Manned validation of a US Navy Diving Manual, Revision 7, VVal-79 schedule for short bottom time, deep air decompression diving

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Abstract
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Introduction: The US Navy air decompression table was promulgated in 2008, and a revised version, calculated with the VVal-79 Thalmann algorithm, was promulgated in 2016. The Swedish Armed Forces conducted a laboratory dive trial using the 2008 air decompression table and 32 dives to 40 metres' seawater for 20 minutes bottom time resulted in two cases of decompression sickness (DCS) and high venous gas emboli (VGE) grades. These results motivated an examination of current US Navy air decompression schedules.

Methods: An air decompression schedule to 132 feet seawater (fsw; 506 kPa) for 20 minutes bottom time with a 9-minute stop at 20 fsw was computed with the VVal-79 Thalmann algorithm. Dives were conducted in 29°C water in the ocean simulation facility at the Navy Experimental Diving Unit. Divers dressed in shorts and t-shirts performed approximately 90 watts cycle ergometer work on the bottom and rested during decompression. VGE were monitored with 2-D echocardiography at 20-minute intervals for two hours post-dive.

Results: Ninety-six man-dives were completed, resulting in no cases of DCS. The median (IQR) peak VGE grades were 3 (2–3) at rest and 3 (3–3) with limb flexion. VGE grades remained elevated two hours post-dive with median grades 1 (1–3) at rest and 3 (1–3) with movement.

Conclusions: Testing of a short, deep air decompression schedule computed with the VVal-79 Thalmann algorithm, tested under diving conditions similar to earlier US Navy dive trials, resulted in a low incidence of DCS.

Introduction

The US Navy air decompression tables have been widely used in military and commercial diving. The standard air tables (USN57) that had been in the US Navy Diving Manual since 1959 were replaced by the air decompression table that first appeared in the US Navy Diving Manual, Revision 6 (2008).[1] This table (USN-Rev6) integrates air decompression, in-water air/oxygen decompression, and surface decompression with oxygen into a single table, and introduces a 20 feet of seawater (fsw) last stop in place of the traditional 10 fsw last stop. USN-Rev6 was computed with the Thalmann algorithm and VVal-18M parameter set, which produced no-stop limits for dives deeper than 80 fsw that were longer than the USN57 no-stop limits. Testing of some of these longer no-stop limits resulted in cases of severe decompression sickness (DCS).[2] The longer USN-Rev6 no-stop limits were edited to the corresponding no-stop limits from USN57.[1,2] A slightly modified version of the air decompression table (USN-Rev7), computed with the Thalmann algorithm and VVal-79 parameter set, was promulgated in the US Navy Diving Manual, Revision 7 (2016). The reason for this latter change was that the VVal-79 Thalmann algorithm computes no-stop limits in accord with those in USN57, and therefore could be implemented in the navy dive computer (NDC).[3] In USN-

Footnote: The US Navy air decompression table measures depth in feet seawater (fsw) and this paper describes test dives conducted using fsw. Where fsw were the original unit, conversions to kPa use 1 fsw = 3.0643 kPa (Naval Sea Systems Command. US Navy Diving Manual, Revision 7, Change A. Washington (DC): Naval Sea Systems Command; 2018, Chapter 2, Underwater Physics, Table 2-10). This paper converts metres of seawater (msw) to fsw using the US Navy convention for calculation of decompression schedules that 1 fsw = 0.3048 msw, as a result 40 msw = 132 fsw (Gerth WA, Doolette DJ. VVal-79 Thalmann algorithm metric and imperial air decompression tables. Research Report NEDU TR 16-05. Panama City (FL): Navy Experimental Diving Unit; 2016). This US Navy conversion differs from the conventional definition that 10 msw = 100 kPa. For clarity, conversions of msw to kPa are not given.

