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DAN News

Deep Stops: Can Adding Half the Depth of A Safety Stop Build in Another Safety Margin?

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By Peter B. Bennett, Ph.D., D.Sc., Alessandro Marroni, M.D., Frans J. Cronjé, M.D., International DAN

Although decompression tables have been significantly modified over the last 20 years, with many now giving much shorter times at depth than the original U.S. Navy tables, the incidence of decompression illness (DCI) has changed very little. Even the recent introduction of dive computers has not made a significant impact on dive injuries.

Decompression illness incidence remains consistent with the distribution for sex, age and training among divers, regardless of the computers or tables they use. The problem, as previously elaborated in Alert Diver1 appears to be a too-short time of ascent; this is the only parameter that has changed very little over the last 40 years and, accordingly, appears to possibly be the real controller of the incidence of DCI.

Ascent Rates: A Quick History

Historical guidelines as to rates of ascent are pertinent. In the 19th century, for example, the French physiologist Paul Bert in 1878 quoted rates of 3 feet per minute and the English physiologist John Scott Haldane in 1907 recommended ascent rates between 5 and 30 feet (1.5 and 9 meters) per minute. From 1920-1957, rates of 25 feet (7.5 meters) per minute were recommended.

Then in 1958, during the production of the U.S. Navy Diving Manual, the rate of ascent to be proposed came under review. Cdr. Francis Douglas Fane of the U.S. Navy West Coast Underwater Demolition Team wanted rates for his frogmen of 100 feet (30 meters) per minute or faster. The hardhat divers, on the other hand, considered this impractical for the heavily suited divers who were used to coming up a line at 10 feet (3 meters) per minute. Thus, a compromise was reached at 60 feet (18 meters) per minute, which was also a convenient 1 foot per second.

So from 1957 until 1993 the U.S. Navy tables have consistently advocated an ascent rate of 60 feet per minute, based on this purely empirical decision, with many recreational diving tables and even early computers following suit. In recent years this has been slowed to 30 feet per minute with a recommended safety stop for three to five minutes at 15-20 feet (4.5-6 meters). However, this still brings the diver quite rapidly to the surface, often after some 30-60 minutes at depth.

Decompression Illness

The incidence of DCI as reported annually in the DAN America Report on Decompression Illness, Diving Fatalities and Project Dive Exploration shows an average of these types of DCI:

- 25 percent decompression sickness (DCS) Type I (pain or rash only);
- 64.95 percent DCS Type II (neurological); and
- 9.8 percent AGE (arterial gas embolism).

Thus for recreational scuba divers, most injuries are primarily neurological rather than pain-only. Additionally, they probably originate from the brain or spinal cord rather than from the connective tissue of the joints.

According to the 1906 Haldanian decompression theory (developed by Scottish physiologist John Scott Haldane), dissolved gas uptake and elimination was simplified by using five "tissue" exponentials. This was later changed by the U.S. Navy to six exponentials - i.e., 5-, 10-, 15-, 20-, 40-, 80- and 120-minute tissue halftimes.

Since it was assumed that the "fast" tissues could take up and eliminate gas rapidly, DCS was generally believed to be due to gas supersaturation in the "slow" tissue exponentials. Consequently, table strategies focused on either adding or modifying the parameters for slow tissues. Eventually decompression algorithms, developed by Dr. Albert Buehlmann of the University of Zurich, ended up with 16 tissue halftimes ranging from four to 635 minutes. Still, DCS was not eliminated and the question remained - why?

Although the mathematical concept of "tissues" or "compartments" used in the production of dive tables were never designed to reflect true anatomical tissues, we do know that certain parts of the body respond more rapidly to gas pressure changes than others. Accordingly "fast" tissues with 5-, 10-, or 20-minute halftimes are likely to represent blood and the highly perfused (spread with fluid, especially by blood vessels) neurological tissue of the spinal cord and brain. Conversely, the connective tissues of the joints are poorly perfused and require a much longer time - perhaps 40-, 80- or 120-minute halftimes - to take up gas and achieve sufficient supersaturation to form bubbles on ascent.

Mathematically speaking, it takes six halftimes to 98 percent fill a given "tissue" or "compartment" with dissolved inert gas. So, in Table 1 (see below), the fast "5-minute tissue" is 98 percent full in 30 minutes, whereas the slow "60-minute tissue" takes 360 minutes to become 98 percent full.

