SECTION J

Dive Tables and Dive Computers: Their History and Utility

WHY DO DIVERS NOT ROUTINELY USE DIVE TABLES?

There is probably no more intimidating subject to many divers than dive tables and their high tech cousins, dive computers. Everyone learns to use "no decompression" tables during the basic open water course, but most newly-certified divers seem to quickly forget what they learned. From simple observation it is apparent that few recreational divers bother consulting any printed table when diving. Nonetheless, most divers do dive "by the tables." There are two explanations for this paradox.
It is common to make some mistakes with dive tables in a classroom, where there is good lighting, a stable desk and all the time in the world to calculate and check answers. Understandably, new divers often feel awkward and unsure when figuring out dive tables under open water conditions, which may include a rocking, crowded boat with no convenient place to sit and calculate. Dive tables are difficult unless one uses them routinely, so most recreational divers (particularly those who dive infrequently) never learn to feel comfortable with them. The typical recreational diver seems happy to let others worry about dive tables, recognizing that he or she can dive safely at a resort, where the day's dives *are* planned by the tables but *by someone else*. For example, diver Jill may be told she can do a first morning dive to 80 feet for 30 minutes and, after an appropriate surface interval, dive to 50 feet for 40 minutes. After these two dives she may be back on shore by noon. The resort then offers either an afternoon shallow dive commencing around 2 p.m., or a night dive. In any given scenario the dives are planned and executed by standard dive tables; all Jill has to do is show up and not exceed the resort's planned dive profiles. In effect, someone else employs the tables for her safe diving.

Other divers may use a dive computer which, unlike printed tables, take into account multi-level diving. Dive computers give more latitude than the tables, since tables assume you spend all bottom time at maximum depth. The dive computer incorporates a complex algorithm for nitrogen uptake and elimination, so it is actually a highly sophisticated set of tables, more detailed and reliable than anything printed that requires human calculations. Of course computers can be abused, but divers who use them properly are, in effect, "diving by the tables." (Manufacturers recommend that printed tables be taken on a dive as backup in case of computer loss or failure, but this is not a common practice.)

HOW IS A DIVE TABLE USED?

Before discussing the origin of dive tables it will be useful to walk through a modern dive table. Figure 1 shows the U.S. Navy Dive Table for no-decompression diving. You may be familiar with other dive tables. When using PADI, NAUI or other recreational tables, you will find different letter group designations and times. In particular, the times allowed at depth are less than allowed by the U.S. Navy. However, in principle all dive tables are the same. They all include three parts: 1) no-decompression time limits; 2) surface interval times; 3) residual nitrogen times.

The first part of the U.S. Navy Table includes the depth in the two left hand columns, the no-decompression time limits in the third column and then a string of letters called "Group Designation," with a column of numbers under each letter. Each letter is important if you do a repetitive dive. If you dive only once for the day (i.e., make no repetitive dive), the letters and the columns of numbers under them would be unnecessary.

Let's say you plan a dive to 60 feet/18.2 meters. The no-decompression table shows you can stay at that depth for up to 60 minutes and then surface without having to make a decompression stop. (Other tables allow a shorter time at this depth. In any case, standard practice is to do a 3-5 minute safety stop at 15 feet/3 meters.) Depending on how long you actually stay at 60 fsw, you choose the appropriate letter group. If you stay only 10 minutes you are in letter group B; 25 minutes, E; the full 60 minutes, J; etc. For any depth between the depths shown, you must use the next highest depth. For any time between the times shown, use the next higher time.

Before continuing it is important to emphasize just what these letters represent. Each letter represents an amount of extra nitrogen accumulated on the dive. *The higher the letter the more extra nitrogen is accumulated*. Each letter also represents a length of time it will take that extra nitrogen to leave the body (off-gas) once the diver is on the surface. *The higher the letter the longer it will take the extra nitrogen to off-gas.* This time is the 'residual nitrogen time,' an important concept in dive tables. If your next dive takes place beyond the residual nitrogen time range for all the group designation letters in the table, then the letter group is superfluous; the rest of the table also becomes unnecessary. For the U.S. Navy table shown, this length of time is 12 hours; if you have a surface interval more than 12 hours between consecutive dives the letter group designation is not relevant. (In other words, the letter groups are not needed if you don't plan a repetitive dive.)

Letter groups are used on repetitive diving because you will accumulate more nitrogen on the next dive, which *must be added* to the residual nitrogen of the preceding dive. Instead of worrying about the actual quantity of nitrogen, the letter groups indicate the length of time it will take the residual nitrogen to leave the body (i.e., the residual nitrogen time); this time can then be used to calculate an appropriate length of time for your next dive.

Figure 1. First part of U.S. Navy Dive Tables. See text for discussion. Reprinted from U.S. Navy Diving Manual, Vol., 1.

Figure 1 (continued). Parts 2 and 3 of U.S. Navy Dive Tables. See text for discussion. Reprinted from U.S. Navy Diving Manual, Vol. 1.

1. Using the U.S. Navy Table, you dive 51 feet. You stay at this depth without the need for decompression:
a. As long as your air lasts
b. 100 minutes
c. 60 minutes

2. Using the U.S. Navy Table, you dive to 72 feet for 30 minutes. Your letter group designation is:
a. F
b. G
c. H

TEST YOUR UNDERSTANDING

Now enter the second part of the U.S. Navy Table. Here you start with your letter group designation. Let's assume you dove to 60 feet for 30 minutes; you are therefore in letter group F. The second part of the table asks "Mr. (or Ms.) F, how long are you to remain on the surface?" The answer is the surface interval time (SIT). The longer your SIT, the more the residual nitrogen from the first dive will be dissipated, and the less nitrogen you will have on entering the water again.

