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MANIPULATING FREQUENCY OR DURATION OF AIR BREAKS DURING OXYGEN DECOMPRESSION DID NOT REVEAL A DIRECT CONTRIBUTION OF OXYGEN TO DECOMPRESSION STRESS

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14. ABSTRACT
Oxygen is breathed at decompression stops to enhance inert gas washout and accelerate decompression. However, there is evidence that high inspired partial pressure of oxygen can contribute to the risk of decompression sickness (DCS), presumably because oxygen can accumulate in tissues where it can contribute to bubble formation and growth and can reduce blood flow and inert gas washout. More frequent or longer air breaks than used conventionally during oxygen decompression may mitigate accumulation of oxygen in tissues, and allow oxygen breathing time to be reduced without increasing the risk of DCS. The incidence of DCS following oxygen decompression dives with conventional air breaks, longer air breaks, and more frequent air breaks were compared in a two-phase, adaptive group sequential trial. Venous gas emboli (VGE) and symptoms of oxygen toxicity were also recorded. Dry resting dives to 132 feet of sea water (fsw) equivalent air depth for 155 minutes were followed by 251 minutes of decompression stops, with oxygen breathing at 50, 40, 30, and 20 fsw. Three air break schedules were tested: cycles of 30/6, 24/12, and 12/6 (minutes oxygen/minutes air). There were differences in oxygen breathing time but no difference in decompression stop times. In phase one, 52 to 54 man-dives were conducted with each air break schedule. Two DCS occurred on each of the 24/12 and 30/6 schedules and none on the 12/6 schedule. Phase two continued comparison of the 12/6 and 30/6 schedules, and stopped at a planned interim evaluation with six DCS in 82 dives on the 12/6 schedule and two DCS in 96 dives on the 30/6 schedule. There was no difference in VGE grades between the three schedules. Fewer symptoms of oxygen toxicity followed the 12/6 schedule than the other two schedules. Unconventional air break schedules that sacrifice oxygen-breathing time for more frequent of longer air breaks did not increase the efficiency of decompression.

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CONTENTS

INTRODUCTION

Breathing an inert gas such as nitrogen at increased pressure, results in uptake of the inert gas into the body tissues. With decompression, ambient pressure can drop below the sum of tissue gas partial pressures (supersaturation), in which case bubbles may form and cause decompression sickness (DCS).[1] The probability of DCS (P_{DCS}) is minimized by decompressing slowly, usually by making decompression stops, to limit bubble formation and growth while allowing gas washout from tissues. Inspired and arterial inert gas partial pressures equilibrate rapidly, but the inert gases in the body tissues equilibrate with arterial blood at rates proportional to tissue blood flow and the difference between tissue and arterial inert gas partial pressures. Decompression stops are shortened by breathing oxygen (oxygen decompression), which accelerates inert gas washout by minimizing arterial inert gas partial pressures and thereby maximizing the inert gas washout gradient. Oxygen decompression is a feature of many U.S. Navy diving procedures and for rescue of personnel from a pressurized disabled submarine (DISSUB).[2] Some of these procedures require many hours of hyperbaric oxygen breathing, and future capabilities will require even longer exposure to hyperbaric oxygen. Ever longer periods of oxygen breathing incur increasing risks of pulmonary and central nervous system oxygen toxicity. A method is needed to enhance the effectiveness of oxygen decompression while minimizing the risks of oxygen toxicity.

In many decompression algorithms used to prescribe decompression schedules, only the inert gas partial pressures are considered to vary in tissues, and tissue and venous oxygen partial pressure (PO_2) are ignored or fixed at a small value — the latter convention is used in the U.S. Navy Thalmann Algorithm that is the basis for many U.S. Navy decompression procedures.[3] In such algorithms, an increase in inspired PO_2 contributes to P_{DCS} or decompression time only insofar as oxygen displaces inert gases. However, in animal experiments, breathing a high PO_2 while on the bottom contributes to P_{DCS}[4,5], presumably because oxygen accumulates in tissues and contributes to gas supersaturation in a similar manner as do the inert gases. In humans breathing operationally relevant PO_2's on the bottom (typically ≤1.4 atm), the contribution of oxygen to P_{DCS} is small at best.[6,7]

The situation during oxygen decompression is different from breathing a high PO_2 on the bottom. First, oxygen is more likely to accumulate in tissues relevant to decompression: a) oxygen decompression employs higher inspired PO_2's (1.6–2.5 atm) than breathed on the bottom; and b) oxygen breathing is employed during long, shallow decompression stops that are governed by compartments with slow gas exchange, compartments presumed to represent tissues with low blood flow and low oxygen consumption, and in which oxygen is likely to accumulate. Secondly, bubbles are likely to form during decompression to the oxygen-breathing stops[8], and once bubbles have formed, any increase in tissue PO_2 can contribute to their growth. Finally, hyperoxia is well established to cause vasoconstriction and reduce blood flow to tissues[9], which could reduce washout of inert gas from tissues. Indeed, whole-body nitrogen washout is reduced by hyperoxic breathing mixtures compared to normoxic breathing mixtures.[10] Thus oxygen-enhanced inert gas washout may be eroded by vasoconstriction with prolonged oxygen breathing. Collectively these effects may offset some of the benefits of oxygen-accelerated decompression. Aspects of these potential oxygen effects have been incorporated into some decompression models and algorithms.[11-13] However such contribution of oxygen to decompression stress during decompression has not been investigated experimentally.

The most operationally relevant strategy to reduce tissue oxygen during oxygen decompression is manipulation of air breaks. Hyperbaric oxygen breathing is interrupted with periods of air breathing (air breaks) to delay the onset of oxygen toxicity. When oxygen decompression was introduced in the U.S. Navy, oxygen was breathed continuously.[14,15] Air breaks during oxygen decompression first appear in the U.S. Navy Diving Manual in 1982 (Volume 2, Mixed-Gas Diving, Change 1 to Revision 1). Air breaks were introduced as 30-minute oxygen breathing periods followed by five-minute air breaks, and decompression tables were not recalculated but instead air breaks were considered 'dead time' during which no inert gas washout occurs. These same conventions are still used today. The basis for the air break schedule is not documented, but cycles of 30-minute oxygen periods / five-minute air breaks is the shortest air break and highest oxygen time / air time ratio that has been shown to extend hyperbaric oxygen tolerance in animals (see Clark 2005[16] for a recent review of the animal data), and may have been chosen for minimum impact on decompression under the presumption that oxygen does not contribute to decompression stress. However, substantial vasoconstriction develops during 30 minutes of hyperoxia and considerably longer than five minutes air breathing is required to restore blood flow[17], presumably because tissue oxygen levels decline slowly. It is possible that longer or more frequent air breaks may enhance decompression by allowing the oxygen accumulated in tissue and in bubbles to be metabolized and by restoring tissue blood flow and inert gas washout.

We were unable to find any reports evaluating the impact of any air break schedules on the efficiency of oxygen decompression. In this context, two decompression schedules for the same dive depth and bottom time differ in efficiency if they have different P_{DCS} for the same decompression time (or different decompression time for the same P_{DCS}). We hypothesized that the U.S. Navy diving air break schedule may not be optimum for decompression, and that oxygen breathing time could be reduced without increasing P_{DCS} by employing more frequent or longer air breaks than used conventionally.

METHODS

DECOMPRESSION SCHEDULE DESIGN

The primary outcome measure in this trial was the difference in incidence of DCS between an oxygen decompression dive with brief, infrequent ('conventional') air breaks and otherwise identical dives that have less oxygen breathing time and longer or more frequent air breaks ('experimental' air breaks). This design avoids confounding by different total decompression stop time (TST) or stop depth distributions.

The U.S. Navy Diving Manual prescribes a schedule of 30-minute oxygen periods followed by 5-minute air breaks for oxygen decompression in diving operations.[18] However, for the purposes of this study, a 'conventional' air break schedule was defined as 30-minute oxygen periods followed by 6-minute air breaks (30/6). Two experimental schedules were defined: 24-minutes oxygen periods followed by 12-minute air breaks (24/12) and 12-minute oxygen periods followed by 6-minute air breaks (12/6), which represented longer and more frequent air breaks, respectively. In all three schedules the oxygen / air break cycle times were even multiples of 18 minutes. This facilitated design of a decompression schedule in which the two experimental air break schedules had the same oxygen breathing times, and travel from stops occurred with subjects on the same breathing gas on all three air break schedules.

The principal requirements for the decompression schedule were: 1) a P_{DCS} likely to result in a measurable incidence of DCS; and 2) sufficiently long oxygen decompression time with many oxygen / air break cycles to allow any differences arising from the air break schedules to manifest. Additional desirable characteristics of the decompression schedule include a P_{DCS} not so high as to result in unacceptably frequent or severe DCS that would be a concern for safety of the subjects. In previous experiments comparing wet, working air decompression dives, we have limited probabilistic decompression model-estimated P_{DCS} to 7%[19], because dives with higher estimated P_{DCS} are associated with severe DCS.[20] However, P_{DCS} for the present dry, resting dives are likely overestimated by current probabilistic decompression models, which do not incorporate effects of exercise, so we arbitrarily set the limit at 8%. Also for subject safety, the total duration of breathing high PO_2 should be limited to minimize pulmonary oxygen toxicity. Consideration of the oxygen exposure included the fact that subjects with DCS would receive additional hyperbaric oxygen exposure during recompression treatment. To this end it was decided to use a 0.46 atm PO_2 breathing mixture (used in U.S. Navy saturation diving and considered not to contribute to pulmonary oxygen toxicity[21]) for the bottom time, and to limit the oxygen decompression to about four hours, the maximum in the U.S. Navy Air Decompression Table.[18] Also in consideration of pulmonary oxygen toxicity, it was decided to begin pure oxygen breathing at 50 feet of sea water (fsw), as is done in U.S. Navy surface decompression with oxygen ($SURDO_2$) procedures, but instead of completing oxygen decompression at 40 and 30 fsw, to continue decompression to a last stop depth of 20 fsw, as in U.S. Navy in-water air/oxygen decompression procedures.[18]

It was desirable that the dive profile be deep enough to accrue the decompression obligation in a relatively short time, so that the dive could be completed within a reasonable work-day, but not so deep as to require air decompression stops deeper than 50 fsw. To this end it was decided to use a 113 fsw bottom depth, which with 0.46 atm PO_2 has an equivalent air depth of 132 fsw. This had the advantage of being relevant to DISSUB rescue operations, where there is a requirement to decompress rescue personnel from exposure to a maximum disabled submarine internal equivalent air depth of 132 fsw. With all these constraints it was relatively straightforward to generate a schedule by trial and error (Table 1).

Table 1. Decompression schedule

Bottom Depth (fsw)	Time* at Bottom	Stops (fsw, mins†)					TST
		60	50	40	30	20	
113	155	5	11	60	72	103	251
	0.46 atm PO_2	Air	O_2/Air				

Descent rate 10 fpm. Ascent rate 30 fpm. *Time at Bottom in minutes does not include descent or ascent. †Stop times at 60 and 50 fsw do not include travel to stops. 50 fsw stop time begins with diver-subjects confirmed on oxygen. Stop times at 40–20 fsw include travel to stops. Stop times include air break times.

In this decompression schedule, the 60 fsw stop was an air decompression stop and was inserted primarily to effect the exchange of chamber atmosphere from the bottom gas to air (see in the Diving section on page 6). Oxygen breathing began at the 50 fsw stop. The two experimental air break schedules had 42 minutes less oxygen breathing time than the conventional air break schedule, and as result higher P_{DCS} estimated by the NMRI-98[13] or the BVM(3)[22,23] probabilistic decompression models (Table 2).