Rev7, a few decompression schedules for bottom times just exceeding the no-stop limit have longer stop times than in USN-Rev6, but most decompression schedules are unchanged.[3]

In 2010, the Swedish Armed Forces adopted USN-Rev6, using a metric version based on the approximate conversion of 10 fsw to 3 metres' seawater (msw). Recently, the Swedish Armed Forces Diving and Naval Medicine Center (DNC) conducted a small series of laboratory man-dives using the 2008 air decompression table.[4,5] Twenty dives to 40 msw for 20-minute bottom times were conducted using the USN-Rev6 140 fsw (530 kPa) / 20-minute bottom time air decompression schedule, which prescribes a 7-minute decompression stop at 20 fsw (6 msw; 163 kPa). An additional 12 dives to 40 msw for 20-minute bottom times were conducted on a modified schedule with a 7-minute decompression stop at 6 msw and an additional 3-minute stop at 3 msw for a total stop time of 10 minutes. These 40 msw dives resulted in high grade venous gas emboli (VGE) and two resulted in mild DCS (shoulder pain and skin marbling) treated with recompression. One DCS followed each of the original and modified schedules.

This DNC trial was the first laboratory man-dive testing of air decompression schedules, other than the no-stop limits, from these tables. The air decompression table was promulgated on the basis that the air decompression times were longer than in the standard air tables being replaced, and on the basis of evaluation of the schedules with probabilistic models of DCS. The DNC result did not conclusively establish a problem with the air decompression tables but motivated a large-scale laboratory test of the USN-Rev7 schedules for short bottom time, deep air decompression dives. This study was first reported in Navy Experimental Diving Unit (NEDU) technical report 19-06.[6]

Methods

This study protocol was approved by the NEDU Institutional Review Board (Department of the Navy human research protection program approved protocol 18-17, DoN-HRPP Number NEDU.2018.0006) in accord with the Declaration of Helsinki.

DECOMPRESSION SCHEDULE SELECTION

In USN-Rev7, the 140 fsw for 20 minutes air decompression schedule prescribes a longer stop time (13 minutes) than the 7-minute stop time schedule in USN-Rev6 tested at DNC. However, because the DNC test of the 140 fsw schedule was conducted at 40 msw (132 fsw), the results remained relevant to current US Navy air decompression prescriptions. Table 1 shows relevant schedules and their estimated probability of DCS (P_{DCS}).[7] For instance, the 130 fsw (500 kPa) / 20-minute bottom time schedule in USN-Rev7 requires an 8-minute air decompression stop at 20 fsw, and a 132 fsw (506 kPa) / 20-minute bottom time dive that could be conducted using the NDC requires a 9-minute air decompression stop at 20 fsw. Both of these currently approved US Navy schedules are very similar to the dive profile tested at DNC, and the 132 fsw / 20-minute bottom time schedule was selected for testing.

EXPERIMENTAL DESIGN

The principal objective was testing of the VVal-79 schedule for 132 fsw / 20-minute bottom time with a 20 fsw last stop, under dive conditions typical of previous US Navy dive trials. The primary endpoint was DCS and the experimental unit was the man-dive not the diver-subject. The cumulative incidence of DCS in this study was predicted to be low (Table 1), and as is usual for validation of decompression schedules, the trial was designed to reject a decompression schedule with a high cumulative incidence of DCS, but otherwise accept the schedule. The specific hypothesis (H_0) was that the VVal-79 schedule for 132 fsw / 20 min bottom time with a 20 fsw last stop would result in P_{DCS} not higher than 5%, estimated from the observed cumulative incidence of DCS. The trial design had 84% power to detect 5% P_{DCS}.

The experiment was designed as an adaptive group sequential trial with a planned 96 man-dives. Had the cumulative incidence of DCS on the 20 fsw last decompression stop schedule reached pre-planned interim stopping criteria, the trial was planned to switch to testing of an equivalent schedule but with a traditional 10 fsw (132 kPa) last decompression stop. These stopping criteria were not met and the switch did not occur. VGE would have been used as an auxiliary endpoint to compare the two schedules if the trial had proceeded to test the alternative schedule. Details of the trial design and calculation of power are given in the technical report.[6] Although there was not a practicable difference in estimated P_{DCS} between the 10 fsw and 20 fsw last stop schedules (see Table 1), the change from a 10 fsw to 20 fsw last stop was a substantive change to US Navy air decompression procedures introduced with USN-Rev6 and USN-Rev7 that had not been subject to extensive testing.

