmosphere" (abbreviated "ATM") as a unit measurement of pressure equal to the pressure caused by Earth's atmosphere at sea level (14.7 psi).

Like air, water causes pressure by its weight. But of course, water is considerably denser (i.e., heavier for a given volume) than air. As it turns out, a column of sea water one inch in cross-section would need to be only about 33 feet (10 meters) tall to weigh 14.7 pounds. Therefore, at a depth of 33 feet (10 meters) beneath the sea surface, the total ambient pressure is about 29.4 psi, or 2 ATM -- 1 ATM caused by the weight of the air in Earth's atmosphere, plus 1 ATM for the weight of 33 feet (10 meters) of seawater. To avoid confusion, when people discuss pressures underwater, the unit "ATA" (referring to "atmospheres absolute") is often used to represent the total, "absolute" pressure caused by both the water and the air above the water.



As is illustrated in the diagram at right, the ambient pressure increases underwater at an almost linear rate with increasing depth*. For every 33 feet (10 meters) of depth in sea water, the ambient pressure increases by an an additional 14.7 psi (1 atm). At a depth of 99 feet (30 meters), the ambient pressure is 4 ATA -- one ATM caused by the Earth's atmosphere, plus 3 ATM for every 33 feet (10 meters) of depth. Similarly, the ambient pressure 297 feet (90 meters) beneath the surface is 10 ATA. The problem with the long-snorkel idea has to do with the fact that the muscles we use to expand and contract our lungs during breathing are not strong enough to overcome much pressure. Even just a few feet beneath the surface, the pressure is great enough that we cannot expand our lungs against the water pressure to inhale a breath of air from the surface. Our bodies simply are not designed to do that.

One way to overcome this problem is to protect the diver's body from the ambient pressure. "Atmospheric Pressure Diving" technology, the most familiar of which are deep sea submersibles, do exactly that. The pressure on the inside of a submersible is maintained at 1 ATA - the same pressure that we experience at the sea surface. Underwater, the increased ambient pressure acts on the hull of the submersible, not the diver inside. Thus, the person inside the submersible is protected from the ambient pressure at all times and has no difficulty breathing.

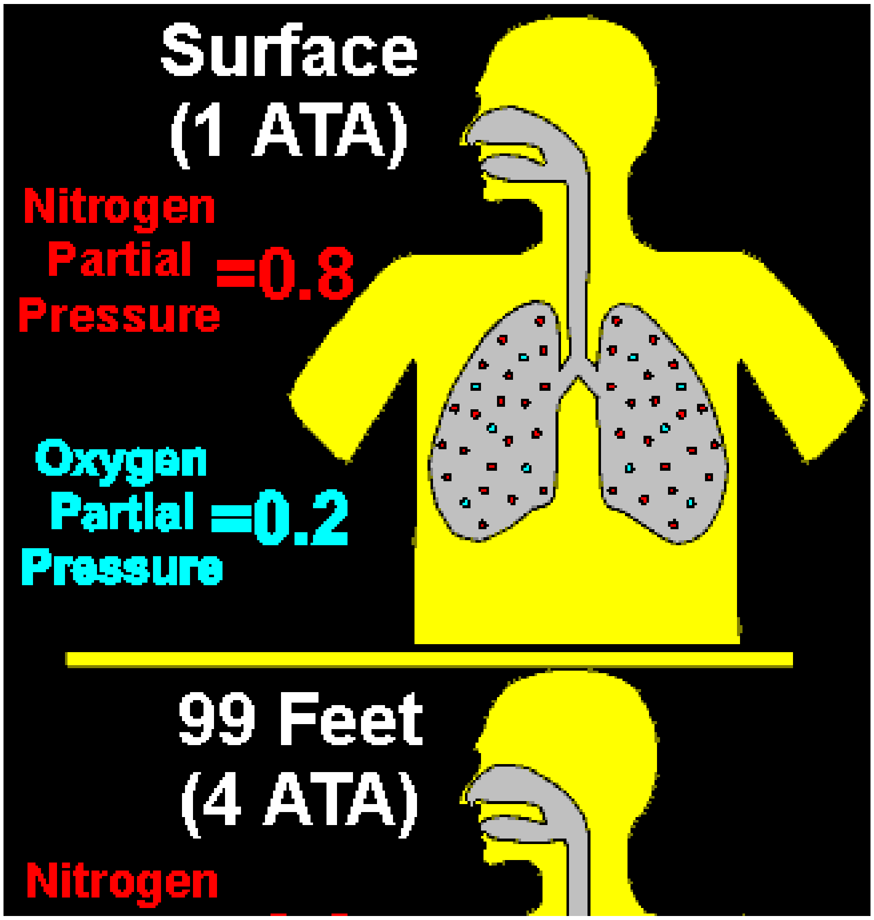
Another way to overcome the problem of breathing under pressure is to provide a pressurized breathing gas mixture to the diver. If the breathing gas supply is delivered at the same pressure as the surrounding ambient pressure, the diver's lungs do not have to work against the water pressure (i.e., the pressure in the surrounding water and the pressure in the inhaled gas supply are balanced). However, when using this sort of "Ambient Pressure Diving" technology, the diver's body is directly exposed to the ambient pressure. More importantly, the gas inhaled into the diver's lungs is pressurized. To understand the physiological ramifications of this, it's important to understand the effects of increased pressure on gases.