Note that the second part of the table is a range of surface intervals. Immediately to the right of letter F is the surface interval 10 minutes to 45 minutes (0:10-0:45). The next surface interval ranges from 46 minutes to one hour 29 minutes (0:46-1:29). Choose the surface interval that includes your SIT. Suppose your SIT is one hour 35 minutes; this SIT falls into the surface interval 1:30-2:28.

Note that all surface intervals are associated with another letter group designation. Beneath the column that contains the surface interval 1:30-2:28. is the letter D; again, the lower the letter, the less extra nitrogen remains in your body. The highest surface interval shown is 12 hours because the Navy tables assume you are rid of all excess nitrogen after 12 hours.

3. If your first dive of the day is 36 feet for 100 minutes, and your surface interval is 35 minutes, what is you final letter designation?

4. If your first dive for the day is 55 feet for 30 minutes, and your surface interval is one hour, what is your final letter group designation?

TEST YOUR UNDERSTANDING

The third part of the table is for the next or repetitive dive. Using the letter group from the second part of the table, follow the column down until you reach the *row* which represents the depth of the repetitive dive. The time shown in the column is the residual nitrogen time, in minutes, to be applied to the repetitive dive.

For example, suppose your first dive of the day and surface interval are the same as in Question 4; in that case your letter group designation is E. Moving down the column under the E, the residual nitrogen times for all the depths shown range from 120 minutes at 20 feet to only 10 minutes at 190 feet. What is the residual nitrogen time you must use in planning your next dive to 50 feet? Looking at the row that contains 50 feet, we see it is 38 minutes. This is the length of time that must be subtracted from the next dive to determine the length of time you can spend at 50 feet. On a first dive to 50 feet you could spend (according to the U.S. Navy Table) up to 100 minutes. Now, on this repetitive dive, your maximum time is 100 minus 38 minutes, or 62 minutes. A repetitive dive must take into consideration the amount of residual nitrogen in your body after preceding dive(s). In terms of nitrogen, diving to 50 feet is very different for a repetitive dive than for a first dive.

5. Your first dive is 70 feet for 40 minutes, followed by a surface interval of one hour. You plan your next dive to 50 feet. Using the U.S. Navy Tables, how long, in minutes, can you stay at that depth on your second dive without decompression?

a. 100
b. 56
c. 44

6. Your first dive is 60 feet for 33 minutes, followed by a surface interval of 45 minutes. You plan your next dive to 45 feet. Using the U.S. navy Tables, how long, in minutes, can you stay at that depth on your second dive without decompression?

a. 100
b. 53
c. 47

TEST YOUR UNDERSTANDING

WHAT IS THE ORIGIN OF DIVE TABLES?

The first dive tables were devised by the Englishman John Scott Haldane and colleagues in the period 1906-1908, following their landmark experiments on goat decompression. Why goats? As stated in the original paper (Boycott 1908):

...goats were very suitable animals in that slight symptoms were presented to our notice in a definite objective form. The lesser symptoms of caisson disease cannot be neglected, and there are reasons for supposing that their occurrence is not exactly conditioned by those experimental circumstances which in a more severe form produced serious and fatal results. They cannot be properly detected in mice or guinea-pigs or even in rabbits. Goats, while they are not perhaps such delicate indicators as monkeys or dogs, and though they are somewhat stupid and definitely insensitive to pain, are capable of entering into emotional relationships with their surroundings, animate and inanimate, of a kind sufficiently nice to enable those who are familiar with them to detect slight abnormalities with a fair degree of certainty.

The animals, 85 in number, used in the present experiments were a mixed collection of ordinary English goats of no particular breed...The commonest symptom which we have observed [of decompression sickness] consists of the exhibition of signs indicating that the animal feels uneasy in one or more of its legs. The limb, most commonly a fore-leg, is held up prominently in the air and the animal is evidently loth to bear weight upon it.

These decompression pioneers found that goats could avoid the bends if ambient pressure did not drop by more than half at any one time. Thus, in a hyperbaric chamber, a goat could go from a depth of 165 ft. (6 atm.) to 66 ft. (3 atm.), or from 99 ft. (4 atm.) to 33 ft. (2 atm.), without encountering the bends. A change in pressure greater than this 2:1 drop did lead some goats to manifest limb pain. A result of these experiments was the first set of "dive tables" listing depths and times at depth that could prevent decompression sickness. Decades before their work, the Frenchman Paul Bert had pointed out the importance of very slow decompression to prevent symptoms of caisson disease, but Bert's "experiments were not sufficient to furnish data as to what rate of decompression would be safe. Nor has subsequent human experience in engineering undertakings solved this problem" (Boycott 1908). In contrast to any prior work, the research on goats provided the theory, the data *and* feasible guidelines for safe decompression (the 1908 paper by Boycott, et. al. runs to 120 pages).

WHAT IS THE THEORY BEHIND DIVE TABLES?

The theory behind dive tables is based on our limited understanding of how nitrogen is taken up on compression (descent) and given off on decompression (ascent). This is a complex subject, all the more so because there is really no unified theory to account for all observations. Haldane's original theory, and one that has more or less stood the test of time, is that nitrogen is taken up and given off in "exponential" fashion. The rate of tissue nitrogen uptake is highest following an increase in ambient pressure; the rate of uptake then decreases as time passes. Similarly, after a lowering of ambient pressure the rate of nitrogen output is greatest, then gradually falls off as time passes (Figure 2).

Haldane assumed that the rate of uptake and output were the same. For example, if it takes two hours to fully saturate a tissue after a pressure increase, it will take two hours for the loaded nitrogen to leave when the pressure decreases, and the rate of leaving will be a mirror image of the rate of entry (Figure 2).

Figure 2. Exponential rise and fall of nitrogen in tissues with change in ambient pressure.

Haldane also knew that the rate of nitrogen uptake and elimination are not uniform within the body; there is a spectrum of uptake and elimination times among all the different tissues and even among the same type of tissue located in different organs. This spectrum exists because of different solubilities of nitrogen in various tissues (fat, bone, cartilage, muscle, tendon, etc.), and because of different rates of blood flow (perfusion) to those tissues.