DIVING AND INSTRUMENTATION

Sixty-one qualified military-trained divers gave written informed consent. Four divers did not participate in diving. Of the 57 participating divers, all but two were male. At the time of their first dive in this study, the 55 male divers who completed experimental dives had mean (SD) age of 36 (7) years, body weight of 91.6 (12.5) kg, height of 1.81 (0.06) m, and BMI of 28 (3). The two female divers were: age 37 and 30 years; body weight 74 and 55 kg, height 1.60 and 1.52 m; and BMI 29 and 23.

Subjects were required to avoid hyperbaric or hypobaric exposure for a minimum of 48 hours before and following any experimental dive. Subjects were restricted to one

Table 1
NMRI-98 estimated P_{DCS} of some relevant schedules. TST = total stop time

Profile	Schedule	20 fsw (min)	10 fsw (min)	TST (min)	P_{DCS}% (NMRI98)	P_{DCS} 95% pred. limits
132 fsw / 20	USN-Rev 6 140/20	7	–	7	1.91	1.41–2.53
132 fsw / 20	USN-Rev 6 + safety stop	7	3	10	1.81	1.32–2.43
140 fsw / 20	USN-Rev 6 140/20	7	–	7	2.25	1.66–2.95
140 fsw / 20	USN-Rev 7 (VVal-79)	13	–	13	2.15	1.58–2.86
132 fsw / 20	AIR III-79 NDC (VVal-79)	9	–	9	1.94	1.43–2.58
132 fsw / 20	10 fsw last stop (VVal-79)	1	9	10	1.99	1.46–2.65

alcoholic drink for 24 hours pre- and post-dive, and were instructed to be well-hydrated prior to the dive. Otherwise divers were allowed to follow their normal routine since this study was a test of operational procedures. Subjects were allowed to participate in multiple experimental dives in this trial. Subjects participated in one to four experimental dives (median = 2).

All experimental dives were completed in the wet pot of the ocean simulation facility at NEDU. The wet pot was set up to accommodate four divers at a time. Divers' breathing gas (79% N_2 / 21% O_2) was surface-supplied to full face masks. Divers wore t-shirts and shorts and the wet pot water temperature was actively controlled to a target of 29 ± 2°C. In the wet pot, subjects assumed a semi-prone position (approximately 15° head-up inclination to mimic fin-swimming) on custom-built, hysteresis-braked, underwater cycle ergometers (model HB210, Magtrol; Buffalo, NY). Divers were fully submerged with mid-chest approximately two feet below the wet pot water surface. The wet pot air space was compressed by the introduction of compressed air at a target descent rate of 60 fsw·min^{-1}, until the pressure at diver mid-chest level (chamber air pressure plus 2 fsw hydrostatic pressure) was equivalent to 132 fsw.

Immediately on reaching bottom, subjects began exercising on the cycle ergometers. Subjects pedaled at a target cadence of 60 rpm at a work rate of approximately 90 watts. This results in a diver oxygen consumption of about 1.6 L·min^{-1}, similar to previous US Navy decompression trials.[8,9] Subjects exercised continuously until three minutes before the end of bottom time. They then rested on the cycle ergometers until the end of bottom time and throughout decompression. The wet pot was decompressed at 30 fsw·min^{-1} to the first decompression stop and to the surface.

VENOUS GAS EMBOLI (VGE) DETECTION

For up to two hours during the post-dive observation period, subjects were monitored at approximately 20-minute intervals for VGE. The actual examination times were at mean (range) 16 (10–25), 35 (27–45), 56 (48–67), 76 (69–87), 96 (87–107), and 115 (104–127) minutes post-dive.

For each examination, the subject reclined in the left decubital position while the heart chambers were imaged (apical long-axis four-chamber view) with a trans-thoracic two-dimensional (2-D) echocardiogram. VGE in the right heart chambers were graded according to an ordinal scale adapted from Eftedal and Brubakk[10,11] and defined in Table 2. At each examination, VGE in the right heart chambers were graded three times: after the subject had been at rest for approximately one minute and then after forceful limb flexions of the right elbow and the right knee. For the flexion conditions, the grades were the maximum sustained for the following periods: grades 2 and 3 for at least four cardiac cycles; and grades 4a, 4b, and 5 for at least 0.5 s. The four cardiac cycle period follows from the grade 2 definition and the 0.5 s period was arbitrary. The resting grade and the maximum grade of all conditions (rest, arm movement, and leg movement) were used for analysis; the latter will hereafter be referred to as 'movement' VGE.