Table 2. Air break schedules, UPTD, and probabilistic decompression model-estimated P_{DCS}.

Air Break Schedule	Oxygen Periods (Minutes)	Air Periods (Minutes)	Total Oxygen Time (Minutes)	UPTD*	P_{DCS}†	
					NMRI-98	BVM(3)
12/6	12	6	168	432	7.48%	7.00%
24/12	24	12	168	432	7.63%	7.06%
30/6	30	6	210	539	4.63%	4.36%

*Unit Pulmonary Oxygen Dose calculated from the equations of Harabin et al.[24] †Model-estimated P_{DCS} for the decompression schedule in Table 1 with indicated air break schedule.

EQUIPMENT AND INSTRUMENTATION

All experimental dives were completed in “A”–“E” chambers of the Ocean Simulation Facility (OSF) at the Navy Experimental Diving Unit (NEDU). The plug was installed to isolate A”–“E” chambers from the trunk and the wet pot, which were not used in these dry dives. Chamber bunk mattresses were stacked on the deck and against the walls to construct couches for seating.

Pure oxygen was supplied to the subject using a modification of the OSF built-in breathing system (BIBS). An unmodified Scott II BIBS mask is an oral-nasal mask with two diaphragm-and-tilt-valve regulators. The inhalation regulator is connected via hose and quick disconnect to the OSF BIBS manifold which supplies breathing gas regulated at 80–120 psi above chamber pressure. The exhalation regulator is connected via hose and quick disconnect to the exhaust manifold through which gas is exhausted from the chamber through parallel back pressure regulators that can maintain 0–15 psi under-pressure relative to inside the chamber when there is a greater pressure differential from inside to outside the chamber. To avoid potential leakage of chamber air around the oral-nasal mask face seal, the BIBS were modified by eliminating the oral nasal mask and instead connecting the inhalation and exhalation regulators to a MK 25 underwater breathing apparatus t-bit. Subjects breathed oxygen through the t-bit mouthpiece while wearing a nose clip. To protect the back-pressure regulators from saliva, a water trap was installed in the exhalation hose between the subject and the exhalation manifold.

To monitor breathing gas, gas flow through nylon sampling tubes from each chamber, driven by the pressure differential from inside to outside the chamber, was directed to oxygen (paramagnetic) and carbon dioxide (infrared) gas analyzers. During oxygen breathing, a flow of gas from the OSF BIBS manifold was usually directed to the gas analyzer of an unoccupied chamber (usually “A” chamber). Oxygen fraction, carbon dioxide fraction, and ambient temperature, and “B” and “D” chamber pressure in fsw was recorded every two seconds to a computerized data acquisition system. These data will be used to construct dive profiles for future incorporation into the U.S. Navy decompression database.

DIVING

Sixty-six qualified U.S. Navy divers gave informed consent under NEDU Institutional Review Board approved protocol 14-52/40070. Four subjects did not participate in diving. At the time of their first dive in this study, the 62 subjects who completed experimental dives had mean (S.D.) age of 35 (7) years, body weight of 200 (24) pounds or 90.8 (11.1) kg, height of 71 (3) inches or 1.80 (0.06) m, body mass index (BMI) of 28 (3), body fat percentage estimated from body dimensions[25] of 19 (5). All 62 subjects were male. Individual subject details are given in Appendix A. Prior to their enrollment in the study, a Diving Medical Officer judged all subjects to be physically qualified for diving on the basis of review of medical records and a physical examination. Immediately before each experimental dive, subjects reported any current injury or illness and their amounts of exercise and sleep, any alcohol consumed, and any medications used in the previous 24 hours. On the bases of this self-report and a brief interview, a Diving Medical Officer either cleared or disqualified subjects for participating in each experimental dive.

Subjects were required to avoid any hyperbaric oxygen exposure above 1.6 atm PO_2 for 72 hours prior to the experimental dive, and hyperbaric or hypobaric exposure for a minimum of 48 hours before and following any experimental dive. These restrictions were to avoid any cumulative toxic effects of hyperbaric oxygen exposure and to avoid alterations in tissue inert gas partial pressures, gas supersaturation, and bubble growth that could influence P_{DCS} of the experimental dive.

Subjects were allowed to participate in multiple experimental dives in this trial, but no more frequently than once a week. Subjects diagnosed with DCS were not allowed to participate in another experimental dive until a Diving Medical Officer cleared them — typically 28 days after symptoms resolved, depending on DCS classification and treatment. Subjects participated in one to 10 experimental dives (median = 3). The diving watch bill was designed so that return subjects completed an approximately equal number of dives on each of the three schedules in phase 1 and completed an approximately equal number of dives on each of the two down-selected schedules in phase 2 (see Experimental Design on page 8 for an explanation of the two-phase design). The schedule of each subject's participation in experimental dives is given in Appendix B.

Forty-six days of diving took place in 5 blocks: 6–20 April 2015; 28 July–6 August 2015; 4–26 April 2016; 6-22 June 2016; and 12-27 June 2017. One dive per day was conducted, Monday through Thursday, at approximately the same time each day (the time of day of completing decompression ranged from 14:46 to 15:10).

Three to six subjects, designated (Red, Green, Yellow, Blue, Orange, White), participated in each experimental dive. Subjects wore chamber shoes, cotton shorts, and a t-shirt, and sweat pants and hooded sweatshirt as necessary for thermal comfort. Blankets were also available in the chamber for additional warmth. Once subjects were comfortably seated in "A" and "B" chambers, these chambers were compressed with air to 41 fsw to establish a chamber atmosphere PO_2 of approximately 0.46 atm. From this depth, compression to 113 fsw continued with nitrogen. Target chamber compression rate was 10 ± 1 fsw/min, target travel time was therefore 11 minutes and 18 seconds. At 113 fsw, a chamber atmosphere PO_2 of 0.46 atm (approximately 10% oxygen by volume) was maintained by the addition of oxygen as necessary. Subjects breathed the chamber atmosphere. Subjects spent most of the bottom time seated and watching movies. Subjects were directed by the Dive Watch Supervisor to stand and move about once every hour, but were otherwise free to move about the chambers as necessary at any time.

The following steps were taken to establish a chamber atmosphere of air (21% oxygen by volume) for the decompression stops. Prior to the end of bottom time, "C"–"E" chambers were compressed on air to 62 fsw. At the end of the time at bottom, "A" and "B" chambers were decompressed at 30 fsw/min to 60 fsw. On travelling through 62 fsw, the seal between "B" and "C" chamber would break and "A"–"E" chamber would all travel to 60 fsw together. At 60 fsw, the subjects moved into "C"–"E" chambers, where they began breathing the air atmosphere, and closed the hatch between "B" and "C" chambers. This hatch was sealed by decompressing "A" and "B" chambers to the surface. At the surface, "B" chamber was ventilated to establish an air atmosphere, and was later compressed on air to 40 fsw to meet "C"–"E" chambers.

At the end of the 5-minute 60 fsw stop, "C"–"E" chambers were decompressed to 50 fsw where the subjects began breathing oxygen using the BIBS mouthpiece while wearing a nose-clip. Air breaks were taken by removing the BIBS mouthpiece and nose-clip and breathing chamber air. All subjects began and ended oxygen breathing periods simultaneously under direction from the Dive Watch Supervisor. Throughout the decompression stops at 50, 40, 30, and 20 fsw, subjects remained seated while breathing oxygen but were free to move about the chamber during air breaks, and were directed to do so once an hour. When "B"–"E" chambers were all at 40 fsw, and during an air break, some subjects moved from "D" to "B" chamber; the additional space allowing greater comfort. At the end of the 20 fsw stop, subjects removed their BIBS and nose-clip if not already on an air break, and the chambers were decompressed to the surface.

After surfacing, subjects were observed for two hours during which time they generally remained seated and at rest. A Diving Medical Officer interviewed all subjects at 10 minutes and approximately two hours after surfacing, and again the following day (mean 19, range 15–26 hours after surfacing). The principal purpose of these interviews was to establish standard times at which subjects were definitely free of signs and symptoms of DCS; this information is required for incorporating these data into the U.S. Navy decompression database. Subjects were instructed to immediately report any unusual signs and symptoms that occurred outside of these interview times.

VENOUS GAS EMBOLI DETECTION

During the two-hour post-dive observation period, subjects were monitored periodically for venous gas emboli (VGE). Subjects were examined one at a time in the same order as their diver-subject designation (Red, Green, Yellow, Blue, Orange, White). The examinations were at approximately 29 (range 13–56), 66 (range 39–101), and 103 (range 80–127) 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) echocardiograph. VGE in the right heart chambers (which appear as brightly echogenic spots) were graded according to an ordinal scale adapted from Eftedal and Brubbak[26,27], and defined in Table 3. 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 around the right elbow and the right knee. For the movement condition, the grade was assigned to the highest signal sustained for about 0.5 s. Usually this maximum grade was obvious and sustained for 1–2 cardiac cycles, but in doubtful cases, a video buffer of the preceding 15 s (162 frames) was reviewed and the maximum grade sustained for about 5 frames (about 0.5 s) was assigned. Grades were assigned at the time of measurement and video recording of the measurements were not saved. Measurements were made by four different ultrasound operators throughout the study, but for continuity one of the investigators (usually DJD) attended all sessions, and the assigned grades were generally the consensus of the operator and investigator. For each man-dive, the maximum grade of all resting examinations and the maximum grade of all movement examinations (arm and leg) were used for analysis. These maxima of all examinations will be referred to as VGE grade without additional qualification.

Table 3. VGE grading scale

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

Several changes were made to VGE detection over the course of the study. For the first 45 man-dives (6–20 April 2015), VGE were detected using a Siemens Medical Solutions Acuson Cypress Portable Colorflow Ultrasound System with a 2.5 MHz cardiac probe. This machine became inoperable and was replaced with a Sonosite M-Turbo ultrasound, and VGE were detected with a p21 5-1 MHz cardiac probe and 2-D harmonic imaging mode. For the first 81 man-dives (6–20 April 2015 and 28 July–6 August 2015), VGE were graded according to the original Eftedal and Brubbak scale[26] in which grades 4a and 4b in Table 3 are collapsed into a single grade. In August 2015, an expanded version of the Eftedal and Brubbak scale, which includes the 4a and 4b grades, was endorsed in the consensus guidelines for the use of ultrasound for diving research[27], and the division of grade 4 into 4a and 4b was adopted because it provides better alignment with the VGE grading scale previously used at NEDU[28] — grades 3 and 4a align with the previous NEDU grade 3 and grades 4b and 5 align with previous NEDU grade 4. This alignment will facilitate future comparisons between the present and earlier data collected at NEDU. In the present report, VGE were analyzed using the original Eftedal and Brubbak scale (with 4a and 4b collapsed into a single grade 4).

OXYGEN TOXICITY SYMPTOM SURVEY

Subjects completed a 10–item self-assessment survey at the time of their pre-dive, the two-hour post-dive, and 19-hour post-dive medical assessments. Subjects were asked to grade seven symptoms of oxygen toxicity on an ordinal scale from 0-4 (categories: none, mild, moderate, moderately severe, severe). Two additional items, visual changes and ear problems, requested a grade and a free response describing the changes or problems. A tenth item requested a grade and free response describing any other complaints. The frequency of post-dive symptoms was collated. Post-dive responses were counted if the grade exceeded the corresponding pre-dive grade. Other complaints clearly not related to oxygen exposure (e.g., musculoskeletal pain) were not counted. Post-dive symptom surveys were excluded from analysis if the pre-dive survey was missing. Symptom surveys were excluded from analysis from subjects who received an additional hyperbaric oxygen exposure, because of treatment of DCS, prior to the 19-hour post-dive survey.