Perfusion can vary by type of tissue (none for the cornea of the eye; high for all nerve and brain tissue), or by activity (less perfusion for muscles at rest than for muscles exercising). To account for the various tissue types, and the enormous range in perfusion, designers of tables theorized a fixed set of "compartments," each with its own "half-time." It is important to keep in mind that they are not actual anatomic compartments, and not even types of tissues, but only theoretical constructs to cover the range of possible nitrogen uptake and excretion times within the body.

The idea of using theoretical compartments is simply to approximate what is happening in the body. Rather than worry about the actual half times of many specific tissues with their varying rates of blood flow, scientists (starting with Haldane) simply said something like: 'Let's just divide all the tissues with their varying blood flow into several compartments. If we include what is likely the fastest tissue half time (usually 5 minutes) and the slowest tissue half time (several hours), we should be able to simulate what actually happens throughout the body.' In their pioneering work Haldane and his colleagues assumed five such compartments, with half times of 5, 10, 20, 40, and 75 minutes.

Understand then, this is just a model for the real world. What really happens is far more complex than any model, which is one reason why any model should be tested as widely as possible. By assuming uptake and excretion times for the various compartments, Haldane and others were able to arrive at tables for avoiding the bends *which work in practice.* And keep in mind that "work in practice" means most of the time, not all the time.

WHAT IS "SATURATION"?

"Saturation" and "half-time" are two very important concepts in the design of decompression tables. Models for both printed tables and computer algorithms are based on assumptions of half times to "full saturation" for various tissue compartments.

In the context of decompression theory, saturation means how "filled up" a tissue is with a gas such as nitrogen. Tissues can be unsaturated, partly saturated, or fully saturated with nitrogen (or any other inert gas). Full saturation means that blood or tissue has all the nitrogen it can hold *for the ambient pressure to which it is exposed*. It also means that the pressure of gas in the tissue equals the pressure of gas in the ambient air.
Thus "saturation," at least in terms of an inert gas such as nitrogen, refers both to an amount of gas and to the pressure of that gas. Any tissue that is fully saturated with nitrogen at a given pressure could still hold more nitrogen at a higher pressure.

7. The pressure of nitrogen in any tissue of the body at sea level is .78 atm. N2. If the pressure of nitrogen in tissue is higher than .78 atm., more gas will dissolve in that tissue; this statement follows from:
a. Boyle's law
b. Henry's law
c. Charles' law

8. Assume that compartment X in a diver's body is fully saturated with nitrogen at two atmospheres (33 fsw). This means that compartment X (choose all correct statements):
a. holds all the nitrogen it can hold at two atmospheres.
b. has a nitrogen pressure twice that at one atmosphere.
c. is in equilibrium with the ambient nitrogen pressure.
d. is a fast tissue.

9. Assume that compartment X in a diver's body is fully saturated with nitrogen at two atmospheres (33 fsw). The diver then quickly descends to 66 fsw. At that point, compartment X (choose all correct statements):
a. Is no longer fully saturated with nitrogen.
b. Is half saturated with nitrogen.
c. Begins loading additional nitrogen.
d. is a slow tissue.

TEST YOUR UNDERSTANDING

HOW DO HALF TIMES AFFECT NITROGEN LOADING AND UN-LOADING?

Given enough time, a diver at 33 fsw will eventually saturate all body tissues to two atmospheres of total gas pressure. Of this total gas pressure, the partial pressure of nitrogen, PN_2, will be 2 x .78 = 1.56 atm. How long will it take *all the tissues* to reach two atm. total pressure (and a PN_2 of 1.56 atm.)? In other words, how long for all the tissues to become fully saturated at the new ambient pressure?

The answer is complex, because the body does not load up on nitrogen evenly. A spectrum of nitrogen loading rates exists because of different tissue types and rates of perfusion; as a result, half times range from minutes to hours. (Remember, a half-time is the time it takes any given tissue or compartment to fill with one half the nitrogen it will accumulate on reaching full saturation at a given pressure.)

Fat tissue has a long half time because it takes fat a long time to saturate with nitrogen when exposed to a higher pressure (it has a high solubility for nitrogen) and because perfusion of fat is relatively poor comprared to other tissues; it is therefore a "slow tissue." Nerve tissue is considered to have a fast half time because it takes a shorter time than most tissues to load up on all the nitrogen it can contain when the pressure increases (higher solubility) and because it is so well perfused. (The fastest "tissue" is blood in contact with the lungs, since it picks up nitrogen quickly the inhaled air. Half-times of tissues used for dive table modeling do not include blood.)

Let's look more closely at a *single* compartment, one with a half time of 20 minutes taken to 33 fsw (Table 1). A 20-minute half time means that half the nitrogen that will enter that compartment will do so in the first 20 minutes, at which point the nitrogen pressure will be

That leaves 1/2 (.78) PN_2 to go before the compartment is fully saturated with the final nitrogen pressure of 1.56 atm. Note that when the compartment is fully saturated its PN_2 will equal the ambient pressure, which is also the gas pressure in the lungs.

TABLE 1. Half-times to full saturation with nitrogen for a component with 20-minute half time, at depth of 33 fsw (two atm.).

half-time period	**length of half time (minutes)**	**total elapsed time (minutes)**	**Per cent of full saturation**	**PN_2* of: lungs comp**
First	20	20	50	1.56 1.17
Second	20	40	75	1.56 1.365
Third	20	60	87.5	1.56 1.46
Fourth	20	80	93.75	1.56 1.51
Fifth	20	100	96.875	1.56 1.535
Sixth	20	120	98.5	1.56 1.55

* measured in atmospheres of nitrogen
** compartment

Although the first 0.39 atm. of nitrogen entered in 20 minutes, the next 0.39 atm. of nitrogen *does not* enter in the next 20 minutes. This is because the rate of entry slows as the compartment fills; it loads nitrogen according to the exponential curve shown in Figure 2. In the next 20-minute period, half of the amount of nitrogen that can enter will do so; the same thing holds for each subsequent 20 minute period, until the compartment is fully saturated.

