DEVELOPMENT AND VALIDATION OF NO-STOP DECOMPRESSION PROCEDURES FOR RECREATIONAL DIVING: THE DSAT RECREATIONAL DIVE PLANNER

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ABSTRACT

The multi-year development of the RDP by DSAT included the generation of a new "model" for recreational diving and an extensive test program involving repetitive and multilevel dives. The RDP adapted the Haldane computational algorithm used by the U.S. Navy to the special needs of recreational divers. No-stop limits for the recreational range of 12 to 39 msw adapted from Spencer's (1976) empirical data on Doppler-detected bubbles in divers were fitted to a smooth curve having essentially a square root relationship between depth and allowable exposure time. We "back calculated" ascent-limiting M-values from the no-stop limits to prepare multilevel dive procedures for the RDP. For repetitive dives the RDP uses the 60 min compartment instead of 120 min as used for the U.S. Navy air tables, effective because the RDP diver makes only no-stop dives. The new algorithm was tested at the Institute of Applied Physiology and Medicine in Seattle. A total of 911 individual repetitive and multilevel dive profiles were run, in 437 single-day sequences; 809 with exercise, and 228 in open water. Careful examination of divers and monitoring of intravenous gas bubbles using Doppler ultrasonics revealed no DCS symptoms and few bubbles, allowing us to conclude that the RDP is reliable for single days of repetitive and multilevel diving. A second phase involved 4 dives per day for 6 days; 475 dives were conducted with no DCS, but with more bubbles than were found in single-day diving. A case of DCS resulted from a limited series of 6 dives/day. Overall we conclude that this program succeeded in developing and validating a new mode of decompression management for recreational diving, for up to 4 dives/day.

INTRODUCTION

This report describes an ongoing development project lasting over nearly a decade that has evolved into a refined decompression concept designed exclusively for recreational diving. "Recreational diving" is defined by the practice of training agencies in the U.S. as diving with air as the breathing gas to a maximum depth of 39 msw (metres of sea water, a unit of pressure equal to 0.1 bar) and without planned decompression stops. This new system is known as the RDP (Recreational Dive Planner); its primary implementation is as a circular slide-rule type device known as The Wheel. The development and testing of the RDP was supported by Diving Science and Technology Corp., a corporate affiliate of PADI, the Professional Association of Diving Instructors.

The motivation for development of a new decompression method was that even though they have served well in that role, the venerable U.S. Navy Standard Air tables are not well suited to recreational diving. They were not designed for the no-stop, often repetitive and multilevel, diving performed by recreational divers, but rather were intended for deeper dives,

for longer times, with decompression stops as a primary intent. Both repetitive and no-stop diving were more or less afterthoughts in the USN development process, and multilevel dives are not available at all. Both the USN time and depth groupings are rather broad from the recreational perspective, with the result that some shallow repetitive dives are excessively penalized. A new set of decompression procedures was needed that could be optimized for the patterns of recreational diving; these should be designed for short, no-stop dives with multilevel and multiple repetitive dive capability.

Table I. Comparison of no-stop times. Dive depth in fsw shown at left, with maximum allowable times by the USN, British Navy, and RDP.

Depth	US Navy	British Navy	RDP
30	None	232	---
40	200	137	140
50	100	72	80
60	60	46	55
70	50	38	40
80	40	27	30
90	30	23	25
100	25	18	20
110	20	16	17
120	15	12	14
130	10	11	12

METHODS

Development of the RDP

The RDP was developed by adapting the empirically-based Haldane computational algorithm used by the U.S. Navy to the special needs of recreational divers (this work primarily by Rogers). The first step was to derive no-stop limits for the recreational range of 12 to 39 msw. These were adapted from Spencer's (1976) empirical data on bubble development in divers, which were determined using Doppler ultrasonics bubble detection of venous gas bubbles. The Spencer times were fitted to a smooth curve having essentially a square root relationship between depth and allowable exposure time, following a suggestion by Hempleman (1975). Unlike the USN times which are all rounded to the nearest 5 min, the RDP times for the deeper dives are rounded to the nearest minute. These are shown in Table I ("fsw" is pressure in feet of sea water; 1 fsw = 1/33 atm, 3.2568 fsw = 1 msw).

