WHAT ASCENT PROFILE FOR THE PREVENTION OF DECOMPRESSION SICKNESS?

I – Recent Research on the hill/Haldane ascent controversy

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Editorials by Bennett (1-6) in the Divers Alert Network magazine *Alert Diver* noted that although decompression tables had been modified over the last twenty years and computers, many giving much shorter times at depth than the U.S. Navy tables, had virtually taken over recreational diving, the incidence of decompression sickness had changed very little. In fact, the incidence was very consistent with the distribution for sex, age and training among divers rather than use of different computers or tables. The problem, it was inferred, was the rate of ascent, which had changed very little over the last 40 years and was the real controller of incidence of decompression illness.

In the 19th century, for example, Paul Bert in 1878 quoted rates of 3 ft/min (.9 m/min) and Haldane in 1907, 5 ft/min (1.5 m/min) up to 30 ft/min (9.1 m/min). From 1920-57 rates of 25 ft/min (7.6 m/min) 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 (7). Cdr. Fane of the West Coast Underwater Demolition Team wanted rates for his frogmen of 100 ft/min (30.4 m/min) or faster. The hard hat divers on the other hand considered this not practical for the heavy suited divers used to coming up a line at 10 ft/min (3 m/min). Thus a compromise was reached of 60 ft/min (18.2 m/min), which was also a convenient 1 ft/sec (0.3 m/sec) (2). So from 1957-1993 the U.S. Navy tables advocated, on this purely empirical approach, 60 ft/min (18.2 m/min) and many early computers followed suit.

Lehner et al (8) simulated no stop air dives in sheep and pygmy goats with no decompression stops. The ascent rate was 60 ft/min (18.2 m/min) followed by an exposure to 8000 ft (2438 m) altitude to provoke DCS. After long bottom times of 4 hours and 24 hours, most DCS was in the form of the 'chokes' and limb pain, usually designated Type I DCS in human diving. On the other hand, no stop dives from relatively deep with 30 min bottom times, provoked a lot of cases with paraplegia or quadriplegia, indicating spinal cord DCS Type II. In the sheep, the DCS cases were less than 10% pain only for the long shallow dives and 68% neurological in the 30 min deep dives. This is not dissimilar from the distribution in recreational divers seen in the DAN annual reports with an average 25% DCS Type I, 64.95% DCS Type II and 9.8% AGE. Thus for scuba divers most injuries are primarily neurological, rather than pain only, and therefore are probably originating from the spinal cord, rather than the connective tissue of the joints.

The Haldane hypothesis is based on gas uptake and elimination from five exponentials with tissue half times later changed by the U.S. Navy to six, i.e. 5, 10, 20, 40, 80 and 120 mins. Since it was assumed that the fast tissues could load and unload rapidly when DCS occurred, it was generally believed to be due to supersaturation in the slow tissue exponential. The remedy was to add or modify the slower tissues. Thus Buehlmann tables ended up with 16 tissue half times from 4-635 mins but DCS still occurred. If we try to relate these empirical half times in some way to the tissues of the body, then the ' fast' tissues such as 5, 10 and 20 min are more likely to be related to blood, and the highly perfused neurological tissue of the spinal cord and brain. The connective tissues of the joints, on the other hand, are poorly perfused and require a much longer time to take up gas and achieve sufficient supersaturation to form bubbles on ascent such as 40, 80 and 120 mins.

Therefore if one was making a dive to 100 ft (30.4 m) for say 25 mins (Table 1), the tissues with the most saturation are the short blood and neurological tissues (5, 10 and 20 min possibly) of the spinal cord and brain. Upon ascent to the surface at 60 ft/min (18.2 m/min) the gas will not have sufficient time to be eliminated. The supersaturation developed will generate bubbles in the blood and especially the spinal cord, i.e. the fast tissues (4).