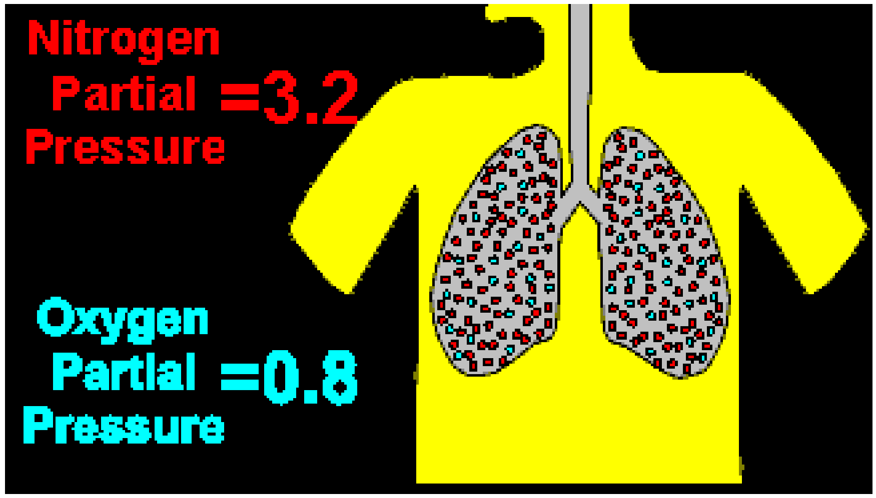
As mentioned above, gas is composed of molecules. As the pressure of the gas increases, these molecules (which are in constant motion) get packed more closely together. At a higher pressure, a given number of gas molecules will occupy a smaller volume (or a given volume will be occupied by a larger number of gas molecules). For example, if you had a balloon filled with gas at the surface, and then pulled that balloon underwater, the balloon would shrink in size. In fact, if you brought the balloon down to a depth of 33 feet (10 meters), it would be half the size it was at the surface. At 66 feet (20 meters) it would be one-third the size it was at the surface; at 99 feet (30 meters) it would be one fourth the size, and so on. If, at a depth of 99 feet (30 meters), you wanted to expand the balloon to its original size, you would have to fill it with four times as many gas molecules as were required at the surface. Returning the re-inflated balloon back to the surface would cause it to grow to four times its original size. It doesn't require much imagination to understand what would happen to a diver's lungs if he or she took a full breath at depth, and held it while ascending to the surface. This is why the golden rule of diving is "never hold your breath". People who forget this rule (for example, in a state of panic), run the risk of suffering from ruptured lungs, allowing gas bubbles to directly enter the blood. It's called *embolism*, and it can lead to serious symptoms including paralysis and death.

A key point here for understanding other aspects of diving physics and physiology, is to realize that the greater the pressure, the more tightly packed (i.e., more highly concentrated) gas molecules are.

***Note:** Because water is very slightly compressible, the relationship between depth and pressure is not *exactly* linear all the way to the bottom of the sea; however, for the purposes of diving technology, the deviation from a linear relationship is trivial.

