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***“The Importance of Deep Safety Stops”***



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## **Rethinking Ascent Patterns From Decompression Dives**

Before I begin, let's make something perfectly clear: I am a fish-nerd (i.e., an ichthyologist). For the purposes of this commentary, that means two things. First, it means that I have spent a lot of time underwater. Second, although I am a biologist and understand quite a bit about animal physiology, I am not an expert in decompression physiology. Keep these two things in mind when you read what I have to say.

Back before the concept of "technical diving" existed, I used to do more dives to depths of 180-220 feet than I care to remember. Because of the tremendous sample size of dives, I eventually began to notice a few patterns. Quite frequently after these dives, I would feel some level of fatigue or malaise. It was clear that these post-dive symptoms had more to do with inert-gas loading than with physical exertion or thermal exposure, because the symptoms would generally be much more severe after spending less than an hour in the water for a 200-foot dive than they would after spending 4 to 6 hours at much shallower depths.

The interesting thing was that these symptoms were not terribly consistent. Sometimes I hardly felt any symptoms at all. At other times I would be so sleepy after a dive that I would find it difficult to stay awake on the drive home. I tried to correlate the severity of symptoms with a wide variety of factors, such as the magnitude of the exposure, the amount of extra time I spent on the 10-foot decompression stop, the strength of the current, the clarity of the water, water temperature, how much sleep I had the night before, level of dehydration...you name it...but none of these obvious factors seemed to have anything to do with it. Finally I figured out what it was - fish! Yup, that's right...on dives when I collected fish, I had hardly any post-dive fatigue. On dives when I did not catch anything, the symptoms would tend to be quite strong. I was actually quite amazed by how consistent this correlation was.

The problem, though, was that it didn't make any sense. Why would these symptoms have anything to do with catching fish? In fact, I would expect more severe symptoms after fish-collecting dives because my level of exertion while on the bottom during those dives tended to be greater (chasing fish isn't always easy). There was one other difference, though. You see, most fishes have a gas-filled internal organ called a "swimbladder" - basically a fish buoyancy compensator. If a fish is brought straight to the surface from 200 feet, its swimbladder would expand to about seven times its original size and crush the other organs. Because I generally wanted to keep the fishes I collected alive, I would need to stop at some point during the ascent and temporarily insert a hypodermic needle into their swimbladders, venting off the excess gas. Typically, the depth at which I needed to do this was much deeper than my first required decompression stop. For example, on an average 200-foot dive, my first

decompression stop would usually be somewhere in the neighborhood of 50 feet, but the depth I needed to stop for the fish would be around 125 feet. So, whenever I collected fish, my ascent profile would include an extra 2-3 minute stop much deeper than my first "required" decompression stop. Unfortunately, this didn't make any sense either. When you think only in terms of dissolved gas tensions in blood and tissues (as virtually all decompression algorithms in use today do), you would expect more decompression problems with the included deep stops because more time is spent at a greater depth.

As someone who tends to have more faith in what actually happens in the real world than what should happen according to the theoretical world, I decided to start including the deep stops on all of my decompression dives, whether or not I collected fish. Guess what? My symptoms of fatigue virtually disappeared altogether! It was nothing short of amazing! I mean I actually started getting some work done during the afternoons and evenings of days when I did a morning deep dive. I started telling people about my amazing discovery, but was invariably met with skepticism, and sometimes stern lectures from "experts" about how this must be wrong. "Obviously," they would tell me, "you should get out of deep water as quickly as possible to minimize additional gas loading." Not being a person who enjoys confrontation, I kept quiet about my practice of including these "deep decompression stops". As the years passed, I became more and more convinced of the value of these deep stops for reducing the probability of decompression sickness (DCS). In all cases where I had some sort of post-dive symptoms, ranging from fatigue to shoulder pain to quadriplegia in one case, it was on a dive where I omitted the deep decompression stops.

As a scientist by profession, I feel a need to understand mechanisms underlying observed phenomena. Consequently, I was always bothered by the apparent paradox of my decompression profiles. Then I saw a presentation by Dr. David Yount at the 1989 meeting of the American Academy of Underwater Sciences (AAUS). For those of you who don't know who he is, Dr. Yount is a professor of physics at the University of Hawaii, and one of the creators of the "Varying-Permeability Model" (VPM) of decompression calculation. This model takes into account the presence of "micronuclei" (gas-phase bubbles in blood and tissues) and factors that cause these bubbles to grow or shrink during decompression. The upshot is that the VPM calls for initial decompression stops that are much deeper than those suggested by neo-Haldanian (i.e., "compartment-based") decompression models. It finally started to make sense to me. (For a good overview of the VPM, read Chapter 6 of *Best Publishing's Hyperbaric Medicine and Physiology*; Yount, 1988.)

Since you already know I am not an expert in diving physiology, let me explain what I believe is going on in terms that educated divers should be able to understand. First, most readers should be aware that intravascular bubbles are routinely detected after the majority of dives - even "no decompression" dives. The bubbles are there - they just don't always lead to DCS symptoms. Now; most deep decompression dives conducted by "technical" divers (as opposed to commercial or military divers) are very-much sub-saturation dives. In other words, they have relatively short bottom-times (I would consider 2 hours at 300 feet a "short" bottom time in this context). Depending on the depth and duration of the dive, and the mixtures used, there is usually a relatively long ascent "stretch" (or "pull") between the bottom and the first decompression stop as

calculated by any theoretical compartment-based model. The shorter the bottom time, the greater this ascent stretch is. Conventional mentality holds that you should "get the hell out of deep water" as quickly as possible to minimize additional gas loading. Many people even believe that you should use faster ascent rates during the deeper portions of the ascent. The point is, divers are routinely making ascents with relatively dramatic drops in ambient pressure in relatively short periods of time - just so they can "get the hell out of deep water".

This, I believe, is where the problem is. Maybe it has to do with the time required for blood to pass all the way through a typical diver's circulatory system. Perhaps it has to do with tiny bubbles being formed as blood passes through valves in the heart, and growing large due to gas diffusion from the surrounding blood. Whatever the physiological basis, I believe that bubbles are being formed and/or are encouraged to grow in size during the initial non-stop ascent from depth. I've learned a lot about bubble physics over the last year, more than I want to relate here - I'll leave that for someone who really understands the subject. For now, suffice it to say that whether or not a bubble will shrink or grow depends on many complex factors, including the size of the bubble at any given moment. Smaller bubbles are more apt to shrink during decompression; larger bubbles are more apt to grow and possibly lead to DCS. Thus, to minimize the probability of DCS, it is important to keep the size of the bubbles small. Relatively rapid ascents from deep water to the first required decompression stop do not help to keep bubbles small! By slowing the initial ascent to the first decompression stop, (e.g., by the inclusion of one or more deep decompression stops), perhaps the bubbles are kept small enough that they continue to shrink during the remainder of the decompression stops.

If there is any truth to this, I suspect that the enormous variability in incidence of DCS has more to do with the pattern of ascent from the bottom to the first decompression stop, than it has to do with the remainder of the decompression profile. DCS is an extraordinarily complex phenomenon - more complex than even the most advanced diving physiologists have been able to elucidate. The unfortunate thing is that we will likely never understand it entirely, largely because our bodies are incredibly chaotic environments, and that level of chaos will hinder any attempts to make predictions about how to avoid DCS. But I think that we, as sub-saturation decompression divers, can significantly reduce the probability of getting bent if we alter the way we make our initial ascent from depth.

Some of you may now be thinking "But he said he's not an expert in diving physiology - why should I believe him?" If you are thinking this, then good - that's exactly what I want you to think because you shouldn't trust just me. So, why don't you dig up your September '95 issue of DeepTech (Issue 3) and read Bruce Weinke's article? I know it covers some pretty sophisticated stuff, but you should keep re-reading it until you do understand it. Why don't you call up aquaCorps and order audio tape number 9 ("Bubble Decompression Strategies") from the tek.95 conference, and listen to Eric Maiken explain a few things about gas physics that you probably didn't know before. While you're at it, why don't you order the audio tape from the "Understanding Trimix Tables" session at the recent tek.96 conference? You can listen to Andre Galerne (arguably the "father of trimix") talk about how the incidence of DCS was reduced dramatically when they included an extra deep decompression stop over and above what was required by the tables. On the same tape you can listen to Jean-Pierre Imbert

of COMEX (the French commercial diving operation which conducts some of the world's deepest dives) talk about a whole new way of looking at decompression profiles which includes initial stops that are much deeper than what most tables call for. Why don't you ask George Irvine what he meant when he said he includes "three or four short deep stops into the plan prior to using the first stop recommended by each of the [decompression] programs" in the January, '96 issue of DeepTech (Issue 4)? If that's not enough, then check out Dr. Peter Bennett's editorial in the January/February 1996 Alert Diver magazine; he's talking about basically the same thing in the context of recreational diving. If you really want to read an eye-opening article, see if you can find the report on the habits of diving fishermen in the Torres Strait by LeMessurier and Hills (listed in the References section at the end of this article). The lists goes on and on. The point is, I don't seem to be the only one advocating deep decompression stops.

