Empirical Evaluation of Extensions to No-Stop Limits for Deep Air Diving

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INTRODUCTION

The original Haldane decompression table (1) allows limited duration no-stop air dives to a maximum depth of 66 fsw. These tables were adopted by the U.S. Navy in the 1916 *Navy Department Diving Manual*.

The U.S. Navy subsequently undertook a series of 2143 experimental no-stop air dives to depths ranging from 100 fsw to 200 fsw with ascent at 50 fsw/min breathing air or oxygen (2). Detailed descriptions of these dives are not available, but results motivated the extension of no-stop dives to a maximum depth of 130 fsw in the U.S. Navy Standard Decompression Table first published in the 1943 *Navy Department Bureau of Ships Diving Manual*.

The depth range and durations of no-stop dives were further expanded in the U.S. Navy Standard Air Decompression Table (USN56) (3), which are the tables that have appeared in each revision of the *U.S. Navy Diving Manual* from 1959 to the present. The revised no-stop limits for nine depths were tested with two to four man-dives each.

The VVal-18 Thalmann Algorithm (4) underlies current U.S. Navy closed-circuit nitrox decompression tables, diver-carried Navy Dive Computers, the Navy Dive Planner, and the Topside Decompression Monitor presently being developed. The algorithm generally prescribes longer air dive decompressions than USN56 but permits longer no-stop limits than those allowed by USN56 for air dives deeper than 80 fsw. No-stop limits calculated to incur a 2.3% risk of decompression sickness (P_{DCS}) with two structurally different probabilistic models; BVM(3) (5) and USN93 (6); are similar to VVal-18 no-stop limits. Only limited test data exist for such longer no-stop limits.

METHODS

Selected VVal-18, BVM(3)-2.3%, and USN93-2.3% no-stop limits were to be tested for incidence of decompression sickness (DCS) with 100 man-dives each under the sequential stopping rule of P_{DCS} exceeding 5% with 90% confidence.

Divers (n=89) wearing 5–7 mm neoprene wet suits, breathing surface-supplied air via full face masks, and immersed in 55 °F (13 ° C) water in the NEDU Ocean Simulation Facility wet pot, were compressed at 60 fsw/min, performed 100 watt cycle ergometer work while on bottom, and then were decompressed directly to surface at 30 fsw/min.

Detailed human-use protocols for the study were reviewed and approved by the NEDU Institutional Review Board.

Man-dive results were combined with data from no-stop air dives conducted in seven other military laboratory trials since 1949 (7).

Two logistic models of form given in Eq. 1 (8) were fit with logistic regression to the combined data, one model for ALL DCS and another model for central nervous system (CNS) DCS only.

$$\ln\left(\frac{P_{DCS}}{1-P_{DCS}}\right) = \beta_0 + \beta_1 \ln(fsw) + \beta_2 \ln(BT) \qquad \text{Eq. (1)}$$

RESULTS

Series A testing was terminated early after the fourth DCS. Although the raw DCS incidence was acceptable, 1.4% (0.5%,3.2% 90%CL), all DCS cases were Type II with CNS manifestations.

Shorter Series B no-stop limits were tested under the hypothesis of a lower incidence of CNS DCS than that of Series A. This hypothesis was rejected, and Series B testing was terminated after the second Type II CNS DCS.

Results are summarized in Table 1.

Table 1. Present no-stop data

Series	Depth/BT (fsw/min)	Prescribed by	Man-dives	DCS
A	130/20	VVAL18	84	2
	150/15	VVAL18	100	1
	190/11	USN93, 2.3% P_{DCS}	100	1
B	130/16	BVM(3), 2.3% P_{DCS}	57	0
	150/12	BVM(3), 2.3% P_{DCS}	51	1
	190/9	VVAL18	40	1

BRIEF CASE DESCRIPTIONS

- "Heavy" legs, abdominal pain, numbness, paraesthesias, 40 minutes postdive
- Visual field deficit, 25 minutes postdive
- Right leg weakness and paraesthesia, balance difficulty, 20 minutes postdive. Recurrence of symptoms after first hyperbaric oxygen (HBO) treatment.
- "Heavy" legs, paraesthesias, progressing to paralysis below waist, 18 minutes postdive. Recurrence of symptoms after first HBO treatment
- Right hip pain and weakness, left flank pain, altered mental status, visual field deficit, balance difficulty, 10 minutes postdive
- Nausea, fatigue, dizziness, uncoordinated gait, altered mental status, blindness, 17 minutes postdive

The combined data (Table 2) encompass 1061 no-stop air dives with 25 DCS cases (2.4%), including 14 cases (1.3%) with CNS symptoms. The CNS DCS cases tend to appear where particular no-stop limits have been extensively tested. The majority of dives (68%) are deeper than 110 fsw.

Table 2. Combined present and historical no-stop data

fsw	BT (min)	Man-dives	DCS	CNS DCS
40-44	200-205	107	3	2
54-84	40-113	85	0	0
94	32-48	24	1	0
97-104	14-60	112	5	0
114	23-34	12	1	0
120-124	18-29	32	0	0
130-134	16-24	153	2	2
144	13-15	12	0	0
147-154	8-36	262	10	7
164-174	7-11	20	0	0
189-190	5-11	167	2	2
196-200	8-10	35	0	0
228-265	5-8	40	1	1

ALL DCS and CNS DCS models achieved significant fits (likelihood ratio with null model, $p < 0.001$) to these combined data with all coefficients significant (Wald test, $p < 0.0001$). Model-estimated iso-risk lines are plotted with no-stop limits in Figure 1.

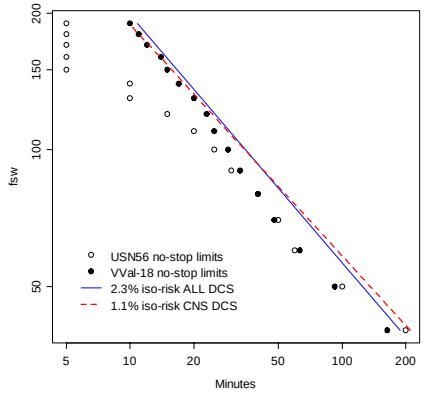

Figure 1. Observed rates of DCS for USN56 and VVal-18 air diving no-stop limits and model-estimated iso-risk lines.

All VVal-18 no-stop limits are shorter than (lie to the left of) limits on the ALL DCS 2.3% iso-risk line. 2.3% is the approximate overall incidence of all DCS in the combined data and is the mean P_{DCS} estimated for the VVal-18 no-stop limits with USN93 and BVM(3). The latter two models were calibrated with information from no-stop, decompression, multilevel, repetitive, and saturation dives - information richer than in the no-stop only data used here.

The VVal-18 no-stop limits for dives deeper than 110 fsw fall near the 1.1% iso-risk line for CNS DCS. 1.1% is the incidence of CNS DCS in the present data and close to that of the combined data set.

CONCLUSIONS

The severity of DCS makes longer no-stop limits deeper than 110 fsw prescribed by VVal-18, BVM(3)-2.3%, and USN93-2.3% unacceptable.

The presently tested limits are associated with a 1.1% incidence of CNS DCS predicted by a logistic model.

Testing of USN56 no-stop limits is in progress under the hypothesis that deep, working, no-stop dives of any duration may predispose to CNS DCS.

The preponderance of no-stop data deeper than 110 fsw and the occurrence of CNS DCS generally on schedules subject to extensive testing make it possible that a low incidence of unacceptably severe DCS may be a feature of no-stop limits at any depth.

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