Partial Pressure



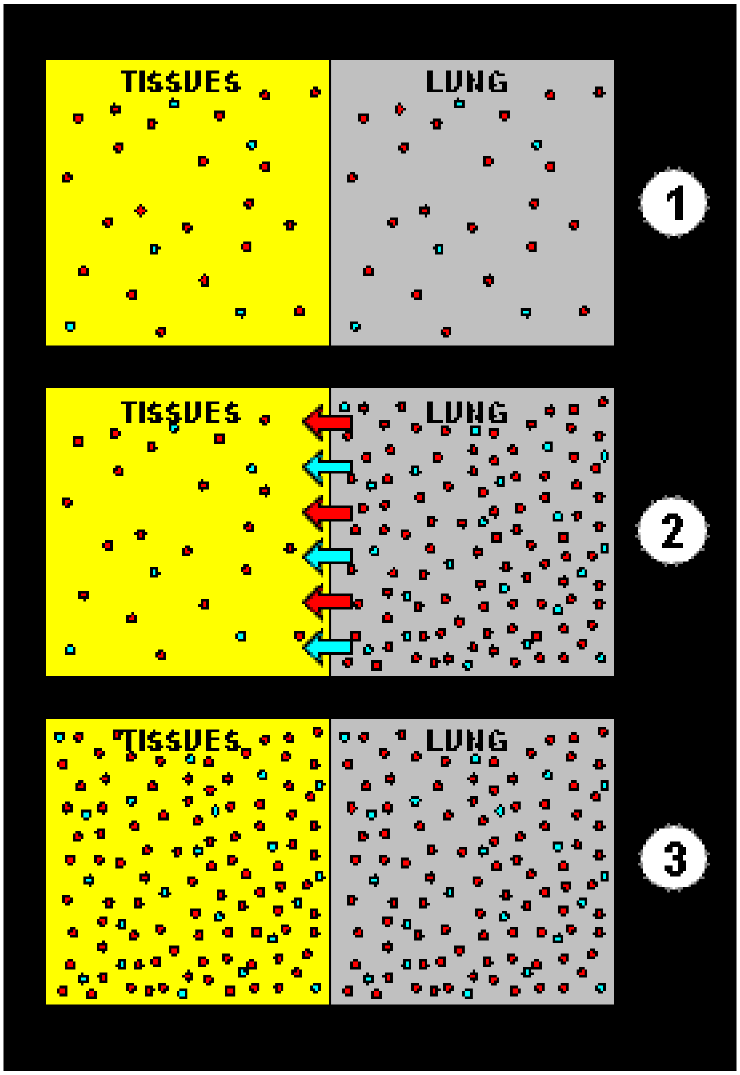


To understand the physiological ramifications of breathing various gas mixtures under pressure, it is useful to understand the concept of *partial pressure*. The partial pressure of a particular gas constituent in a gas mixture is a representation of the portion of the total pressure of the gas mixture exerted by the particular constituent. If you add up all the partial pressures of all the different components of a gas mixture, their total would be equal to the total pressure of the mixture. As confusing as this may sound, partial pressures are actually quite easy to calculate: all you need to know is the fraction of each gas constituent in the mixture, and the total pressure of the gas mixture.

For example, consider a person breathing air (a gas mixture containing approximately 80% nitrogen and 20% oxygen) at sea level. As discussed earlier, the ambient pressure at the sea surface is 1 ATA. Therefore, the pressure of the air which the person inspires is also 1 ATA. To get the partial pressure of nitrogen in the inspired air, simply multiply the fraction of nitrogen in the breathing mixture (80%) by the total pressure (1 ATA), and you calculate a nitrogen partial pressure of 0.8 ATA. Similarly, multiplying 20% oxygen times 1 ATA results in an oxygen partial pressure of 0.2 ATA. Now consider what happens when that same person descends to a depth of 99 feet (30 meters), where the ambient pressure is 4 ATA. In order for that person to be able to breathe at all, the inspired air pressure must be the same as the ambient pressure. Therefore, the inspired partial pressure of nitrogen is 80% times 4 ATA, or 3.2 ATA. The oxygen partial pressure is 20% times 4 ATA, or 0.8 ATA. At 99 feet (30 meters), the ambient pressure is four times greater than it is at the surface, and the partial pressures of each of the gases is also four times greater (although the percentages of each gas are the same in both cases). As discussed earlier, the gas molecules are more closely packed when under pressure; at a depth of 99 feet (30 meters), there are *four times as many* gas molecules (both nitrogen and oxygen) in a lung-full of air as there are at the surface. An easy way to think of partial pressures of gases is that the partial pressure represents an absolute *concentration* of that gas, regardless of depth or pressure. If a person breathed a gas mixture containing 80% oxygen at the surface, the oxygen partial pressure would be 0.8 ATA, which is exactly the same partial pressure of oxygen when breathing air at a depth of 99 feet (30 meters). In both cases (80% oxygen at the surface and air at 99 feet/30 meters), the concentration of oxygen molecules in the lungs (i.e., the total number of oxygen molecules in the lungs on each inhaled breath) is the same.

Just a word on notation: in their gaseous forms, both oxygen and nitrogen are *binary molecules*; that is, they are bound in pairs of atoms. An oxygen gas molecule consists of two oxygen atoms bound together, and a nitrogen gas molecule consists of two nitrogen atoms bound together. The notation for oxygen is the letter "O", so oxygen gas is referred to as "O_2"; the subscript "2" indicating two atoms of oxygen. Similarly, nitrogen gas is referred to as "N_2", and carbon dioxide as "CO_2". When discussing partial pressures of gases, the gas notation is usually prefaced by a capital "P". Thus, "oxygen partial pressure" is written as "PO_2", and "nitrogen partial pressure" is written as "PN_2".