Are you still skeptical? Let me ask you this: Do you believe that so-called "safety stops" after so-called "no-decompression" dives are useful in reducing probability of DCI? If not, then you should take a look at the statistics compiled by Diver's Alert Network. If so, then you are already doing "deep stops" on your "no-decompression" dives. If it makes you feel better, then call the extra deep decompression stops "deep safety stops" which you do before you ascend to your first "required" decompression stop. Think about it this way: Your first "required" decompression stop is functionally equivalent to the surface on a dive that is taken to the absolute maximum limit of the "no-decompression" bottom time. Wouldn't you think that "safety stops" on "no-decompression" dives would be most important after a dive made all the way to the "no-decompression" limit?

Some of you may be thinking, "I already make safety stops on my decompression dives - I always stop 10 or 20 feet deeper than my first required stop." While this is a step in the right direction, it is not what I am talking about here. "Why not?", you ask, "I do my safety stops on no-decompression dives at 20 feet. Why shouldn't I do my deep safety stops 20 feet below my first required ceiling?" I'll tell you why - because the safety stops have to do with preventing bubble growth, and bubble growth is in part a function of a change in ambient pressure, not a function of linear feet. Suppose that, after a dive to 75 feet, you make a safety stop at 20 feet. Well, the ambient pressure at sea level is 1 ATA. The ambient pressure at 75 feet is about 3.3 ATA. The ambient pressure at your 20-foot safety stop is 1.6 ATA - which represents roughly the midpoint in pressure between 3.3 ATA and 1 ATA. Now, suppose you're on a dive to 200 feet (about 7 ATA) and your first required decompression stop is 50 feet (about 2.5 ATA). The ambient pressure midpoint between these two depths is 4.75 ATA, or a little less than 125 feet. Thus, on this dive you would want to make your deep safety stop at about 125 feet - exactly the depth I used to stop to stick a hypodermic needle in my little fishies.

But of course, the physics and physiology are much more complex than this. It may be that ambient pressure mid-points are not the ideal depth for safety-stops - in fact, I can tell you with near certainty that they are not. From what I understand of bubble-based decompression models, initial decompression stops should be a function of absolute ambient pressure changes, rather than proportional ambient pressure changes, and thus should be even deeper than the ambient pressure mid-point for most of our decompression dives. Unfortunately, I seriously doubt that decompression computers



will begin incorporating bubble-based decompression algorithms, at least not in their complete form. Until then, we decompression divers need a simpler method - a rule of thumb to follow that doesn't require the processing power of an electronic computer. Perhaps the ideal method would be simply to slow down the ascent rate during the deep portion of the ascent. Unfortunately, this is rather difficult to do - especially in open water. Instead, I think you should include one or more discrete, short-duration stops to break up those long ascents. Whether or not it is physiologically correct, you should think of them as pit-stops to allow your body to "catch up" with the changing ambient pressure.

Here is my method for incorporating deep safety stops:

- 1) Calculate a decompression profile for the dive you wish to do, using whatever software you normally use.
- 2) Take the distance between the bottom portion of the dive (at the time you begin your ascent) and the first "required" decompression stop, and find the midpoint. You can use the ambient pressure midpoint if you want, but for most dives in the "technical" diving range, the linear distance midpoint will be close enough and is easier to calculate. This depth will be your first deep safety stop, and the stop should be about 2-3 minutes in duration.
- 3) Re-calculate the decompression profile by including the deep safety stop in the profile (most software will allow for multi-level profile calculations).
- 4) If the distance between your first deep safety stop and your first "required" stop is greater than 30 feet, then add a second deep safety stop at the midpoint between the first deep safety stop and the first required stop.
- 5) Repeat as necessary until there is less than 30 feet between your last deep safety stop and the first required safety stop.

For example, suppose you want to do a trimix dive to 300 feet, and your desktop software says that your first "required" decompression stop is 100 feet. You should recalculate the profile by adding short (2-minute) stops at 200 feet, 150 feet, and 125 feet. Of course, since your computer software assumes that you are still on-gassing during these stops, the rest of the calculated decompression time will be slightly longer than it would have been if you did not include the stops. However, in my experience and apparently in the experience of many others, the reduction in probability of DCI will far outweigh the costs of doing the extra hang time. In fact, I'd be willing to wager that the advantages of deep safety stops are so large that you could actually reduce the total decompression time (by doing shorter shallow stops) and still have a lower probability of getting bent - but until someone can provide more evidence to support that contention, you should definitely play it safe and do the extra decompression time. One final point. As anyone who reads my posts on the internet diving forums already knows, I am a strong advocate of personal responsibility in diving. If you choose to follow my suggestions and include deep safety stops on your decompression dives, then that's swell. If you decide to continue following your computer-generated decompression profiles, that's fine too. But whatever you do, you are completely and entirely responsible for whatever happens to you underwater! You are a terrestrial

mammal for crying out loud - you have no business going underwater in the first place. If you cannot accept the responsibility, then stay out of the water. If you get bent after a dive on which you have included deep safety stops by my suggested method, then it was your own fault for being stupid enough to listen to decompression advice from a fish nerd!

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I would like to thank Eric Maiken for explaining bubble physics to me and for adding some theoretical foundation to my silly ideas.

## **Diving Physics and "Fizzyology"**

### ***Introduction***

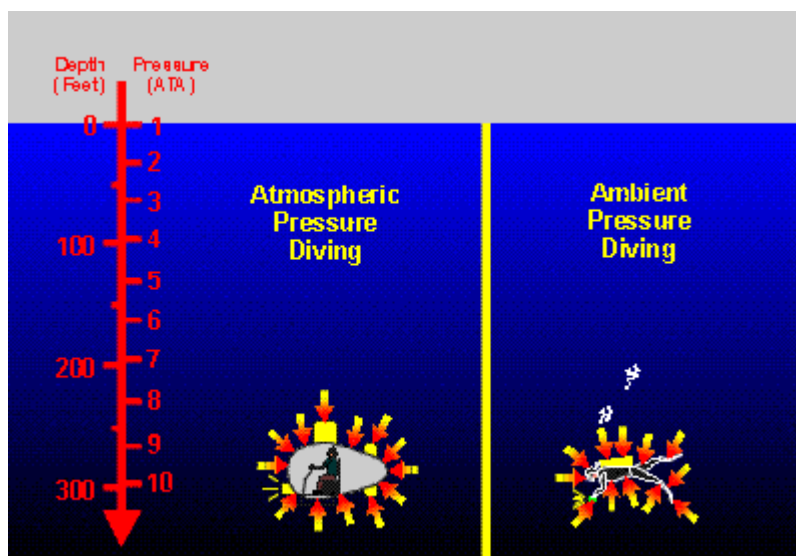
Like all animals, human beings need oxygen in order to survive. When we breathe, we extract oxygen from the air, and use that oxygen for metabolism, which is how we convert the food we eat into useable energy to do the things that we do. One of the by-products of metabolism is carbon dioxide; whenever 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 overcome 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 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.

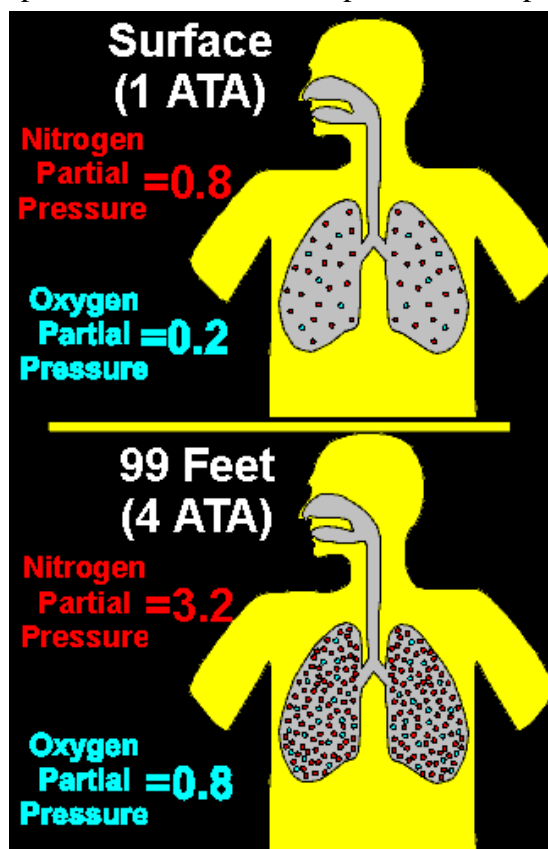
As mentioned above, gas is composed of molecules. As the pressure of the gas increases, these molecules (which are in constant motion) get packed more closely together. At a higher pressure, a given number of gas molecules will occupy a smaller volume (or a given volume will be occupied by a larger number 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.

