Implications of Haldanian decompression theory on safe ascent profiles for sport dives

by Glenn Lawyer
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Contents

1 Zeroth aid (accident prevention)

Some ideas to help you avoid needing the next section.

- A 5 minute safety stop significantly reduces the risk of DCI.
- Diving to the limit of the tables significantly increases the risk of DCI.
- A long, shallow dive (15 meters) can be as dangerous as a short, deep dive (30-40 meters). Make the safety stop.
- When diving below 20 meters, an additional 5 minute stop at half the maximum depth dramatically reduces bubbling.
- Avoid post-dive exercise. Avoid post-dive re-warming (i.e. hot shower) after a long, deep, or stressful dive.
- Most tables and computers do a poor job of accounting for dives that push the model assumptions. Such situations require a conservative approach to the tables. This includes difficult and/or stressful dives, and multi-day repetitive diving. After several days of heavy diving, a dry day is recommended.
- Multi-day diving when limited to a single dive per day slightly reduces the per-dive risk of DCI. Possible mechanisms to explain this observation are explained by the VPM decompression model, which is not covered in this paper.

2 First aid

The ground rule is: ***If a diver becomes unwell in any way on the same day that they have been diving, they should be placed in a horizontal position, given 100% oxygen, and their condition urgently discussed with a diving physiscian.*** It does not matter how cautiously you have been diving. If you have been diving, and notice anything strange, it is reasonable to expect that you have DCI. Many incidents affect divers who did not violate the tables or their computers. Many times the symptoms are not severe, and are easily confused with other possible causes. If you have been diving, and are not well, it could be DCI and first aid should begin immediately.

Mild symptoms of DCI include, but are not limited to:

- fatigue.
- nausea.
- skin rash / itching.

Serious symptoms of DCI include, but are not limited to:

- pain - particularly in joints, abdomen, lower back.
- unusual weakness, numbness, tingling, paralysis.
- dizziness, difficulty with vision or speech.
- difficulty in breathing, severe cough, bloody frothy mouth.
- decrease or loss of consciousness, convulsions.
- death.

The following ordered list of **first aid procedures** is adopted from *Deeper into Diving*, p. 85-87 (first aid):

1. If the symptoms are severe, or become severe, contact emergency services. Strongly encourage the attending medical staff to contact a diving medical expert.
2. Lay the diver down horizontally, without raising the legs (unless the diver is experiencing severe shock). Maintain the diver in a horizontal position.
3. Establish and maintain: **A**irway **B**reathing **C**irculation.
4. Administer the highest concentration of oxygen available for as long as the supply lasts.
5. Arrange for recompression.
6. Encourage a responsive and stable victim to drink non-alcoholic fluids. Keep the rate at or below 110 ml (four ounces) per 15 minutes. Record the amount given and the time.
7. Record details of the dive (profile, conditions), first aid given, and diver's condition. Also record diver's personal information (name, address, telephone, personal contacts).

3 Theory

3.1 Historical context

The main body of the theory was published by J.S. Haldane in 1908. Haldane associated decompression illness with nitrogen gas pressures in the tissues that were highly elevated with respect to ambient pressure. The supersaturated nitrogen would form bubbles in the victim's body, leading to the observed symptoms.

Haldane theorized that nitrogen absorption and release by the body would follow an exponential curve. This curve could be parametrized by a half-time. A half-time is the time required for a tissue to absorb or release half of the gas needed to match ambient pressure.

He also realized that different parts of the body would absorb and release nitrogen at different rates. Rather than try to make a physical model that would accurately track nitrogen loading in specific anatomical structures, he used a simplifying assumption. He selected a range of half-times which he believed would cover the rates occurring in real tissue. Haldane's five half-times were 5, 10, 20, 40, and 70 minutes. Each of these half-times became a "tissue compartment" in his model. It is common to use only the word tissue as an abbreviation. One should remember, however, that this does not refer to specific tissues in the body, but rather to a number of specific bodily tissues that share approximately the same nitrogen absorption/release times.

Using this tissue model, it was possible to estimate nitrogen partial pressures in the body for a given depth exposure profile. Numerous experiments lead Haldane to believe that the body could withstand a halving of pressure without symptoms, even after long and/or deep exposures. Noting that air contains 79% nitrogen, a reduction by half of the ambient pressure when breathing compressed air can be restated as a 1:58 allowable drop in tissue nitrogen pressure relative to ambient pressure. This allows the model to be used for alternate gas mixtures.