Henry's Law

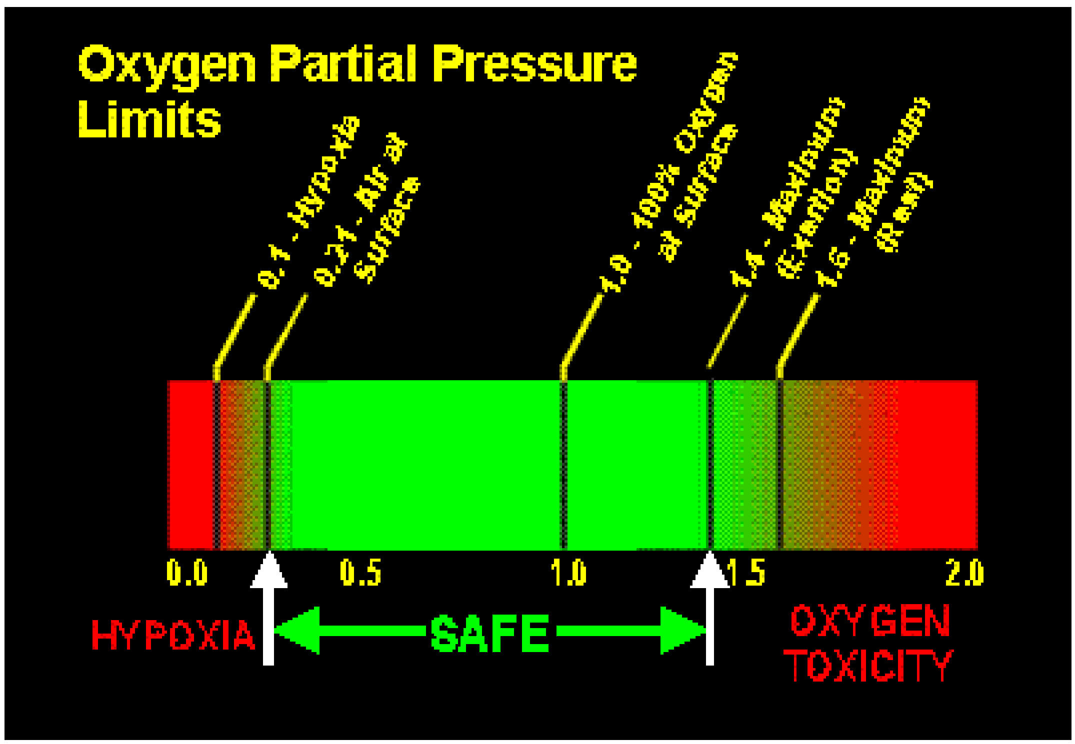


Henry's Law states that *"The amount of any given gas that will dissolve in a liquid at a given temperature is a function of the partial pressure of that gas in contact with the liquid..."* What this means for divers is that gas molecules will dissolve into the blood in proportion to the partial pressure of that gas in the lungs (as "warm-blooded" creatures, our core body temperature remains relatively constant).

In the diagram at right, the top figure (1) represents a close-up of the interface between the lungs and the blood and tissues of a diver. At sea level, the dissolved gases in the blood and tissues are in proportion to the partial pressures of the gases in the person's lungs at the surface. As the diver descends underwater, the ambient pressure increases, and therefore the pressure of the gas inside the lungs increases correspondingly. Because the partial pressures of the gases in the lungs are now greater than the dissolved partial pressures of these gases in the blood in tissues, gas molecules begin to move from the lungs into the blood and tissues (represented by the blue and red arrows in the middle figure, 2). Eventually, the concentration of the dissolved gases in the blood and tissues will be proportional to the the partial pressures in the breathing gas (i.e., a state of *equilibrium*).

The physiological complexities of "Ambient Pressure Diving" are a direct result of the effects of these increased dissolved concentrations of gases in the blood and tissues, and how those increased concentrations affect the way our bodies work.

Oxygen



Oxygen is the only gas we really need to breathe in order to stay alive. If we don't breathe oxygen (or if we don't breathe enough oxygen), we soon die. Interestingly enough, *too much* oxygen can be a bad thing also. At right is a diagram illustrating the range of oxygen concentrations that we can breathe safely. The green and red bar represents a scale of inspired oxygen partial pressures (PO_2), ranging from zero oxygen on the left, to a PO_2 of 2.0 ATA on the right. Through evolution, our bodies have become optimized to breathe oxygen at a partial pressure (PO_2) of 0.21 ATA. If the inspired PO_2 is much less than this, our bodies begin to shut down -- leading to unconsciousness when the PO_2 drops below about 0.1 ATA (i.e., 10% oxygen at sea level). This is called *hypoxia*. Breathing more than 0.21 ATA oxygen is generally fine ... up to a point. If the inspired PO_2 is maintained above about 0.5 ATA for prolonged periods of time (many hours to days), people begin to suffer what is usually referred to as "pulmonary" or "chronic" *oxygen toxicity*. The effects of this include a burning sensation or irritation in the lungs, and can affect breathing. Except for people who spend days under pressure at a time (e.g., commercial divers on oil rigs), this form of oxygen toxicity is not much of a problem for divers.