EXPERIMENTAL DESIGN

The primary outcome measure in this trial was the incidence of DCS with VGE used as an auxiliary outcome. Comparison of the three schedules in Table 2 followed a two-phase, adaptive sequential design.

Phase 1

The purpose of this phase of the trial was to identify the most promising (lowest P_{DCS}) of the two experimental air break schedules for continued testing in phase 2. Forty-eight man-dives were planned for each of the three schedules. At the end of Phase 1, the two experimental schedules were compared on the basis of incidence of DCS and on VGE grades. Insufficient DCS cases were expected after 48 man-dives for formal statistical testing. Difference in VGE grades was assessed using the Wilcoxon rank sum test. We have shown that for comparisons of decompression procedures using only VGE as an endpoint, 48 man-dives per schedule provides 80% power to distinguish a difference of one VGE grade at two-sided significance of $\alpha=0.05$.[29]

Phase 2

Up to 77 additional man-dives (for a total of 125) were planned on each of the conventional air breaks schedule and the experimental air break schedule selected in phase 1.

One purpose of this study was to establish if experimental air breaks could improve the efficiency of decompression. However, there are other advantages of longer or more frequent air breaks, such as less oxygen usage and shorter exposure to toxic doses of oxygen, that would make them desirable if such schedules were no less efficient in terms of TST than conventional air break schedules (more efficient use of oxygen). Therefore, it is desirable to test for practical equivalence in, as well as for a difference in, P_{DCS} of the conventional versus experimental air breaks. Practical equivalence is not established by insufficient evidence to reject a conventional null hypothesis of no difference. Instead, the experimental design tested whether or not the P_{DCS} of conventional and experimental air break schedules differed by an amount that is of practical importance. For the present experiment, a difference in P_{DCS} between conventional and experimental air breaks schedules of more than 1.5% was considered of practical importance for the present experiment. This is half the estimated difference in P_{DCS} between the conventional and experimental air break schedules (Table 1 and Table 2) and is equivalent to a difference of about 20 minutes in oxygen decompression stop time.

A difference in P_{DCS} was assessed from any difference in observed incidence of DCS. The outcome of each man-dive was categorized according to the Weathersby et al. 1988 criteria for the U.S. Navy decompression database.[30] The categories are A1) definite DCS requiring recompression; A2) “marginal DCS” or “niggles”; B) unknown outcome (data cannot be used); C) not DCS. These categories are described in more detail in Appendix C. The test statistic was the number of DCS on the experimental schedule minus the number of DCS on schedule C (x_{exp}-x_{conv}). The trial was to stop if any of the stopping rules in Table 4 was met.

Table 4. Stopping rules for determining risk difference between conventional and experimental schedules.

Stop with 80% confident >1.5% different	
# DCS $\lvert x_{exp}-x_{conv}\rvert \geq$	in # man-dives (or fewer)
3	72
4	120
5	125

The data was evaluated at the end of phase 1 and then each time another 24 man-dives, excluding any category B outcomes, were collected on each schedule. The stopping rules are based on 80% confidence of at least a 1.5% difference in DCS risk, but the number of man-dives at interim evaluations are rounded to the nearest multiple of 24.

The null hypothesis was formulated as (H_0): $P_{DCS.exp} \geq P_{DCS.conv}$+1.5%. This null hypothesis is in accord with probabilistic decompression model predictions and current belief that air breaks do not enhance the efficiency of decompression. Formulating the null hypothesis in this way recognizes that rejecting H_0 if the experimental air breaks schedules are actually less efficient than conventional air breaks would provide support for a potentially dangerous change to present U.S. Navy diving procedures. If the trial continues to 125 man dives without stopping (indeterminate outcome) or stops with a negative value of x_{exp}-x_{conv} (stop-low), H_0 is rejected. Monte Carlo simulations indicate this trial design has a conditional probability of rejecting H_0 if H_0 is true of 1.9%. If the trial stops with a positive value of x_{exp}-x_{conv} (stop-high), H_0 is retained. This trial has an estimated 11.9% conditional probability of retaining H_0 if H_0 is false. The conditional probabilities of possible trial outcomes (R) for alternative hypotheses (H) are given in Table 5. The method of performing these power calculations is illustrated in Figure 1 and Figure 2 and detailed in Appendix C of NEDU TR 15-04.[31]

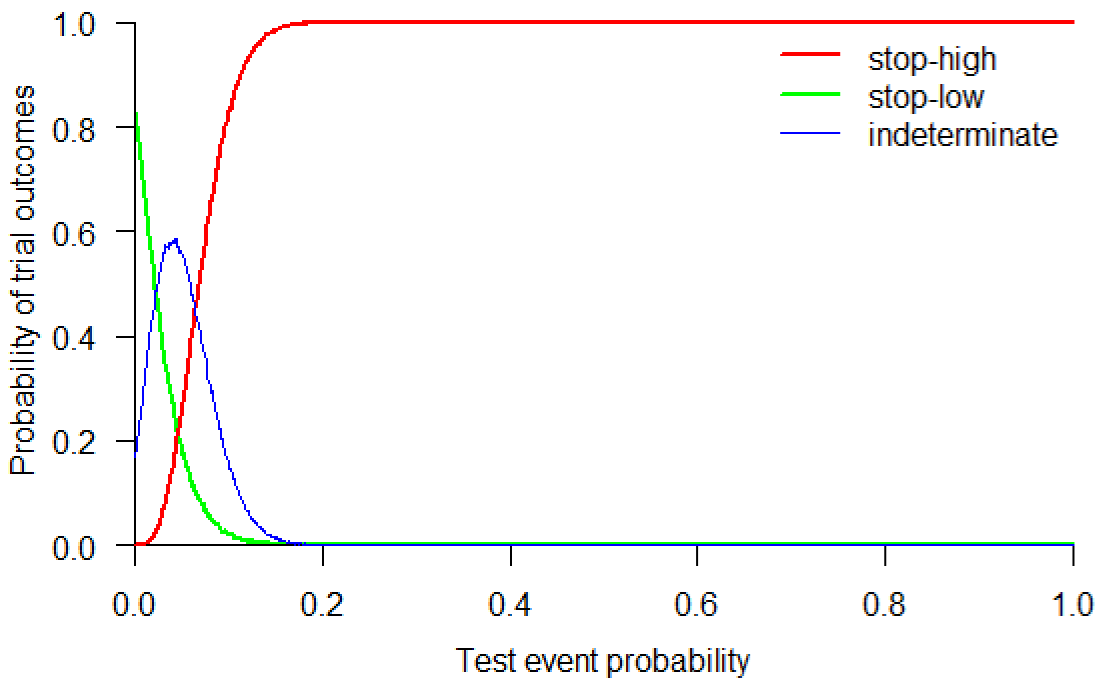

Figure 1. Monte Carlo simulation of the proposed trial showing the probability of trial outcomes (y-axis) for different actual P_{DCS} of the experimental air break schedule (x-axis) and for an estimated P_{DCS} of the conventional schedule of 0.046. Stop-high is the outcome of stopping with a positive value of x_{exp}-x_{conv} (experimental air breaks riskier than conventional air breaks, accept H1).Stop-low is the reverse outcome (accept H2) and indeterminate is continuing to 125 man-dives on each schedule (accept H0).

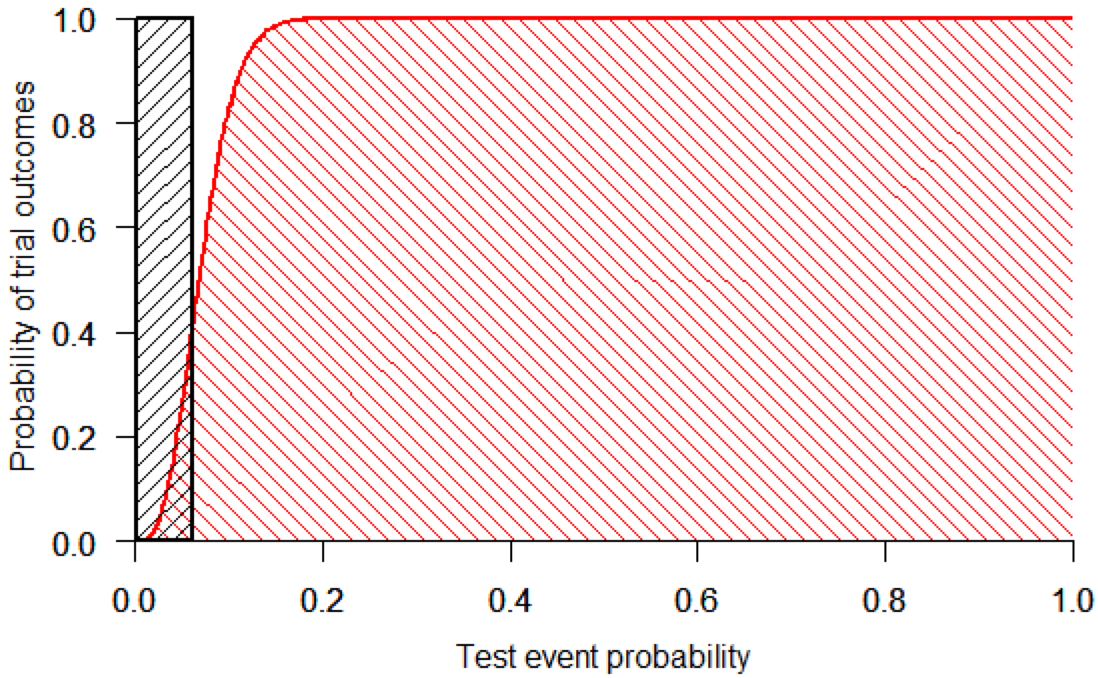

Figure 2. Example power calculation: probability of retaining H_0 if H_0 is false. Determination of the conditional probability of a stop-high trial outcome (retaining H_0) given real P_{DCS} of the experimental air break schedule ($P_{DCS.exp}$) is not more than 0.015 greater than the estimated P_{DCS} of the conventional air break schedule. Graph shows the stop-high component of the trial simulation given in Figure 1. The area inside the rectangle is the probability of all possible trial outcomes for real probability of $P_{DCS.exp}$ < 0.046+0.015 [*P*(A)]. The area under the reject distribution is the probability of a stop-high trial outcome for all real $P_{DCS.exp}$ [*P*(B)]. The intersection of these two areas (cross-hatched area) is the probability of a stop-high trial outcome for real $P_{DCS.exp}$ < 0.061 [*P*(A∩B)]. The conditional probability of a stop-high trial outcome given real $P_{DCS.exp}$ < 0.0.61 [*P*(B|A)] is the cross-hatched area divided by the rectangular hatched area [*P*(A∩B)/*P*(A)], which is 11.9%.