Mathematically, an exponential curve (Figure 2) will never reach 100%; each additional half time will only get the pressure (or concentration) half way to the final 100%. For practical purposes in designing decompression tables, six half times is considered full saturation. After six half times the compartment is 98.5% saturated (and another half-time would add only an extra 0.75%).

The concept of six half times to full (98.5%) saturation holds true regard-less of the pressure change or the length of the half time. At 66 fsw the body (or any tissue or theoretical compartment) could hold 3 x 0.78 atm. of nitrogen; at 99 fsw, 4 x 0.78 atm. of nitrogen, etc. The rate at which nitrogen approaches these pressures will depend only on the half time of the individual compartment; in each case the percentage of loading will be the same after six half times (98.5%).

Table 2 shows the first six half times for the *same* 20-minute half time compartment as in Table 1, this time taken to a depth of 99 fsw (4 atm.). Notice that at either depth, each succeeding half time adds a lesser *quantity* of nitrogen to the compartment (as reflected in the pressure of nitrogen). In the first half time, half the total nitrogen that will be taken up due to the higher ambient pressure enters the compartment. Subsequent half times load less and less nitrogen. (The same process reverses when the ambient pressure is lowered; see Figure 2.)

TABLE 2. Half-times to full saturation with nitrogen for a component with 20-minute half time, at depth of 99 fsw (four atm.).

half-time period	**length of half time (minutes)**	**total elapsed time (minutes)**	**Per cent of full saturation**	**PN$_2$* of: lungs comp**
First	20	20	50	3.12 1.95
Second	20	40	75	3.12 2.535
Third	20	60	87.5	3.12 2.83
Fourth	20	80	93.75	3.12 2.97
Fifth	20	100	96.875	3.12 3.05
Sixth	20	120	98.5	3.12 3.085

* measured in atmospheres of nitrogen
** compartment

SO WHAT DO HALF-TIMES AND SATURATION HAVE TO DO WITH DIVE TABLES?

Haldane reasoned that if he knew what pressure change *will not* cause DCS, and also the rate various tissues saturate and desaturate with nitrogen, a table could be designed to prevent DCS. Experimentally his group showed that goats did not develop DCS if any stage of decompression was no greater than 2:1. Right away, therefore, he determined it is safe to dive indefinitely to 33 fsw. (We now know this is not correct. The goats were compressed for only a few hours, not long enough for the very slow tissues to fully saturate; the longest half time is much longer than the 75 minutes Haldane assumed, probably more like 12 hours. If a diver stays at 33 fsw until full saturation, decompression is mandatory to prevent the bends. In recreational diving, shallow-depth dives are not long enough to reach full saturation.)

Haldane's main concern was for deeper dives. What about a dive to 99 feet (4 atm.)? At this depth one must be concerned about decompression, and therefore tissue half-times. Lets look at five different compartments, each with its own half-time, at 99 fsw (Table 3). We see that the five minute compartment controls the dive, i.e., it determines that a decompression stop is mandatory at 30 feet, so the diver can let off nitrogen accumulated in the fast tissues. If the diver did not stop on ascent at 30 feet he would exceed the safe 2:1 decompression ratio and greatly increase his chance of developing the bends.

TABLE 3. Nitrogen loading at depth of 99 fsw (four atm.) after 20 minutes, for five different theoretical tissue compartments with half times of 5, 10, 20, 40, and 80 minutes. (fsw - feet sea water)

half time (min)	**No. periods**	**% saturation**	**atm. N_2**	**atm. N_2 for 2:1 drop**	**fsw for 2:1 drop**
5	4	93.75	2.97	1.49	30
10	2	75	2.54	1.27	16
20	1.0	50	1.95	0.98	6.6
40	0.50	25	1.37	< 0.78	surface*
80	---tissue not at risk for bubbles---			< 0.78	surface*

* can surface without experiencing a 2:1 drop in ambient pressure

From considerations such as these Haldane and colleagues were able to design the first set of dive tables.

WHAT IS SUPERSATURATION?

Supersaturation occurs when the nitrogen pressure in the tissue is higher than the ambient pressure. To some extent a state of supersaturation always occurs on ascent from a dive; for a brief period the nitrogen pressure in some of the tissues will be higher than in the lungs and blood, since they (lungs and blood) will be the same as the ambient pressure (Figure 3).

Supersaturation is not a problem if it is held to a small degree. When the degree of supersaturation is large, bubbles can form and cause decompression sickness. Bubbles form because the exit of nitrogen from supersaturated tissue is too great for the gas to merely dissolve in the blood.

In a sense supersaturation and decompression go hand in hand. Whenever the nitrogen pressure is higher in the body (or any part thereof) than in the ambient environment, decompression will start (nitrogen will start to leave the supersaturated tissue). In fact every time you fly in an airplane, drive up a mountain or ascend in an elevator, your tissues become transiently super-saturated with nitrogen and start to decompress, i.e., nitrogen starts to leave. Clearly, from an evolutionary viewpoint, decompression is something the human body is designed to handle - up to a point.

Figure 3. Supersaturation. When the ambient pressure decreases the amount of nitrogen in the tissues suddenly becomes higher than can be sustained by the lowered ambient pressure; nitrogen begins to exit the tissues.

Haldane surmised, from his experiments with goats, that the human body could actually tolerate a two-fold degree of supersaturation before bubbles would form, i.e., a halving of ambient pressure. As pointed out earlier, we now know this is not always a safe degree of supersaturation, particularly after long shallow dives. A supersaturation of 1.5:1 is safer. When the amount of tissue nitrogen is no more than 1.5 times the level called for by the ambient nitrogen pressure, decompression sickness is unlikely to occur.