However, as the inspired PO_2 starts to climb above about 1.2 to 1.4 ATA, another kind of oxygen toxicity, called "CNS" (for "Central Nervous System") or "acute" oxygen toxicity, becomes a significant problem. Although a variety of subtle symptoms such as muscular twitching in the face and tunnel vision have been attributed to this kind of oxygen toxicity, the really important symptom is severe, uncontrolled convulsions. Although these convulsions do not appear to cause any sort of permanent damage by themselves, the problem of a diver experiencing such convulsions being able continue to hold a regulator in his or her mouth is obvious. More than a few divers have drowned underwater, apparently a result of oxygen-induced convulsions. This is perhaps the most serious and insidious of diving maladies, because it comes on unpredictably and without warning, and usually results in the death of the afflicted diver.

There is no clear understanding on the exact biochemical processes involved with CNS oxygen toxicity, nor is there a clear consensus on what the "safe" upper PO_2 limit should be. Convulsions have occurred in divers breathing an inspired PO_2 as low as 1.2 ATA, but such cases usually involve extenuating circumstances (such as medical conditions in the divers which pre-dispose them to convulsions). Conversely, commercial divers in Europe have routinely breathed oxygen partial pressures as high as 1.9 ATA in the water, and hyperbaric chamber facilities regularly expose patients to 2.8 ATA of oxygen (or more) without difficulty. Amid the ambiguities, two trends seem very consistent. The first is that high levels of exercise (perhaps more specifically, high levels of CO_2 in the blood) appear to increase the probability of suffering from a convulsion. Secondly, divers immersed in water have a lower tolerance to elevated concentrations of inspired oxygen than do divers kept dry in a hyperbaric chamber or undersea habitat. (this over and above the fact that divers in a dry habitat are much more likely to survive a convulsion than are divers immersed in water). Another unavoidable reality regarding oxygen toxicity is the extreme range of variation both between individuals, and within a single individual.

When immersed underwater, most divers regard a PO2 of 1.4 ATA as a safe upper limit during periods of physical exertion, and 1.6 ATA during periods of rest.

Nitrogen

Eighty percent of the gas molecules in air are nitrogen (N_2). Our bodies do not need or use nitrogen for metabolism, so it serves little function in a breathing gas mixture, other than to dilute the concentration of oxygen. When high concentrations of nitrogen become dissolved in our bodies, however, nitrogen can affect our central nervous system. Familiar to all divers is the effect known as "nitrogen narcosis". Cousteau called it "rapture of the deep", and its effects have been likened to alcohol inebriation. When breathed at high concentrations, nitrogen can impair our neurological abilities. The exact biochemistry is not known, but the symptoms include impaired judgement, loss of short-term memory, slowed response time, and sometimes euphoria. Obviously, just as one should not drive while intoxicated, diving with impaired mental abilities is at the very least unwise. As with oxygen toxicity, there is a wide range of variation in susceptibility to nitrogen narcosis both between, and within individuals. There is some evidence that repeated exposure can lead to an "adaptation" effect, but this is a topic subject to continued debate. Some divers begin to notice the symptoms while breathing air as shallow as 90 feet (27 meters) or so, while other claim to suffer no incapacitation at depths in excess of 200 feet (61 meters). Impairment likely occurs at lower PN_2 levels than those at which divers begin to detect overt symptoms. In any case, the greater the inspired PN_2, the more severe the narcosis. There is some evidence that oxygen also contributes to narcosis, but probably only at concentrations above which CNS oxygen toxicity would be of primary concern.

Nitrogen plays another important role in limiting conventional scuba diving: it's involvement with *decompression sickness*. This will be discussed in greater detail in the following section on decompression.