Table 5. Conditional probabilities of trial outcomes

		Real Condition		
		H_0 is True	H_1 is True	H_2 is True
Trial Result	R_0: Stop-High	98.1%	22.3%	1.8%
	R_1: Indeterminate	1.6%	55.3%	39.1%
	R_2: (Stop-Low)	0.3%	22.4%	59.1%

H_0: $P_{DCS.exp} \geq P_{DCS.conv}+1.5$
H_1: $P_{DCS.conv}+1.5 > P_{DCS.exp} > P_{DCS.conv}-1.5$
H_2: $P_{DCS.exp} \leq P_{DCS.conv}+1.5$

RESULTS

A total of 232 man-dives were completed. This diving was conducted with few deviations from the schedules. On one dive (2015-04-15, 30/6 schedule) the 50 fsw stop was accidentally timed from arrival at 50 fsw rather than the beginning of oxygen breathing. The resulting 13 s omitted time at 50 fsw was added to the 40 fsw stop. On another occasion (2016-04-06) the ascent to the first decompression stop was slowed because the exhaust vent inside the chamber was partially blocked by a plastic bag. The ascent lasted 6 min 33 s rather than the scheduled 1 min 46 s target ascent. No change was made to the decompression schedule because of the slow ascent. On this same dive, Red diver had two unscheduled air breaks, as a result of BIBS malfunctions, for a total of two minutes. In accord with a procedure specified in the protocol, Red diver received an additional eight-minute oxygen period at 20 fsw, but the remaining divers were brought to surface at the scheduled end of the 20 fsw stop.

DCS AND VGE IN PHASE 1

More man-dives than originally planned were completed on each of the three schedules in phase 1. In order to collect VGE grades for 48 man-dives on all schedules, phase 1 was extended after some VGE data were discarded. Following one dive on the 24/12 schedule (2016-04-04), very poor 2-D echocardiographic images were obtained in all six subjects by a trainee ultrasound operator. The investigator (DJD) supervising the measurement chose to discard the suspect VGE data from that dive. Figure 3 summarizes the VGE grades for phase 1 with the suspect grades excluded. There was no difference in VGE grade between the 12/6 and 24/24 schedules for the resting (p=0.6436) or movement (p=0.7467) conditions (two-sided Wilcoxon signed-rank test). Including the discarded VGE grades (rest: 0, 0, 0, 0, 0, 1, and movement: 0, 0, 0, 0, 1, 3) changes the p-values (rest p=0.8820 and movement p=0.2930) but does not fundamentally alter this result. There was no significant difference in the cumulative incidence of DCS (Table 6) between the 12/6 and 24/12 schedules (p=0.4954, two-sided Fisher exact test). The purpose of phase 1 was to down-select schedule 12/6 or 24/12 for continued testing along with 30/6 in phase 2. In the absence of any statistical difference in either VGE grades or cumulative incidence of DCS between the two experimental air break schedules, the 12/6 schedule, on which no DCS occurred was down-selected for continued testing in phase 2.

Table 6. Number of dives and DCS on the three air breaks schedules in phase 1

	12/6	24/12	30/6
DCS	0	2	2
Marginal DCS	1	4	4
dives	52	54	54

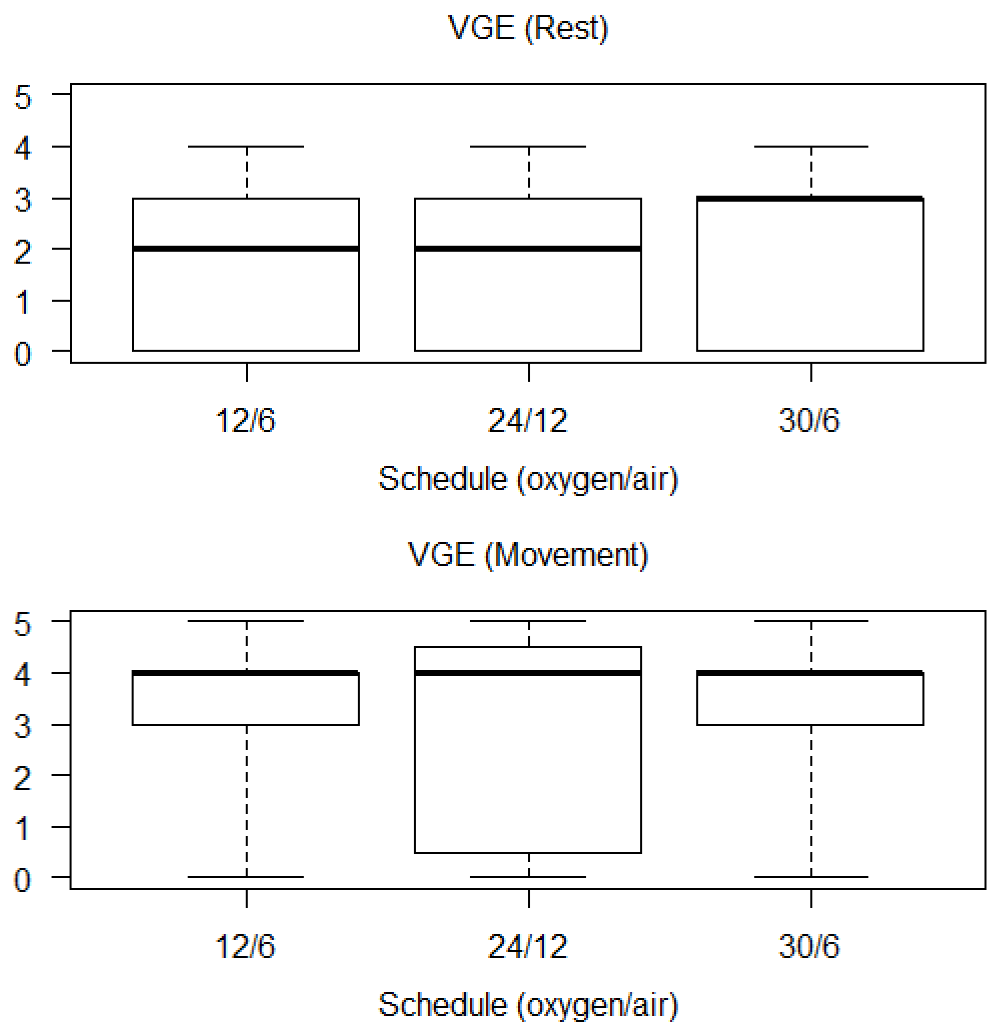

Figure 3. VGE grades following phase 1 dives. The data are the maximum grade (original EB scale grades, y-axis) of any exam for the rest condition (top panel) and the movement condition (bottom panel). The box and whisker plots indicate the median, interquartile range, and the range.

DCS AND VGE IN PHASE 2

During phase 2, no further cases of DCS occurred on the 30/6 schedule and six cases of DCS were treated following the 12/6 schedule (Table 7). After the sixth DCS case, 82 man-dives had been completed on the 12/6 schedule. The difference in DCS on the 12/6 and 30/6 schedules was in accord with the stopping rule given in row 2 of Table 4, and diving on the 12/6 schedule was provisionally suspended. Diving on the 30/6 schedule continued until 96 man-dives were collected — an interim evaluation point in the group sequential trial. No further cases of DCS occurred on the 30/6 schedule, so the stopping rule in row 2 of Table 4 was satisfied without need for further diving on the 12/6 schedule. The observed cumulative incidence (95% exact binomial confidence limits) of DCS on the 12/6 schedule was 7.32% (2.37, 15.25) and on the 30/6 schedule was 2.1% (0.25, 7.3), and these observed proportions did not differ significantly (exact binomial test $p>0.05$) from the NMRI-98 or BVM(3) model-estimated P_{DCS}'s (Table 2).

Table 7. Total number of dives and DCS on the three air breaks schedules (phase 1 and 2)

	12/6	24/12	30/6
DCS	6	2	2
Marginal DCS	1	4	5
dives	82	54	96

Both schedules resulted in high VGE grades (Figure 4). VGE had not diminished by the end of the monitoring period, and there was no significant difference in resting or movement VGE grades between the 66 minute and 103-minute (final) measurements for either schedule ($p>0.2$ for all cases, two-sided Wilcoxon signed-rank test). There was no difference in VGE grade between the 12/6 and 30/6 schedules for the resting ($p=0.9225$) or movement ($p=0.7591$) conditions (two-sided Wilcoxon signed-rank test).

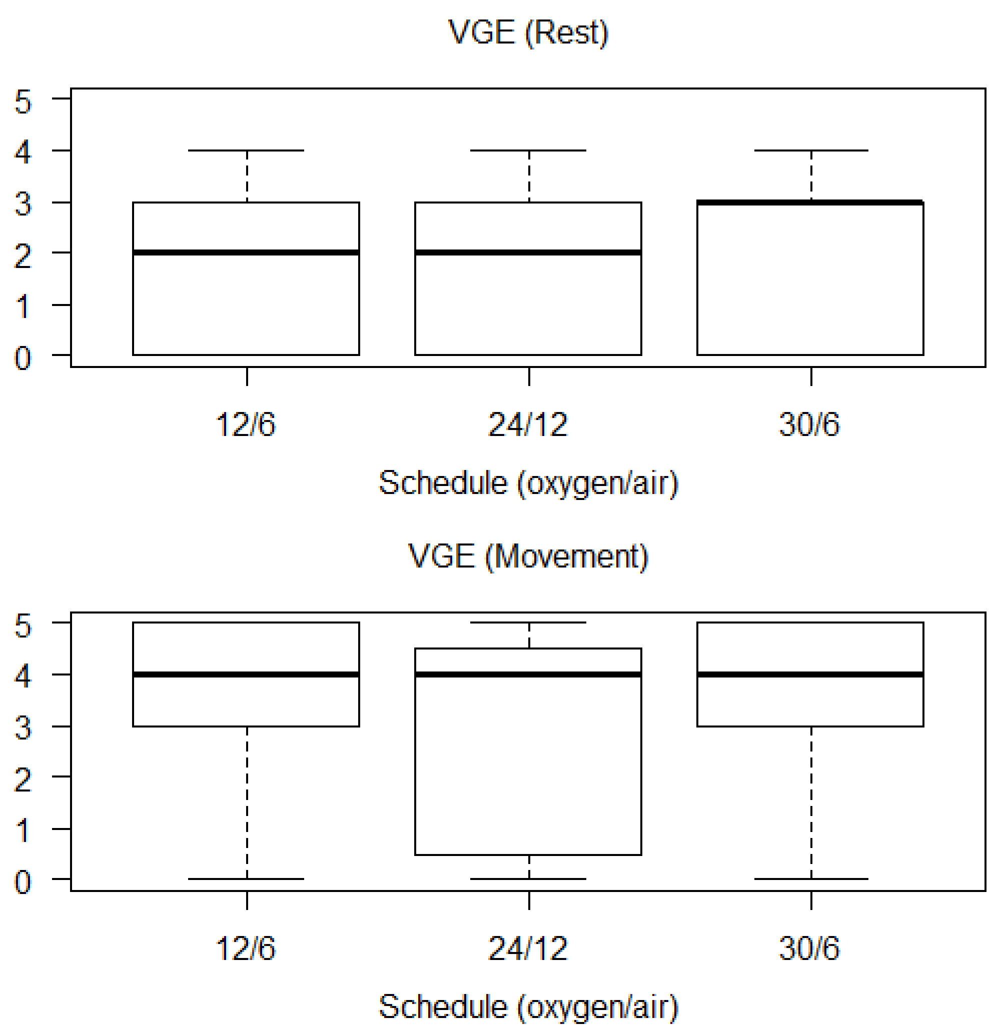

Figure 4. VGE grades following all dives (phase 1 and 2). The data are the maximum grade (original EB scale grades, y-axis) of any exam for the rest condition (top panel) and the movement condition (bottom panel). The box and whisker plots indicate the median, interquartile range, and the range.