HAVE THE TABLES BEEN MODIFIED FOR RECREATIONAL DIVING?

Haldane's tables were first adopted first by the British Navy, and later (1915) by the U.S. Navy. In the 1930s these tables were modified by the U.S. Navy, based on empiric observation of DCS incidence in sailors diving various profiles in a hyperbaric chamber. In its modifications the U.S. Navy always allowed for a certain percentage of bends in its divers, realizing that zero percentage is not realistic for deep diving, and that a decompression chamber is available for immediate treatment (at least on training dives). When scuba diving began to emerge as a popular activity, American training agencies adopted the U.S. Navy tables, with slight modifications. In recent years PADI developed a set of dive tables specifically for recreational use, following studies using a technique called doppler ultrasound.

WHAT IS DOPPLER ULTRASOUND?

Doppler ultrasound is a laboratory method of detecting bubbles in the blood. Sound waves beyond the range of human hearing (ultrasound) are transmitted through a probe (about the size of a short pencil) pressed against the chest, over the diver's heart. The probing starts immediately after the completion of an actual or simulated (chamber) dive. As bubbles move through the heart - and toward the point of the probe - they reflect sound waves coming from the probe. The reflection of sound waves as the blood passes through the heart is "read" by the doppler probe as bubbles. The device can also determine the size and relative quantity of the bubbles.

Bubbles are never normal in the blood, so any detected are presumed to arise from nitrogen leaving tissues too quickly. Although bubbles are the root cause of decompression sickness, finding them in the blood does not always mean the diver has DCS; they could be "silent," meaning too small or too few to cause any problems. In fact many divers manifest silent bubbles.

To cause symptoms the bubbles must reach a "critical size." Finding only tiny bubbles is usually considered not significant; finding larger bubbles is a great concern because of their potential to cause symptoms at any time. With doppler ultrasound many different divers and dive profiles can be tested, especially with a hyperbaric chamber where the conditions are easily con-trolled. Gradually, over time, a safe dive table can be devised for the population that was tested. (With or without bubbles, any symptoms of DCS during a controlled test means the *table has failed that diver*.)

PADI uses its proprietary tables, but other training organizations use modifications of U.S. Navy or yet other tables, such as the Canadian DCIEM tables (Defense and Civil Institute of Environmental Medicine). The most important test for any table is probably the test of time. As any table designer will admit, a table isn't worth much unless it has been tested in the field.

DOES DIVING "BY THE TABLES" GUARANTEE A DIVER WON'T DEVELOP DCS?

Obviously not. The original tables were based on many assumptions and experimental work on goats. Haldane's observation, that bends could be avoided if ambient pressure did not decrease by more than half at any one time, was later shown to be invalid for shallow dives of long duration.

Haldane also assumed five tissue compartments for nitrogen uptake and elimination, but later analyses have found that nine or more compartments, with much longer half-times for the slowest compartment, is a more reliable assumption. The prevention of decompression sickness remains an imperfect science, but research and much testing since 1908 have helped refine dive tables considerably.

Since Haldane's era the U.S. Navy has refined and tested tables extensively. Through the 1980s the Navy tables were the standard for all recreational diving, even though they were based on the square wave concept (i.e., the total time is assumed spent at the deepest depth). In the 1980s Diving Science and Technology, a scientific arm of PADI, created tables specifically for the recreational diver. DSAT used doppler ultrasound testing after both in-water and hyperbaric chamber dives.

There are theoretical problems with Doppler ultrasound testing, not the least of which is that much of the testing is carried out in a hyperbaric chamber. (In the DSAT tests some of the dives were conducted in open water.) A hyperbaric chamber can create the pressure changes of diving but little else. Water temperature, the feeling of water against the skin, visibility conditions (which may affect breathing and level of stress), ocean currents, the fear of drowning Ä these and numerous other factors simply can't be simulated in any dry chamber.

Another, and perhaps greater, drawback of the doppler technique is that bubble *detection* may not correlate with development of DCS. It has not been shown that bubbles detected in blood coursing through the heart signifies bubbles in the tissues, around the nerves, in the brain, etc. In addition, *not* detecting bubbles in the blood right after a dive doesn't mean they won't show up later. There may be an excess amount of nitrogen in some very slow tissues that won't release bubbles for several hours (or longer).

The mechanisms that cause DCS are not well understood, and bubble detection is simply a technique to monitor one aspect of the problem in a group of volunteer divers. That the tables work when tested on a small group does not, of course, guarantee that they will work for everyone, all the time. The population of recreational scuba divers is simply too diverse for any table to be tested for all the varying characteristics of people (age, weight, percentage of body fat, level of fitness) and dives (depth, time, rate of ascent, water temperature, visibility levels, etc.) that will encompass all situations.

Since different people can react differently to decompression, no table can be considered 100% safe. The standard dive table is thus only a *conservative guide* to safe diving for the whole population, and not a personal safety guide for each diver. It is a fact that some people diving within standard dive table limits *have* developed DCS.

There is no perfect table, nor will there ever be. Nonetheless, years of experience with available dive tables shows they are far better than nothing and, miraculously, seem to keep most divers from ever getting bent. Only a few hundred DCS cases are reported to DAN every year, which is a small number for such a potentially hazardous activity that is practiced millions of times a year. (See Section P.)

WHAT IS THE DIFFERENCE BETWEEN SQUARE WAVE AND MULTI-LEVEL DIVING?

Dive tables are conservative in large part because they assume all bottom time is spent at the deepest point reached. This type of diving is called *square wave*: down to a depth, level off for a set time, then up to the surface, at an ascent rate no faster than 60 feet a minute. Figure 4 shows two sequential square wave dives as envisioned by the dive tables; the second dive is always at a shallower depth than the first.