Decompression

"What it all boils down to, is that no one's really got it figured out just yet."
- Alanis Morissette

The malady known as *Decompression Sickness*, or more commonly, the "bends", has been well-documented for many years. Starting with early caisson workers constructing bridges in pressurized chambers, it was soon evident that if people breathed compressed gas under elevated pressure for a period of time, and then returned to normal sea-level pressure, a wide variety of symptoms (including fatigue, mild to severe pain in the joints, rashes or itchy patches, dizziness, nausea, disorientation, numbness, mild to severe paralysis, loss of vision or hearing, unconsciousness, and even death) often ensued. The U.S. Navy and other organizations spent a great deal of time and resources conducting experiments in order to better understand the physiological processes involved with this mysterious syndrome. It was soon learned by theory and empirical data that by slowing down the rate of ascent back to surface pressure after exposure to elevated pressure, the symptoms could be reduced or eliminated. A set of "decompression tables" -- schedules that describe slow, staged ascent patterns back to the surface after exposures to various depths for various lengths of time (a process called "decompression") -- were eventually released for use by the general diving public. Unfortunately, no matter how "conservative" these schedules were, they were not perfect. In many cases, people following the schedules would suffer decompression sickness symptoms anyway. Moreover, a great many dives that followed ascent patterns much *less* conservative than the schedules suggested, resulted in no decompression symptoms at all. Clearly, there were many other factors to the decompression "story" than simply depth and time. Thus began a long and continuing effort to understand all the actual factors involved, and produce a mathematical model that was better able to predict optimal ascent patterns (i.e, decompression schedules). As it turns out, this is an extraordinarily difficult undertaking.

If you ask a random, non-diving person on the street to explain what's really going on inside a diver's body that leads to decompression sickness, the answer is likely to be "I don't know".

If you ask the same question of a typical scuba diving instructor, the answer will likely be that nitrogen is absorbed by body under pressure (a result of Henry's Law); and that if a diver ascends too quickly, the excess dissolved nitrogen in the blood will "come out of solution" in the blood to form tiny bubbles; and that these bubbles will block blood flow to certain tissues, wreaking all sorts of havoc.

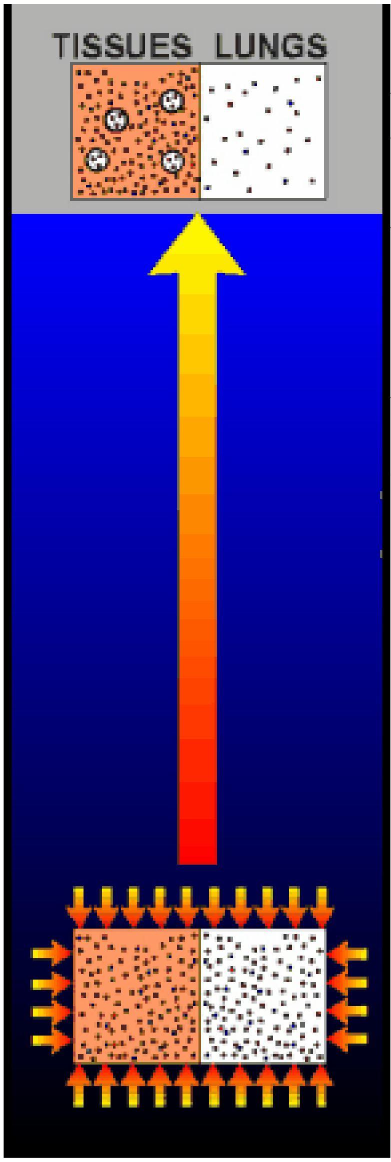
Pose the question to an experienced hyperbaric medical expert, and you will probably get an explanation of how "microbubbles" already exist in our blood before we even go underwater; and that ratios of gas partial pressures within these bubbles compared with dissolved partial pressures in the surrounding blood (in conjunction with a wide variety of other factors) determine whether or not these microbubbles will grow and by how much they will grow; and that if they grow large enough, they may damage the walls of blood vessels, which in turn invokes a complex cascade of biochemical processes called the "complement system" that leads to blood clotting around the bubbles and at sites of damaged blood vessels; and that this clotting will block blood flow to certain tissues, wreaking all sorts of havoc. You will likely be further lectured that decompression sickness is an unpredictable phenomenon; and that a "perfect model" for calculating decompression schedules will never exist; and that the best way to calculate the best decompression schedules is by examining probabilistic patterns generated from reams of diving statistics.

If, however, you seek out the world's most learned scholars on the subject of decompression and decompression sickness, the top 5 or 6 most knowledgeable and experienced individuals on the subject, the ones who *really* know what they are talking about; the answer to the question of what causes decompression sickness will invariably be: "I don't know". As it turns out, the random non-diving person on the street apparently had the best answer all along.

What follows is a very coarse description of what *seems* to be going on, and what we think *might* have something to do with what causes decompression sickness.