Results

Ninety-six man-dives were completed with no diagnosed incidents of DCS. Since stopping criteria were not reached, all dives were conducted on the 20 fsw last stop schedule. The observed cumulative incidence of DCS on the 132 fsw / 20-minute bottom time schedule with a 20 fsw last decompression stop was 0% (95% exact binomial confidence interval: 0%, 3%), and the observed proportions did not differ significantly (2-sided exact binomial test $P > 0.05$) from the NMRI-98 model-estimated P_{DCS} (Table 1).

It is conventional to express VGE as the peak grade of any examination time. The median (interquartile range) peak VGE grade at rest was 3 (2, 3), and the median peak VGE grade with movement was 3 (3, 3). Figure 1 illustrates the VGE grades at each examination time and shows that the highest VGE measurements at rest typically occurred at the 56-minute post-dive examination. VGE typically were detected throughout the two-hour post-dive observation period. At the end of the two-hour post-dive observation period, the median VGE grades remained elevated at grade 1 with rest and grade 3 with movement. Figure 1 illustrates the significant inter-subject variability in VGE grades.

Five subjects had no observable VGE at the 56- and 76-minute examination times, therefore, in accord with the study protocol, they were not examined at the 96- and

Table 2

VGE grading scale. For the flexion conditions, the grades were the maximum sustained for the following durations: grades 2 and 3 for at least 4 cardiac cycles; and grades 4a, 4b, and 5 for at least 0.5 s

Grade	Definition
0	No observable bubbles
1	Occasional bubbles
2	At least 1 bubble every 4 heart cycles
3	At least 1 bubble every heart cycle
4a	At least 1 bubble per cm^2 in every image
4b	At least 3 bubbles per cm^2 in every image
5	'White-out', single bubbles cannot be discriminated

115-minute examination times. These five individuals were given scores of 0 for the last two exam times to calculate the medians and interquartile ranges in Figure 1.

Discussion

The results support the specific hypothesis (H_0) that the VVal-79 schedule for 132 fsw / 20-minute bottom time with a 20 fsw last stop would result in a P_{DCS} not higher than 5%. The results indicate with high confidence that the P_{DCS} of the tested schedule is less than 3%, well below the 5% approximate upper limit of normal exposure dives in US Navy air decompression procedures.[3]

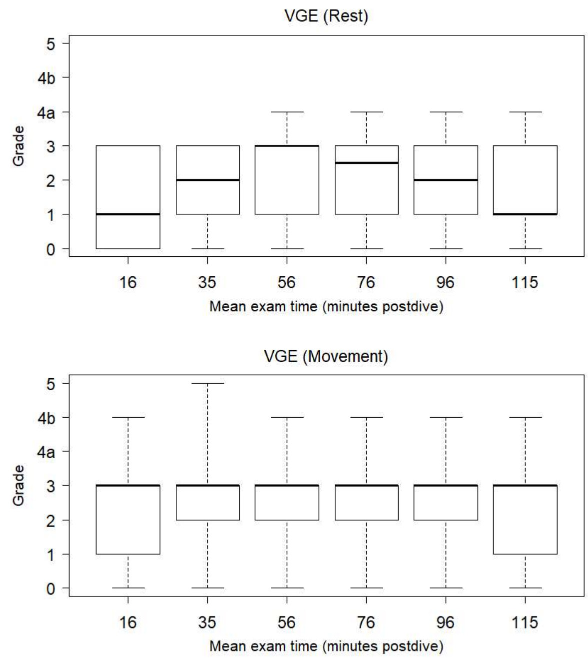
The elevated VGE grades in this study (hereafter referred to as the NEDU study) were consistent with the results of the DNC study. The median VGE at rest in the DNC study was KM (Kisman-Masurel) grade III. Three of the divers in the DNC study were treated with normobaric oxygen because of KM grade IV (maximum grade) that was still present one-hour post-dive.[4,5]

Excluding the three man-dives from the DNC study that were censored by oxygen breathing, the cumulative incidence of DCS observed in that study was 2/29 = 6.8% (95% exact binomial confidence interval: 0.8%, 22.8%). The observed cumulative incidence of treated DCS in the NEDU study (0/96) did not differ significantly from that of the DNC study (Fisher's exact test P = 0.052). However, the DNC study reported suspicious symptoms of heaviness and unease in one diver that occurred and resolved overnight between medical examinations.[4] If combined with the treated cases, this additional possible case of DCS results in an observed cumulative incidence (3/29) significantly higher than that of the NEDU study (Fisher's exact test P = 0.012). This latter difference motivates an examination of differences in the two study designs. The major differences were the total stop time, the number of dives in the preceding 48 hours, the water temperature and dress of the divers, and the diver activity levels on bottom and during ascent.