The USN implementation of the Haldane method used half-time compartments (sometimes called "tissues") of 5, 10, 20, 40, 80, and 120 min. The RDP added 30 and 60 min compartments in an effort to smooth the "coarseness" in the range of 12-15 msw (with limited success), and longer half times to deal with multilevel and repetitive diving. The final set of half times are shown in Table II.

Table II. RDP M-values. Ht is compartment half time.

Ht	RDP
5	99.08
10	82.63
20	66.89
30	59.74
40	55.73
60	51.44
80	49.21
100	47.85
120	46.93
160	45.78
200	45.07
240	44.60
360	43.81
480	43.40

To permit the calculation of multilevel and repetitive dives we derived a set of ascent-limiting M-values by "back calculation" from the no-stop limits; these are also shown in Table II. The descent was considered in the calculation rather than assuming a "square" profile; this makes the M-values slightly more conservative. We used these to prepare multilevel and repetitive dive procedures for the RDP. The U.S. Navy repetitive diving tables were calculated based on gas loading in the 120 min compartment. The RDP took a fresh approach to repetitive diving, using the 60 min compartment instead of the 120 min compartment. Because the RDP diver makes only no-stop dives, a shorter half time for repetitive dives is more appropriate and it provides more efficiency. The RDP follows familiar techniques of using "pressure groups" and calculating the decay of residual nitrogen during the surface interval in the same manner as USN. The RDP uses 26 pressure groups instead of the 16 used by USN.

Multilevel dives, which are not part of the USN tables, were calculated using the M-values of Table II with standard Haldane exponential-exponential techniques (described in the detailed report, Hamilton et al, 1994, and in Schreiner and Kelley, 1971). Range limits were introduced to ensure that the next level was significantly shallower than the previous one. Groups were defined by iterative calculation.

A final step in the development was to put the new procedures onto a calculation device that could be used by the diver to calculate a sequence of no-stop dives, including square, multilevel, and repetitive patterns. The Wheel does not calculate dives with stops.

Validation testing

Because the computational algorithm was new it required testing. This was particularly true of the calculation of multilevel dives (no one had ever tested multilevel dives in the laboratory) and the repetitive dives based on the 60 min compartment. The testing was done using simulated dive profile sequences in a hyperbaric chamber, some supplemented by an equivalent series of open water dives. Phase I tested repetitive and multilevel dive profiles, based on a single day of diving. Phase II tested 6-days of multiday diving.

Tests were run at the Institute of Applied Physiology and Medicine in Seattle (Powell was the PI for the testing, with profiles selected by Rogers). Subjects were "informed" recreational divers from the local area. A wide variety of square, multilevel, and repetitive dives to at least the table limits were calculated with the RDP algorithm based on gas loadings; this made them a little less conservative than the RDP would produce. Pressure changes were at the traditional rate of 18 msw/min.

A total of 911 individual dives were run in Phase I, in 437 daily sequences or "sets". Some dives were multilevel, and all daily sets included repetitive dives; 809 dives were with exercise. A significant portion of Phase I, 228 dives, were open water dives in the cold waters of Puget Sound; some of these were short of the maximum allowable bottom time because of the cold, but all would have required stops by USN rules. Divers were monitored with precordial Doppler ultrasonic bubble detection after each of the repetitive dive sets, and after individual dives where possible. Divers were standing while being monitored, and the determination was repeated after the diver flexed by doing two deep knee bends. Scoring was according to the Spencer method (Spencer and Johanson, 1974). The "worst case" score was used for evaluation, and most of the analyses considered whether bubbles occurred or not. A few readings could not be graded and are excluded. In addition to the Doppler monitoring the divers were carefully examined for signs or symptoms of decompression sickness (DCS).

