What Ascent Profile for the prevention of Decompression Sickness?

II - A field model comparing Hill and Haldane Ascent modalities, with an eye to the development of a bubble-safe decompression algorithm.
DAN Europe DSL Special Project 01-2002 "Haldane vs Hill – Speed of Ascent Study".

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Introduction

Circulating venous gas bubbles have been found to be a common occurrence in the otherwise uneventful recreational dives monitored during the DAN Europe's Project SAFE DIVE.

Doppler monitored bubbles have been detected in 37,4% of all the monitored dives. 25,4% of the dives produced Low Bubble Grade recordings only, while 12% produced High Bubble Grades and 2,4% produced Very High Bubble Grades, between grade 3 and 4 according to the Spencer scale.

Repetitive dives showed a different incidence of post dive VGE, with only 15% of the repetitive dives bubble free and HBG and LBG recorded in 67% and 18% of the repetitive dives, respectively.

The DAN Europe SAFE DIVE project showed that post dive High Bubble Grades are directly related to Fast to Medium Half Time Tissues, and Nitrogen Venous Partial Pressure greater than 80% of the allowed M Value for that tissue.

The modification of the ZH-L8 ADT algorithm by the introduction of a *Proportional M-Value Reduction Concept (PMRC)* to the fast and medium HT Tissue compartments, without altering the original speed of ascent to and between any planned stop resulted in a modified ascent slope and in the introduction of extra deep stops during the ascent. This eliminated the occurrence of significant post-dive Doppler detectable Venous Gas Emboli.

The results also showed no apparent relation between "instant" speed (the actual speed of ascent calculated from the depth/time profile of the UWATEC computer) and post-dive Doppler bubble detection.

Contradictory results were observed during several test chamber dives with "instant" speeds of up to 25 meters per minute and no bubble signal detection, versus significant high bubble grade signals after dives made according to the standard ZH-L8 ADT algorithm, with "instant" speeds of ascent never faster than 10 meters per minute.

These observations suggest that the Delta-P imposed on the leading tissue, irrespective of the "instant" speed of ascent in any given tract of the ascent slope, is the critical factor for precordially detectable bubble production.

This fits with a "Haldanian" approach to decompression computation.

Haldane theorized that divers could ascend quickly to a depth that was half the absolute pressure of their deepest descent. He then plotted a slow return to the surface with stops to eliminate the excess nitrogen. Leonard Hill 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 (8).

A special field study was started, in cooperation with DAN America, to test this hypothesis.

Materials and Methods

The study was done with a group of 15 volunteer divers who, after having read and signed an informed consent form, accepted to dive on 8 different weekends, each one of 8 possible combinations of ascent rate and decompression stops of the same dive to 25 m for 25 min, followed by a repetitive dive to 25 m for 20 min after a 3 hours and 30 minutes surface interval. The ascent rates being of 18, 10 and 3 m/min, with or without 5 min stops at 15 and 6 meters. The 18 m/min ascent profile without any stop was intentionally not tested for safety reasons.

At the time this paper is being prepared 7 out of 8 profiles have been dived, 6 of which by the majority of the volunteer divers and profile number 7 by 3 volunteer divers, while profile number 8 is still being completed. Two volunteer divers dropped out of the study before completing the fifth profile, due to pregnancy. Some divers did not, occasionally dive the repetitive dive profile due to feeling too cold or excessively adverse sea conditions.

In total, up to now, we analyzed 24 dives for profile 1-1R, 25 dives for profile 2-2R, 27 dives for profile 3-3R, 21 dives for profile 4-4R, 19 dives for profile 5-5R, 17 dives for profile 6-6R, and 6 dives for profile 7-7R, for a total of 139 man-dives and 834 Doppler Readings.

The divers served as their own control for precordially detected Doppler Bubbles and possible symptoms of DCS.

TABLE I - Matrix of the experimental Dive Profiles

Profile	Depth	Time	Ascent Speed m/min	Stop 15 m	Stop 6 m	Total Ascent Time minutes
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

All dives were recorded for time/depth profile by " DAN Europe Black Boxes" – modified UWATEC computers as described in our previous work (1,2) – which were worn by the divers to assure objective dive profile recording and the availability of data ready for mathematical analysis of the computed tissue saturation.