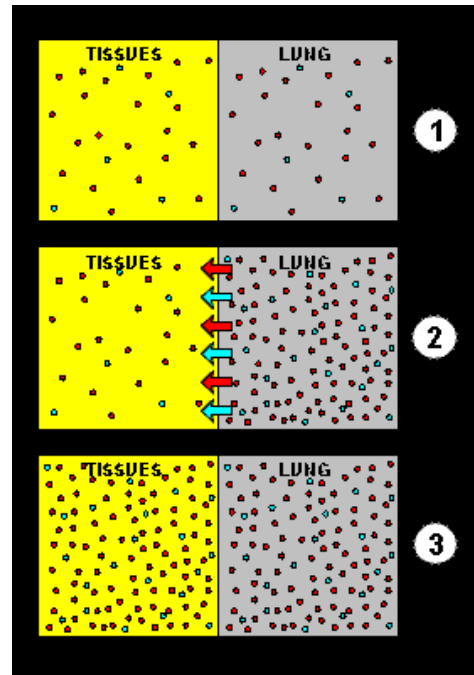
Just a word on notation: in their gaseous forms, both oxygen and nitrogen are binary molecules; that is, they are bound in pairs of atoms. An oxygen gas molecule consists of two oxygen atoms bound together, and a nitrogen gas molecule consists of two nitrogen atoms bound together. The notation for oxygen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

## 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.

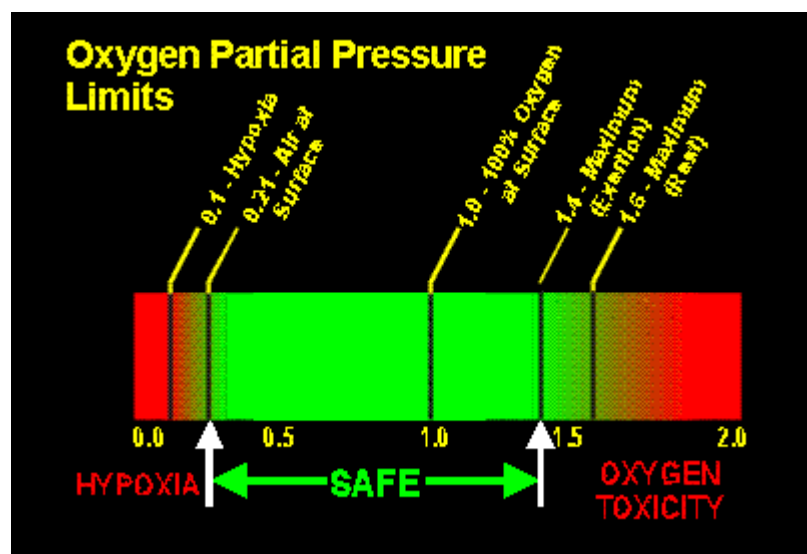
Because the partial pressures of the gases in the lungs are now greater than the dissolved partial pressures of these gases in the blood in tissues, gas molecules begin to move from the lungs into the blood and tissues (represented by the blue and red arrows in the middle figure, 2). Eventually, the concentration of the dissolved gases in the blood and tissues will be proportional to the 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<sub>2</sub>), ranging from zero oxygen on the left, to a PO<sub>2</sub> of 2.0 ATA on the right. Through evolution, our bodies have become optimized to breathe oxygen at a partial pressure (PO<sub>2</sub>) of 0.21 ATA. If the inspired PO<sub>2</sub> drops much below 0.1 ATA (i.e., 10% oxygen at sea level), our bodies begin to shut down. This is called hypoxia. Breathing more than 0.21 ATA oxygen is generally fine ... up to a point. If the inspired PO<sub>2</sub> 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<sub>2</sub> 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 to 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<sub>2</sub> limit should be. Convulsions have occurred in divers breathing an inspired PO<sub>2</sub> 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<sub>2</sub> 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 PO<sub>2</sub> 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<sub>2</sub>). 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 others claim to suffer no incapacitation at depths in excess of 200 feet (61 meters). Impairment likely occurs at lower PN<sub>2</sub> levels than those at which divers begin to detect overt symptoms. In any case, the greater the inspired PN<sub>2</sub>, 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: its 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" --

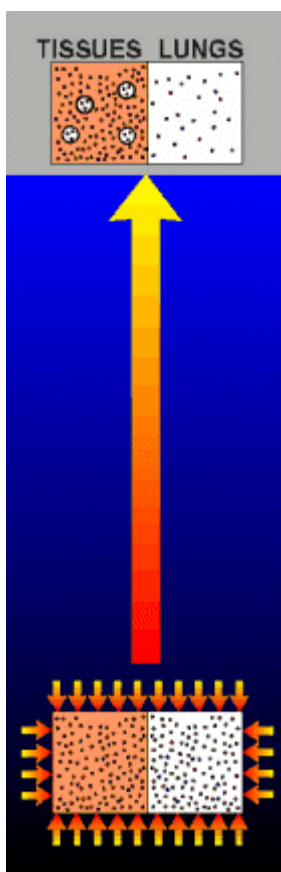
schedules that describe slow, staged ascent patterns back to the surface after exposures to various depths for various lengths of time (a process called "decompression") -- were eventually released for use by the general diving public. Unfortunately, no matter how "conservative" these schedules were, 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.

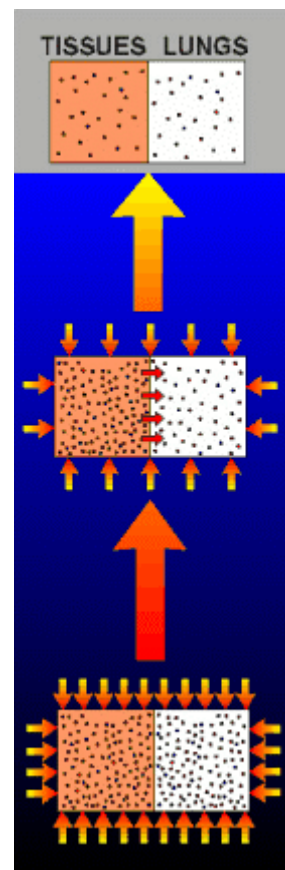


What follows is a very coarse description of what seems to be going on, and what we think might have something to do with what causes decompression sickness.

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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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 way 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.

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## **Confessions of a Mortal Diver: Learning the Hard Way**

### ***Some Background***

As a high-school student, I had been granted several wonderful opportunities to experience my life's calling - the study of coral reef fishes - in some pretty exotic places; most notably Christmas Island in the central Pacific, and the Micronesian island of Palau. At Christmas Island, I had met one of this world's most genuinely kind and sincere individuals - an aquarium fish collector by the name of David Wilder. David had taken me on many 200+foot dives off the slopes of Christmas, and it was with David that I experienced my first clinical Decompression Sickness (DCS). It was on a dive to 110 feet to collect a new subspecies of butterflyfish (which I later named *wilderi* in honor of David), and we limited our bottom time to only twelve minutes. After surfacing (with conservative decompression), I felt a mild pain in my left shoulder, which I successfully treated with in-water recompression. That was July 14th, 1985.

Three months later, David, along with Boota Taie and Tebano Sukong, were emergency air-lifted to the Hyperbaric Treatment Facility in Honolulu after all of them experienced severe decompression sickness. David suffered from paralysis which has confined him to a wheelchair for the rest of his life, Boota was initially paralyzed but later regained his ability to walk after a few weeks of treatment, and Tebano suffered nothing more than moderate pain in both of his shoulders. A fourth diver, Utrie Taie (Boota's brother), never left Christmas - he died of DCS-related complications before the rescue plane arrived.

The story of their accident is long, dramatic, and full of heroic efforts and unfortunate circumstances, and would require pages of text to adequately recount. But their story is not the topic of this article. I mention it only as background to my own story, to underscore the irony, and to illustrate that in spite of my first-hand experience with a tragic DCS accident, I was too thick-skulled to learn from the mistakes which David and his companions must pay for the rest of their lives.

I visited David at the Hyperbaric Facility almost every day for the three months of his treatment. Through these visits I learned much about DCS and its treatment, and I spent a great deal of time talking with Dr. Robert Overlock, David's "bends doctor". It was also through these visits that I met John Kraemer, an entrepreneur/fish enthusiast who was a friend of David and who was going to establish an aquarium fish collecting station in Palau. I was eighteen years old and just finishing up my first semester as a

college freshman at the University of Hawaii. After my earlier travels abroad, I was quickly becoming bored with the mundane academic life. John needed someone to help him set up his station in Palau; I had experience in Palau and was looking for something more exciting than college classes. Some long discussions over dinner, a hand-shake partnership, a lot of preparation, and three months later I was on my way to Palau.