Uncertainty about the efficacy of basing repetitive dives on the 60 min compartment when used for multiple dives over several days led to a second test program, Phase II. Phase II was in two parts. Phase IIa looked at 6 dives per day by 4 divers, and after only 2 days a case of DCS caused that regime to be abandoned (by prior agreement). Phase IIb involved 4 dives per day for 6 days, with 20 diver-subjects (12 male, 8 female); 475 dives were conducted (a few were missed). Exercise was *ad libitum* on a rowing machine, and most performed some exercise on most dives. The "safety stop" called for by the RDP for all dives to the maximum time limit was performed. Doppler monitoring was essentially the same as for Phase I, 20-25 min and again 45-50 min after each dive, rest and flex. An additional investigator also listened to and scored the tapes. Again the highest grade for each monitoring session was used for analysis.

RESULTS

Phase I

The results from the Phase I study are summarized in Table III. This shows that bubbles were detected in 70 of 911 individual dive exposures followed by decompression, or 7.7%. Of the daily dive sets 58 or 437 showed some bubbles, 13.3%. Bubbles were scattered evenly over the entire set of dives, without favoring either "first" or repetitive dives. There was no higher incidence of bubbles in the inwater dives than in the chamber.

Phase IIa

As mentioned, there was a case of DCS at the end of the second day in the dives of Phase IIa. Of the 179 decompressions 44 had bubbles, 24.6%. The DCS was not in the diver with the most bubbles. It occurred in the night, in a knee that had been injured 3 years before in a motorcycle accident; treatment was routine.

Phase IIb

Of the 20 subjects, 3 had no bubbles at all, two had only one instance, and two had only two instances. Grades I and II were detected in 5 subjects, and 7 accounted for all the Grade III scores. We plotted the time course of Doppler scores for each subject throughout each 6-day series. Half of these, the results for 10 subjects, are shown in Figure 1 and the others in Figure 2. A profile of the 6-day exposure is shown in the center of each figure, which provides a graphical look at the overall exposure series. The horizontal axis shows time in days, and the vertical axis shows Spencer grades (in arabic numerals) for the individual subjects and depth in fsw for the profiles. Vertical bars show the Doppler grades, the highest score for as many as 8 values determined from each dive; that is, the "worst case" score for readings at rest and after flexing, on the first and second determinations, with each score judged by the two investigators. A very small bar, essentially a dot, shows where a reading was taken with a score of zero.

There is a strong tendency for the first two dives of the day to have lower scores than the later two, but we do not see a notice-

Table III. Summary of Phase I Doppler scores. A multilevel dive is one decompression so is one dive. A repetitive pair, two dives in one day, is two dives or two decompressions, but one dive set.

Total number of individual dives (decompressions)	911
Number of dives with exercise	806
Number of dives without exercise	105
Number of dive sets (diver days)	437
Number of dive sets with exercise	377
Number of dive sets without exercise	60
Total number of decompressions with bubbles	70
Total number of dive sets with bubbles	58
Percentage of dives with bubbles (70/911)	7.7%
Percentage of dive sets with bubbles (58/437)	13.3%
Percentage of dives with exercise & bubbles (64/806)	7.9%
Percentage of dives w/o exercise, with bubbles (6/105)	5.7%
% of dives w/ bubbles, readings at rest (16/911)	1.8%
% of dives with bubbles, after flexing (68/911)	7.5%
Number of inwater dives	228
Percentage of inwater dive sets with bubbles (10/228)	4.4%
Number of male dive sets	318
Percentage of dive sets by male divers (318/437)	72.8%
Percentage of male divers with bubbles (43/318)	9.8%
Number of female divers	119
Percentage of dive sets by female divers (119/437)	27.2%
Percentage of female divers with bubbles (15/119)	12.6%
Number of dives by male divers with bubbles	52
% of dives with bubbles, by male divers (52/670)	7.8%
Number of dives by female divers with bubbles	18
% of dives with bubbles, by female divers (18/241)	7.5%

able tendency for the number of bubbles to increase from day to day. No cases of decompression sickness were reported.