Doppler Recordings were performed by specially trained members of the volunteer divers' group, using an Oxford Instruments 3,5 MHz probe with an 'in-house' assembled digital recorder, trained according the methods developed by our group and qualified as "Research Technicians" (1,2).

The recordings were made over 1 minute and every 15 minutes up to 90 minutes after the dives, and subsequently evaluated in undisturbed laboratory conditions by a blinded evaluator.

The Doppler Bubble Signals were scored according to the Spencer Scale (3) and also according to a Doppler Bubble Grading System that we designed, as a variant of the Spencer method, as follows (4-6):

? LBG – Low Bubble Grade: occasional bubble signals, Doppler Bubble Grades (DBG) lower than 2 in the Spencer Scale

? HBG – High Bubble Grade: Frequent to continuous bubble signals, DBG 2 and higher in the Spencer scale.

Occasional very high DBG were rated HBG+ grading, when bubble signals reached grade 3,5 in the adapted Spencer scale described below.

A further adaptation to the Spencer Scale was made, introducing "half grades" to allow for a more linear grading, as follows (Expanded Spencer Scale – ESS):

- ? Grade 0 = No Bubble Signals
- ? Grade 0,5 = 1-2 sporadic Bubble signals over the 1 minute recording
- ? Grade 1 = up to 5 Bubble signals over the 1 minute recording
- ? Grade 1,5 = up to 15 Bubble signals over the 1 minute recording, with bubble showers
- ? Grade 2 = up to 30 Bubble signals over the 1 minute recording
- ? Grade 2,5 = more than 30 Bubble signals over the 1 minute recording, with bubble showers
- ? Grade 3 = virtually continuous Bubble signals over the 1 minute recording
- ? Grade 3,5 = continuous Bubble signals over the 1 minute recording, with numerous bubble showers
- ? Grade 4 = continuous Bubble signals over the 1 minute recording, with continuous bubble showers

A " Bubble Score Index - BSI" was obtained for each dive and for the combined " Dive plus Repetitive Dive" for each experimental profile as follows: all the ESS gradings obtained from the all the Doppler Readings were summed up and divided by the number of volunteer divers participating in each experimental dive profile. The resulting " BSI" was considered an index of the decompression stress imposed on the divers by that specific profile.

All the dive profile data, downloaded from the DAN Europe Black Boxes were mathematically analyzed and plotted against the maximum allowed M valued for each of the 8 tissue compartments of the Bühlmann ZHL8-ADT algorithm, to allow for comparison between the Doppler BSI and the computed tissue saturation, expressed as a percentage of the M Value, during the different phases of the ascent and at reaching the surface.

A total of 139 man-dives and 834 Doppler readings were made and analyzed.

Results

The results from the group of 15 volunteer divers who dived 7 of the 8 profiles show that the highest Doppler scores are observed after the no stop ascents (pure Hill approach) with a 5 and 10 min HT tissue saturation exceeding 60 and 80% of the allowed M Values. For these dives the BSI reached values of 8,79 for the speed of ascent of 3 m/min and of 7,34 for the speed of ascent of 10 m/min.

Medium-high Doppler scores were observed after the dives with a stop at 6 m for 5 minutes (the current hybrid Hill-Haldane approach), with a 5 and 10 min HT tissue saturation exceeding 30% and 65% respectively and BSI of 8,53 for the 3m/min speed of ascent, 7,38 for the 18 m/min speed of ascent, and 5,50 for the 10 m/min speed of ascent.

When the deep stop was introduced (pure Haldanian approach), the 5 and 10 minutes tissue tensions dropped to 25% and 50% respectively and the observed BSI (Doppler bubble score index) reached their minimum, with BSI of 3,25 for the 18m/min speed of ascent and 2,03 for the 10-m/min speed of ascent.

Table II – Fast Tissue Saturation and Bubble Scores after the different experimental dive Profiles

Ascent Rate	Stops	5 min Tissue Saturation (0 – 100 %)	10 min Tissue Saturation (0 – 100 %)	Bubble Score BSI	Total Time to Surface minutes
3 m/min (Profile 2)	No Stop	48	75	8.79	8
3 m/min (Profile 5)	6 m / 5 min	30	60	8.53	13
3 m/min (Profile 8)	15 + 6 m / 5 min	To be done	To be done	To be done	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	5.50	7.5
10m/min (Profile 6)	15 + 6 m / 5 min	25	52	2.03	12.5
18 m/min (Profile =)	No Stop	Not tested	Not tested	Not tested	Not tested
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	Not available yet at time of submission	Not available yet at time of submission	3.25	11.5

Note: The 3 m/min speed of ascent (experimental profile 8) has not been dived yet. The mathematical analysis of the tissue saturation for profile 6 is not yet completed at the time of the submission of this paper and will be presented

Not only the variation of the speed of ascent and the introduction of the " deep stop" at 15 meters favorably affected the general Bubble Score Index after these experimental open water dives, but also the distribution of Doppler Bubble readings and the relative incidence of Zero, Low Grade, High Grade and High Grade Plus readings among the divers and over time was positively influenced, as shown in Table II.