### ***Testing the Limits***

During the first few months of our stay in Palau, we spent our time completing the necessary tasks of establishing any business - making contacts, spending money, learning the ropes, filling out legal forms, and applying for permits. By the end of June of 1986, we were at the point where we could do nothing more - all of the formalities had been fulfilled, and all the forms had been filed - we needed only to have our Foreign Investment Application approved by the Palauan Foreign Investment Board, and they wouldn't be meeting again until July 15th. I had unlimited access to a 15-foot Boston Whaler, I had all the SCUBA tanks I wanted, I was surrounded by some of the world's best dive sites, I was young, and I was feeling pretty damned immortal. All in all, it was an extremely hazardous and potentially disastrous combination.

I still regard those two weeks as the most fantastic diving experience of my life. For those of you unfamiliar with Palau, it is blessed with perpetually glassy surface conditions, underwater visibility approaching 400 feet at times, some of the most spectacular drop-offs on earth, and an incredibly vast array of marine life. Palau has been designated one of the 8 underwater wonders of the world. I dived everyday, four or five times a day, pushing my limits a little bit further each time. I was not ignorant - I had completed my diving education through the level of Divemaster. But I was naive - I thought that I could continue getting away with dive profiles which now make me shudder.

Halfway through this fortnight of diving bliss, the eminent Dr. John "Jack" Randall, one of the world's leading authorities on coral reef fishes, visited Palau. He needed a boat and a diving partner, and I, a budding coral reef fish researcher, was more than thrilled to take him diving wherever he wanted to go. We dived every day, collecting amazing fish specimens, seeing fantastic things, and generally having a blast. I was having the time of my life! As the date of his departure - July 15th - drew nearer, we had accomplished all of his objectives except one. He wanted to make a dive at the legendary Palauan Blue Holes, a huge and elaborate cavern system located along one of the island's most spectacular drop-offs. I had been in Blue Holes a number of times before, and each time had encountered some fantastic or unusual fish species. I was anxious to take him there, and we decided to go July 14th - the day before his departure - exactly one year after I had been mildly bent at Christmas Island.

### ***Exceeding the Limits***

We spent the morning loading our gear and driving the hour-long boat ride from the dive shop to Blue Holes. When we arrived, I set the anchor and quickly got ready to

get in the water. I rigged my tank and regulator and put on my fins. When I grabbed my mask, the glass plate fell onto the floor of the boat. I had brought a really nice black silicone mask to Palau with me, but some puppies had found it and had torn it to shreds. The only replacement I could find in Palau was this cheap rubber mask with an oval glass plate, which kept falling out. With no small amount of dexterity, I reassembled the mask and re-attached the metal band, which held it all together, just as I had done many times before. As I plunged over the side of the boat and descended through the fabulous caverns, I was in awe at the incredible visibility of at least 400 feet. The main body of the cavern opens to a drop-off with an enormous gape of about 200 feet across. The top of this entrance is at a depth of about 90 feet. The floor of the cavern is a steep sandy slope that begins at 70 feet at the back of the cave, drops to 150 feet at the mouth, and continues down into the abyss. Four large circular holes, about 30 feet in diameter, connect the ceiling of the cave at 50 feet to the reef-top at 10 feet: a truly spectacular system.

I had spent a good deal of time exploring the cave system on previous dives, and I decided to follow the sand slope down outside the cavern on this dive, rather than further explore its insides. I wore only a single aluminum 80 cu. ft. cylinder, and in those days of overconfident stupidity, I had no qualms about dropping down to 250 feet for a quick look around with such meager equipment. Jack had loaned me one of his old mechanical decompression meters (a.k.a. "Bendomatic"), so I used it as a guide for decompression. Arriving at 250 feet, I experienced one of the most intense moments of awe - the closest thing I've had to a religious experience - in my entire life. I looked back up the slope through the incredibly clear water, and even from that depth, I could see the boat hanging lazily over the edge of the drop, I could see ripples in the surface, I could even see the anchor line connecting the boat to the reef - from 250 feet away! (No kidding!) A small Gray Reef shark swam along the reef a hundred feet above - 150 feet below the surface - and a White-tip Reef shark lay resting on the sand a few yards away. But the most spectacular sight of all (by far) was the cathedral-like columns of light penetrating the darkness of the cavern, emanating from the four round "chimneys" which give the Blue Holes its name. Given this setting, along with the comfortable numbness of narcosis and the warmth of the surrounding 82-degree water, I was feeling content with just staying there - forever.

The spell was broken when I suddenly noticed a vast school of small fishes off to my right. I could recognize that they were a group of fishes called "Anthias" (or "Fairy Basslets"), but the color pattern of black and white bars was unlike any known species. I frantically tried to collect a few specimens with the hand nets I had, but they were evasive. With the narcosis, it seemed like I was down there for hours. I knew it was deep - really deep - and I had this constant nagging feeling that I really should get the hell out of there soon. But the needle on my decompression meter wasn't yet in the red, and my pressure gauge read 1100 psi, so I ignored my pangs of concern and continued my efforts. I chased and herded and swung my hand nets in a desperate effort to collect this unknown species. Finally, after what seemed like hours of bottom time (but was actually about 15 minutes), I managed to catch one of the fish and without hesitation I headed back towards the surface.

Ascending past 200 feet, I noticed a slight breathing resistance in my regulator. Two breaths later, it was clear that I was running out of air. My gauge still registered 1100 psi, but the breaths were getting progressively more difficult - time to pick up the

pace. At 150 feet, it was like sucking air through a hypodermic needle. I stared at my gauge, still reading 1100 psi, and could not understand what was happening. All of a sudden, the needle dropped instantaneously to zero - the needle had been stuck! By this time, I was rocketing towards the surface at break-neck speed. I barely made it.

I climbed in the boat, where Jack was fiddling with his underwater camera, and I forgot about my perilous ascent as I groped through my collection bucket to find the unusual fish I had collected. On the surface, the black and white bars appeared in their true colors of red and yellow. I held it up to Jack, expecting him to confirm that I had indeed collected a new species, and he said "Oh yes. That's *Pseudanthias lori*. I named that fish after my daughter because I collected the first specimens on her birthday." It turns out he had collected the beast more than 20 years before. Oh, well.

At about that time I began to notice a curious pain in the middle of my thigh, slowly increasing in intensity. "That can't be bends", I thought. "if it were bends, my joints would be hurting, not the middle of my thigh...that's what all the textbooks say, anyway...". Textbooks aren't always right. Within minutes I began to notice a moderate pain in my left shoulder, followed by pain in my right shoulder. Then my elbows, followed by my knees, thighs, wrists... Yep, I was bent all right. Not getting overly excited about the situation, I calmly rigged a second tank, briefly described my situation to Jack, then rolled over the side of the boat before Jack could tell me any different. Descending below 15 feet, all of the pain completely vanished. Just to insure the bubbles were squeezed back down, I made a brief "spike" to 125 feet. I then slowly ascended to 60 feet for 2 minutes, then 50 feet for 5 minutes, 40 feet for 5 minutes, 30 feet for 20 minutes, then finished the bottle off at 20 feet.

Climbing back into the boat, I didn't feel any symptoms of DCS. Jack was still finishing his second dive, so I rigged a third tank, just in case. About fifteen minutes later, I felt a very mild twinge in my left shoulder. I decided to spend a few more minutes decompressing while waiting for Jack to return. I "spiked" to 60 feet, slowly ascended to 40 feet for a few minutes, stopped at 30 feet for five minutes, then spent the next forty minutes hanging just below the boat at 10-20 feet. My tank was still about half full, so I climbed back into the boat saving the rest of the air...just in case I wanted to make another dive. Jack returned and was naturally concerned with my well being. I assured him that I had fixed myself and was just fine, that he needn't worry about me, and that I was a big boy and could take care of myself.

We ate lunch and talked about fishes and fish scientists, and I listened as Jack retold some of his better diving stories (and believe me; after nearly fifty years of diving, with perhaps 30,000 dives under his belt, he tells some good diving stories!). Two hours went by and I all but forgot about my little mishap during the morning dives. Jack wanted to use half of his third tank to photograph some fishes in a particular boat channel on the way back from the dive site. Since there was nothing in the channel of interest to me, I decided to let Jack dive it solo while I waited in the boat.

Three and a half-hours post-bends, and I felt fine. No pain, no weakness, no excessive fatigue; nothing. At that time, my story was only an anecdote - a little tale to tell my friends back home. It was an in-water recompression success story. It was a nice little example of how one should not trust their instruments more than their intuition. It would have served as a harmless reminder of the potential hazards of deep diving. If I

had gone home at that point, that day would not have been much different from many others. But I didn't go home. Consequently, that day; that sunny July 14th, exactly one year after my first and only previous clinical DCS hit; would profoundly alter the rest of my life.

When Jack finished his dive in the channel, he said that he wanted to use the rest of his tank on a bounce dive to 140 feet to collect a particular rare fish species he had seen on another reef. I pulled anchor and headed off to Augulpelu reef, commonly referred to by visiting divers as "Short Drop-off".