OXYGEN TOXICITY SYMPTOMS

Surveys were not analyzed for eight dives after which the subject received hyperbaric oxygen treatment for DCS prior to the 19-hour post-dive survey. A pre-dive survey was missing for one dive. Of the remaining 223 dives, 54 dives (24%) were followed by reports of potential symptoms of oxygen toxicity at either the two-hour or 19-hour post-dive survey. For 14 of these dives, excessive fatigue was the only reported symptom. Excessive fatigue is relatively non-specific for oxygen toxicity, and if excluded, only 41 dives (18%) were followed by reports of potential symptoms of oxygen toxicity. The occurrence of symptoms for each of the air break schedules is given in Table 8. There was a significant difference in proportion of dives followed by symptoms between the three schedules when fatigue was excluded (p=0.0429) but not if fatigue was included (p=0.0795, two-sided χ^2 test). The proportion of dives followed by oxygen symptoms was significantly different between the 12/6 and 30/6 schedules when fatigue was excluded (p=0.0234) but not if fatigue was included (p=0.0680, two-sided Fisher exact test).

Table 8. Occurrence of any oxygen symptoms by air break schedule

	12/6	24/12	30/6
Dives with symptoms (%)	12 (15%)	16 (31%)	26 (27%)
Dives with symptoms excluding fatigue (%)	7 (9%)	12 (24%)	21 (22%)
Total number of dives included	77	51	95

Symptoms were generally described as “mild”; of 117 reported symptoms, 88 (75%) were graded as mild, 10 (9%) were graded as moderate, and 19 were indicated as present but not graded. Table 9 shows the frequency of symptom responses (yes, mild, or moderate) at two hours and 18-24 hours post-dive. The one report of visual complaints or changes was described as “distance visual acuity” (presumably diminished). Two of the descriptions of ear problems at 18 hours were fullness requiring frequent clearing and one description was “dry”. The other reports of ear problems were not accompanied by descriptions. The descriptions of “other complaints” were: agitation, anxiety while breathing oxygen, dry lungs, chest congestion, and difficulty running (this complaint was not accompanied by a positive response to the exercise intolerance question).

Table 9. Count of oxygen symptoms reported at the two-hour and 19-hour post-dive interviews

	Two-hour			19-hour		
	Yes	Mild	Mod.	Yes	Mild	Mod.
Inspiratory burning	1	10	2	1	5	1
Cough	1	9		3	9	
Chest pain or tightness		8	1	1	7	
Shortness of breath		4		1	2	
Unreasonable fatigue		9	2	4	11	3
Exercise intolerance					3	
Dry eyes	1	5	1		1	
Visual complaints or changes		1				
Ear problems		1		3	1	
Any other complaints	2	1		1	1	

DISCUSSION

The results do not support the hypothesis that unconventional air break schedules that sacrifice oxygen-breathing time for more frequent or longer air breaks can increase the efficiency of oxygen decompression. This trial stopped with a greater cumulative incidence of DCS on the 12/6 compared to the 30/6 schedule (positive value of x_{exp}-x_{conv}), indicating with high confidence that more frequent than conventional air breaks during oxygen decompression do not enhance the efficiency of oxygen decompression. Indeed, the results indicate that the more frequent air breaks and less oxygen time increased the P_{DCS} compared to a conventional air break schedule. This result is in accord with conventional thinking, and probabilistic decompression model-estimated P_{DCS} for the experimental and conventional air break schedules (Table 2). The 12/6 schedule was selected over the 24/12 schedule for continued testing in phase 2, despite no significant difference in cumulative incidence of DCS or VGE grades between these two experimental schedules. However, it is unlikely that the trial results would have been different had the 24/12 schedule, with longer than conventional air breaks, been selected for continued testing in phase 2, since the two experimental air break schedules had similar model-estimated P_{DCS} (Table 2), and the 24/12 schedule had already accumulated two incidents of DCS at the end of phase 1, at which point no DCS had occurred on the 12/6 schedule.

The lack of difference in VGE grades between the schedules does not contradict the DCS outcome. Analysis of VGE data collected at NEDU using similar protocols to the present study indicates that, whereas a difference in VGE grades is indicative of a difference in P_{DCS}, failure to find a difference in VGE grades should not be interpreted as no difference P_{DCS}.[28] Although the trial stopped with a greater cumulative incidence of DCS on the experimental than on the conventional air break schedule, the difference was not large, and the difference in P_{DCS} between the schedules may not be sufficiently large to manifest as a difference in VGE grades. Nevertheless, the limitations in the VGE monitoring protocol should be acknowledged. The VGE measurements were relatively infrequent and there was no indication VGE grades were declining at the final measurement, so it is possible that the peak VGE grade was not consistently captured. It is unlikely however that such aliasing affected one schedule more than the other so that a true difference in VGE grades was not observed.

The fewer self-reports of symptoms of oxygen toxicity on the 12/6 schedule than on the 30/6 schedule is in accord with the lower dose of hyperbaric oxygen on the experimental schedule (see UPTD in Table 2). Although fewer dives were conducted on the 24/12 schedule, it is of interest that despite the lower dose of hyperbaric oxygen, a similar percentage of dives resulted in symptoms of oxygen toxicity on this schedule as on the conventional air break schedule. It may be that shorter than conventional oxygen periods are more important than longer than conventional air breaks in reducing pulmonary oxygen toxicity. This advantage of shorter oxygen periods is consistent with previous observations of extension of pulmonary oxygen tolerance in humans, although only a few different oxygen / air break schedules have ever been tested (20/5, 30/30, and 60/15), all at 2.0 atm PO_2, and in very few subjects.[32]

We were unable to find any previous experimental evaluation of the impact of any air break schedules on efficiency of oxygen decompression. However, the contribution of a single air break to P_{DCS} has been assessed in the context of oxygen pre-breathing. Oxygen pre-breathing is used to washout inert gas from body tissues before decompression, and is a technique typically employed before decompression from saturation, where all body tissues are equilibrated with the inspired inert gas partial pressure. In some circumstances, the pre-breathe may be “interrupted” out of operational necessity. Generally, a single, relatively brief interruption of oxygen pre-breathe prior to ascent from ground level to altitude or prior to no-stop ascent from depth results in an increased cumulative incidence of DCS compared to uninterrupted prebreathe.[33,34] Interrupted oxygen pre-breathe is a different situation to air breaks during decompression. During an interruption of oxygen pre-breathe, all tissues reacquire nitrogen, whereas during an air break, nitrogen continues to washout of the tissues that are governing the oxygen decompression stop, because these tissues are supersaturated.

There are some data describing oxygen decompression using unconventional air break schedules, but the experiments were not designed to evaluate the air break schedules themselves. The decompression schedule development in support of the ADS-IV deep diving system and Sealab III employed several air break schedules comprising equal periods of oxygen and air (10-, 20-, and 30-minute periods).[35,36] However, these were deep heliox dives, and long air breaks during oxygen decompression may exploit slower uptake of nitrogen than washout of helium that is likely in tissues with slow gas exchange[37], making these data of limited relevance to oxygen decompression from air or nitrox exposures. The development of oxygen-accelerated decompression schedules for DISSUB survivors saturated at shallow equivalent air depths and DISSUB rescue personnel after long, shallow air exposures employed 60-minute oxygen periods followed by 15-minute air breaks.[38,39] Although each of these trials successfully employed unconventional air break schedules, none directly compared the decompression efficacy of different air break schedules.

It is of interest that the NMRI-98 and BVM(3) probabilistic decompression models provided similar estimates of P_{DCS} for the three schedules tested in the present work, and these estimates were in accord with the observed cumulative incidences of DCS. In one sense, the similarity of the estimates between the two models is not surprising since both models are calibrated with similar data; the BVM(3) calibration data is a subset comprising 77% of the NMRI-98 calibration data.[13,22] However, the BVM(3) calibration data does not contain any dives with oxygen decompression, whereas the NMRI-98 calibration set includes an additional 1013 man-dives using oxygen decompression or $SURDO_2$.[13,22] The NMRI-98 probabilistic decompression model is a gas content model in which P_{DCS} is a function of supersaturation in three tissue compartments with different gas exchange half times. Oxygen contributes to supersaturation, but in two compartments PO_2 is fixed at a small value, whereas in the compartment with the intermediate nitrogen half time, the contribution of oxygen is more complex. At inspired PO_2 above 0.86 atm, oxygen is taken up and washes out of the intermediate compartment like an inert gas, and can therefore have a greater contribution to P_{DCS} than if fixed at a small value. This latter elaboration of the model structure and the additional calibration data were used to improve NMRI-98 model estimates of P_{DCS} for oxygen decompression dives compared to earlier models in which PO_2 in all compartments did not vary.[13] In the BVM(3) model, P_{DCS} is a function of calculated bubble volumes in three tissue compartments. In all compartments, PO_2 is a fixed value such that changes in inspired PO_2 contribute to P_{DCS} only insofar as oxygen displaces nitrogen. It is interesting that without elaborations on the role of high inspired PO_2, BVM(3) correctly estimated the P_{DCS} of these oxygen decompression dives. These observations, along with the experimental results, suggest that elaboration of role of oxygen in probabilistic decompression models is not necessary for diving applications.

The present data are the first to compare the decompression efficiency of different air break schedules during oxygen decompression. Although different air break schedules can be used, the results do not support the hypothesis that unconventional air break schedules can increase the efficiency of oxygen decompression. These results do not motivate a change from the U.S. Navy convention of using cycles of 30-minute oxygen and five-minute air break times for oxygen decompression.

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APPENDIX A SUBJECT CHARACTERISTICS

