Effect of varying deep stop times and shallow stop times on precordial bubbles after dives to 25 msw (82 fsw)

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[1]Duke University Medical Center, [2,3]DAN Europe Foundation Research Division, Division of Baromedicine, University of Baromedicine, University of Malta Medical School, [4]DAN Southern Africa, [5]Center for Hyperbaric Oxygen Therapy, Military Hospital, Bruxelles, [6]Haute Ecole, Paul Henri Spaak, Occupational and Environmental Physiology Department, Bruxelles, Belgium

Bennett PB, Marroni A, Cronje FJ, Cali-Corleo R, Germonpre P, Pieri M, Bonuccelli C, Leonardi MG, Balestra C. Effect of varying deep stop times and shallow stop times on precordial bubbles after dives to 25 msw (82 fsw). Undersea Hyperb Med 2007; 34(6):399-406. In our previous research, a deep 5-min stop at 15 msw (50 fsw), in addition to the typical 3-5 min shallow stop, significantly reduced precordial Doppler detectable bubbles (PDDB) and "fast" tissue compartment gas tensions during decompression from a 25 msw (82 fsw) dive; the optimal ascent rate was 10 msw (30 fsw/min). Since publication of these results, several recreational diving agencies have recommended empirical stop times shorter than the 5 min stops that we used, stops of as little as 1 min (deep) and 2 min (shallow). In our present study, we clarified the optimal time for stops by measuring PDDB with several combinations of deep and shallow stop times following single and repetitive open-water dives to 25 msw (82 fsw) for 25 mins and 20 minutes respectively; ascent rate was 10 msw/min (33 fsw). Among 15 profiles, stop time ranged from 1 to 10 min for both the deep stops (15 msw/50 fsw) and the shallow stops (6 msw/20 fsw). Dives with 2 ½ min deep stops yielded the lowest PDDB scores – shorter or longer deep stops were less effective in reducing PDDB. The results confirm that a deep stop of 1 min is too short – it produced the highest PDDB scores of all the dives. We also evaluated shallow stop times of 5, 4, 3, 2 and 1 min while keeping a fixed time of 2.5 min for the deep stop; increased times up to 10 min at the shallow stop did not further reduce PDDB. While our findings cannot be extrapolated beyond these dive profiles without further study, we recommend a deep stop of at least 2 ½ mins at 15 msw (50 fsw) in addition to the customary 6 msw (20 fsw) for 3-5 mins for 25 meter dives of 20 to 25 minutes to reduce PDDB.

INTRODUCTION

Recent research in divers indicates that a deep stop, during decompression from a 25 msw (82 fsw) dive, significantly reduces precordial Doppler detectable bubbles (PDDB) and "fast" tissue compartment (5 min, 10 min, 20 min) gas tensions (1-3). This research showed that the introduction of a deep stop at 15 msw (50 fsw), in addition to the conventional 3-5 min shallow stop at 3-5 msw (10-15 fsw), significantly reduced or eliminated PDDB over a 90 minute period after surfacing. The results suggest that supersaturation of "fast tissue compartments" (e.g. 5, 10 and 20 min compartments) may be responsible for the predominantly neurological forms of decompression illness (DCI) reported in recreational scuba divers. This may be perhaps due to inadequate gas elimination from the spinal cord with its "fast" half time of 12.5 mins rather than the slower compartments used in many decompression algorithms.

Most decompression computer algorithms and dive tables used by recreational divers today have their foundations in the original ideas of Haldane or Hill (4, 5). Haldane modeled gas uptake and elimination on 5 exponentials of "fast" to "slow" tissue compartments, i.e. with 5, 10, 20, 40 and 75 min half times. Later this was increased by Buehlmann to as many as 16 or 8 tissue compartments (6, 7). The common premise was that as long as none of these compartments became supersaturated beyond a certain critical threshold, decompression sickness (DCS) could be avoided. Haldane also introduced the concept that it was safe to come from 6 ATA to 3ATA as it is from 4 ATA to 2 ATA etc. or a 2:1 ratio of absolute depth. This ratio of ½ the absolute depth was gradually modified over past decades, and now ranges from 4 to 1 for fast tissue compartments to less than 2 to 1 for slow tissue compartments.