The next major step in the evolution of Haldane's model was Robert Workman's research using U.S. Navy data in the 1960's. Workman adjusted the theoretical safe levels of tissue nitrogen supersaturation. Haldane's fixed level of 1.58 was increased, and varied linearly with depth. Workman further allowed fast compartments to tolerate greater supersaturation than slow compartments. The assumption was that tissues with short half-times release nitrogen quickly and are thus less susceptible to effects of overpressure.

Table 1: Büllman tissue half times.

fast	medium	slow	long
4.0	27.0	109.0	305.0
8.0	38.3	146.0	390.0
12.5	54.3	187.0	498.0
18.5	77.0	239.0	635.0

At the end of the 1960s, Heinz Schreiner solved the differential equation for gas exchange when ambient pressure changes at a constant rate. This made possible the direct calculation of inert gas partial pressure in each tissue compartment. Schreiner was also able to fill in some of the physiological gaps in the theory by considering gas transport in the blood and solubility of gasses in real tissues.

The main text on decompression theory seems to be *Tauchmedizin* by Albert Bühlmann, with the first edition dating 1983 and the most recent dating 1995. Bühlmann refined the ideas expressed above, and brought them together into one published work. He is credited with making the theory and calculations available to the general public for the first time. Variations of this algorithm form the basis of many of the diving tables and computers in use today. Bühlmann's model is the one presented here.

3.2 The ZH-L 16 model

Bühlmann's basic model is referred to as the ZH-L 16 model. The "ZH" stands for the University of Zurich, where Bühlmann worked, "L"for limits, and 16 for the number of tissue compartments used. Tissues are considered to be fully saturated after 6 half times. Half-times in minutes can be converted to saturation times in hours by dividing by 10. The T_{27} tissue becomes fully saturated after 2.7 hours at a given pressure. Nitrogen half-times in the 16 compartments defined by Büllman are shown in Table 1.

Schreiner's formulas were applied to calculate tissue pressures throughout the dive profile. A tissue compartment's partial pressure of nitrogen (ppN_2) after exposure to a fixed ambient pressure (constant depth) is calculated using the tissue's beginning nitrogen partial pressure (ppN_2^O), inspired nitrogen partial pressure (ppN_2insp), half-time (T), and time of exposure (t). The formula is as follows.

$$ppN_2 = ppN_2^O + \left(ppN_2insp - ppN_2^O\right) * \left(1 - 2^{-t/T}\right) \tag{1}$$

The formula becomes slightly more complex when the ambient pressure changes during the exposure. One additional parameter is needed, the rate of increase of inspired gas pressure with change in ambient pressure (R). This rate is the descent rate expressed in bars ($1/10^{th}$ of the rate in meters) multiplied by the inspired nitrogen partial pressure. It is assumed that this rate is constant. Inspired gas pressure is that at the start of the exposure. Confusingly, the tissue half-time (T) is replaced with a half-time constant (k). The half-time constant is $ln2/T$, the natural log of 2 divided by the half-time. The reason for the switch is to match Schreiner's notation. The equation can also be written in terms of the half-time without reference to k. The equation is

$$ppN_2 = ppN_2insp + R\left(t - 1/k\right) - \left(ppN_2insp - ppN_2^O - (R/k)\right) e^{-kt} \tag{2}$$

When the rate R is zero, this formula reduces to the constant depth formula (after the required manipulation to replace k with T.)

Inspired gas pressures are slightly lower than the pressure of the gasses before they are inhaled. Several physiological factors contribute to this. Alveolar gas (the gas in the alveoli of the lungs) is only partially replaced at each breath. Further, it is constantly losing oxygen and gaining carbon dioxide. Finally, air absorbs moisture from the mouth and bronchial passages before arriving at the alveoli. This absorbed water vapor will dilute the concentrations of inert gasses. This last factor, by the way, is a contributing factor to dehydration while diving since the breathing gas is usually quite dry.

The actual effect these factors have on the gas is to reduce the ambient partial pressure of inert gasses by between 0.0493 to 0.0627 bar. Büllman used the larger value, Schreiner used the (more conservative) smaller. As we are following Büllman 's model, we use his value and calculate the inspired nitrogen pressure for divers breathing compressed air to be

$$ppN_2insp = (amb - 0.0627) * 0.79 \tag{3}$$

This value of ppN_2insp should be used in both equations (1) and (2). If not, the resulting estimates for tolerable inert gas supersaturation may be exaggerated. At sea level, ppN_{2insp} is 0.74.