Short Drop-off is a large offshore reef near Koror, the main town of Palau. Although its name may imply a drop-off which bottoms-out at moderate depth, it is actually a sheer vertical cliff beginning just below the surface and plummeting hundreds of feet straight down. Its name actually comes from the fact that it is close to the dive shop and requires only a short boat ride to get there. Jack had seen a rare species of dartfish at 140 feet on an earlier dive there, and he wanted now to use his remaining air to quickly drop down and collect some with a small amount of rotenone (a fish poison). When we arrived at Short Drop-off, I said I would use the remaining air in my tank to drop down to 140 feet to make sure we were in the right place. "No way!" Jack said. "After getting bent this morning, there's no way I'm going to let you go back down there." After I reminded him that he was not my mother and that he was a guest on my boat, and convincing him that I was fully capable of taking care of myself (yeah, right), I grabbed my gear and jumped over the side. I went straight down to 140 feet, saw the fish he was looking for, then came straight back to the surface; total time underwater: 5 minutes. I waited as he prepared his small portion of fish poison and prepared to make his dive. The plan was that he would drop down, find the fish, spread the chemical, then return to the surface. After waiting a few minutes for the fish to succumb, I would drop down, collect the first few fish (if placed immediately in clean water, fishes collected in this method often revive. I wanted some live ones for my aquarium, so I wanted to go down first and collect the first few.). While I decompressed, Jack would go down and collect the rest of the fish. All in all a very efficient plan (except for the fact that, given my state of nitrogen saturation, I would be committing virtual suicide.)

Jack went down, found the fish, distributed the rotenone, and came back to the boat. He told me that he left his powerhead at the spot where he put the rotenone, and that in order to find it, I should go down to the big sea-fan at 140 feet and turn right. (He left the powerhead because sometimes, in the presence of dying fishes, sharks tend to get a bit excited.) He tried one last time to convince me not to go back down, but I wasn't about to listen to him. I knew everything there was to know about everything, and there was nothing this world famous researcher with nearly 50 years of diving experience could possibly know that I didn't already know better. I was nineteen - I was immortal. Or so I thought...

I followed Jack's directions to the rotenone station with utmost precision...except for one minor detail. Instead of turning right at the big sea fan, I turned left. Four minutes into my dive, I realized my blunder and headed back (up current) from whence I came. Passing the big sea fan, I continued along the ledge at 140 feet for a short distance and came upon Jack's powerhead. I looked around, but saw no fish – absolutely none! I looked at my gauge, which read 1000 psi, and continued searching for fish (I just

hated to come back empty handed). A few minutes later, I suddenly remembered about my earlier faulty pressure gauge reading and grabbed for the gauge again. It registered 750 psi - at least my gauge was still working. I finally saw a few disoriented fish. I quickly collected them, and started for the surface. At 120 feet the breathing started getting tight. I was breathing hard after my exertion, and the regulator wasn't delivering what I needed. I looked at my pressure gauge, and it still read 750 psi. I was struck with horror when it suddenly jerked down to zero. I was on the surface less than a minute later. Jack was fully rigged and about ready to roll over the side of the boat. "Where the hell were you!" he shouted. "You were only supposed to be down a couple of minutes! Are you all right? Do you have enough air to decompress?". "Yeah, I'm fine", I said, not wanting to admit to him my blunder of trusting the faulty gauge - again. He briskly replied "Then get back down and decompress!!" With that, he fell over the side of the boat and went down to collect the rest of the fish specimens.

I clambered aboard the boat and hauled my gear in. The weather was mild, and the sea was glassy and mirror-flat. I began breaking down my gear and stowing equipment. I briefly looked at my catch of fish - nothing exciting, and all dead. I stood up and looked down the reef at the boat owned by the "Fin `n' Fins" dive shop. I recognized the dive guide as my friend Melvin, and I waved to him. He saw me and waved back shouting "How was your dive?". I yelled back "Great...just great." I watched him help the tourist divers into the boat, pull anchor, and motor off towards the dive shop. When his wake reached my boat, it rocked a little and I lost my balance slightly. I reached for the steering console of the 15-foot Boston Whaler, but my hand wouldn't go where I wanted it too. At first I didn't think much of it, but a few seconds later I realized that both of my hands and arms had lost all coordination! My body went cold and I broke out into a sweat. I fought off panic as my brain scrambled to fully comprehend the situation. "Oh Jesus!...Oh, Jesus!" was all I could say. I looked out at Melvin's boat, but he was already too far away to hear my yelling over the roar of his engines. I continually moved my arms about, trying desperately to prove that they were really O.K. But they were getting worse. I can't explain the incredibly horrifying feeling of losing control of one's appendages - it's something which can only be understood through experience, and I wouldn't wish the experience on anyone. My arms were starting to go numb.

I began pacing back and forth trying to think of what to do, when I noticed my legs were also losing coordination and getting numb. Suddenly I became very dizzy, and I knew that if I didn't do something soon, I would probably die. In the two minutes since I had surfaced from the dive, my body had deteriorated with every breath. I quickly got down on my back on the floor of the boat and wrapped my legs over the steering console. I maneuvered my body so that I was in a near-vertical head-down position, using the console for support. As I lay there, upside down, my head cleared up and I was no longer dizzy. Slowly, my arms began to regain some coordination, although my hands and fingers seemed to have minds of their own. I decided that I had to find some way to get back in the water and recompress. After a minute in the headstand position, I got back to my feet and grabbed my regulator. There were five tanks on board, and I knew that at least three of them were dry. I frantically cracked the valves on each one, but only one of them had any air at all. I put my regulator on that one, turned on the air, and saw that it had 100 psi remaining. I didn't waste any time on a backpack, fins, or weight belt - I just wanted to get underwater fast. I grabbed my

mask and heard a loud "CLINK" as the glass plate fell to the deck of the boat. What timing!

In retrospect, I can say with confidence that the ensuing few moments represent one of the five most intense moments of my life. With fingers that did not seem to pay much attention to the instructions from my brain, I desperately tried to reassemble the pieces of my mask. I don't know how I managed to stay calm through those moments, but I know for certain that if I had panicked, I would not have been able to get the mask back together. Somehow, I was able to repair it. Holding the tank under my arm and placing the regulator in my mouth, I rolled off the boat and pulled myself along the gunwale to the anchor line. In my efforts to pull myself down the anchor line with a buoyant nearly empty aluminum-80, I suddenly realized how useful a weight belt would have been. It didn't matter much, though, because within a minute, the tank was dry. After that failed recompression attempt, I managed to heave myself back into the boat, where I realized that the symptoms were getting worse again. I got back into my headstand by the console, and waited for Jack's return.

A few minutes later (I'm not really sure how long because my mind was considering options at a blistering pace for what seemed like an eternity), I heard Jack's bubbles breaking the surface near the boat. I quickly got to my feet and saw that he was decompressing on the anchor line. I very gingerly grabbed my mask, put on my fins, and jumped over the side. I dived down to Jack, who was about 10 feet under, and motioned that I needed to buddy-breathe. I did what I could to explain my predicament using hand signals, and although he didn't grasp the full extent to which I had DCS, he got the gist of it. He showed me his pressure gauge which read 500 psi, and it suddenly dawned on me that by buddy-breathing with him, I was now cutting into his decompression gas supply. I wasn't sure what to do at that point, because if I didn't decompress some, I would be screwed; but if I kept buddy-breathing with him, then he might not have enough decompression time and he might get bent too. Jack must have realized the mental dilemma I was struggling with because he motioned that he was O.K. and that I should stay with him and share his precious air. Unfortunately, I had forgotten to bring my weight belt, and I was very definitely positively buoyant. In my struggles to stay down, I was using up our air too quickly, and we needed to conserve as much as we could. I took a deep breath, swam down to the bottom ten feet below, and picked up a fairly large rock to use as weight. I wasn't wearing my wet-suit (it would have compounded the buoyancy problem, and the water was warm anyway), so I carefully stuffed the rock down my pants. Despite the fact that I could feel small marine creatures crawling about parts of my body where most people definitely do not want creatures crawling about, I was glad that I was neutrally buoyant.

Underwater, I had regained control of my arms and hands, and my legs felt fine as well. We held each breath as long as we possibly could, and we managed to stay 8 minutes at 10 feet. When we just couldn't suck any more air out of the tank, we surfaced and hauled ourselves back into the boat. I moved my arms and fingers about, and walked around on the boat. Everything seemed to be working fine again, but it was clear that I wasn't out of the woods just yet. Jack and I agreed that we both should get back in the water as soon as possible, and the only way to do that was to go back to the dive shop and get more tanks. Fortunately we were diving at Short Drop-off, so the dive shop was only a ten-minute boat ride away. But it was 4:55 in the afternoon, and

the shop closed at 5pm - we had to hurry. We pulled the anchor right up, started the motor, and headed for Koror.