Table 1. Model Inert Gas Tissue Tensions (9)
100 ft (30.4 m) for 25 mins
HALDANE

Ascent Rate	**5 mins**	**10 mins**	**20 mins**	**40 mins**	**80 mins**
60 ft/min (18.2 m/min)	68	62	45	28	15
20 ft/min (6.1 m/min)	56	56	44	28	16
60 ft/min (18.2 m/min) 3 min at 20 ft (6.1 m)	50	53	42	27	15
5 min at 20 ft (6.1 m)	42	48	40	27	15
3 min at 10 ft (3 m)	48	51	41	27	15
5 min at 10 ft (3 m)	38	46	39	26	15

Alternatively, if you dive to a shallow depth of 40 ft (12.1 m) say for 60 mins, the blood and neurological tissues are certainly saturated but the slow tissues (40, 80 and 120 mins) are now filling heavily. On ascent now the fast tissues (5, 10 and 20 min) will degas quickly to the point where the gradient is not critical for bubble formation. However, the slower connective tissues (40, 80 and 120 mins) are unable to offload so fast and the critical tension for bubble formation may then be reached and pain only DCS I will occur. This theoretical concept is supported by the work of Lehner (8) discussed previously. Slowing of the ascent rate would then be particularly advantageous for the more serious neurological DCS II, but might possibly have less effect on the pain only DCS I.

A review of tissue half times for the body gives

Table 2. Tissue Half times for Human Body (10)

Blood	Very short
Spinal Cord	12.5 mins
Inner Ear	142-238 mins
Joints & Bones	304-635 mins

From Table 1 it may be seen that the fast tissues 5, 10 and 20 mins are loaded with the most gas in a 100 ft 25 min (30.4 m/25 min) dive with a 60 ft/min (18.2 m/min) ascent rate. This would be predicted by Table 2. Further at an ascent rate of only 20 ft/min (6.1 m/min) there is a definite further reduction of the tissue gas. However, the addition of a safety stop at 20 ft for 5 min (6.1 m/5 min) has an even more significant effect than slowing the rate. This is simply because it is a matter of the <u>total time</u> to degas. For a 100 ft (30.4 m) dive at 60 ft/min (18.2 m/min) with no safety stop, the diver will be on the surface in 1.6 mins but our diver’ s spinal cord has a 12.5 min half time so after 25 mins bottom time will be 97% full which cannot be eliminated in 1.6 mins.

Today the safety stop is widely used at 20 ft (6.1 m) for 3-5 mins. Using doppler technology, both Pilmanis (11) and Uguccioni et al. (12) have shown a significant reduction in venous bubbles when utilizing this stop which acts like slowing the ascent rate. Lewis (13) showed that the stop is in fact preferential to slowing the ascent rate. Thus, as indicated previously, a 5 min safety stop is much more effective than a reduced ascent rate because it provides much more time to degas than can slowing the ascent rate from 60 ft/min (18.2 m/min) to 30

ft/min (9.1 m/min). Further, Lewis noted the safety stop is less effective when diving to the No D limits at shallow depths. This is because the 5 min compartment is controlling the dive for depths around 80 to 100 ft (24.3-30.4 m) but as the depth becomes shallower, control shifts, as discussed above, to the slower compartments where a 3 or 5 min stop is increasingly less effective.
It would seem, therefore, that even with a 5 min safety stop at 20 ft (6.1 m), an ascent from 100 ft (30.4 m) at 60 ft/min (18.2 m/min) will be on the surface in 6.6 mins. If only a 3 min stop is taken, which is common, you will be on the surface in only 4.6 mins. Yet we know the spinal cord has a 12.5 mins half time. Again, this is <u>insufficient total time</u> as the spinal cord is virtually fully saturated.

At 30 ft/min (9.1 m/min), the ascent rate more commonly used today, then time to surface from 100 ft (30.4 m) will be 8.3 min, which is better but is still a lot less than the 12.5 mins half time of the spinal cord. At 10 ft/min (3 m/min) plus a 5 min safety stop at 20 ft (6.1 m), then the ascent time would be 15 mins, which is much better. Alternatively one can still ascend at 30 ft/min (9.1 m/min) but have a further stop at about half the depth at 50 ft (15.2 m) for 5 mins to give 13.3 min total time.

This would be typically Haldanian. Haldane theorized that divers could ascend quickly to a depth that was half absolute pressure of their deepest descent (14). He then plotted a slow return to the surface with stops to eliminate the excess nitrogen. Leonard Hill (14) by contrast believed in a linear ascent theory. However, Haldane showed that this was ineffective and still left the nitrogen tension too high on surfacing resulting in DCS – the deep stop was needed. Yet in his published tables he did not use a deep stop.