Simple observation on dive trips suggests that most recreational dives are not square wave at all; they are instead "multi-level." The diver descends some distance at one rate; down further to maximum depth at a different rate; up a little from the bottom at one rate; up a little further at a different rate; perhaps down again to see something missed; up some more; down a little; up; up some more; safety stop; surface. The variations are infinite. Figure 4 also shows two multi-level dive profiles. The first multi-level profile is typical of that observed on many scuba dives, with slight "ups and downs" as the diver gradually makes his way to the surface. The second multi-level dive (Figure 4) shows a smoother ascent from the deepest point reached early in the dive. Note that these dive profiles illustrate the twin rules for all dives: 1) in any given dive reach the deepest point early; 2) in repetitive dives make the deepest dive first.

Because dive tables calculate all bottom time at the deepest point reached (i.e., as a square wave), each multi-level dive is always at an average depth *less* than what the tables would assume for the same dive. As a result, in a multi-level dive (what most recreational divers do), *less* nitrogen is actually absorbed into the diver's tissues than is assumed by the standard dive tables.

Until the advent of dive computers in the early 1980s, printed tables were all one could go by to dive safely and avoid DCS. Even the PADI Wheel, which was specifically designed in the late 1980s for multi-level diving, cannot account for the fact that what you plan and what you dive are often very different. With the PADI Wheel you may plan the following dive: 50 feet for 20 minutes followed by 40 feet for 10 minutes followed by 30 feet for 8 minutes. Chances are you won't dive that plan. Too many factors affect buoyancy, the length of time spent at a given depth, ascent and descent rates, etc., to execute a multi-level dive exactly as planned. Instead the diver needs some device that tracks the dive *as it occurs*; that device is the dive computer.

Figure 4. Two square wave dives (solid line) and two multi-level dives (dashed line). See text for discussion.

WHAT IS THE ORIGIN OF DIVE COMPUTERS?

Until the early 1980s almost all recreational diving was taught by the standards of U.S. Navy tables. Because the Navy tables are not based on multi-level diving profiles, scientists developed algorithms that take into account changes in nitrogen uptake with *continuous changes* in depth. These algorithms were mainly theoretical models until the microchip revolution made them accessible and workable in a hand-held computer. When the algorithm is programmed into a computer that also senses depth (a simple depth gauge) and measures time, you have a "dive computer."

The first commercially available dive computer was the Orca Edge, in 1983. Since then dive computers have become smaller and more versatile. They are now manufactured by many companies, and incorporate one of several algorithms for calculating nitrogen uptake and elimination.

WHAT DO DIVE COMPUTERS DO?

Based on the algorithm used, the dive computer (Figure 5) tracks depth and time every second or so; with this information it continuously computes nitrogen uptake and elimination in the various theoretical compartments assumed by the algorithm. (Among the various computer models the number of compartments ranges from about 6 to 16). Using measurements of depth and time at depth, the computer calculates the nitrogen saturation and de-saturation of each compartment, and rapidly converts this information into a digital readout for the diver. Keeping track of multi-level diving is no problem for the computer. At the same time the computer performs other functions, such as tracking rate of ascent. Not all dive computers function alike, but most are able to provide the following information:

during the dive

- depth
- number of the dive (first, second, etc.)
- time elapsed since dive began
- how many minutes may be spent at current depth before a decompression stop becomes mandatory
- speed of ascent, and some type of message flashed if it is too fast
- water temperature

after the dive

- maximum depth reached
- length of time that can be spent at various depths on the next dive
- when it will be safe to fly (time to desaturation)
-

Dive computers are constantly evolving, and many on the market offer additional features, such as air integration for registering tank pressure(replacing the stand alone air gauge), information about how long air will last at the diver's current rate of breathing, various log or bookkeeping functions, and algorithms for nitrox and perhaps other types of mixed gas diving. Regardless of what features a dive computer has, none can account for individual diver characteristics such as age, weight, percent of body fat and degree of physical conditioning. Although a computer could be designed to accept this type of information, the existing algorithms (like all commercially-available tables) are population-based; they are not designed specifically for the person who buys and uses the computer. (Professional and technical divers sometimes use customized tables, a practice not yet feasible for recreational divers.)

Figure 5. A dive console with air gauge (bottom), computer, compass.

ARE DIVE COMPUTERS PREFERRED OVER DIVE TABLES?

Unlike printed tables, dive computers keep track of where you've been and for how long, and thus give an accurate display of your dive profile. At the same time, based on the algorithm employed, the computer shows if your dive is within the no-mandatory-decompression ("no decompression") limits. Tables cannot track your dive, of course, but they can, if followed, keep you within the no-decompression limits.

So which is better? Some argue that the printed tables are safer because they assume an average depth greater than actually achieved on most dives, and therefore provide a greater margin of safety. This is true in theory. However, even if you went to the exact depth intended (say 55 feet, and stayed the shorter time shown on the tables for a 60-foot depth), the chance for making human error in calculating a repetitive dive is high. Finding the right designated letter group, determining surface interval, keeping an accurate record, etc., all leave much room for making mistakes. Even assuming you accomplished a square-wave dive, you are unlikely to match a computer for computation and record keeping.

Also, all divers know how hard it is to keep track of depth. Many (?all) divers have had the experience of planning a dive to a certain depth, say 60 feet at a wall or over a wreck, and finding they are "suddenly" at 70 or 80 feet; they don't remember descending deeper, but the depth gauge doesn't lie. Or, the diver may not even check his depth gauge and therefore be unaware he went deeper than planned. The computer, of course, not only stores the depth continuously but uses the information to compute when the diver needs to surface, decompress, etc. Obviously tables cannot account for unexpected or unplanned changes in depth. Thus repetitive, multi-level or deep (>60 ft.) diving should be safer with a properly-used computer than with printed tables. This statement does not mean computers are "better" than tables. Computers make it easier for the typical recreational diver to keep track of the dive, and to stay within safe limits while, in many instances, also increasing bottom time.

HOW ACCURATE ARE DIVE COMPUTERS?