DISCUSSION AND CONCLUSIONS

Several additional limits are used with the RDP beyond the Haldane algorithm, for additional conservatism. These are considered just as much a part of the RDP as the numbers on The Wheel. These include limitations on ascent rates (≤60 fsw/min or ≤18 msw/min), the sequence of dives (progressively shallower), no repetitive dives deeper than 100 fsw or 30 msw, a mandatory "safety" stop (when within 3 pressure groups of a limit), and limitations on multiple (more than 3 dives/day) repetitive dives that reach certain gas loading limits based on pressure groups (the "W-X" and "Y-Z" groups). The W-X and Y-Z rules and the safety stop were incorporated into the Phase IIb testing.

An analysis of how closely the calculated gas loadings approached their M-value limits showed that compartments with half times up to about 80 min were essentially at the limit. For longer half times the limit drops off such that by the 480 min compartment the loadings are less than 90% of the M-value. This means that the multiday exposures did not nearly stress the long compartments. We tried to do this in the tests but found this is not possible with realistic no-stop dives of the type done by recreational divers; this does not mean dives do not affect dives done on subsequent days, only that the gas loadings are not at the limit. This shows that concern over multiday repetitive dives with the 60 min compartment may not be warranted, since using this compartment actually limits the exposure and makes it difficult to reach the M-value limit.

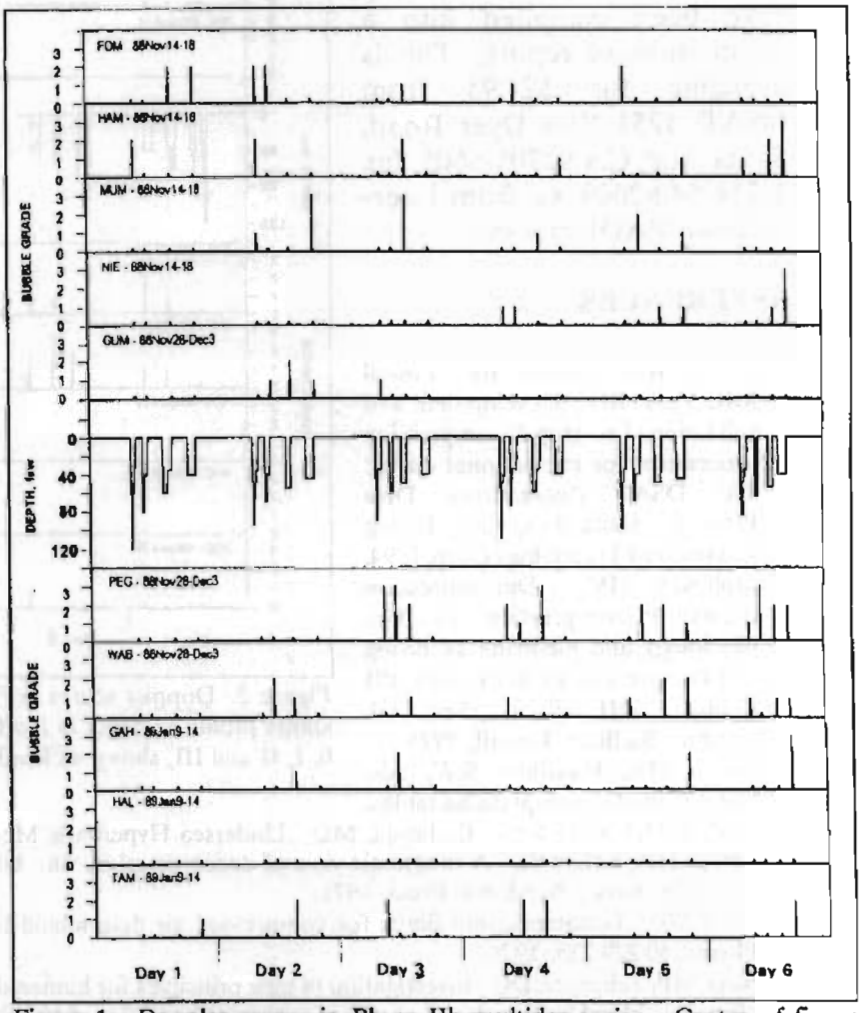

Figure 1. Doppler scores in Phase IIb multiday series. Center of figure shows profile as depth in fsw for the 6 days. Doppler scores are Grades 0, I, II and III, shown as height of bars; see arabic numbers on y-axis.