Büllman kept Workman's idea of a linear relationship between allowable tissue nitrogen partial pressure and ambient pressure. He altered the idea's presentation, however, by replacing Workman's "M" values with an "a" and "b" value. Büllman calculated the minimum tolerable ambient pressure ($Pamb_{tol}$) the tissue can be exposed to without excessive bubbling as follows:

$$Pamb_{tol} = (ppN_2 - a) * b \tag{4}$$

As theorized by Workman, a compartment's ability to withstand supersaturation was related to its half-time. Büllman considered a tissue compartment's a and b values to be

$$\begin{aligned} a &= 2 * \left(T^{-1/3}\right) \\ b &= 1.005 - \left(T^{-1/2}\right) \end{aligned}$$

where T is the tissue half-time.

The a-b values are can used to calculate a safe ascent profile, based on tissue nitrogen pressures as estimated by equations 1 and 2. The diver is to ascend to the shallowest safe depth, remaining there until a new ceiling is approved, and repeating these two steps until the surface is reached. Büllman recommended an ascent rate of 10 meters/minute, and calculated decompression stops at 3 meter intervals.

3.3 Two common misconceptions

A re-occurring misconception is that a slow, linear ascent provides adequate decompression. Many of Haldane's goats suffered and died to prove this wrong. The misconception is inconsistent with the assumption that tissue off-gassing time has an exponential relationship to the difference in pressure between tissue and inspired nitrogen. A 1 minute ascent of 10 meters followed by a 4 minute stop (5 minutes total time) will reduce tissue nitrogen pressures much more than a 5 minute ascent at 2 meters/minute.

A second misconception is that the model was designed to eliminate bubbling. The model assumes that the body can withstand a certain amount of bubbling without injury. Divers with tissues near their maximum tolerable level will almost certainly show bubbling. The $Pamb_{tot}$ represents a level at which symptoms are unlikely to occur, not a level with no bubbling.

3.4 Example: Dive to 30 meters

The theory can be illustrated by a short example. It is assumed that this is the first dive of the series. For the sake of brevity, only the T_{27} tissue will be considered.

The Nordic Standard Table gives a maximum no-decompression bottom time of 20 minutes at 30 meters. A descent is made to 30 m at a rate of 15 meters/minute. The diver remains at depth for 15 minutes, followed by a direct ascent at 10 meters/minute. As the dive is well within the table limits, ascent is made with no safety stop.[1]

Initial tissue ppN_2 is inspired (alveolar) pressure, i.e. $(1-0.0627)*0.79 = 0.74$ bar. Noting that $k = \ln 2/27 = 0.02568$, descent to 30 meters at 15 m/min gives (eq 2):

$$ppN_2 = 0.74 + (1.5 * 0.74)\,(2 - 1/0.02568) - (0.74 - 0.74 - 43.23)\,e^{-0.02568*2}$$

or 0.80 bar absolute.

At 30 meters, the inspired nitrogen pressure is $(4 - 0.0627) * 0.79 = 3.11$ bar. After 15 minutes the tissue pressure is

$$ppN_2 = 0.80 + (3.11 - 0.80) * \left(1 - 2^{15/27}\right)$$

or 1.54 bar absolute.

Surfacing at 10 m/min means that the diver reaches the surface with a tissue pressure of

$$ppN_2 = 3.11 + (1 * 0.74)\,(3 - 1/0.02568) - (3.11 - 1.54 - 38.95)\,e^{-0.02568*3}$$

or 1.57 bar absolute.

Is this safe? The a-b rule (eq 4) says that as long as the current ambient pressure is above

$$Pamb_{tol} = 0.73 = (1.57 - 0.6667) * 0.8126$$

or 0.73, the odds of symptoms are low. Surface pressure is 1 bar, indicating that at least this tissue compartment is within the safe zone. In fact, all tissues are in ranges acceptable to the ZH-L 16 algorithm. According to the model, symptoms are unlikely.

[1] The Nordic tables recommend a 3 minute stop at 3 meters after every dive. The example dive, by eliminating the stop, does in fact violate the tables.

However, theT_{27} tissue nitrogen pressure is at 1.57 bar. This is right at Haldane's limit. The faster tissues are all above this level. Tissue pressures in the T_4, T_8, and $T_{12.5}$ compartments all have ppN_2 over 2 bar. (See table 2). While symptoms may be unlikely, bubbles are to be expected. This could have adverse effects on future dives.