Today we make virtually a direct ascent from 100 ft (30.4 m) and more to the surface or with a 20 ft (6.1 m) stop for often no more than 3 minutes? Surely DCS can be expected under this regime and does occur. Clearly, to fit with Haldane from a 100 ft (30.4 m) dive, we should be instituting a stop at 50 ft (15.2 m) for say 5 mins and then to 20-25 ft (6.1-7.6 m) for 5 mins and so to the surface. The ascent rate should be 30 ft/min (9.1 m/min) in keeping with Haldane too. Experiments by International DAN are underway to test this rationale and determine if this could eliminate bubbles detected by doppler and DCS II from deep diving and will be reported later.

Review of a number of research papers gives further support to the above hypotheses that slower ascent rates and stops can materially reduce the risk of bubble formation and DCS. In fact, Smith and Stayton (15) as long ago as 1978 working with doppler cuffs around the venae cavae of sheep observed more bubbles in ascent at 60 ft/min (18.2 m/min) compared to 30 ft/min (9.1 m/min). In more recent years, Pollard et al. (16) studied the effects of ascent rate and post dive exercise on rats exposed to 240 ft (73.1 m) for 2 hrs with ascent rates of 30, 45 and 60 ft/min (9.1, 13.7 and 18.2 m/min). The results indicated more DCS with post dive exercise and at the faster ascent rates of 45 and 60 ft/min (13.7 and 18.2 m/min). In addition, there was earlier death at 60 ft/min (18.2 m/min) compared to 45 ft/min (13.7 m/min).

Of significant support to this hypothesis of allowing more time to surface than present ascent rates plus a safety stop to permit sufficient off-gassing is afforded by Wong (17) while studying pearl divers. They make up to 10 dives per day at depths from 33 to 105 ft (10 to 32 m) with multiday diving up to 8 consecutive days. As a result of much neurological DCS the ascent rates were modified to 10 ft/min (3 m/min) with a decompression stop at 28 ft (9 m) on oxygen. Using this modified profile 86 divers made 30,095 dives, which were all repetitive and multiday, with only 4 cases of DCS I (musculoskeletal pain).

Further human studies have been carried out by Carturan et al. (18) in 43 male sports divers who made two open water dives at 115 ft (35 m) for 25 min with a surface interval of 24 hrs. Ascent rate for one group was 30 ft/min (9 m/min) and the other at 56 ft/min (17 m/min). Doppler measurements were carried out every 10 min after surfacing. Blind doppler analysis showed statistically supported evidence of higher bubble grades at 56 ft/min (17 m/min) compared to 30 ft/min (9 m/min).

Broome (19) looked at another variable, the influence of ascent profile on DCI risk in an established swine model by use of non-linear ascent profiles. These were compressed to 200 ft (61 m) with air in 5 mins. They were divided into two groups with a total decompression time of 10 mins. One used a linear ascent rate of 20 ft/min (6.1 m/min) to the surface. The other used a 60 ft/min (18.2 m/min) from 200 ft (61 m) to 110 ft (34m) and then 12-9 ft/min (3.7-2.7 m/min) to the surface. Significantly the linear ascent group developed 11 cases of neurological DCS II, nine severe cases (unable to stand) and one death plus 13 cases of skin bends. The fast/slow ascent group had a much lower incidence with only 5 cases of DCS II, one severe case and 6 skin bends – a reduction in risk by a factor of 2. Since the total decompression times were the same, the importance of the slower rate of 12-9 ft (3.7-2.7 m) from 110 ft (34 m) to the surface is clearly important.

Marroni et al. (20, 21) took the above hypotheses and data and applied it to 1,418 monitored scuba dives to endorse the concept that it is ascent rate, total ascent time and the so called fast tissues which are responsible for DCS in recreational divers. During normal diving, depth/times etc. were monitored by ' black box' computers that did not permit the diver to know the nature of the data collected. Doppler bubbles were measured every 15 up to 90 mins and all divers were monitored until 48 hrs after their last dive or altitude change.

Interestingly, as with other such doppler studies, the bubbles did not appear until 30 or 40 mins after surfacing. After repetitive dives, however, 85% of the dives produced bubbles with 18% low grades on the Spencer Scale of 1-2 but a dramatic 67% high grades 3-4. Again, it is pertinent that at 82 ft (25 m) or less, there were zero bubbles. At average 92 ft (28 m) there were low grade bubbles and high grade occurred at 102 ft (31 m), with very high bubble grades at 108 ft (33 m). The Uwatech 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. It was found that the presence of bubbles was directly related to excess gas in the fast to medium half time tissues with half times of 20-80 mins. The faster the tissue the worse the bubbling, which would be expected in the hypothesis of the fast tissue as the controller.

