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REDISTRIBUTION OF DECOMPRESSION STOP TIME FROM SHALLOW TO DEEP STOPS INCREASES INCIDENCE OF DECOMPRESSION SICKNESS IN AIR DECOMPRESSION DIVES

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14. ABSTRACT
Classical decompression algorithms limit hypothetical tissue gas contents and prescribe decompression schedules with most of the total stop time (TST) allocated to shallow decompression stops. More recent bubble-model-based algorithms limit hypothetical bubble profusion and size and prescribe decompressions with TST skewed toward deeper stops. A large man-trial compared the efficiency of these approaches. Divers wearing swimsuits and t-shirts, breathing surface-supplied air via MK 20 UBA, and immersed in 86 °F water were compressed at 57 fsw/min to 170 fsw for a 30 minute bottom time during which they performed 130 watt cycle ergometer work. They were then decompressed at 30 fsw/min with stops prescribed by one of two schedules. The shallow stops schedule, with a first stop at 40 fsw and 174 minutes TST, was prescribed by the, deterministic, gas content, VVAL18 Thalmann Algorithm. The deep stops schedule, with a first stop at 70 fsw, was the optimum distribution of 174 minutes TST according to the probabilistic BVM(3) bubble model. Decompression sickness (DCS) incidence following these schedules was compared. The trial was terminated after the midpoint interim analysis, when the DCS incidence of the deep stops dive profile (11 DCS/198 dives) was significantly higher than that of the shallow stops dive profile (3/192, p=0.030, one-sided Fisher Exact). On review, one deep stops DCS was excluded, but the result remained significant (p=0.047). Most DCS was mild, late onset, Type I, but two cases involved rapidly progressing CNS manifestations. Results indicate that slower tissue gas washout or continued gas uptake offsets the benefits of reduced bubble growth at deep stops.

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INTRODUCTION

Decompression sickness (DCS) is thought to be caused by intracorporeal gas bubbles that form during and after excessively rapid reduction of ambient pressure (decompression). When breathing gas at elevated ambient pressure, such as during underwater compressed gas diving, increasing amounts of the gas dissolve in blood and tissues according to Henry's Law. During subsequent ascent to sea level, the ambient barometric pressure (P_{amb}) may decrease to a level less than the sum of the partial pressures of all n gases dissolved in a particular tissue. In this state the tissue is gas supersaturated by an amount equal to the difference, $\Sigma p_{tis_j} - P_{amb} > 0$, for $j=1, ..., n$ dissolved gases. The gas supersaturated state may be sustained metastably until relieved by physiological washout of gas via the blood and lungs, or may be relieved by *in situ* formation of bubbles from the excess dissolved gas. The risk of DCS is thought to depend on the size, profusion, and location of such bubbles. To manage the risk of DCS, dives are conducted according to depth/time/breathing gas schedules derived with decompression algorithms that implicitly (in gas content models) or explicitly (in bubble models) limit bubble formation by slowing decompression, typically by interrupting ascent with "decompression stops", to allow time for tissue inert gas washout. Although decompression without tissue gas supersaturation and therefore without bubble formation or risk of DCS is possible, such decompression strategies yield schedules that are impractically long for most diving applications. Instead, practical ascent strategies balance the probability of DCS (P_{DCS}) against the costs of time spent decompressing.

In gas content models, P_{DCS} increases with the magnitude and duration of tissue gas supersaturation. In classical "deterministic" gas content models, decompression is scheduled to always keep dissolved gas partial pressures (Σp_{tis_j}) in k modeled tissue compartments less than or equal to a depth-dependent maximum permissible value, $\Sigma p_{tis_{j,k}} \leq M_k = a_k D + M_{0_k}$., where D is the ambient pressure expressed in depth of water, M and M_0 are the maximum permissible tissue pressures (M-values) at D and at the surface, respectively, and a and M_0 are determined experimentally.[1] Such algorithms yield the shortest decompression times when the partial pressure gradients between the modeled compartments and alveolar gas are maximized to achieve the fastest washout of inert gas; i.e., by ascending to the shallowest depth at which $D \geq (P - M_0)/a$ for all compartments. As an ascent progresses, compartments with successively slower gas uptake and washout govern the ascent and progressively lengthen the decompression stops at shallower depths.