An unforeseen consequence of these modifications to prevent DCS is that an important feature of Haldane's 1906 proposal - staged decompression at ½ the absolute depth - has now become lost in the most common forms of recreational diving. Instead a linear ascent at 10 m (30 fsw)/min is common with a "safety" stop at 3-5 msw (10-15 fsw). However, a comparison between the Haldane proposal for decompression (4) and linear ascent of Hill (5) in the early last century was in favor of the Haldane method rather than linear ascent.

In our recent research (3), the introduction of a deep stop at ½ the absolute depth appears to significantly decrease PDDB. Spencer 3 and 4 bubble grades are, in many cases, reduced to zero. In this paper (3) the optimal method for reducing post-dive bubble production and tissue compartment supersaturation during ascent is the combination of an ascent rate of 10 msw (30 fsw/min) with a 5 min deep stop at 15 msw (50 fsw) and a 5 minute shallow stop at 6 msw (20 fsw).

Given the finding that the deep stop prevents the formation of gas bubbles during the initial part of the ascent, the subsequent shallow stop could possibly be shorter. Presumably, a shorter deep stop also may be sufficient to eliminate PDDB. It was therefore proposed that both stops may be shortened and still reduce PDDB. Several recreational diving agencies have empirically recommended stopping for as little as 1 min deep and 2 mins at 6 msw (20 fsw). This is considerably shorter than the 5 mins stops in the recent research protocol (3) and may not be sufficient. The objective of the present research is to vary the times for deep and shallow stops to determine the optimal stop times as evidenced by the least occurrence of PDDB.

METHODS

209 Open Water dives were made to 25 msw (82 fsw) for 25 min by 14 volunteer Italian recreational scuba divers (Sub Novara Laghi) in the same manner as previously reported (3). A total of 15 different dive protocols were followed with varying times at the deep and shallow stops. Some of the dives were to 25 msw (82 fsw) for 20 min following a first dive to 25 msw (82 fsw) for a 3.5 hr surface interval (indicated by asterisks in the tables). The divers wore their own computers to record the depth and times of each dive. They also wore "blacked out" UWATEC dive computers (sampling time 20 seconds) so recorded data could not be seen by them. These were used to permit analysis of the predicted gas tissue compartment saturations for the various profiles and to confirm accurate depth and time profiles for the dives.

An Oxford Instruments 3.5 MHz Doppler probe with a digital recorder was used to make precordial Doppler bubble recordings.

Measurements were made by specially trained members of the diver teams. Recordings, as previously (3), were made with the diver standing, at rest for thirty seconds and again for thirty seconds after performing two knee bends. At 15 min intervals a total of six 1- min recordings were made over a total period of 90 mins post dive. Later the recordings were all analyzed for the presence of bubble signals by a single experienced and blinded researcher.

The presence of PDDB was graded according to three scales as previously described (3): a simplified Doppler Bubble Grading System (DBGS); the Spencer scale (SS); and our modification of the Spencer Scale (the Expanded Spencer Scale or ESS):

- 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
- HBG + - Very High Bubble Grade: bubble signals reaching grade 3 in the SS and 2.5 in the Expanded Spencer Scale (see below)

Expanded Spencer Scale

The original Spencer Scale was adapted by introducing "half grades" to allow a more incremental grading:

- Grade 0 = No bubble signals
- Grade 0.5 = 1 to 2 sporadic bubble signals over the 1 min recording
- Grade 1 = up to 5 bubble signals over the 1 min recording
- Grade 1.5 = up to 15 bubble signals over the 1 min recording, with bubble showers
- Grade 2 = up to 30 bubble signals over the 1 min recording
- Grade 2.5 = more than 30 bubble signals over the 1 min recording, with bubble showers
- Grade 3 = virtually continuous bubble signals over the 1 min recording
- Grade 3.5 = continuous bubble signals over the 1 min recording, with numerous bubble showers
- Grade 4 = continuous bubble signals over the 1 min recording, with continuous bubble showers

To determine a relative index of decompression stress, a "Bubble Score Index – BSI" was calculated for each "Dive plus Repetitive Dive" experimental profile*. Doppler readings from the participants were classified and recorded according to both SS and ESS systems. The six recordings for each diver were then added and divided by the number of participating volunteer divers for each profile to generate a mean score. Only 6 out of the 1,254 Doppler recordings could not be interpreted adequately and these were not included in the analysis.

While some authors have reported concerns with a score based on medians (8, 9), we concur with several others, who support this method (10, 11). The Fisher's exact test was then applied to the HBG and LBG occurrences to test the difference between proportions and the method of small p-values has been applied to calculate the two-sided p-value in analyzing the data (12).