Therefore, if one were to make a dive to 100 feet for 25 minutes (see Table 2 below) - a typical recreational dive - the tissues that would accumulate most of the inert gas would be the fast-saturating blood and neurological tissues (5-, 10- and 20-minute tissues, possibly) of the spinal cord and brain. With the relatively rapid ascent to the surface at 60 feet per minute, or even 20 feet per minute, the gas will not have sufficient time to be eliminated without significant supersaturation, generating bubbles. This supersaturation is likely to be evident in the blood and, more importantly, the spinal cord. Recreational diving challenges the fast tissues rather than the slow ones (as seen in Table 2) and the types of injuries they sustain give this support.

Making A Stop Helps

What is interesting, and not necessarily intuitive, is that an in-water stop with a relatively rapid ascent rate appears to be more effective at eliminating inert gas than a very slow ascent rate. As can be seen from Table 2, a five-minute in-water stop is much more effective than simply slowing the ascent rate, even though the total ascent time is not much different (6.6 minutes vs. five minutes). That total ascent time also remains very short. We know the spinal cord has a 12.5-minute halftime. Thus, 6.6 minutes is an insufficient total ascent time for the spinal cord which is, by then, virtually fully saturated (as seen in Table 1).

At 30 feet per minute (which is the ascent rate more commonly used today with a five-minute safety stop at 20 feet), the time to surface from 100 feet will be some eight minutes. This is better, but still a lot shorter than the 12.5-minute halftime of the spinal cord (not considering that gas elimination is slower than uptake). A plausible alternative might therefore be to ascend at 30 feet per minute but to add an additional "Haldanian" stop at about half the depth (remember, the depth is 100 feet / 15 meters) at 50 feet for five minutes. This gives 13.3 minutes of total ascent time2.

Haldane versus Hill: A Snapshot

In 1906 J.S. Haldane theorized that divers could ascend quickly to a depth that was half the absolute pressure of their deepest descent without getting DCS: the so-called 2:1 decompression stop. This technique became known as stage decompression.

British physiologist Sir Leonard Hill theorized that decompression should be by linear ascent to the surface; he strongly disagreed with Haldane's approach. However, in the end Haldane was able to prove, using goats, that a slow linear ascent was not only ineffective, but unsafe; too much nitrogen remained on surfacing resulting in frequent DCS. The deep stop was needed to dive safely.

Why then today do we make virtually a direct ascent from 100 feet and deeper to the surface? Some have since advocated a brief 20-foot stop, but this is rarely for more than three minutes. Surely DCS could be expected under this Sir Leonard Hill-type decompression regimen.

The key to this anomaly in decompression history is that the U.S. Navy came to believe that the fast tissues could in fact tolerate ratios as high as 4:1. This means that a diver could come from 100 feet to surface without decompression. For the highly selected Navy divers, such rapid decompressions did not appear to pose many problems. However, as soon as recreational divers started using the tables, there was a rapid increase in DCS, most notably neurological decompression sickness.

Since then various empirical strategies have emerged, including - quite recently - the 15- to 20-foot safety stop. It would seem from this discussion, that for deep dives, the shallow stop may be "too little too late" and that an additional deep stop may indeed be necessary to reduce the incidence of DCS in the fast tissues. This would bring us closer to the original 2:1 model of Haldane, which appears more appropriate for the kind of deep, short diving that recreational divers tend to do.

Testing the Ideas

To explore these hypotheses, Professor Alessandro Marroni monitored some 1,418 recreational dives by volunteer Italian sport divers participating in the DAN research initiative Project Safe Dive (the equivalent in Europe of DAN America's Project Dive Exploration).

In his analysis, Dr. Marroni determined that it is ascent rate, total ascent time and fast tissue supersaturation that are responsible for the greatest amount of bubbling and therefore presumably also DCS in recreational divers3.

His parameters included:

- Normal diving;
- Using blinded dive monitors or "black box" computers; and
- Recording Doppler bubbles every 75-90 minutes and 48 hours after the last dive or altitude change.

The Uwatec ZH-L8ADT (black box) computers used permitted an estimate of the amount of nitrogen in blood returning to the heart and the maximum nitrogen partial pressure in any tissue compartment at any time. This was called the leading tissue nitrogen partial pressure, or critical nitrogen tension. Consistent with the hypotheses above, it was found that the presence of bubbles was directly related to excess gas in the fast to medium halftime tissues. The greater the fast tissue supersaturation, the worse the bubbling became.