The study revealed no DCS symptoms and few bubbles, allowing us to conclude that the RDP is reliable for single days of repetitive and multilevel diving. We conclude further that the number of bubbles seen

in Phase IIb may make this exposure "marginal" with respect to what can be judged with Doppler scores. The risk of doing this kind of exposure is reasonable, but it may be higher than for single isolated days of diving. Further, a tentative conclusion—this one based on very limited data—says that 6 dives per day may be too many.

These tests met the criteria of the Undersea and Hyperbaric Medical Society's guidelines for validation of decompression tables, although many of these tests were performed before the guidelines were issued.

The development process and the results of the testing have been compiled into a comprehensive report. This is available for $24.95 from DSAT, 1251 East Dyer Road, Santa Ana, CA 92705-5605, fax 1(714)540-2609, or from international PADI offices.

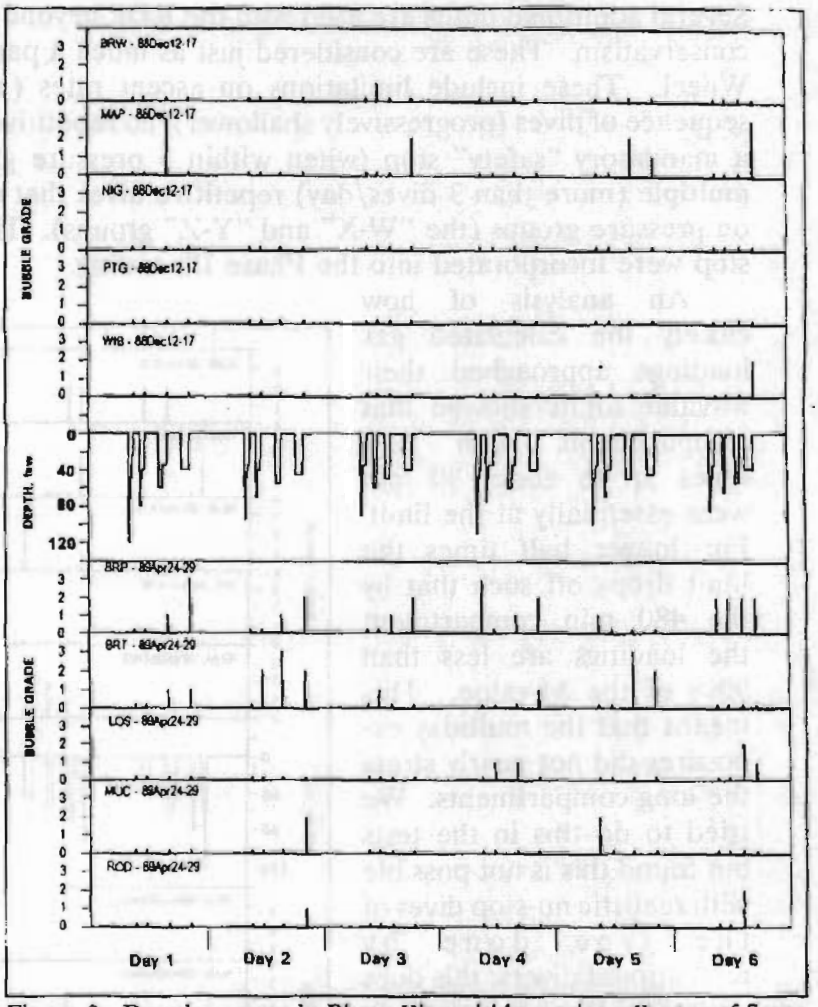

Figure 2. Doppler scores in Phase IIb multiday series. Center of figure shows profile as depth in fsw for the 6 days. Doppler scores are Grades 0, I, II and III, shown as height of bars; see arabic numbers on y-axis.

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