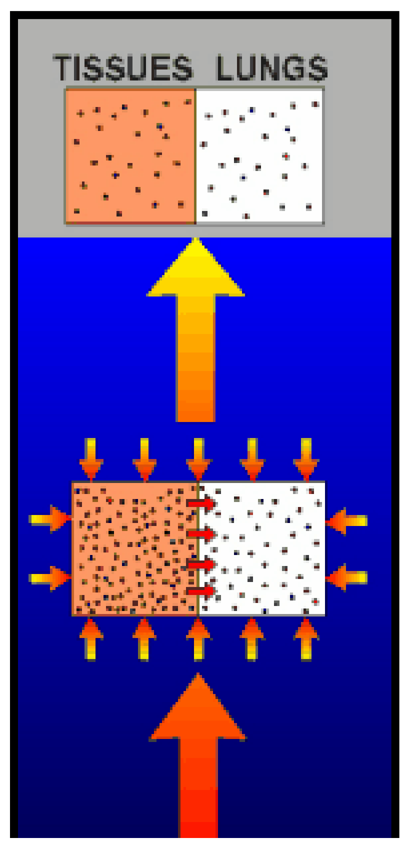
We can probably assume that Henry's Law describes the nature of how gasses actually dissolve in our blood reasonably well. After that, however, things start to get complicated. To begin with, the rules that apply to oxygen are different from the rules that apply to other gas constituents. A lot of the oxygen that dissolves in our blood is immediately bound by *hemoglobin*, the important biomolecule that transports the all-important oxygen throughout our bodies. Furthermore, oxygen is constantly being "consumed" by metabolism, so that the dissolved concentrations are always somewhat lower than the inspired concentrations. It is generally assumed among diving specialists that oxygen usually need not be considered in questions about decompression and decompression sickness, at least not when the inspired PO_2 is within safe limits for CNS oxygen toxicity. Whether or not one could breathe 100% oxygen at great depths without risk of decompression sickness is moot, because risk of oxygen toxicity mandates that dives to depths in excess of about 20 feet (6 meters) should involve mixtures containing a gas or gases other than pure oxygen. For the purposes of this discussion on decompression, we will only consider the gases in the breathing mixture other than oxygen.

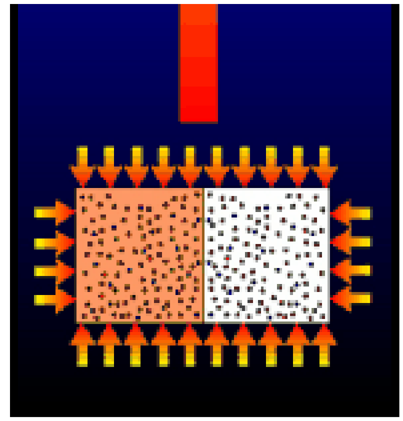
Most divers breathe air when they go underwater. As already discussed, this



results in increased concentrations of nitrogen dissolved in the blood and tissues of the diver. If a diver spends sufficient time at depth, the blood and tissues will have elevated concentrations of dissolved nitrogen in them. These nitrogen molecules are "held" in the blood by the ambient pressure acting on the diver's body at depth (represented by the bottom of the figure at left). If the diver were to suddenly ascend to the surface, the pressure which "held" the nitrogen in solution would be greatly reduced. In this situation, the nitrogen molecules would either form bubbles, or (more likely) cause pre-existing and harmlessly small "microbubbles" in the blood to grow large enough to cause problems. Whether these bubbles cause harm directly by blocking blood flow in capillaries, or by causing clotting via the complement system, it seems almost certain that the bubbles are ultimately what leads to decompression sickness.

The solution to avoiding decompression sickness, then, is to avoid bubble formation and/or growth. Nitrogen does not instantaneously "fill" a diver's body. The process of nitrogen diffusing into the blood and tissues takes some amount of time. If a diver stays shallow enough, or keeps the time at depth short enough, the diver can usually ascend directly to the surface without experiencing symptoms of decompression sickness. Such dives are called "no-decompression" dives. When divers remain at sufficient depth for sufficient time, however, enough nitrogen dissolves into the blood and tissues such that a direct return to the surface leads to a high probability of decompression sickness symptoms. When ascending from such dives, divers must spend time at shallower depths to allow the excess dissolved gas to escape. This is called "Decompression", and is illustrated in the figure at right.





As a diver ascends, the ambient pressure begins to decrease. This means that the pressure of the gas inside the lungs (and thus the partial pressure of nitrogen in the lungs) will also decrease. At this point, a reverse of Henry's Law occurs: nitrogen molecules will move from the blood and tissues into the lungs, and will be vented from the diver with the exhaled breath. The depth at which this decompression is conducted is critical: it must be shallow enough such that the PN_2 in the lungs is lower than the dissolved concentration of nitrogen in the blood, but deep enough such that the ambient pressure is sufficient to prevent significant bubble growth. Usually decompression is performed in "stages" -- at 10-foot (3-meter) intervals. This allows the diver to incrementally return to the surface, allowing the excess dissolved nitrogen to escape from the body.