* The BSI is a unique Doppler bubble scoring system that has been used extensively in research previously published by the authors. It is a surrogate for continuous monitoring, which is impractical for field studies and offers the equivalent of 'area under the Doppler bubble-time curve'. As such, it cannot be compared with peak Doppler grades using any other scoring system. The authors have found utility and consistency when using this method to reflect collective decompression stress.

Tissue Compartment Gas Saturations

As previously (3) the 5 tissue-compartment gas saturation was downloaded from the blacked out depth-time recorders worn by the divers and analyzed using a modified Buehlmann algorithm (9) to predict the saturation peaks for each of the 8 tissue compartments during the ascent. The changes in supersaturation were computed as fractions of their respective M values from commencing the ascent until reaching the surface.

RESULTS

Dive Profiles

The dive profiles were downloaded and compared mathematically to the experimental profile for consistency for time, depth and ascent rate. The results confirmed that the divers observed the prescribed dive profiles with an accuracy of no less than 99.7% for all parameters (SD = 0.0058; p = 0.12 Wilcoxon Signed Rank Test). This shows no significant difference from the experimental profile.

Doppler Bubbles Scores

Table 1 shows the BSI scores for the 15 profiles with varying deep and shallow stop times ranging from 0 to 10 mins. There are three groups of profiles: Profiles 1 to 5 had deep stop times from 0 to 2 minutes. Profiles 6 to 10 are all 2.5 min with shallow stop times gradually decreasing from 5 to 1 minute. Profiles 11 to 15 have deep stops ranging from 3 to 10 minutes. The greatest reduction in BSI was associated with dive profiles with deep stops at 15 msw (50 fsw) greater than 2.5 mins (Profiles 6 to 15). Shorter times, as in protocols 1 through 5 had higher bubble scores. Longer times, as in profiles 11 to 15, gave no further advantage. After the 2.5 min deep stop, the shallow stop at 6 msw (20 fsw) showed no significant difference as the time was shortened between 5 min down to only 1 min (see Profiles 6 to 10).

Without a deep stop at 15 msw (50 fsw) shallow stops as long as 10 minutes did not reduce the BSI as effectively as any profile for which a deep stop of more than 2 minutes was performed. Without a deep stop, a 10 min shallow stop was slightly better than only a

Profile No.	Dives	Depth (m)	15 m Deep Stop (mins)	6 m Shallow Stop (mins)	T Time	BSI
1	24	25	0	0	2.5	7.98
2	26	25	0	5	7.5	6.23
3	21	25	0	10	12.5	5.48
4	16	25	1	3	6.5	8.04
5	18	25	2	3	7.5	3.98
6	24	25	2.5	5	10	2.23
7	7	25	2.5	4	9	2.71
8	6	25	2.5	3	8	3.58
9	6	25	2.5	2	7	2.58
10	7	25	2.5	1	6	3.36
11	8	25	3	2	7.5	4.94
12	8	25	3	1	6.5	5.63
13	25	25	5	5	12.5	2.14
14	4	25	5	2.5	10	5.5
15	9	25	10	0	12.5	2.89

Table 1. Bubble Score Index for various deep (15 msw/50 fsw) and shallow (6 msw/20 fsw) stops on ascent from 25 msw (82 fsw) at 10 msw/min (33 fsw/min).

5 min shallow stop. However, the deep stop appears essential to ensure the lowest bubble production (See Figure 1).

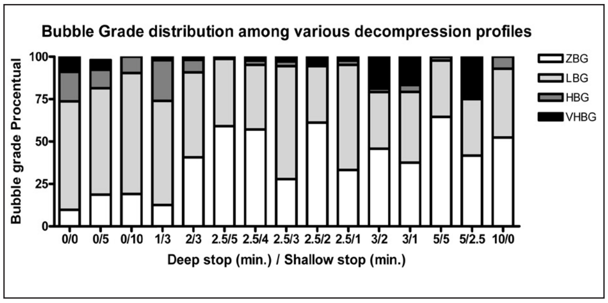


Fig. 1. ZBG : Zero bubble grade; LBG : Low bubble grade; HBG : High bubble Grade VHBG : Very high bubble grade

In Figure 2 the BSI for Doppler bubbles is compared at various times. The highest BSI is with the 1 min deep and 3 min shallow stops (1/3 in the Figure). With no deep stop but a 10 min shallow stop the BSI is less (0/10 in the Figure).