Diver ID*	Age[†]	Height (inch)	Height (m)	Weight (lb)	Weight (kg)	Waist (inch)	Waist (m)	Neck (inch)	Neck (m)	BMI	Body Fat (%)[‡]
1	30	72	1.83	220	99.80	38	0.97	16	0.41	30	22
2	29	72	1.83	220	99.80	38	0.97	16.75	0.43	30	21
3	32	69	1.75	190	86.20	36	0.91	16	0.41	28	19
4	37	74	1.88	241	109.30	42	1.07	17.50	0.44	31	26
5	41	74	1.88	210	95.30	36	0.91	16.50	0.42	27	16
6	33	68	1.73	180	81.60	36	0.91	15	0.38	27	22
7	39	73	1.85	220	99.80	38	0.97	17	0.43	29	20
8	29	67	1.70	230	104.30	40	1.02	16.50	0.42	36	27
9	45	72	1.83	205	93.00	36	0.91	16.50	0.42	28	17
10	37	72	1.83	207	93.90	34	0.86	16.50	0.42	28	13
11	29	70	1.78	234	106.10	38	0.97	18	0.46	33	19
12	28	69	1.75	179	81.20	36	0.91	15	0.38	27	21
13	35	76	1.93	240	108.90	42	1.07	17.75	0.45	29	24
14	38	65	1.65	183	83.00	34	0.86	17	0.43	30	15
15	30	75	1.90	217	98.40	40	1.02	15	0.38	27	26
16	28	68	1.73	170	77.10	33	0.84	15	0.38	26	16
17	27	71	1.80	150	68.00	30	0.76	15.25	0.39	21	7
18	36	68	1.73	185	83.90	40	1.02	17.25	0.44	28	25
19	53	73	1.85	224	101.60	42	1.07	18	0.46	30	25
20	28	73	1.85	230	104.30	42	1.07	18	0.46	30	25
21	27	71	1.80	204	92.50	37	0.94	16	0.41	29	20
22	28	72	1.83	205	93.00	36	0.91	16	0.41	28	18
23	27	70	1.78	169	76.70	35	0.89	14	0.36	24	21
24	39	67	1.70	200	90.70	38	0.97	15.50	0.39	31	26
25	33	66	1.68	190	86.20	38	0.97	16.50	0.42	31	24
26	31	69	1.75	176	79.80	36	0.91	15	0.38	26	21
27	32	76	1.93	185	83.90	34	0.86	15.75	0.40	23	13
28	24	68	1.73	185	83.90	35	0.89	16	0.41	28	18
29	27	72	1.83	196	88.90	38	0.97	15.25	0.39	27	23
30	52	68	1.73	165	74.80	33	0.84	15	0.38	25	16
31	42	74	1.88	205	93.00	35	0.89	16.25	0.41	26	15
32	32	69	1.75	155	70.30	30	0.76	14.50	0.37	23	10
33	34	74	1.88	220	99.80	40	1.02	17	0.43	28	23
34	37	69	1.75	213	96.60	37	0.94	16	0.41	32	21
35	35	70	1.78	180	81.60	31	0.79	15	0.38	26	11
36	28	72	1.83	205	93.00	36	0.91	16.50	0.42	28	17
38	37	73	1.85	195	88.50	34	0.86	17	0.43	26	12
39	29	75	1.90	225	102.10	35	0.89	17	0.43	28	14
41	41	70	1.78	210	95.30	36	0.91	17	0.43	30	17
42	27	71	1.80	170	77.10	33	0.84	14	0.36	24	17
45	57	72	1.83	190	86.20	34	0.86	15	0.38	26	16
47	36	72	1.83	275	124.70	43	1.09	19	0.48	37	25
48	30	74	1.88	222	100.70	40	1.02	16	0.41	28	24
49	42	69	1.75	185	83.90	36	0.91	15.50	0.39	27	21
50	31	74	1.88	200	90.70	36	0.91	15.50	0.39	26	18
51	27	68	1.73	218	98.90	38	0.97	17.50	0.44	33	22
52	44	73	1.85	185	83.90	33	0.84	15.50	0.39	25	14
54	46	74	1.88	215	97.50	39	0.99	16.50	0.42	28	22
56	35	73	1.85	168	76.20	30	0.76	14	0.36	22	9
57	33	72	1.83	192	87.10	36	0.91	14.50	0.37	26	21

Diver ID*	Age†	Height (inch)	Height (m)	Weight (lb)	Weight (kg)	Waist (inch)	Waist (m)	Neck (inch)	Neck (m)	BMI	Body Fat (%)‡
58	47	70	1.78	178	80.70	38	0.97	16	0.41	25	23
59	33	71	1.80	195	88.50	35	0.89	16.25	0.41	27.00	17.00
60	42	69	1.75	156	70.80	32	0.81	14.75	0.37	23.00	14.00
61	36	70	1.78	175	79.40	37	0.94	16.50	0.42	25.00	20.00
62	43	72	1.83	235	106.60	42	1.07	17.00	0.43	32.00	27.00
63	36	69	1.75	217	98.40	37	0.94	16.00	0.41	32.00	21.00
64	28	72	1.83	175	79.40	34	0.86	14.50	0.37	24.00	17.00
65	31	70	1.78	190	86.20	34	0.86	15.75	0.40	27.00	16.00
66	39	71	1.80	210	95.30	37	0.94	16.50	0.42	29.00	20.00
67	30	72	1.83	207	93.90	36	0.91	15.50	0.39	28.00	19.00
68	35	67	1.70	198	89.80	38	0.97	17.00	0.43	31.00	23.00
69	40	72	1.83	235	106.60	41	1.04	17.00	0.43	32.00	25.00

*only divers who completed the experimental profiles are shown; †age at first dive in this study;
‡calculated from height, waist circumference, and neck circumference according to U.S. Navy method[25]

APPENDIX B DIVING SCHEDULE

The following tables show the dates on which each diver participated in the dive trial. Schedules indicated by A: 12/6; B: 24/12; C: 30/6. Shaded boxes indicate DCS cases.

PHASE 1

Diver ID	2015-04-06	2015-04-07	2015-04-08	2015-04-09	2015-04-13	2015-04-14	2015-04-15	2015-04-16	2015-04-20
1				C				B	
2		B				A			
3				C				B	
4									
5									
6									
7			A				C		
8				C				B	
9									
10									
11	C				B				A
12		B				A			
13	C				B				A
14		B				A			
15									
16			A						
17									
18	C								
19					B				
20			A				C		
21				C				B	A
22	C								A
23									
24			A					B	
25									
26		B				A			
27									
28	C							B	
29				**C**					
30									A
31									
32			A				C		A
33							C		
34					B				
35									
36		B				A			
38									
39									
41									
42									
45									
47									
48									
49									
50									
51									
52									
54									
56									
57									

Diver ID	2015-07-28	2015-07-29	2015-07-30	2015-08-04	2015-08-05	2015-08-06
1						
2						
3						C
4						
5		B				
6	**C**					
7	C					
8						
9				B		
10	C					
11		B			A	
12						C
13						C
14	C			B		
15				B		
16						
17			A			C
18						
19			A			C
20	C					
21					A	
22		B				
23			A			
24	C			B		
25					A	
26			A			C
27		B				
28						
29			A		A	
30					A	
31				B		
32						
33						
34			A	B		
35					A	
36						
38		B				
39		B				
41						
42						
45						
47						
48						
49						
50						
51						
52						
54						
56						
57						

Diver ID	2016-04-04	2016-04-05	2016-04-06	2016-04-07	2016-04-11	2016-04-12	2016-04-13	2016-04-14	2016-04-18	2016-04-19	2016-04-20	2016-04-21	2016-04-25	2016-04-26
1			A							A				
2				B										C
3														
4											C			C
5		C			A									
6														
7		C			A				B					
8			A			B								
9														
10								A						
11					A				B					
12														
13														
14				B				A			C			
15		C			A									
16														
17	B				A				B					
18														
19					A				B					
20			A									C	B	
21			A			B						C		C
22														
23											C			
24	B						C			A			B	
25														
26														
27														
28	B													
29	B						C			A				
30		C				B				A			B	
31				B								C		
32														
33														
34				B										
35														
36						**B**								
38														C
39														
41												C		
42	B						C			A				C
45								A					B	
47								A			C		B	
48	B									A				
49				B			C							
50			A			B					C			C
51		C							**B**					
52								A				C		
54			A				C						B	
56								A			C			
57												C		

PHASE 2

Diver ID	2016-06-06	2016-06-07	2016-06-08	2016-06-13	2016-06-15	2016-06-16	2016-06-20	2016-06-21	2016-06-22	2017-06-12	2017-06-13	2017-06-14	2017-06-19	2017-06-20	2017-06-21	2017-06-26	2017-06-27
1							A										
2								C									
4												A		C		C	
5		C				C			A		C						C
7		C															
11						C											
14	A				C			C									
15						C											
19						C					C				C	C	
20					C		A										
21											C				C		
23		C															
24									A								
29				A													
30					C				A								
31			A		C												
36											C						
42													C			C	
45								C				A			C		
47		C					A										
48	A																
49	A								A								
50		C		A													
52	A					C											
54		C		A					A								
56			A		C			C									
57			A														
58				A													
59			A	A													
60										A							
61										A							
62										A			C				
63												A		C			
64											C				C		
65												A				C	
66														C			C
67												A					C
68													C				
69										A							

APPENDIX C CRITERIA FOR DCS AS AN EXPERIMENTAL OUTCOME[a]

A1: DCS requiring recompression

Joint pain persisting at least as long as tabulated below (whether recompressed or not)

Severity	One joint	Multiple joints
Mild	60 min	30 min
Moderate	30 min	15 min
Severe	15 min	8 min

Skin rash or mottling in combination with joint pain of any duration
Dyspnea, unless clearly from barotrauma or anxiety hyperventilation syndrome
Any spinal neurological symptoms supported by signs
Any brain symptoms[b]
Any inner ear symptoms,[c] unless clearly from barotrauma
Any suspicious symptom leading to and relieved by recompression

A2: Marginal DCS (DCS not requiring recompression)[d]

Joint pain not persisting as long as tabulated above
Moderate or severe fatigue
Skin itch in water-immersed divers breathing air or N_2-O_2
Skin rash or mottling as only symptom
Symptoms reported as "DCS not requiring recompression" not fitting other criteria

B: Unknown outcome (data should not be used)

Headache, typical and common for this diver
Vague abdominal or chest pain, not related to trauma or barotrauma
Vague symptoms of any kind not responding to recompression or oxygen therapy attempted <18 hours after dive[e]

C: Not DCS

No signs or symptoms reported
Signs or symptoms reported 24 hours after surfacing
Mild joint pain or fatigue consistent with recent exercise
Sharp pain consistent with joint sprain or impact injury
Vague symptoms similar to Marginal DCS not responding to recompression therapy attempted >18 hours after dive[f]

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[a] Weathersby et al. 1988 criteria[30]; language reflects development for retrospective data review; not used for treatment decisions
[b] e.g., visual blurring, "mental sluggishness"
[c] e.g., unsteadiness, vertigo, hearing loss
[d] Based on perception that lack of treatment will not result in morbidity
[e] Diver may have gone on to develop DCS if not treated
[f] At which time any DCS should have occurred

APPENDIX D DCS CASE NARRATIVES

The tables below give the case narratives written by the attending Diving Medical Officer (some minor editing by one of the authors) for each mishap diagnosed as DCS (Type 1, Type 2, and marginal). The diagnosis of marginal DCS was made by the authors based on the definition in Appendix C. T2 is the time, in minutes since reaching surface, at which the patient first reported having symptoms. T1 is the time, in minutes since reaching surface, at which the patient was definitely symptom free. Marginal cases do not all have T1 and T2 times. T1 time was assigned as follows:

T2 reported	T1 assigned
Reach surface + more than 18 h	Reach surface + 18 h interview time
Reach surface + more than 2 h	Reach surface + 2 h interview time
Reach surface + 20 min to 2 h	Reach surface + 10 min interview time
Reach surface + less than 20 min	Time leaving previous stop depth

This follows the scheme of Weathersby and colleagues[40] except that a reach surface + 30 minute T1 time was not used. Divers were under observation after reaching surface until the 2 hour medical interview and it is unlikely that symptom onset went unreported during this period.