It should be noted that, even though a diver surfacing from a "no-decompression" dive will usually not experience symptoms of decompression sickness, it doesn't mean that bubbles are not being formed or are not growing in the blood. It simply means that the bubbles do not grow large enough to cause obvious symptoms. Damage may still be occurring even in the absence of symptoms, so most divers are urged to spend some time returning to the surface, even after "no-decompression" dives. This practice is referred to as "safety decompression stops", or simply "safety stops".

The topic of decompression is much, much more complicated than this. Additional information can be obtained from some of the references listed below under "Further Reading".

Mixed-Gas Diving

Because of the problems associated with oxygen toxicity, nitrogen narcosis, and decompression sickness, the maximum safe limit for breathing air is about 200 feet (61 meters). To overcome these problems, gas mixtures other than air should be used. Perhaps the most severe and potentially deadly of the limitations is CNS oxygen toxicity. Air contains about 21% oxygen. The maximum safe PO_2 limit of 1.4 ATA is exceeded with air when the ambient pressure is about 7 ATA, or 198 feet (60 meters). The nitrogen narcosis at this depth has been likened to drinking several Martinis; and, for each minute spent at this depth breathing air, about 3 to 8 minutes are required for decompression.

The first step is to solve the CNS oxygen toxicity problem. This is actually relatively easy: to increase the depth at which the PO_2 limit of 1.4 ATA is reached, one need only reduce the fraction of oxygen in the breathing gas. For example, a mixture containing only 10% oxygen would reach a PO_2 of 1.4 ATA when the ambient pressure is 14 ATA - over 400 feet (120 meters) deep! The problem, however, is that if the removed oxygen was replaced by more nitrogen, the effects of nitrogen narcosis would be increased. Thus, to extend the maximum safe depth of diving, both the oxygen *and* the nitrogen must be reduced. The only was to do that is to introduce another constituent to the breathing gas mixture. That constituent is usually *helium*.

Helium has two fundamental advantages over nitrogen for deep diving breathing mixtures. The first advantage is that it does not cause narcosis, even at very high inspired partial pressures. The second advantage is that it is a much smaller molecule, and therefore *much less dense*. Because gas molecules are more closely packed together under higher pressures, the density of the gas is increased. For relatively large molecules, the increased gas density can lead to a significant increase in work of breathing. Helium is less dense at 300 feet (91 meters) than nitrogen is at sea level. These two advantages make helium the gas of choice for deep diving breathing mixtures.

Helium breathing mixtures generally come in two forms: *heliox* -- helium and oxygen without any nitrogen or other gas constituents; or *trimix* -- a combination of three primary gases, including helium, oxygen, and usually nitrogen. Heliox is more often used by military and commercial divers, whereas trimix is more often used by civilian "technical" divers. Each has advantages and disadvantages, but both achieve the same basic result: reduce the concentration of oxygen, reduce or eliminate the nitrogen, and reduce the overall gas density.

Unfortunately, from the perspective of decompression, helium is not an ideal gas for the sorts of dive profiles most civilian deep divers do (i.e., less than one or two hours at depth). Because of its very small molecular size, helium dissolves into the blood and tissues much faster than nitrogen does. More dissolved helium in less dive time means lower ratios of dive time to decompression time. If heliox or trimix were breathed for the entire duration of the dive, including the decompression, total dive times would be extremely long. The rate of decompression from deep dives using helium can be greatly increased if, during the ascent, the breathing mixture is changed to one that does not contain any helium. Because most decompression time is spent at relatively shallow depths, narcosis is not a problem, so air would be adequate.

However, air is not an ideal decompression gas either, because it contains so much nitrogen. Even though the helium comes out of the body quickly when decompressing while breathing air, nitrogen is at the same time entering the blood and tissues. The amount of nitrogen added to the body can be reduced by reducing the fraction of nitrogen in the decompression breathing mixture. Because oxygen does not factor in to decompression dynamics, the nitrogen can be replaced with oxygen. Mixtures containing only nitrogen and oxygen, with more than 21% oxygen, are popularly referred to as *nitrox*. More and more, recreational divers are using nitrox for dives to moderate depths, where CNS oxygen toxicity is not a major concern, and no-decompression times can be extended. For deep diving, nitrox is used to accelerate decompression times.While nitrox is useful for decompression at intermediate depths, pure oxygen can be used at depths of 20 feet (6 meters) or shallower. Without any nitrogen *or* helium, pure oxygen maximizes the rate of decompression, cutting total decompression times down dramatically.

Thus, by using different gas mixtures during different portions of the dive, limits of conventional scuba can be extended and decompression can be optimized. A great deal of additional information on these and related topics is available in a wide variety of publications, some of which are listed below. Divers who are interested in utilizing breathing gas mixtures other than air are encouraged to read as much material as possible, and to seek out proper training in mixed-gas diving techniques.

Further Reading

Note: *This section is not yet complete. More references will be added later.*

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