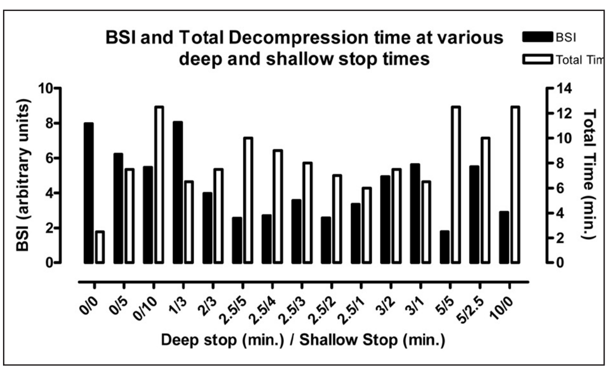
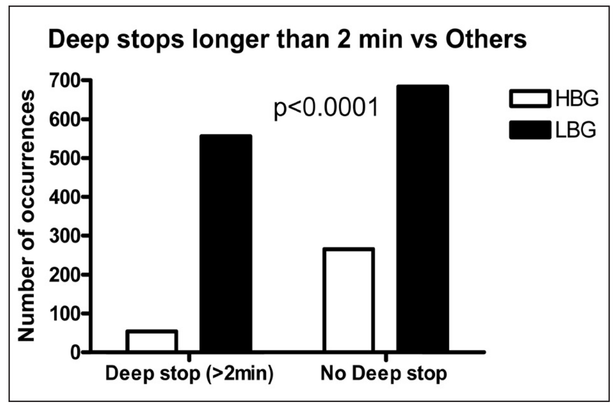


Fig. 2. BSI and total decompression time at various deep and shallow stop times.

On the other hand, if the deep stop is 10 min with no shallow stop (10/0 in the Figure) the BSI is, as discussed above, much the same as for only a 2.5 min deep stop. Again, with a 2.5 min deep stop, decreasing the shallow stop had no significant effect.

Figure 3 shows the statistical significance comparing a deep stop longer than 2 minutes versus no deep stop ($p < 0.0001$). However, if the comparison is done for deep stops overall (even less than 2 minutes) the difference is still at $p < 0.004$ Figure 3. The difference between the proportions of occurrences for the higher bubbles grades (HBG and VHBG) is very significant for the deep stop longer than 2 minutes vs. no deep stop ($p<0.0001$), yet if the comparison is done for the deep stops overall (even less than 2 minutes) the difference is still present ($p<0.004$) by the Fisher exact test (12). the Fisher exact test (12).



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Tissue Compartment Gas Saturations

The calculated tissue compartment gas saturations for the various stop times are shown in Table 2 (See page 404) from data recorded by the UWATEC computers worn by the divers during the dives.

Profile	Stops (Mins) Deep	Stops (mins) Shallow	Tissue Compartment Gradients (1/2 T mins)				BSI
			5	10	20	40	
1	0	0	61	82	81	64	7.98
4	1	3	44	62	70	71	7.38
12	3	1	51	69	76	77	5.63
14	5	2.5	40	61	72	76	5.50
2	0	5	43	65	69	58	5.39
11	3	2	46	65	73	74	4.94
3	0	10	30	49	62	68	4.93
5	2	3	40	56	67	71	3.72
8	2.5	3	42	62	72	77	3.58
10	2.5	1	49	68	75	78	3.36
15	10	0	46	66	78	84	2.89
7	2.5	4	39	64	76	81	2.71
9	2.5	2	41	61	72	78	2.58
6	2.5	5	35	51	64	70	2.23
13	5	5	29	57	70	63	2.14

Table 2. Tissue compartment gradients for 5, 10, 20 and 40 min tissue compartments calculated from UWATEC computers worn by the divers as compared to decreasing BSI. The values are given as percent saturation with 100% fully saturated.

The origin at 5 min deep 5 min shallow stops (Profile 13) showed the lowest tissue saturation of 29 for the 5 min tissue compartment (14) with a BSI of 2.14. The 2.5 min deep and 5 min shallow (6) also showed a low gradient of 35 with a BSI of 2.23. Interestingly the very long shallow stop of 10 mins with no deep stop had a gradient of only 30 but a BSI of 4.93. So lengthening the shallow stop was ineffective at reducing bubbles.