12/6 Schedule

Date Diver ID	Type	T1 (min)	T2 (min)	Narrative
2015-08-05 29	Marginal	121	314	Reported onset at 20:30 last night [20150805] of achy pain in left ankle and foot. Painful with weight bearing, movement and palpitation. Resolved after 90 minutes. Normal full neurological examination this morning [20150806]. No mechanism.
2016-06-06 52	Type 1	11	45	45 minutes after surfacing he reported 2-3/10 deep muscle pain in left shoulder. Pain was pin-point, unaffected by movement and persistent although with waxing and waning intensity. Patient was observed for approximately 60 minutes [until end of 2-hour standard observation period] and pain did not significantly change. A complete neurological examination was conducted with no other signs or symptoms identified. Diagnosis Type I DCS with recommendation of Treatment Table 6. Patient was recompressed to 60 fsw and reported complete relief of symptoms upon reaching 60 fsw. Placed on oxygen and completed Treatment Table 6 with no extensions. No return of symptoms and no additional findings on periodic neurological examination. No return of symptoms during surface examination period. NPQ for diving for 7 days.
2016-06-13 29	Type 1	120	900	Patient reported to sick bay after waking at 06:00 [20170614] with 2/10 left knee pain, worsening to 8/10 pain by the time he reported at 6:30. Neurological examination completed by duty DMT under direct observation [of DMO]

Date Diver ID	Type	T1 (min)	T2 (min)	Narrative
				with no other findings. Pain 8/10 not improved with motion or pressure, at site of previous DCS pain. [Patient] reports that this "feels exactly like the bends". Diagnosis Type I DCS, right knee only. Initiated Treatment Table 6 with significant decrease in knee pain from 8/10 to 3/10 within five minutes after reaching 60 fsw. Relief of DCS pain unmasked underlying musculoskeletal knee pain and some fluid effusion [this underlying] pain worsened by movement and palpitation. Provided additional two oxygen periods at 60 fsw and two additional oxygen periods at 30 fsw. Reached surface at 15:20. Complete neurological exam demonstrated no deficits. 1/10 left knee pain with movement and palpitation over posterior medial tibial plateau.
2016-06-13 59	Type 1	5	150	Surfaced from dive with noted fatigue that was typical of this dive series. Returned home with worsening of fatigue and chills. At approximately 17:30 noted onset of bilateral shoulder pain, left followed by right. Both vague, difficult to localize, not exacerbated by movement and felt pulsing or "coming in waves". Left 5/10 intensity, right 1-2/10. Also with referred left elbow pain from shoulder. Presented to NEDU approximately 19:00. Denied other symptoms to include vertigo, imbalance, personality change. Full neurological exam notable for fever of 100.4 F, joint pain as above, strength and sensation normal despite pain. Treated on Treatment Table 6 with no extensions. During first oxygen period [at 60 fsw] had complete resolution of fatigue and chills, all joint pain, and temperature. End of first oxygen period had only residual "fullness" in left shoulder. No recurrence upon surfacing. Fullness resolved that evening. Next day sharp pain in shoulder with movement but not at rest, thought to be musculoskeletal [mechanical] injury and was not treated. Sharp pain resolved 2 days after dive. 2016-06-27 patient denies any residual symptoms. No joint pain, ROM restriction, fullness, dizziness, imbalance, cognitive changes, personality changes, weakness or numbness. Has resumed normal activity without restriction. Diagnosis: Type I DCS - pain only
2016-06-20 47	Type 1	113	879	After experimental dive noted lightheadedness and nausea consistent with long oxygen breathing periods [subject reported "sea sickness" at beginning of oxygen breathing], this resolved at 17:00 [2016-06-20]. Denied other symptoms. Returned home with fatigue (typical for this experimental dive), woke at 05:30 [2016-06-21] with 7/10 right knee pain. Pain was dull, difficult to localize, not exacerbated with movement and did not improve. Reported to NEDU, full neurological examination normal other than right knee pain. Knee exam unremarkable, no musculoskeletal findings other than restricted range of movement due to pain.. Weakness in leg due to pain, no objective weakness. Denied other symptoms. No return of dizziness or lightheadedness. Treated on US Navy Treatment Table 6 with one extension at 60 fsw. Symptoms improved to 1/10 with residual "fullness" [in knee] during first oxygen period. Fullness resolved during third oxygen period. All pain and fullness

Date Diver ID	Type	T1 (min)	T2 (min)	Narrative
				remained absent upon surfacing. Knee exam normal with full range of movement, no point tenderness, no ligament laxity, fully weight bearing and able to squat without pain.
2017-06-12 60	Type 2	1017	2342	Subject is having abnormal sensation in distal lower extremities bilaterally, starting at knees and extending to feet. Symptoms were noticed when he woke at 06:00 this morning [20170614, 39 h 02 min after surfacing from dive, 21 h 55 min after last schedule examination at which he reported no symptoms]. He describe the symptoms as an “itch” or “fuzziness”, as well as “pins and needles” in his calves “like they were asleep”. Additionally, the subject reported intermittent changes in temperature sensation in lower extremities, from hot to cold and vice versa. He exercised for 45 to 60 minutes [20170614 between 06:00 and 09:15] which did not exacerbate symptoms. At [approximately] 09:15 [20170614] he reported to Diving medical Officer for an evaluation. [DJD: subject reported increased awareness of symptoms when sitting in office following exercise.] Positional changes such as sitting, lying supine, or standing did not change symptoms. He denies any rash or exposure to irritants to skin. He denies any pain, difficulty walking, postural imbalance, numbness, or weakness in his lower limbs. He denies any other new onset of symptoms. Physical and neurological examination was normal, including no objective sensory findings. Subject was treated with a USN Treatment Table 6 with one extension at 60 fsw, recompression began at 09:15 and treatment finished at 14:28. Subject had partial resolution of symptoms during first oxygen period at 60 fsw and complete resolution of symptoms during second oxygen period at 60 fsw. Subjects symptoms did not recur during the treatment. On the surface patient was asymptomatic and neurological examination was normal. Subject reported to sick bay 15 JUN 2017 at 15:01 complaining of increase in hot and cold sensation in lower extremities with feet feeling very cold. He denies any other complaints. His wife has no concerns about cognitive or mood. Physical examination has bilateral dysesthesias of lower extremities. On exam he has heightened awareness of cold and hot in a L4 dermatomal distribution beginning at level of patella and going down to feet. Otherwise normal neurological exam including vibration, light touch, sharp touch, proprioception. Lungs have some mild crackles consistent with mild pulmonary oxygen toxicity. Subject treated with USN Treatment Table 6 with maximum extensions [2 at 60 fsw; 2 at 30 fsw]. Subject describes dysesthesias as level 4 going down to level 1 and shrinking in area during treatment. Subject reported to sick bay 16 JUN 2017 at 10:43. Dysesthesia had increased from 1 [after yesterday’s treatment] to 3. No other complaints except mild cough. Physical exam normal, including lungs. Neurological exam

Date Diver ID	Type	T1 (min)	T2 (min)	Narrative
				normal except for L4 distribution dysesthesia (increased sensation of hot and cold), same distribution as previously. USN TT5 completed. Mostly resolved, limited to single patch on lateral aspect of each calf. Recommend no hyperbaric oxygen treatments over next two days (weekend) 19 JUN 2017 at 11:00. Subject reported on weekend of 17-18 JUN 2017 he had symptom free periods but this morning he has 1/10 pins and needles on a hand-sized patch of his right lateral calf. No other symptoms. Neurological examination normal except for the 180mm by 60mm patch of [subjective] paresthesia. USN Treatment Table 5 completed, equivocal response to treatment. 20 JUN 2017 at 07:00. Subject reports 0-1 symptoms of residual on right calf area. Pins and needles had been felt over preceding 24 hours, barely noticeable when present, but absent at this time. USN Treatment Table 5 completed. Symptoms absent before compression and throughout treatment. No symptoms following treatment. Subject had follow up neurology consult and MRI.
2017-06-12 61	Type 1	10	803	[Experimental data sheet records complaint of “mental fuzziness” and fatigue at 2-hour standard interview; T1 time set at 10-min interview.] Medical Record: Awoke at 04:21 [20170613] with 6/1 sharp pain right knee which subsided to a dull 3/10 pain. Unaffected by weight bearing or motion. Denied any paresthesia, [other] pain, changes in sensations, vision or mood. No history of trauma or injury to knee, no history of DCS. Fit, in no acute distress. Normal gait, knee not tender, not swollen, discolored, or tender to touch, nor to palpation.. Neurological exam [performed by MDV candidate] including sensory dermatomes, gait, Rhomberg, cerebellar, cranial nerves, motor intact. Deep tendon reflexes bilateral at knees, elbow, were within normal limits. As duty UMO I arrived as neurological exam in progress and confirmed gait, DTR, cranial nerves all intact. Patient was recompressed on USN Treatment Table 6 and had full resolution of symptoms by 8 minutes on oxygen at 60 fsw. He finished the regular Treatment Table 6 without event or symptom recurrence.. Completion of Treatment Table 6, he has minor respiration discomfort but clear breathing sounds, completely normal neurological exam.. Diagnosis Type I DCS secondary to exceptional exposure dive experiment, an expected hit so to speak.. Type 1 pain only DCS, classic presentation, fully resolved with treatment. 7 day expect return to full duty.

24/12 Schedule

Date Diver ID	Type	T1 (min)	T2 (min)	Narrative
2015-04-16 8	Marginal	-255	19	Bilateral knee 1-2/10 dull achy pain during ascent. Was able to point to location of pain. Failed first Rhomberg [passed all subsequent Rhomberg attempts], neurological examination otherwise normal. Pain resolved spontaneously during examination [approximately 30 minutes]. History of heavy weight lifting (squats) previous day.
2015-04-16 21	Marginal	-104	31	Foot pain started in left foot at 20 fsw stop. Now in both feet. Left foot 1/10, right foot 3/10, dull ache in arches, like having been on a 6 mile run. No neurological complaints. Relief when removed shoes.
2016-04-04 28	Marginal			Left shoulder and elbow pain during an oxygen period. Vague fullness type pain, rated 5/6, lasting less than 10 minutes
2016-04-12 36	Type 1	-1	5	Subject states that the pain began during the 10 minute observation period [clean time] after surfacing. Describes pain as 5-6/10 dull, constant and deep pain located "inside" his shoulder. He is unable to reproduce the pain with movement or pressure, and states that it feels as if he could "pop" his shoulder to improve the pain. Initially denied any symptoms during routine postdive interview [10 minute clean time] because he felt the pain was going to go away on its own. He also notes that he has some pain on his lower anterior left arm that is made worse when he abducts and externally rotates his arm (as if throwing something). Says that the pain in that area is elicited by movement. States it feels like "burning" that travels from the inside of his arm, up to his shoulder and down to his thumb. He says that when he presses over the affected area that the sensation feels like "tingling" or "stinging". The day prior he did a ring pull-up [exercise] routine (pull-ups / muscle-ups using Olympic [gymnastics] rings). States that he didn't think it was exceptionally strenuous. It should be noted is an avid/competitive cross-fitter [this was a typical exercise routine]. He has significant medical history of acromioclavicular joint degeneration and a supraspinatus partial muscle tear in the currently affected [left] shoulder. He endorses that his presenting pain is different than the pain that is typically associated with these previous injuries. ROS: Pertinent positives noted above. No headache, changes in vision, hearing, nausea or vomiting. No difficulty controlling his bowels or voiding. No altered mood or sensorium. No abdominal numbness or tingling apart from noted. Objective: Vitals: BP 138/78, HR 54. General: no apparent distress; Skin: no discoloration or lesions; Neurological exam normal except strength: left limb limited to pain and sensation to light touch abnormal over quarter-sized area