3.5 Model limitations

The ZH-L 16 model does not compensate for factors associated with increased risk for DCI, such as cold, dehydration, or physical exertion during the dive. Also, the inspired gas pressure varies from individual to individual, depending on fitness, level of activity, and quite possibly other factors. The Büllman value is certainly not appropriate for all individuals, or for all dives. The model, then, provides only a rough approximation of tissue nitrogen levels.

The model assumes that gas absorption and release have the same half-time. Many people now believe that release is slower than absorption. The presence of bubbles is thought especially to reduce the rate of nitrogen release, but not the rate of absorption. This has serious implications for repetitive diving and for multi-day diving.

Defining the a and b values as functions of the half-time is biologically questionable. While the resulting values are probably close, the formulas are better tuned to tissues in the middle ranges. The values for very fast and very slow compartments are probably less accurate. Makers of tables and dive computers tend to adjust the a and b values to fit real-world data.

Büllman published several sets of tissue half times. Each was aimed at a specific application. The values given here are probably not the most appropriate for dive planning.

4 Implications

We now turn our attention to sport diving profiles. Our main concern here is dives to 30 meters or less and within table no-deco limits. DAN reports that many of the DCI cases it deals with occurred with dives that meet this criteria. DAN also found in controlled hyperbaric chamber experiments that 5 out of 580 dives conducted within the limits of the PADI tables resulted in DCI symptoms.

For single dives to 30 meter or less and within the table limits, most of the nitrogen buildup will be in tissues with half times of 27 minutes or less. These tissue compartments represent the brain and spinal cord, among other physical tissues. DAN found that neurological symptoms occurred in 65% of DCI cases reported. This suggests that a major cause of DCI in sport diving profiles is excessive supersaturation of the fast tissues.

4.1 Diving by the tables

Table 2 shows surfacing tissue nitrogen partial pressures in the first 5 compartments for a number of dive profiles. The dives all follow the classic box profile. Descent is made at 15 meters/min, the diver remains at depth for the specified time, and then ascends at 10 meters/min, possibly making a 5 minute safety stop. The first two are dives to 30 meters, one for 15 minutes (the example given earlier) and one for 20 minutes (the table limit) which includes a 5 minute safety stop. The next three are dives to 20 meters. The first has a conservative bottom time, the second is at the limit, and the third is at the limit and includes a safety stop. The final two columns contain a rather conservative dive (15 meters for 70 minutes, 15 minutes less than the no-deco limit) and a rather extreme (and unsafe) dive, 60 meters for 5 minutes with one stop at 3 meters for 5 minutes.

Of the 35 tissue compartments, only one of them is clearly below Haldane's estimated safe value of 1.58. One is at the limit, and the remaining 33 are above. This does, of course, include the results from the rather extreme 60 meter dive. It also, however, includes dives that might be considered non-threatening given current dive tables. Several of the sport-dive profiles have surfacing pressures nearly equivalent to the 60-meter dive.

How does diving by the tables lead to such high values? Recall that the U.S. Navy believed that fast tissues could tolerate supersaturations. Workman's limits went as high as 4:1. Büllman also believed that fast tissues

Table 2: Surfacing tissue ppN_2 in the first 5 compartments after various profiles.

max depth	30	30	21	21	21	15	60
bottom time	15	20	30	40	40	70	5
stop depth		3			3		3
4.0	2.50	1.64	1.96	1.96	1.47	1.80	1.90
8.0	2.37	1.99	2.07	2.12	1.79	1.86	2.22
12.5	2.10	1.98	1.99	2.09	1.87	1.86	2.10
18.5	1.82	1.84	1.82	1.97	1.83	1.82	1.88
27.0	1.57	1.65	1.63	1.78	1.71	1.72	1.65

Each column represents one dive. The top three lines show the maximum depth, bottom time, and depth of a 5 minute safety stop. The remaining lines show the estimated ppN_2 immediately after surfacing for the tissue compartment given in the leftmost column.

could tolerate relatively high levels of supersaturation, though not as high as the U.S. Navy value. His values ranged from 3.26 to 1.9. Table 3 shows the levels for the first 5 tissue compartments, calculated using equation 4.

The justification is that fast tissues off-gas quickly. The model predicts that after as little as 15 minutes, starting from the maximum tissue ppN_2 levels as given in the above table, all tissue pressures will have dropped below Haldane's 1.58 threshold. In general, bubbles are not observed in Doppler studies until 30-40 minutes after surfacing. It is also worth recalling that Dr. Büllman was considered very careful. His limits were not designed only for young, fit, Navy divers with easy and immediate access to hyperbaric chambers, but for his friends and colleagues.