Further, Marroni et al. (20, 21) found that, in repetitive dives especially, so long as the leading tissue nitrogen was below 80% of the allowed M value (i.e. the safe calculated partial pressure of nitrogen that can be safely allowed) or kept the venous nitrogen tension less than 1100 mbars (1 bar = surface pressure) no bubbling occurred. The average depth for zero bubbles was 92 ft (28 m). The introduction of extra deep stops, thereby lengthening the ascent time from 11.2 mins to 18.55 mins, without changing the ascent rate, reduced the high grade bubbles from 30.5% to zero. This also kept the venous and tissue nitrogen tension within the critical 1100 mbars and 80% of the critical fast tissue tensions (i.e. 20-80 min tissue half times).

As a result of this initial work by Marroni et al (20, 21) and the recent theoretical discussions of the hypotheses of Haldane versus Hill by Bennett (22) a matrix (Table 3) was developed for testing by volunteer divers which evaluated the effect of ascent rates of 3, 10 and 18 m/min (10, 33, and 59 ft/min) and stops at 6 m (20 ft) (Hill) or 6 m and 15 m (20 ft and 49 ft) (Haldane). The studies used blacked out UWATEC computers to measure gas tensions of various ' tissues' of 5, 10, 20, 40 and 80 min half time. We were particularly interested in the ' fast tissues' . Initial results are shown in Table 4.

The highest doppler score of 7.5 is with no stops – a Hill type of ascent and the 5 min tissue is 60% full. Few of us dive that way today since the introduction of the safety stop. With the stop at 6 m (20 ft) for 5 min (rather than the 3 min most divers take today), there is a definite reduction in the 5 min tissue to only 35%, and the bubble score has dropped as well to 4.1. When, like Haldane, the deep stop is introduced, the 5 min tissue tension drops still more to only 25% and the bubble score to a very low 1.7 for a total ascent time of 12.5 min. Clearly this supports the Haldanian deep stop approach, which appears more favorable than Hill' s linear ascents.

Why should doppler bubbles be correlated with spinal cord DCS? There are three possibilities, i.e., bubbles being so numerous they pass through the lungs, or bubbles collect in the spinal venous plexus, or autochonous bubbles form. In these cases the higher doppler scores may have a direct relationship to bubbles affecting spinal cord damage.

Table 3. Matrix of Dives Tested

Dive Profile	Research Diver	Diver	Depth meters	Dive Time Including Descent	Ascent Speed m/min	Total Ascent Time minutes	Decompression Stop meters	Decompression Stop minutes
1			25	25	10	2.5	No Stop	No Stop
1R			25	20	10	2.5	No Stop	No Stop
2			25	25	3	8	No Stop	No Stop
2R			25	20	3	8	No Stop	No Stop
3			25	25	18	1.5+5	6	5
3R			25	20	18	1.5+5	6	5
4			25	25	10	2.5+5	6	5
4R			25	20	10	2.5 + 5	6	5
5			25	25	3	8+5	6	5
5R			25	20	3	8+5	6	5
6			25	25	10	2.5+5+5	15	5
							6	5
6R			25	20	10	2.5+5+5	15	5
							6	5
7			25	25	18	1.5+5+5	15	5
							6	5
7R			25	20	18	1.5+5+5	15	5
							6	5
8			25	25	3	8+5+5	15	5
							6	5
8R			25	20	3	8+5+5	15	5
							6	5

However it is not certain at present if a deep stop may actually reduce the incidence of neurological decompression sickness in recreational divers, although many technical divers have found it to be very successful in practice.

Table 4. Repetitive Dive Ascent Profiles from 25 m (82 ft) for 25 mins / 25 m (82 ft) for 20 mins

Ascent Rate	**Stops**	**5 min Tissue (0-100%)**	**Bubble Score**	**Total Time to Surface**
1. 10 ft/min (3 m/min)	None	60	7.75	8 min
2. 30 ft/min (9 m/min)	6 m/5 min (20 ft/5 min)	40	4.1	7.5 min
3. 30 ft/min (9 m/min)	15 m/5 min (49 ft/5 min) 6 m/5min (20 ft/5min)	25	1.7	12.5 min

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