There are two boat channels through the barrier reef between Short Drop-off and the dive shop. The main channel is clearly marked, but it is farther away and it would take us half an hour to get to the dive shop if we used it. The other channel leads straight to the dive shop and would require only 10 minutes, but it was unmarked and could be safely used only on a clear day. Since I didn't see any rain clouds, and since time was of the essence, I opted for the short cut. Jack said he felt a mild pain in his neck, so I told him to get down on his side and elevate his feet while I drove the boat.

Just as I was entering the channel, a rainsquall like none I had ever seen suddenly announced its presence. Raindrops the size of marbles pounded my face and visibility dropped to 20 feet. I couldn't see the reef - in fact I couldn't see anything at all due to the rain hitting my eyes. I grabbed my mask, which fell apart; then I grabbed Jack's mask. Unfortunately, Jack's mask had prescription lenses installed, so I couldn't see very well. But at least I could see better than I could with the rain in my eyes, so I slowly motored on. Looking for the reef was useless, so I had to go on my memory of the direction of the channel. I almost ran head-on into another, larger, fishing boat coming out the channel. My legs were starting to feel numb. That was another of the five most intense moments of my life.

I somehow managed to weave the boat through the channel without hitting the reef, and the squall passed on. At full throttle, I glided the boat between patch reefs and around the maze of small islets towards the dive shop. Fifteen minutes after we had pulled anchor (delayed by the rainsquall), we arrived at Fish 'n' Fins Dive Shop. Francis Torribiong, the owner, had just locked up and was about to leave. "Wait!" I yelled. "We need tanks!". Francis called back "What?!? You want to do more dives?". "I'm bent!", I replied. He called back "What?! Bent!? Who's bent?!" "I am," I yelled, "and maybe Jack too." Without hesitating, he ran to the dive locker, unlocked the door, and instructed two of his employees to bring us some tanks. As I pulled-up alongside the dock, I took one step toward the bowline...and fell flat on my ass. My legs were more than numb, they were virtually incapable of standing or walking. It was clear that this episode wasn't going to be over anytime soon. Francis said he only had two full tanks. He told one of his employees to drive our boat and take us out to the harbor to recompress. Meanwhile, he would fill more tanks and alert the hospital to start preparing the recompression chamber.

Twenty-two minutes after leaving Short Drop-off, Jack and I once again plunged into the water. By this time, my legs were numb, weak, and totally uncoordinated. The numbness wasn't so much a tingly sensation, but rather a reversal of temperature sensation (i.e. the cold water felt warm on my legs). My arms and fingers were moderately uncoordinated, but not nearly as bad as they were back on the boat at Short Drop-off. As I descended this time, however, something was different - the symptoms did not go away. I followed the steep slope down to 80 feet, where it bottomed out into mud. The poor visibility compounded my uneasiness about the fact that my symptoms were unchanged, even at this depth. I had an overwhelming urge to remain as deep as I could until the symptoms vanished, but Jack (and my common sense) convinced me not to stay at 80 feet more than two minutes. I certainly didn't need any more nitrogen



in my body! Five minutes later I was at 40 feet; ten minutes after that I was up at 30 feet. After 20 minutes at thirty feet, I began the long wait at 20 feet.

At about 7:15 in the evening (an hour after entering the water this last dive), I was down to 500 psi in my tank. Jack had long-since gotten in the boat and was waiting with the Dive Shop employee. I wanted to stay out there, underwater, as long as I could - at least until the chamber was ready for me. I surfaced and asked Jack if he had any air left; he had none. They decided to leave me there, go back to the dive shop for another tank, and then bring it back to me. They gave me a flashlight (it was night), and I descended back to the reef, 20 feet below. I was alone. Fatigue was beginning to set in. My mind began to wander. I wondered what I would do if the boat never came back. Would I be able to swim back to the dive shop? At night? Half paralyzed? What if a shark got me? What if the chamber isn't working? Will I get worse? Will I be confined to a wheelchair for the rest of my life? Am I going to die? I kept pointing the flashlight straight up.

Fifteen minutes later, the boat glided to stop directly above me, and an anchor fell to the reef a few feet away. I shined the light up at the white hull of the boat, and saw that they were lowering a SCUBA cylinder with regulator over the side. They hung it beneath the boat at a depth of twenty feet. I decided to leave some air in the tank on my back, just in case I needed it later, and I began breathing off the new cylinder. I spent the next hour and fifteen minutes alone in the darkness, thinking about life in general, thinking about the ludicrous mistakes that day, and wondering what price I was going to have to pay for them. There were many thoughts of "If I had only..." and "Why didn't I just...?", and there were many, many regrets. I also thought about David Wilder...and Utrie Taie. At one point during my long wait, another boat came to a stop alongside the one I hung below. I could see flashlights moving about and pointing down at me, and it was clear that the occupants of the two boats above were exchanging information. It was nearly nine o'clock at night, and I had spent more than six hours of that day underwater. My body was saturated with nitrogen, and probably filled with tiny bubbles. I was exhausted. I freed my mind of the sobering realities of the situation just long enough to appreciate the amazing light show going on around me. The water was rich with bioluminescent planktonic organisms, which would glow bright green when disturbed. Passing fish left glittering green trails of light behind them as they swam. I was momentarily bemused by the thousands of tiny sparkles of light I created in the wake of my arm as I swung it through the water. But my amazement didn't last long.

When I had finally breathed the last few breaths of air out of the SCUBA cylinders, I came to the surface. Jack was still on the boat, and he asked me how I was feeling. It was difficult to assess my state in the weightlessness underwater, but back on the boat I could confirm that my condition had not improved. But it hadn't gotten any worse, either. I was informed that the recompression chamber was ready and waiting for me, and we unanimously agreed that I would be better-off in the controlled, dry, and warm environment of the chamber than I would be underwater. Besides, I was at the limits of exposure; my fingertips looked like white raisins, and my jaw and lips were fatigued from holding a regulator for such a long time. Arriving at the dive shop, I did my best to hobble to my feet, but had to be virtually carried off the boat. On shore, and with a great deal of concentration, I was able to stand on my own and even walk the

three or four yards to Francis' car. I plunked down on the back seat, and lifted my legs inside. Someone shut the door, and Francis drove off towards the hospital.

During the short drive, I remembered what one of the American Peace-Corps students had told me: "If you ever find yourself sick while in Palau, the last place you want to go is the hospital. It's appalling!" Francis was driving, and I said, "So I bet you think I'm pretty stupid, huh?" He only said "No, Richard, I don't think you're stupid. Just relax." I sat for a moment and said, "I'm really sorry to keep you up so late at night." "Don't worry about it." he said, and we were quiet for the rest of the trip.

### ***The Long Road to Recovery***

At the hospital, Francis helped me out of the car, and semi-carried me through the entrance and down a long hallway. We came to the room with the recompression chamber. It was a yellow cylinder, about six feet long and two feet in diameter, with a number of pipes, valves, and miscellaneous other contraptions fastened to its sides. About a dozen SCUBA cylinders were lined up along one end, the first connected by a high-pressure hose to the chamber. I was placed on a stool and given a quick physical to evaluate my condition. After answering a few questions, they asked me to undress, wrapped me in a sheet, and asked me to try to walk over to the chamber. With a lot of concentration, I was able to walk, one uncoordinated and shaky step at a time, all the way over to the chamber. I climbed in and they closed the big round metal door. As they were pressurizing the chamber I looked out the small round window above my head and could see Francis reading the owner's manual. Although this seemed a bit disconcerting, I was really too tired to care. I remembered how Boota Taie, one of the divers from Christmas Island, was bent to about the same degree that I was, and he almost totally recovered after extensive treatment. I never allowed myself to believe that my prognosis was any different. The chamber was only capable of simulating a depth of 165 feet, and it required the air from several SCUBA tanks to pressurize it that much. I don't remember the exact profile they treated me with, but it involved breathing pure oxygen through a mask for four twenty-minute bouts (with 5-minute air breaks) at a simulated depth of 60 feet, and the full treatment lasted over six hours. I remember hearing voices outside: Jack was telling the doctors what had happened, and insisted that he should pay the bill. John Kraemer visited me and gave me a great deal of moral support. Other, unfamiliar voices discussed possible plans of action. I talked over the microphone system and recounted all of the dives I had done that day. After that, all I could do was lie and wait.

About an hour into the treatment, my legs began to feel very tingly. At first I thought that in the cramped quarters in that steel coffin, the blood circulation to my legs had been constricted and my legs had fallen asleep. But I soon realized that the sensation was obviously bends-related. I didn't worry much about it, I decided that it must be due to fatigue. I was extremely tired. When the treatment finally ended at 3:15 in the morning, more than twenty hours after I had awakened the previous morning, I could barely keep my eyes open. I was so tired that I could think of nothing else besides sleep. I've never been more physically and emotionally exhausted in my life. I was too tired, even, to care that I was by that time unable to move my legs, and could only barely move my arms. I only wanted sleep.