TABLE III – Incidence of Doppler Detected Bubbles after the different experimental dive Profiles					
Dive Profile	**BSI**	**Grade 0 %**	**Low Grade %**	**High Grade %**	**Very High Grade %**
1 – 1R	7.34	9.7	63.9	17.4	9.0
2 – 2R (worst)	**8,79**	**10.0**	**50.6**	**19.4**	**20.0**
3 – 3R	7.38	16.0	56.2	19.8	8.0
4 – 4R	5.50	16.7	67.4	11.2	4.7
5 – 5R	8.53	5.3	63.2	21.9	9.6
6 – 6R (best)	**2.03**	**60.8**	**37.2**	**2.0**	**0.0**
7–7R (next to best)	***3.25***	***41.7***	***55.6***	***2.7***	***0.0***

The best results, both expressed as total Bubble Score Index, and as shown by the relative incidence of zero, Low Grade and High Grade Precordial Doppler bubble readings, were obtained when the extra deep stop at 15 meters was introduced (profiles 6 and 7 - pure Haldane), while the worst results were obtained for the linear direct ascent to the surface with a speed of 3 meters per minute (profile 2 - pure Hill).

Conclusions

The fact that the majority (65%) of Decompression Sickness cases within the Recreational Diving Community are neurological in nature and that the spinal cord should be considered a fast compartment, with a half-time of 12,5 minutes, made us think and believe that the answer to the dilemma of the frequent "unexplainable" neurological decompression sickness cases is to be found, among other possible factors, in the improvement of the ascent profile, with a special attention to the short half-time compartments – the "Fast Tissues" .

This lead to the series of studies started with DAN's project Dive Safety and Safe Dive and continuing now, in America and Europe, with Project Dive Exploration, the Diving Safety Laboratory and their related " Special Projects", such as this " Speed of Ascent Study"

The results of the current study, although still limited to 7 of the 8 experimental dive profiles, show that the addition of an extra deep stop, in addition to the currently recommended "safety stop", to the ascent profile from "normal No-Decompression" recreational compressed air dives, kept the computer-estimated PltN2 levels (Leading Tissue Nitrogen Levels) of the fast and medium HT compartments within the tissue supersaturation M-Values indicated as safe by our previous studies and according to our " Proportional M-Value Reduction Concept" (PMRC), and greatly reduced Precordial Doppler Detected Gas Bubbles. This is confirmed in this study of 15 volunteer divers exposed to 139 repetitions with a dive matrix to 25 meters for 25 minutes, followed by a repetitive dive to 25 meters for 20 minutes after a 210 minutes interval, and repeating the dive on 8 different weekend dives following 8 different ascent profiles, with speed of ascent of 3, 10 and 18 meters per minute, with or without 5 minute stops at 15 and/or 6 meters. The volunteer divers acted as their own control.

These observations also confirm that the Delta-P imposed on the leading tissue, irrespective of the absolute speed at any time of the ascent ("instant speed"), is the critical factor for the production of precordially detectable bubbles, and, possibly, for the development of DCI in recreational dives.

The results indicate that slow, linear ascents (Hill approach) may be significantly more bubble-productive than ascents with even more rapid rates to reach intermediate stops and a similar total time to de-gas.

From our present data it would appear that the best combination to minimize post-dive bubble production is a speed of ascent of 10 meters per minute combined with "Haldanian type" stops, generally respecting to the 2:1 Haldanian decompression principle, which has, despite its good initial results, changed over time with the advent of decompression ratios as high as 4:1 for certain tissues, particularly for the fast half-time compartments.

The study will continue with a revision of the currently accepted recreational diving practices, with regard to an optimal ascent modality, by the implementation of a new algorithm to respect and resemble the observed biological results.

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