Adding A Deep Stop

On the other hand, it was found that even in repetitive dives, bubbles could be avoided as long as the leading tissue nitrogen was kept below 80 percent of the allowed M value, or less than 11 mbars (1 bar = surface pressure). The M value is the safe calculated partial pressure of nitrogen that can be safely allowed. A practical way to achieve this was by the introduction of an additional deep stop. This simple procedure lengthened the ascent time from 11.2 mins to 18.55 minutes, without changing the ascent rate, and reduced the previously recorded 30.5 percent incidence of high-grade bubbles to zero.

International DAN research studies have recently clearly confirmed these hypotheses: 15 divers were enrolled in a study and each given eight possible combinations of ascent rates, and either a shallow stop, or a deep and a shallow stop. The repetitive dives were to 80 feet (25 meters) for 25 minutes; the surface interval was three hours, 30 minutes; and the final dive was to 80 feet for 20 minutes. Ascent rates were 60, 30 and 10 feet per minute. The matrix is shown in Table 3 and the results of 181 dives are shown in Table 4.

Clearly, the best decompression schedule is Profile 6 (see highlights in both tables). With an ascent rate of 33 feet (10 meters) per minute, and two stops at 45 feet (13.5 meters) and 9 feet (2.7 meters) respectively, this profile had the lowest bubble score of 1.76.

Other Experiences with Deep Stops

From time to time in diving history, the concept of the "deep stop" has reappeared. Brian Hills noted that Australian pearl divers, who previously endured many fatalities and severe DCS in places like Broome and Thursday Island, eventually devised their own means of decompressing to stop this. The whole secret to their success was empirically adding deeper initial stops.

In more recent times, recreational technical divers have also devised their own decompression methods which have led to two so-called "bubble models" for computation. The Wienke Reduced Gradient Bubble Model (RGBM) and the Yount Variable Permeability Model (VPM) both attempt to predict when bubbles form and then calculate decompressions to prevent bubble formation before surfacing.4

NAUI technical divers have used the Wienke RGBM model quite extensively with no recorded incidence of DCS. This data as well as the results of this IDAN research in divers were discussed at a NAUI workshop in Florida in early 2003. As a result, NAUI has now suggested that a deep stop might well be incorporated in recreational diving by taking a one-minute stop at half the depth and followed by a two-minute safety stop at the 15- to 20-foor level instead of the three minutes currently recommended. We are currently testing this concept with our Italian diver research teams.

Future Research

The International DAN research project on deep stops is continuing. Additional areas of research include reducing the time of the deep stop and possibly introducing nitrox and / or oxygen routinely at the shallow stop, as used by the pearl divers of yesteryear and the technical divers today.

The secret of the deep stop rests in the paradigm shift of "beating the bubble" versus "treating the bubble." The former utilizes the deep stop to ensure that the fast tissue critical gas supersaturation is not exceeded and stops bubbles from forming in the first place. The long ascent to the 20-foot stop, as is currently done, involves "treating the bubble"; we know this produces 30 percent asymptomatic or so-called "silent bubbles" on the surface, which may be indicators of decompression stress or even potential DCS.

The missing link of this research is the unknown relationship between Doppler-detectable bubbles and neurological DCS. For the moment, it is our hope that by eliminating the 30 percent so-called silent bubbles in the heart, we will also be stopping their occurrence in the spinal cord too. More research is needed in this regard.

A Note From The Researchers:

A large amount of data, some of which is presented in this article, has been presented by the International DAN (IDAN) group in different formats at scientific meetings in Hawaii, Malta, Copenhagen and Brussels. The most recent data will be presented at the Undersea and Hyperbaric Medical Society meeting in Sydney May 25-26, 2004. A formal paper has been accepted for publication in the journal Undersea Biomedical Research.

This is ongoing research that investigates the value of deep stop at half the depth of the dive, with studies on deep through shallow profiles, reverse dive profiles and variations of time at the deep and shallow stops.

These observations and conclusions are relevant only to the types of recreational dives studied. They should not be extrapolated to deeper and longer decompression dives without additional research and analysis.