4.2 The deep stop solution

Some evidence, however, suggests that the Büllman limits may be too liberal. The statistics reported by DAN earlier suggest that the limits have a risk of neurological DCI of roughly half of a percent. As a part of the DAN research initiative Project Safe Dive, Dr. Marroni studied 1418 recreational dives made during the 1990s. He concluded that ascent rate, total ascent time, and fast tissue supersaturation were responsible for the greatest amount of

Table 3: Büllman allowable tissue nitrogen supersaturations at sea level.

Half time	Max $ppN2$
4.0	3.26
8.0	2.55
12.5	2.26
18.5	2.06
27.0	1.90

bubbling. After repetitive dives, Doppler studies showed that 85 percent of the dives produced bubbles, with a dramatic 67 percent registering as high grade on the Spencer Bubble Scale. High grade bubbles are associated with a greater likelihood of DCI.

Dr. Marroni found that the best way to reduce bubbling was to keep tissue nitrogen pressures under 80% of the allowed value. This was done by adding a deep stop at or near half the maximum depth. In a separate DAN study, adding a 5 minute stop at half the maximum depth proved the most effective way to reduce or eliminate bubbling.

Table 4 shows the theoretical nitrogen loads for the same depth and bottom times as given in table 2, after the addition of deep stops. The exception was the dive to 15 meters, to which a single stop at 3 meters was added. The 60 meter dive included three stops, at 30, 15, and 3 meters. All stop were calculated to be 5 minutes long.

While many of the values still exceed Haldane's 1.58 limit, the ppN_2 supersaturation is greatly reduced in comparison to table 2. This corresponds nicely with the reduction in post-dive bubbles observed by Dr. Marroni in divers following profiles similar to those in table 4.

4.3 Implementing deep stops in practice

This text is not about reducing bottom times. Plan your bottom times as usual, either from the table or by your computer. What should be adjusted is the ascent plan. The most important adjustment is in your thinking. A concept stressed in many technical diving programs is that the concept of a no-decompression stop dive is somewhat misleading. Nitrogen is absorbed on all dives, even free dives. Omitting decompression stops in "no-deco" dives

Table 4: Surfacing tissue ppN_2 in the first 5 compartments with deep stop profiles.

max depth	30	30	21	21	15	60
bottom time	15	20	30	40	70	5
stop depths	15, 3	15, 3	10, 3	10, 3	3	30,15,3
4.0	1.38	1.39	1.29	1.29	1.27	1.43
8.0	1.71	1.77	1.58	1.60	1.50	1.90
12.5	1.75	1.86	1.67	1.74	1.61	2.01
18.5	1.67	1.80	1.65	1.75	1.65	1.94
27.0	1.52	1.65	1.55	1.67	1.61	1.77

Each column represents one dive. The top three lines show the maximum depth, bottom time, and depths for 5 minute safety stops. The remaining lines show the estimated ppN_2 immediately after surfacing for the tissue compartment given in the leftmost column.

may not be life threatening, but it does not contribute to their safety.

Based on Haldane's many experiments, downplaying the softening of limits that took place in the 1960-1990's, and looking at evidence from recent research, it is recommended that:

- The 3 meter stop be lengthened to 5 minutes.
- For dives below 20 meters, a 5 minute stop be added at half the maximum depth.

Adding one stop for 5 minutes at half the maximum depth is certainly not the theoretically optimal ascent profile. It is, however, an easily remembered rule. It is also easy to apply during a dive.

An alternate way to consider the issue is based on tissue half-times, more specifically the $T_{12.5}$ compartment. This compartment represents the spinal cord (among other tissues). It loads fast enough to absorb significant amounts of nitrogen in a typical sport dive. Two stops for 5 minutes each and a travel time of 10 meters/minute implies that an ascent from greater than 20 minutes will take approximately one half-time for this compartment.

When faced with insufficient air for both the deep and the shallow stop, the deep stop should be shortened or eliminated. If this happens, extending the shallow stop provides some compensation. Eliminating the deep stop will increase the risk of bubble formation in fast tissues. Since it is assumed that the dive was made within table limits, the risk of symptoms is low. The main implication of the bubbles would be to reduce nitrogen off-gassing times for any following dive.

5 Sources

The following sources were of use in compiling this document.
Web pages:

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  www.diversalertnetwork.org/medical/articles/article.asp?articleid=17

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  www.diversalertnetwork.org/news/article.asp?newsid=514

Articles and PDFs available from the internet: (see, for example, www.oceanwreckdivers.com/technical_references.php, or www.decompression.org.)

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