When I awoke at 10:30am, I was in a room full of other patients with a wide assortment of maladies from broken legs to burns to cancer. Otherwise, I was alone. I could just barely wiggle my feet slightly, and both arms were numb and uncoordinated. There was a clear demarcation in feeling across my chest just below my collarbone. My entire body below this demarcation felt the way my lower lip feels after my dentist fills a cavity - numb. I had lost all bladder control, and had been hooked up to a urinary catheter. It was difficult to breathe lying down because my diaphragm was non-functional. When my chest muscles expanded my lungs, there was nothing to prevent my other organs from filling the space, and I had a hard time fully ventilating my lungs. John Kraemer came in and sat by the bed. I told him how it all happened, and I wasn't quite sure whether or not he was really pissed-off at my irresponsibility. He told me that once word had spread of my accident, someone broke into my apartment and stole an airline ticket and \$400.00 in cash, along with my brand-new spear gun. (The nerve of some people!) John was dressed up because he was on his way to the government building to meet with the Foreign Investment Board regarding our permit to do business. I was supposed to attend that meeting, but I had to cancel - health reasons. Jack stopped by on the way to the airport and offered more moral support. He had to leave, but he would contact me after he returned to Hawaii. Francis also came by and asked me for a detailed description of how I felt. He told me they were preparing the chamber for another treatment, and I should be ready to go back in that afternoon. I told him I hadn't made any other plans, and that I probably wasn't going anywhere, seeing as I couldn't walk and all.

The second chamber treatment lasted eight hours, and was generally uneventful. There was neither any improvement in my condition, nor did I get any worse. Francis told me they had made arrangements with a Coast Guard C-130 to take me up to Guam, where there was a more fully equipped and staffed recompression chamber. John came by again and told me the Foreign Investment Board had flatly refused our permit to do business. He said it had nothing to do with my accident, but rather was some sort of political thing. He was going to try again, but I was clearly out of the picture. The next morning I was put aboard the Coast Guard plane and flown in a pressurized cabin over to Guam. The attendants were incredibly kind and helpful, and I never really had a chance to thank them. The flight was long and grueling - there were no windows near me. For my in-flight meal, I was fed intravenously.

In Guam, I rode inside a military ambulance to the U.S. Navy Hyperbaric Facility. I was greeted by an assortment of very friendly military personnel, most of whom were officers. I was given a thorough examination, and tested carefully for various reflexes and sensory responses. It was there where I was first introduced to the "wheel of death", as I call it - a shiny stainless steel wheel of very very sharp needles, attached to a short metal handle. The idea behind this simple torture device is that a doctor could roll the needle wheel over a person's body to locate exactly where the demarcation between normal and impaired sensory perception was. The doctors determined that the line of sensory impairment was a few inches above my nipple-line. Below that line, the wheel of death felt like the wheel of a toy motorcycle. It was then when I really began to realize the extent of my injury. Sharp pain was entirely absent from most of my body, and an ice cube on my foot felt like a hot coal. But when the doctor tickled my toes with the tip of a feather, I could feel it just fine - as though there were nothing was wrong with me at all. I was even able to feel a tiny ant crawling across my big toe.

After a great deal of poking, prodding, questioning, and swapping tasteless paraplegic jokes, I was again put inside a big steel chamber. This chamber was very different from the one in Palau: it was about 4 feet in diameter and twelve feet long, and had two beds and all sorts of instruments inside. I was accompanied this time by two attendants who took care of my every need (emptying catheter bags and whatnot) and continuously monitored my condition. This time I was initially pressurized to a simulated depth of 165 feet, and brought to the surface again over an eight-hour period. Afterwards, I was placed on a cot in the middle of the commanding officer's office floor. The doctor in charge was Dr. Cy Severns. Although he knew a great deal about treating DCS cases, he was not the resident expert. The real "bends Doc" of that facility was out of town, and the general consensus among the half dozen military officers who kept me entertained was that I should be flown to Hawaii. I watched as they made a long series of telephone calls to various places - including the Pentagon - to make arrangements to fly me out to Hawaii. After a while, they brought me a telephone and asked me if there was anyone I'd like to call. I decided that it might be a good time to break the news to my parents, and a few minutes later, I heard my mother's voice over the receiver. She already knew about the accident because the doctors in Palau had called. She had answered the phone when it rang, and she heard the voice say "Yes, hello, this is the Palau Hospital calling concerning Mr. Richard Pyle...is Dr. Robert Pyle there please?" My mom replied "This is Mrs. Pyle, I'm Richard's mother..." After a long pause, the doctor said "Uh, I think I'd better speak with his father..." With that, my mom solemnly gave the phone to my dad, went in the living room, and told my sister "That was the Palau Hospital...I think Richard's dead." For half an hour, she and my sister sat in silence, listening to my dad say "Uh huh...Uh huh...Yes, I understand..." Although my dad told her that I was alive, she was nonetheless exceptionally pleased to hear my voice over the phone when I talked to her from Guam.

After a second chamber treatment in Guam, my condition was reassessed and we were all delighted to find that the numbness demarcation line on my chest had dropped to several inches below the nipple line. I was asked to sign a form saying that the military could, should they so desire, send me a bill for the flight (although they never did), and I was taken by ambulance to the military airfield and put aboard a humongous jet bound for Honolulu. If the two-hour plane ride from Palau to Guam seemed bad, this ten hour excursion from Guam to Hawaii was going to be a living hell. It was. Again, no windows, no movie, and intravenous dinner. But seriously, those men and women of the 8th MAS were truly a fantastic bunch of people, and I am eternally grateful for their help and encouragement throughout the long and boring flight.

After we finally arrived in Honolulu, I was loaded onto yet another ambulance and rushed to Kewalo Basin, where the Hyperbaric Treatment Facility is located. As they opened the ambulance door, I could see that the place was exactly as I remembered it from the times I had visited David Wilder. There was Dr. Overlock, the same doctor who treated David, looking me over as they brought me off the ambulance. "Hi" I said, "remember me?". "Yes" he said, "I sure do." He repeated many of the same tests that were given to me in Guam, and he finally asked me to try to sit up. I could barely lift my head, so he helped prop my torso upright. Within seconds, I began feeling very light headed and I started to faint. They carefully laid me back down and I regained consciousness. They took my blood pressure - it was 40 over 17 (no kidding).

Apparently, because of the paralysis, all of my veins and arteries had completely dilated; so I was basically just a big sack of Jell-o.

Thus began the long series of treatments at the Honolulu recompression facility. The first few treatments were 12 hours in duration, but most of the rest were standard eight hour "Hyperbaric Oxygen" ("HBO") treatments. These consisted of an initial "spike" to a simulated 220 feet, a slow ascent to 60 feet breathing a special enriched-air nitrox mixture, four 20-minute periods of breathing pure oxygen (with 5-minute "air breaks" in between) at 60 feet, a long haul on pure oxygen at 30 feet, then a very slow ascent to the surface. I was given one such treatment per day, then taken to a nearby hospital to spend the night. I had many visitors at the hospital. Besides my parents, Jack Randall came by several times to check on my progress. Many other friends visited as well. Between visits, I became involved with an assortment of television soap-operas – there really wasn't much else for me to do. I was subjected to a series of tests to determine the full extent of damage to my body. For one of them, numerous electrodes were attached to my scalp, and electrical probes were fastened to my toes and fingers. I was administered a rapid succession of fairly painful electrical shocks which were detected by the electrodes on my head. That test revealed that there was permanent damage on my spinal cord - scar tissue - which would have unknown permanent affects.

Slowly, day by day, I began to recover. I wasn't able to stand on my own for a full week after the accident. I could barely walk on my own another week later. My legs were still very weak, and I still had no feeling of sharp pain or hot/cold below my waist. The treatments themselves were not exactly an exercise in comfort either. As you can well-imagine, breathing pure oxygen at three atmospheres absolute for extended periods is quite toxic, and can cause any number of a wide variety of side-effects. Fortunately, I never had any problems with CNS (acute) oxygen toxicity - I never convulsed. But after a week or so, I began feeling the effects of cumulative oxygen exposure and pulmonary or "whole-body" oxygen toxicity. My fingertips lost all feeling, and I would get terribly nauseous. Every day I entered that chamber, I would succumb to extreme abdominal discomfort, and I would inevitably vomit (you can imagine how the fine aroma of puke can quickly permeate the air inside a steel can). Also, each day I came out of the chamber, I was nearly deaf for several hours. I never understood why breathing high partial pressures of oxygen could lead to deafness -I suppose it's possible that Dr. Overlock tried to explain it to me, but I probably couldn't hear him.