DISCUSSION

These results give further support to the findings reported in the previous paper (3) that a deep stop significantly reduces PDDB.

However, the correlation with lower fast tissue compartments is not as strong due to the aberration of Profile 3 with a low gradient but high BSI. According to the present results, the optimal time for a deep stop at 15 msw (50 fsw) is 2.5 mins for a 25 msw (82 fsw) profile. Shorter times increase the BSI. Further it would seem that after the 2.5 min deep stop, the shallow stop time at 6 msw (20 fsw) makes little difference to the BSI but could be less than the 3 to 5 min currently recommended.

Results of our earlier deep stop research and technical diving data were discussed at the U.S. National Association of Underwater Instructors meeting in 2003 in Florida. NAUI has since recommended that instead of the 3 min safety stop at 20 fsw (6 msw), divers should take a 1 min stop at half the bottom depth and a 2 min stop at 20 fsw (13). The present data do not support this recommendation as shown by Profile 4 whose high BSI is virtually the same as Profile 1 with no stops. A time of 2.5 mins appears necessary for the deep stop at 15 msw (50 fsw) after a 25 msw (82 fsw) dive. The data indicates that the shallow stop is not as important as a deep stop for this profile, but for practical purposes, the original 3-5 min shallow stop could be retained as it also attenuates the risk for pulmonary barotrauma.

Our research seeks to control bubble growth by the intervention of a deep stop to prevent supersaturation at depth and bubbles forming at that time but growing in size with ascent in accordance with Boyle's Law. If the deep stop is effective in stopping this bubble formation, the shallow stop, as the present research indicates, becomes much less important. This method of decompression may be designated as "beating the bubble" rather than "treating the bubble".

Deep stops also have been commonly used by recreational technical divers who have empirically devised their own methods for decompression. This has led to other methods for determining ascent profiles based on reduction of bubbles rather than supersaturation, such as the Wienke 'Reduced Gradient Bubble Model (RGBM)' (14). The RGBM is now utilized in a number of dive computers. There have been no extensive formal field trials validating the RGBM, but a data bank has been created to record some dives: By 2004, some 2,300 dives had been recorded with 20 cases of DCI, mainly after repetitive dives with nitrox and using reverse profiles (15).

A recent French paper (16) investigated the use of deep stops in three protocols tested in the wet compartment of a decompression chamber. In Profile I eight subjects dived to 60 msw (192 fsw) and in Protocol I used a deep stop beginning at 27 msw (86 fsw) followed by many other stops to the surface. Protocol II was a repetitive dive to 50 msw (160 fsw), a 3 hr surface interval followed by the second dive with the deep stop at 18 msw (58 fsw). Protocol III went to 60 msw (192 fsw) but used a single shorter stop at 25 msw (80 fsw). Using PDDB scoring, it was concluded that these experimental deep stop profiles provided no benefit compared with the standard MN 90 French Navy decompression table. Though no times are given for the stops, from the graphs they appear to be only about 1 min. If so, these could have been ineffective, as was the case with a similar too short deep stop from our 25 msw (82 fsw) dives. The depth of 60 msw (192 fsw) is also much deeper than our present work and may require different stop times and stop depths to significantly reduce the PDDB scores.

As a result of our deep stop research (3), the Italian Recreational Diver Federations have recommended the use of a 2.5 min deep stop at 15 msw (50 fsw) from a 25 msw (82 fsw) dive and similar dives during ascent so it will soon be possible to compare diving with and without the deep stop and the incidence of DCS resulting from its use for correlation with PDDB. However, reduction of PDDB may nevertheless help to make recreational diving safer. This would be consistent with the comments by Nishi et al. (8) who state "the incidence of DCS is higher when many bubbles are detected and that the incidence of DCS is low when few or no bubbles are detected. Thus, when evaluating decompression profiles, dives which produce many bubbles in a majority of the divers can be considered stressful with a higher risk of DCS and should be avoided. Conversely dives which produce few or no bubbles in the majority of divers can be considered safe."

CONCLUSIONS

We conclude that 2.5 min at 15 msw (50 fsw) is the optimal deep stop time following 25 msw (82 fsw) dives for 20 to 25 min for preventing PDDB. Shorter or longer times are not as effective. The shallow stop at 6 msw (20 fsw) for 3-5 mins normally recommended does not seem as important. However, longer times do not afford additional benefit in reducing PDDB.

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