References

1 January/February 1995 editorials by Peter Bennett in the American Divers Alert Network magazine Alert Diver "No Fast Ascents - No Bends."

2 For dives to 80 feet and deeper, the five-minute compartment controls the decompression as it is

rapidly saturated and quickly becomes supersaturated during ascent. For these dives an in-water stop at 20 to 50 feet is very effective in clearing the fast compartment. Conversely for shallow dives with long bottom times, the addition of a deep stop is less effective; the slow tissues are the controllers and a three- or five-minute stop becomes less effective.

3 Interestingly, as with other such Doppler studies, bubbles did not appear until 30 or 40 minutes after surfacing. After repetitive dives, however, 85 percent of the dives produced bubbles, with 18 percent as low grades on the Spencer Scale of 1-2, but a dramatic 67 percent as high grades 3-4. The latter are associated with a greater likelihood of DCS.

4 This is in contrast to most decompression tables or computer algorithms today, which are based on Haldanian gas uptake and elimination in the body tissues without the deep stop. Data up to now show that these dissolved-gas-only theories will result in an average of about a 30 percent incidence of so called "silent bubbles" recorded at the surface by doppler listening technology over the heart.

The relationship of silent bubbles to DCS, however, remains unknown at present.

Table 1. Tissue Halftimes: "Fast" Versus "Slow" Tissues

Tissue Halftime 5 minutes (Fast)		Tissue Halftime 60 minutes (Slow)	
5 minutes	50 percent full	60 minutes	50 percent full
10 minutes	75 percent full	120 minutes	75 percent full
15 minutes	87.5 percent full	180 minutes	87.5 percent full
20 minutes	93.8 percent full	240 minutes	93.8 percent full
25 minutes	97 percent full	300 minutes	97 percent full
30 minutes	98 percent full	360 minutes	99 percent full
Tissues need the same or longer time for complete desaturation.			

Table 2. Model Inert Gas Tissue Tensions for 100-Foot Dive for 25 Minutes

Ascent Rate	Haldane Tissue Gas Tension 1/2 Times				
	5 mins	10 mins	20 mins	40 mins	80 mins
A. 60 ft/min	68	62	45	28	15
B. 20 ft/min	56	56	44	28	16
C. 60 ft/min 3 min at 20 ft	50	53	42	27	15
D. 5 min at 20 ft	42	48	40	27	15
E. 3 min at 10 ft	48	51	41	27	15
F. 5 min at 10 ft	38	46	39	26	15

Table 3: Matrix of the Experimental Dive Profiles

Profile	Depth (m)	Time (min)	Ascent Speed m/min	Stop @ 15 m	Stop @ 6 m	Total Ascent Time (min)
1	25	25	10	0	0	2.5
1R	25	20	10	0	0	2.5
2	25	25	3	0	0	8
2R	25	20	3	0	0	8
3	25	25	18	0	5	6.5

3R	25	20	18	0	5	6.5
4	25	25	10	0	5	7.5
4R	25	20	10	0	5	7.5
5	25	25	3	0	5	13
5R	25	20	3	0	5	13
6	25	25	10	5	5	12.5
6R	25	20	10	5	5	12.5
7	25	25	18	5	5	11.5
7R	25	20	18	5	5	11.5
8	25	25	3	5	5	18
8R	25	20	3	5	5	18

Table 4: Fast Tissue Saturation and Bubble Scores after the Different Dive Profiles

Ascent Rate	Stops	5 min Tissue Saturation (0-100 percent)	10 min Tissue Saturation (0-100 percent)	Bubble Score BSI	Total Time to Surface (mins)
3 m/min (Profile 2)	No Stop	48	75	8.79	8
3 m/min (Profile 5)	6 m / 5 min	30	60	8.07	13
3 m/min (Profile 8)	15 + 6 m / 5 min	22	49	3.51	18
10 m/min (Profile 1)	No Stop	61	82	7.34	2.5
10 m/min (Profile 4)	6 m / 5 min	43	65	5.23	7.5
10m/min (Profile 6)	15 + 6 m / 5 min	25	52	1.76	12.5
18 m/min (Profile 3)	6 m / 5 min	42	60	7.38	6.5
18 m/min (Profile 7)	15 + 6 m / 5 min	28	55	3.23	11.5

To read the original paper, UHM 2004, Vol. 31, No. 2, see the accompanying graphic.