While the NEDU study was conducted with a total stop time of 9 minutes at 20 fsw (per the VVal-79 Thalmann algorithm), the DNC study conducted 20 dives with a total stop time of 7 minutes at 6 msw (in accord with USN-Rev6) and an additional 12 dives with a total stop time of 10 minutes (7 minutes at 6 msw and 3 minutes at a 3 msw safety stop). The NMRI-98 probabilistic-model-estimated P_{DCS} of the three schedules are very similar (see Table 1), indicating that the differences in total stop time between the schedules are trivial.

Figure 1

The maximum VGE grade (modified Eftedal Brubakk scale grades, y-axis) of any exam for the rest condition and the movement condition. The box and whisker plots indicate the median, interquartile range, and the range



To participate in the NEDU study, all subjects had to refrain from hypo- or hyperbaric exposure for 48 hours preceding their experimental dive. The only exceptions to this rule were three divers who participated in a study dive approximately 24–27 hours after surfacing from a preceding study dive that was aborted during descent. In the DNC study, on the day preceding the 132 fsw / 20-minute bottom time air decompression dives, 20 of the 32 divers performed a decompression air dive (51 msw for 10-minute bottom time with a 2-minute stop at 6 msw) followed approximately 4 hours later by a no-decompression air dive (24 msw for 25-minute bottom time). No cases of DCS were diagnosed following the first diving day. Of the two DCS cases treated after the second diving day, following the 40 msw / 20-minute bottom time air decompression dives, one occurred in the dive series group and one occurred in the group of divers who only performed the single dive. The DNC study reported no significant difference in VGE grades between the dive series group and the single dive group.[4,5]

While it has long been held that multi-day diving is a risk factor for DCS, there is also evidence that dives conducted during the preceding days actually lead to acclimatization and decrease DCS risk.[12]

In the DNC study, divers wore dry suits and undergarments in 9–10°C water, while in the NEDU study, divers wore t-shirts and shorts in 29°C water. A large series of experimental air decompression dives established that colder temperature during decompression significantly increases the risk of DCS.[13] Notably, while cold during bottom time decreases the risk of DCS, this effect is not as pronounced as the effect during decompression.[13] However, neither the DNC nor NEDU studies assessed the thermal status of the subjects during the dive, limiting our ability to determine the impact of any thermal differences on the risk of DCS.

In the DNC study, divers performed 'light swimming' for 10 minutes of their bottom time and during decompression. For the other 10 minutes of their bottom time, the DNC divers solved a jigsaw puzzle. The NEDU divers exercised on bottom and rested during decompression. Exercise during bottom time has been shown to increase the risk of DCS, possibly due to increased blood flow to and increased gas uptake by exercising muscles.[12] The evidence regarding exercise during decompression indicates that light exercise during decompression decreases the risk of DCS by increasing gas washout.[12,14] This evidence suggests that the exercise profile of the NEDU study conveyed a higher risk of DCS compared to the DNC study.

In a departure from previous air decompression procedures, USN-Rev6 and USN-Rev7 introduced a 20 fsw last decompression stop instead of a 10 fsw last decompression stop due to the operational advantages of a deeper last decompression stop. The 20 fsw last stop was promulgated without man-testing but on the basis of evaluation with probabilistic models of DCS, which showed no difference in the P_{DCS} of the 20 fsw and 10 fsw last decompression stops.[15] The present results, along with those of the DNC study, are the first test of the 20 fsw last decompression stop instead of a 10 fsw last air decompression stop in US Navy air decompression procedures.

Conclusions

Testing of a short, deep air decompression schedule computed with the VVal-79 Thalmann algorithm, tested under diving conditions similar to earlier US Navy dive trials, resulted in low incidence of DCS.

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