This is a subject of much debate in the dive community. The real question is, "If I use the computer properly, will it to keep me from getting the bends?" Obviously, the computer *computes* accurately; but is the algorithm on which it is based sufficient to prevent the bends? The answer is both "yes" and "no."
No, because some divers using computers properly *have* developed DCS; documented cases are reported to Divers Alert Network every year. The reason(s) are unknown, but most likely have to do with individual susceptibility and diving at or close to the computer's limits. There is significant variation among computers in the times allowed at various depths (because the algorithms differ), but too little is known about this variation to blame any particular algorithm for a DCS problem. There is surprisingly little published information about the various computer algorithms in terms of actual testing; however, there is also no evidence that any particular algorithm is "dangerous" or "unsafe." (If there is, I am unaware of it).

The answer is also "yes" because the vast majority of divers who follow their computer do not develop the bends, even though their profiles may exceed what would be allowed with square-wave-based dive tables. In one respect, at least, computer algorithms have been more conservative than tables -- in their allowed rate of ascent. Dive computers have long allowed for an ascent rate much slower than the training agencies' old recommendation of 60 ft./minute. (Training agencies now recommend an ascent rate no faster than 30 feet/minute). Some computers allow for different rates of ascent, faster at deeper depths, then slower at shallower depths. A typical allowed rate of ascent above 60 fsw is 30 to 35 feet/minute; if the diver is rising faster than this rate the computer will flash SLOW or provide an audible signal to the diver.

In summary, a modern dive computer, used wisely, is accurate - but not infallible.

WHAT ARE ODD DIVE PATTERNS?

Odd dive patterns include those dives that violate the twin rules of reaching the deepest point early in any dive, and of making each subsequent dive shallower than the one before it. Odd dive patterns, which are thought to increase the risk of decompression sickness, include (Figure 6):

on a single dive
- reverse time profile
- bounce diving
- sawtooth profile

on consecutive dives
- second dive deeper than first, third deeper than first or second, etc.

Figure 6. Odd dive patterns (not recommended). S=start of dive; F=finish.

Odd dive patterns obviously differ from either of the multi-level patterns shown in Figure 4 The reverse time profile (reaching the deepest point late in the dive) effectively shortens the time available for off-gassing (decompression), since nitrogen is being continually accumulated until the very end of the dive. When the deepest point is reached first, as is recommended, some of the nitrogen loaded at the deepest depth is being unloaded throughout the dive, during the gradual ascent to the surface.

Bounce and sawtooth diving probably increase DCS risk because of silent bubble formation at depth. On ascent any silent bubbles that form begin to release nitrogen harmlessly. However if the diver quickly returns to the deepest depth, more nitrogen will enter the tissues; *that* nitrogen, on re-ascent, will then flow into the existing bubbles, which expand further. Thus the risk of DCS increases by diving immediately after formation of any silent bubbles; bounce or sawtooth diving is one way to do this.

HOW ARE COMPUTERS ABUSED?

There are many ways dive computers can be improperly used or abused. Like any tool, the dive computer cannot keep a person from hurting himself or herself. Perhaps a dive computer's greatest drawback is that it may impart a false sense of security to the diver.

"The best dive computer is the human brain" is a frequently quoted slogan. Rely mindlessly on a dive computer and you are asking for trouble. In no particular order, here are some ways a dive computer can be improperly used or abused, and increase the risk of a diving accident.

1) By exceeding the computer's limits, such as: ascending too fast; repetitive diving to depths greater than allowed; staying too long at depth when you should be ascending; flying before the computer says it is safe.

2) Pushing the limits of the computer. There is frequent debate about whether a given computer is "conservative" or "liberal" in the diving it allows. Regardless, it is foolish to push the limits of any dive computer (or dive table, for that matter). If you have made four dives in a day, and the computer says you can do a fifth dive to 40 feet for 18 minutes, and you decide to do that dive for 18 minutes "because the computer says I can," you are pushing the envelope of safety and increasing your risk of DCS. Common sense says it would be safer to either not dive or, if you do, go to less than 40 feet or for less than 18 minutes (or both).

3) Diving odd patterns (Figure 6). The computer will track them and not sound any alarms. However, in theory these patterns increase risk of DCS.

4) Ignoring non-computer factors. The computer algorithm assumes a "typical" or average population of divers. The computer does not know if its owner was up all night with an upset stomach, had three martinis for breakfast, is dehydrated, or is using a thin lycra skin in water that calls for a heavy wet suit. All of these factors might increase risk for DCS but they are unknown to the computer.

5) Not using the computer on all repetitive dives. If some part of a diver's console is malfunctioning he may borrow someone else's, and end up using a different computer, or perhaps none. He may reason: "It's only one dive." If it is his only dive in the past 24 hours, no problem (assuming the dive is planned by the tables). But if it is one of several repetitive dives, he is making a big mistake; the computer will know nothing about his nitrogen uptake on previous dives, and its calculations will be invalid for protecting him from DCS. This will also be the case for all subsequent repetitive dives, no matter which computer he uses.

6) Relying on the computer worn by a dive buddy. Dive buddies *never* have identical dive profiles. A buddy team, where only one buddy has a computer, should dive by the tables and not by the computer. Relying on a buddy's computer, especially for repetitive diving, is very risky.

7) Letting the computer separate a dive team. If each member of a buddy team has his/her own computer, and the algorithms differ, the *pair* must dive by the more conservative computer. If the diver with the more liberal computer stays down (because the computer says he can) while the one with the more conservative computer ascends, the situation becomes a "same ocean, same day dive," not a buddy dive. Staying together as a buddy team should take precedence over any computer's algorithm.

8) Not maintaining the computer properly. The computer is no good if its battery runs out at 75 feet. Low battery signals should not be ignored.

8) Using a computer at altitude when it is programmed for sea level. Altitude diving (above 2000 feet) requires a different set of dive tables than what is used at sea level. (Many computers now automatically adjust for altitude.)