Date Diver ID	Type	T1 (min)	T2 (min)	Narrative
				ventral left forearm which appears to change location and quality throughout exam - when marked, takes specific shape of flexor carpi radialis. Assessment: left shoulder pain Type I DCS. Left forearm pain/weakens muscle strain of the flexor carpi radialis vs neuropraxis due to physical activity. While coincident with the dive and suspicious of Type II insult, this symptom is entirely reproducible with a history of muscle strain or a neuropraxis. Subject achieved symptom resolution 16 minutes into his first oxygen period at 60 fsw [USN Treatment Table 6]. Pain in forearm was exaggerated with stretching but remained stable throughout treatment. No additional symptoms or complications. Completed treatment table and observed for 1 hour. The following morning was reevaluated. His shoulder pain remained resolved. However there continued to complain of symptoms in his forearm as mentioned above. He received a USN Treatment Table 9 which resulted in no change in symptoms. It was again felt that his forearm symptoms were musculoskeletal [mechanical] in nature and unrelated to a decompression injury. He was advised rest and short course of non-steroidal anti-inflammatory medication. In the following days his forearm symptoms improved.
2016-04-18 51	Type 1	16	117	Came to sick Call and complained of bilateral "ball of foot fullness" and 4/10 left knee pain. No objective findings on complete neurological examination. Initiated USN Treatment Table 6 for type I DCS. Complete resolution of knee pain at 15 minutes into first oxygen period at 60 fsw. One extension at 60 fsw. Foot fullness/numbness lessened at 60 fsw and resolved during first oxygen period at 30 fsw. One extension at 30 fsw. DCS Type I with lymphatic involvement. Subject reports experienced period cramp-like pain in the plantar surface of each foot throughout the 2-hour post-dive observation period. At the 2-hour [post-dive] interview the patient claimed that the pain had passed. Patient reported to sick bay on Tuesday [morning [20160419] with reported 4/10 left knee pain and bilateral "air-cushion" sensation on the ball of both feet. Sleep was undisturbed by symptoms. DMO completed a neurological examination of the patient and reported no objective findings, specifically there were no areas of sensory deficit to either gross touch or blunt/sharp two-point discrimination. No motor weakness and no DTR abnormalities. Coordination good, Rhomberg negative, mini-mental normal. Subject was started on [USN] Treatment Table 6. Subject reported 100% resolution of knee pain and a 25% improvement in both feet 15 minutes into the first oxygen period at 60 fsw. By the third oxygen period at 60 fsw the subject reported 85% improvement in the left foot and 100% recovery in the right foot. One oxygen extension was given at 60 fsw.. Subject reported complete resolution

Date Diver ID	Type	T1 (min)	T2 (min)	Narrative
				of foot symptoms bilaterally during the first 60-minute oxygen period at 30 fsw. A total of three oxygen periods was provided at 30 fsw. Subject surfaced without complaints of DCS symptoms. Subject could reproduce some of the left knee pain by manipulating the joint through some awkward positions but this is not believed to be a residual DCS symptom. Similarly, subject reports some right foot plantar discomfort with direct pressure but this too is not believed to be related to DCS. Diagnosis: Type I DCS with lymphatic involvement bilateral lower extremities.

30/6 Schedule

Date Diver ID	Type	T1 (min)	T2 (min)	Narrative
2015-04-06 18	Marginal	122	449	Increased fatigue at home (severe), chills, persisted at night [evening of 20150406], no weakness or pain. Patient woke at 23:00 [20150406] with right ankle 3/10 pain [subject did not volunteer that pain woke him up] that increased to 5/10 [subject does not find the pain scale meaningful], sharp, lateral malleolus. Subject did not want to call DMO or undergo treatment. Subject went back to sleep at 24:00 with pain still present. Subject woke up this morning [of 20160407] with no symptoms beside mild pulmonary [oxygen toxicity] symptoms. Currently no neuromuscular deficits.
2015-04-09 29	Type 1	123	524	Approximately midnight subject woke experiencing leg pain with right knee and ankle presenting with 4/10 sharp aching pain and left knee presenting with 6/10 sharp aching pain. Presented at NEDU treatment chamber. His examination did not reveal any neurological findings. He was treated with US Navy treatment table 6 for Type I (pain only) DCS. Exam: Musculoskeletal - FROM in all planes. Lower extremity pain was not reproducible with range of movement, compression or palpation; Mental status - alert and oriented to person, place and time. There was no slurring of speech, psychomotor changes, anxiety, depression or psychosis; HEENT - normocephalic, no visual field deficits, hearing grossly intact; Lungs - clear to auscultation in all fields; Abdomen - soft without tenderness. Neurological exam: MS - alert oriented to person place time and situation. No psychosis and affect was normal; Motor - 5/5 strength in all planes in upper and lower extremities; Reflexes - symmetric and intact. No pronator drift; Cerebellar - no ataxia or nystagmus, negative Rhomberg. RAM intact. Heel-to-shin bilaterally normal. Duck walk normal; Sensory - proprioception and soft touch intact. CNII-XII intact. USN Treatment Table 6. complete and permanent resolution of right knee, leg, and ankle pain upon reaching 45 fsw on descent to 60 fsw. Left knee pain reduced from 6/10 to 4/10 immediately upon reaching 60 fsw. Improved to 3-4/10 during two 20 minute oxygen period extensions at 60 fsw. Improved to 1-2/10 by end of air break after first oxygen

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				period at 30 fsw. One oxygen period extension at 30 fsw. 1/10 left nkee pain persisted on reaching surface at 08:54 [2015-04-10]. Remainder of physical and neurological examination normal. Subject stated pain was not so severe that he would seek treatment for it.
2015-07-28 6	Type 2	119	341	Patient initially complained of odd feeling in feet when walking and toe swelling starting 21:00 night of the dive. Was evaluated by DMO 18 hours after surfacing and found no signs of edema, was cleared. 48 hours after the dive patient seen by DMO, reported fatigue, forgetfulness, and change in "mentality", with feeling of fugue or fogginess. Also continued with reported feet swelling without evidence of objective edema. Exam remained normal, focused neurological exam revealed no gross deficits. Notably, this dive series has led to fatigue in a large portion of subjects, not thought to be related to DCS insult. 72 hours after dive, patient again seen by DMO. Cognitive changes were subjectively improved per patient but wife (an ED physician) and colleagues were now noting a personality change – a diminished affect. A complete neurological exam was performed and revealed an abnormal Romberg (patient immediately staggered when closed eyes and had drift of arm), trace/questionable swelling in both plantar feet near arches (no edema above that level) and enlarged (1.5 cm), firm, non-tender right inguinal lymph node. Due to corroboration of personality change, persistence of symptoms and objective changes in neurologic exam, patient was diagnosed with Type 2 DCS with neurologic symptoms. Feet and lymphadenopathy were also concerning for lymphatic bends, although swelling was never profound. Hyperbaric treatment was commenced [20170731] with a Treatment Table 6 with 2 extensions at 60fsw. During treatment, patient had immediate improvement in cognitive symptoms and balance, however foot edema was unchanged. Patient was examined in person by DMO 18 hours after completion of treatment, reported continued resolution of symptoms. Full neurologic exam was normal. Plantar edema had resolved and progressed to ecchymosis. Lymphadenopathy had improved. 36 hours after first treatment (now 5 days after initial dive), patient reported return of symptoms during interview with Master Diver. Patient's wife reported cognitive and mood changes/lability most notably a feeling of "distance" from reality. Also a short temper was reported by his wife. He also reported continued subtle imbalance when walking. Although, he continued to drive in on a one-hour commute without issues and was able to walk. Exam including a complete neurologic exam demonstrated an abnormal Romberg improved from his initial exam three days after the dive, but worse than after his first Treatment Table 6. Foot edema and lymphadenopathy was resolved, ecchymosis

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				was improving. It was decided to treat the patient again for recurrent symptoms of Type 2 DCS. The patient continued to receive recurrent hyperbaric treatments on the following schedule for a total of 9 treatments: 31 Jul: Treatment Table 6 with 2 extensions at 60 fsw 1 Aug: Break, as symptoms reportedly were resolved. 2 Aug: Treatment Table 6 with 2 extensions at 60 fsw 3 Aug: Treatment Table 6 with 1 extensions at 60 fsw and 1 extension at 30 fsw 4 Aug: Treatment Table 6 modified: 2 periods at 60 fsw, 3 periods at 30 fsw 5 Aug: Treatment Table 6 modified: 2 periods at 60 fsw, 2 periods at 30 fsw 6 Aug: Planned break due to suspected pulmonary O2 toxicity symptoms 7 Aug: TT9 8 Aug: TT9 9 Aug: TT9 10 Aug: TT9 All symptoms always resolved during the first oxygen period at depth and remained resolved immediately after treatment completion. However, each morning symptoms would return, improved from the morning prior but worse than those after treatment completion. Objective signs, including abnormal Romberg, were normal by morning of 3 Aug. Treatments were continued for vague subjective symptoms of cognitive distance, irritability at home and subjective balance changes. Symptoms continued to sequentially improve each day until the morning of 11 Aug when patient reported durable resolution of symptoms after treatment on 10 Aug. Patient continues to report durable symptoms resolution today on 28 Aug 2015. Reports no return of distant feeling or balance changes. During treatments after 04 Aug, patient began to develop symptoms of mild chest tightness and burning after treatments. This was likely a combination of pulmonary O2 toxicity and fatigue due to prolonged breathing on BIBS and hood. After the hood was adjusted to allow for more even flow, symptoms improved. After break on 06 Aug and switch to TT9 symptoms resolved for remainder of treatments. Pulmonary exams remained normal. Patient had lab work and MRI completed. Only MRI brain was completed as there were no peripheral deficits

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				indicating an MRI spine. Results are summarized below: ROS: denies numbness, weakness, change in cognition, forgetfulness, fatigue, change in energy, imbalance, incoordination, change in vision, change in hearing, difficulty breathing, chest pain. MRI Brain (03 Aug): Right temporal lobe cystic structure most likely representing perivascular space as described (1.8 cm fluid filled cystic space without mass effect or enhancement) in otherwise normal brain MRI. Neurological exam: Normal. Normal mental status/cognition (short and long term memory, aaox3, counting backwards). Strength 5/5 all extremities. Complete sensory exam normal to sharp touch. CN 2-12 intact. Romberg normal. Finger to nose normal. Rapid alternating movement normal. Gait normal. Heel to shin normal. A/P: Type 2 DCS with lymphatic component: Resolved with 9 hyperbaric treatments. Primary symptoms of imbalance, vague cognitive changes and lymphadenopathy- all now resolved. No residual pulmonary O2 toxicity symptoms. MRI completed per dive manual requirements. Findings not dive related. PFO waived, see below. Patient is now symptom free for 30 days after incident. As patient is experimental subject, will locally return to full duty. See note below. Temporal Lobe Cyst: unchanged from last MRI. No apparent symptoms. Cognitive changes like this not likely related to temporal lobe, and stability in size reassuring for relation to symptoms during DCS treatments.
2015-08-06 13	Marginal	120	897	Subject returned to admit to [previously unreported] symptoms after dive. 1/10 dull, deep elbow pain onset approximately 14 hours after dive, lasting 15 minutes. Continued to recur every 2-3 hours for 2-3 days, always resolving in 15 minutes. No mechanism of injury. Would improve with massage. No change with movement. Resolved completely after 3 days. Denies other complaints to include numbness, weakness, personality change.
2016-04-05 51	Marginal	125	140	Reported two events overnight. At 17:30 [20160405] dull aching pain with tingling in right arm and left leg lasting 5 minutes. At 20:00 [20160405] recurrence of similar pain only in right leg lasting five minutes.[DJD: difficult to assign as marginal because so minor and because of weight lifting]
2016-04-13 54	Marginal			Subject reported moderate fatigue and sharp pain in lateral right knee associated with movement and weight-bearing, resolved overnight.
2016-06-21 45	Marginal	118	189	No current complaints. Last night at approximately 18:00 [2016-06-21] had transient 1/10 right knee pain, vague, difficult to localize lasted 15 minutes, resolved spontaneously, no recurrence. No clear etiology, no history of similar knee pain in the past. [Subject is a DMO and thought it was DCS until it spontaneously resolved]