Day by day, I continued on. Despite the physical troubles I was having from the oxygen, I was eager to go into that chamber each day; because each time I came out, I could detect a small improvement in my condition. Also, breathing hyperbaric oxygen has some other good side effects too. During several of my treatments, I was joined by another patient, a woman who had taught SCUBA for many years, who was suffering from severe osteoporosis. Before she began the HBO treatments, she had been confined to a wheelchair because of her problem. But after a few months of one treatment per week breathing hyperbaric oxygen, her condition improved dramatically - she could walk with only a moderate limp. Also, a nasty gash on my leg I had received in Palau refused to heal for weeks. But within days of starting the HBO treatments, the wound healed right up.

There were two notable incidents during this long series of treatments in the chamber. The routine of each treatment began with a fairly rapid pressurization of the chamber to a simulated depth of 220 feet. Just like filling a SCUBA tank quickly, the chamber would get warm on pressurization, so as soon as we reached maximum depth, the outside tenders would ventilate the air inside to cool it down. These ventilations were incredibly loud inside the chamber. After a minute of ventilation, the inside tender would give me the mask, which delivered the EAN mixture, and I would put it on and breathe from it throughout the rest of the treatment. After many such treatments, the process became routine. On one occasion, just after initial pressurization, I habitually reached up and grabbed the mask and put it on. The tender, who was a medical technician rather than a seasoned diver, was understandably influenced by the nitrogen narcosis, and had no qualms about me putting the mask on - he even assisted by handing it to me. For a full minute, throughout the ventilation process, I breathed from that mask without problem. It tasted fine, I felt fine, and everything was okay. When the roaring sound of the ventilation stopped, a voice from the outside tender came over the speaker: "Uh, did you verify the hook-up on that mask?" The insider tender, a bit bewildered and somewhat under the influence of nitrogen narcosis, said "What...what do you mean?" The voice on the speaker came back "Did you check to make sure the mask was hooked up to the right gas supply?" The tender looked around and all of a sudden realized that he hadn't checked, and that I was breathing pure oxygen at a simulated depth of 220 feet! That's an oxygen partial pressure of about 7.7! Needless to say, the problem was immediately corrected, there was a lot of yelling going on outside the chamber, and I never even noticed the difference. After that, we always waited until the ventilation process was complete before I breathed from the mask, and we always verified which mixture it was connected to.

Another time, again just after initial pressurization, the tender waited for the completion of ventilation, verified that the mask was connected to the correct breathing mixture, then handed the mask to me. I took hold of the mask and brought it towards my face. When it was about half an inch away, I was horrified as the mask suddenly grabbed my face like some terrible monster and instantly sucked all the air out of my lungs! The mask clung to my face with incredible strength. Its hose was accidentally connected to outside ambient pressure, and the simulated 220 feet pressure inside the chamber was trying to force my lungs out my throat!! I frantically pulled and tugged at the mask trying to tear it off my face, but it wouldn't budge. It gripped my face with a vengeance. The tender quickly understood what was going on and helped me try to struggle it free. I finally grasped the edge of the mask where it formed a seal with my face, and ripped the thing off (aided by the strength of adrenaline). There was no physical harm done - after a few moments I was able to catch my breath. Again, a lot of yelling was going on outside, and the problem was quickly corrected. After that, I was very careful whenever I put that mask on!

Through intensive physical therapy, my legs increased in strength. I regained control of my bladder, eliminating the need for a catheter. I began walking up and down stairs for additional exercise. I had many long discussions with Dr. Overlock regarding the theory and practice of recompression treatment, and long discussions about the physiology of bends as well. He explained to me that my injury was analogous to a shotgun wound to my spinal cord, and he made certain that I understood that many of my nerve cells had died forever. He explained that my recovery was not a result of

new nerve growth, but rather a result of my brain learning new nerve pathways to send signals to the rest of my body. He explained how I was now much more susceptible to DCS, that a subsequent hit would very likely occur in my central nervous system, and that I had used up just about all of the "extra" nerve pathways in my spinal cord. He made it clear, in no uncertain terms, that if I continued to dive I would be much more likely to get bent, and that full recovery from such a hit would be much less likely. Basically, he did his best to convince me to give up diving for good.

After 28 treatments, I could walk on my own (very slowly, and with a substantial limp), although I still had no sharp pain or hot/cold feeling in my legs. The increments of improvement in my condition with each passing day had diminished to the point where I really couldn't detect them. So finally, more than a month after the accident, the decision was made to stop the chamber treatments. I was afraid that my condition would remain that way forever. True, I could walk, and I was certainly in better condition than I had been a month earlier, but I couldn't run, I couldn't jump, and my body was still suffering from some serious impairment. But Dr. Overlock assured me that the chamber treatments were yielding diminishing returns, and that only time would heal my wounds. He said the healing would continue for a couple of years, but he could not tell me how much my condition would improve.

As the months passed, my ability to walk continued to very slowly improve. With practice, I was able to conceal my limp and appear to walk normally, but it took a great deal of effort. Climbing stairs was not much of a problem, but coming down them was difficult. Even stepping off a curb required a great deal of concentration. I was able to contract the muscles in my leg fairly smoothly, but I was unable to relax them at a controlled rate. Also, my legs would occasionally convulse spastically and uncontrollably. The feeling in my legs did not improve as quickly - I still could not feel any sharp pain, or distinguish hot from cold in my legs.

In order for my father's insurance to pay for the bills, I had to be enrolled as a full-time student. So, in spite of my handicap, I returned to the University of Hawaii the next semester and did my best to hobble around campus from class to class. I did not dive again at all for nearly a full year. I understood Dr. Overlock's concerns about my diving again, but I knew in my heart that I could never give up diving. In fact, I knew that I could never give up deep diving. Otherwise, life slowly returned to normal. I had lost a lot of weight during the accident, and I slowly began to put it back on. I continued with an assortment of leg exercises, and my condition very slowly improved.

I limited my first post-bends dive, nearly a year after the accident, to a maximum depth of 25 feet. As the months passed, I slowly increased that to 60 feet, then 130 feet; always following an extremely conservative decompression profile. On my first post-bends dive to 180 feet, I was very nervous. After a ten-minute bottom time, I decompressed for well over an hour. One of the effects of my impaired legs was that after long exposures to water, they would feel weak and numb. It was terrifying every time I surfaced from a deep dive with long decompression because my legs would feel almost exactly the same as they had felt in Palau, right after the accident. On the decompression line, I would continually monitor the coordination of my fingers by touching each fingertip to my thumb in rapid succession. Every time we returned to

the harbor after a dive, I would trot around the parking lot to determine if my legs were fully functional.

Two years after the accident, I was able to walk almost totally normally, and I could even jog reasonably well. The feeling in my legs had improved, but was far from normal. By December of 1987, a year and a half after the accident, I had logged nearly 200 post-bends dives, more than half below 200 feet. In all of these, I never experienced any CNS DCS symptoms. Also in December of 1987, on Christmas day at, of all places, Christmas Island, I made my first post-bends dive to 300+ feet on air. Decompression was scary, because an effect of extreme nitrogen narcosis for me was numbness in my legs. The numbness didn't wear off for almost an hour after the dive, and I didn't leave the water for almost two hours. But I was fine.

It's now been 6 years since the accident. I've made well over fifteen hundred post-bends dives, more than two thirds of which were in excess of 180 feet. I've also made dozens of air dives beyond 300 feet, and I've begun using mix to penetrate depths of more than 400 feet. In all of this deep diving, I have not experienced any further DCS symptoms. And so it continues.

### ***Retrospective***

In retrospect, I now feel I understand the fundamental factor that led to my severe bends hit that sunny July 14th in Palau. It wasn't because I went too deep or stayed too long. It wasn't because of the decompression meter I was using. It wasn't even because my pressure gauge malfunctioned. Although these were all contributing factors, they were not the fundamental reason I got bent. The real reason was that I had a very bad attitude about deep diving. I got caught in a trap that snares many young, bold, and "immortal" divers - the trap of overconfidence. Since I was continuously pushing the limits - and getting away with it - I felt overconfident about pushing the limits even further. I was sure that I would never get bent. I regarded all of the emphasis on safe diving practices and self discipline as "sport-diver crap", and I felt as though I was exempt from following conventional guidelines. I was wrong...almost dead wrong!

So why, then, do I continue to dive deep? It would be naive of me to think that I have "learned my lesson". The risk of decompression sickness follows anyone who breathes gases at greater than one atmosphere pressure - that risk cannot be avoided, and it increases with increased depth of diving. Will I ever get bent again? To be honest, I don't know. Many friends and colleagues feel as though I'm living on borrowed time. Maybe I am. But at least I have changed my attitude about deep diving. I no longer view it as a test of my abilities, or as a means to demonstrate my courage. Statistics of diving accidents suggest that I am more likely to get bent again, now that I've been hit once already. I'm not convinced this is true, but whenever I find myself hanging on a decompression line after a deep dive, I always assume that it is.