10. Two divers go as a buddy team to 60 fsw. Only diver B has a computer. Using tables, Diver A determines she can dive to 60 fsw for 40 minutes. Twenty minutes into the dive they are both at 40 fsw. Diver B's computer shows he can stay at this depth another 30 minutes. Which of the following statements is correct?

a. Both divers should surface after 40 minutes bottom time.
b. Both may surface after 50 minutes bottom time.
c. Diver A should surface after 40 minutes, while diver B can stay an extra 10 minutes.
d. A compromise of 45 minutes total bottom time should be reached, and then both should surface.

11. A diver goes to 60 fsw with her computer; at 10 a.m. it shows a 'no decompression time' of 35 minutes. At 10:15 a.m. she is at 42 fsw; her computer shows a no decompression time of 40 minutes. Assuming she stays at 42 fsw until her ascent begins, she should be at her safety stop by:

a. 10:35 a.m.
b. 10:40 a.m.
c. 10:55 a.m.
d. 10:20 a.m. ; her computer is malfunctioning
e. the time her tank pressure reaches 500 psi

12. A tissue compartment has a half-time of 10 minutes. After a doubling of ambient pressure how many minutes will it take for the compartment to become fully (98.5%) saturated?

a. 20
b. 30
c. 40
d. 50
e. 60

13. A compartment is considered fully saturated at 6 hours. It's half time in minutes is:

a. 20
b. 30
c. 40
d. 60
e. 120

14. A diver goes to 99 fsw breathing a nitrox mixture (68% nitrogen, 32% oxygen) and stays 15 minutes. How many half times would it take for his 30-minute compartment to become fully saturated with nitrogen at that depth?

a. 4
b. 6
c. cannot determine without more information

15. State whether each of the following statements about nitrogen loading is true or false.

a. A compartment with a 30-minute half time will gain the same percentage of nitrogen when going from 30 fsw to 60 fsw as when going from 60 fsw to 120 fsw.
b. On a dive to 33 fsw some compartments, if at a depth long enough, will end up with a PN2 greater than 2.0 atm.
c. Assume two divers, A and B, of identical weight and body composition, go to 33 fsw. Diver

A stays 60 minutes and diver B stays 120 minutes. At the beginning of ascent the two divers will have the same amount of nitrogen in their tissues.
d. Assume that it takes 12 hours for a body to fully saturate at a depth of 33 fsw. If diver A has been at this depth for 24 hours and diver B for 13 hours, the two divers should have the same PN2 in their tissues.
e. Fully saturated with nitrogen means the tissue holds all the nitrogen it can ever hold, no matter what the circumstances.
f. A diver whose tissues are fully saturated with nitrogen at 33 fsw will change to 'partly saturated' if she descends to 66 fsw.

16. State whether each of the following statements about computers is true or false.
a. Diving within the computer's limits will prevent any diver from getting the bends.
b. All dive computers used by recreational divers give essentially the same 'no decompression times' for the same dive profiles.
c. It is acceptable for two divers to use one computer if they plan to hold hands the entire dive.
d. Computers can extend the length of a dive over the time allowed by dive tables.
e. The computer can remember numbers and perform calculations more reliably than the people.
f. The computer algorithm is more reliable than the information provided in a standard set of printed dive tables.
g. "The best dive computer is the human brain" means that if the depth reading or the 'no decompression time' on the computer don't seem correct during a dive, you should ignore them and use your intuition.

TEST YOUR UNDERSTANDING - answers

1. c. 60 minutes (use the next highest depth, which is 60 feet)
2. b. Letter group G
3. Letter group H. Since you dove to 36 feet, you use 40 fsw as your depth in the table; the letter group after the first dive is therefore I. Entering the second part of the table, your surface interval time of 35 minutes is in the surface interval 0:34-0:59 minutes. Moving down that column you reach the new letter group H.
4. Letter group E
5. c. 44 minutes. After your first dive you are in letter group H. After an hour surface interval you are in letter group G. For a planned second dive to 50 feet your residual nitrogen time is 56 minutes, which must be subtracted from the bottom time shown in part one for a dive to 50 feet. One hundred minutes minus 56 minutes = 44 minutes bottom time on the second dive.
6. b. 53 minutes. After your first dive you are in letter group G. After a 45 minute surface interval you are in letter group F. For a planned second dive to 45 feet you must use the next higher row, 50 feet; your residual nitrogen time is 47 minutes, which must be subtracted from the bottom time shown in part one for a dive to 50 feet. One hundred minutes minus 47 minutes = 53 minutes bottom time on the second dive.
7. c. Henry's law.
8. a, b, and c are true.
9. a and c are true.
10. a. A buddy team with only one computer should dive by the tables.
11. c. 10:55 a.m. The no decompression time lengthens as the depth becomes shallower. Her computer is working fine.
12. e. 60 minutes
13. d. 60 minutes
14. b. 6 half times.
15. a. true

b. false. The maximum PN_2 at 33 fsw is 2.0 atm.
c. false. Diver B will have much more nitrogen in his tissues since he is exposed to the ambient pressure for a longer period; at this depth and time neither diver is fully saturated with nitrogen.
d. true. Since full saturation occurs in 12 hours, both divers have the same nitrogen pressure in their tissues (two atm. PN_2 at 33 fsw).
e. false. Fully saturated means a tissue holds all the nitrogen it can for the ambient pressure to which it is exposed.
f. true
16. a. false
b. false
c. false
d. true
e. true.
f. false. Statements 'e' and 'f' serve to clarify the term 'reliable' in regards to dive computers. Computers are certainly more reliable than people at remembering information and making calculations. However, the computer algorithm itself is not more reliable than the information available in a set of printed tables.
g. false. The slogan means that one should always employ common sense and not become a slave to a computer. Computers invariably compute accurately, but they cannot imbue any diver with the ability to make correct decisions.

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