In bubble models, P_{DCS} increases with the profusion, size, and duration of tissue bubbles, all of which may theoretically be mimimized by ascents with initial decompression stops deeper or longer than the initial stops prescribed by gas content models.[1] Decompression schedules with such deep stops have shapes that depart substantially from the shapes of schedules prescribed by the gas content models. Comparatively deep initial decompression stops result in less tissue gas supersaturation and therefore less bubble formation than at a shallower initial stop. Compared to bubbles at a shallow stop, bubbles that form at a deep stop remain more compressed according to Boyle's Law and have a lower gas influx from surrounding tissue because of smaller bubble surface area and lower diffusion gradient between tissue and bubble. Bubble formation at any stop may also substantially slow gas washout because relieving the gas supersaturation in the host tissue also reduces the partial pressure gradient for tissue-to-blood gas exchange, an effect that is mitigated by reduced bubble formation at deep stops.

Both gas content (shallow stops) and bubble model (deep stops) approaches lead to practical decompression schedules; however, whether one approach is more efficient than the other is unknown. In this context, two decompression schedules for the same dive depth and bottom time differ in efficiency if one has a shorter required decompression time for the same P_{DCS} or a lower P_{DCS} for the same decompression time. The U.S. Navy has a continuing need for more efficient decompression procedures. For instance, the newly introduced U.S. Navy air decompression tables[2] have substantially longer air decompression times than the tables they replaced but provide only small reductions in estimated P_{DCS}.[3] Redistribution of these long air decompression times according to a bubble model resulted in substantial reductions in estimated P_{DCS} and was the motivation for the present work.[4] All current U.S. Navy air and N_2-O_2 decompression procedures are based on gas content algorithms and the present work was undertaken to determine whether a bubble model approach should be pursued to develop future air and N_2-O_2 decompression procedures. Thus, present work entailed tests of the hypothesis that deep stop air decompression schedules are more efficient than shallow stop schedules. Preliminary accounts of this work have appeared in conference proceedings.[5,6]

METHODS

SCHEDULE SELECTION

The experimental philosophy was to compare DCS incidence following air decompression dives conducted according to either a gas content model (shallow stops) schedule or a bubble model (deep stops) schedule. These dive profiles were identical except for different distributions of the same total decompression stop time (TST) among the allowed stop depths (all at 10 fsw increments from surface). Therefore, a difference in DCS incidence would reflect different efficiencies in the two decompression schedules. Additional details of schedule selection and experimental design are given in NEDU protocol 05-23/32174[7] but the principal aspects are as follows.

The two dive profiles required a non-zero incidence of DCS, but the incidence and severity of DCS was constrained to allow testing to continue until a significant difference in DCS incidence emerged. Dives also required a long TST to allow a substantial difference in the distribution of decompression stop depths and stop times between the gas content model and the bubble model schedules with potentially large difference in DCS incidence.

To meet these requirements, candidate shallow stops dive profiles followed decompression schedules prescribed by the Thalmann Algorithm with the VVal-18 parameter set,[3,8] which underlies the N_2-O_2 decompression tables in the *U.S. Navy Diving Manual, Revision 6*. The Thalmann Algorithm is a classical “deterministic” algorithm in which decompression is determined from the calculated compartmental dissolved gas contents and a table of M-values. In the Thalmann Algorithm, when a compartment is supersaturated, compartment gas kinetics may switch from exponential to linear, slowing gas washout and prolonging decompression stop times.

Candidate deep stops dive profiles followed schedules prescribed by the BVM(3) “probabilistic” decompression model,[9,10] in which the instantaneous risk of DCS is a function of compartmental bubble volumes and the P_{DCS} is the time integral of instantaneous risk during and following the dive. Probabilistic decompression models are used to estimate the P_{DCS} of a dive profile and, in conjunction with a two-stage search algorithm, produce decompression schedules.[9,11] The first stage in this process, of relevance to the present study, is to minimize P_{DCS} by iterative redistribution of a specified TST among different decompression stop depths. The second, optional, stage, is to minimize TST for a target P_{DCS}.

Candidate dive profile pairs each comprised a VVal-18 Thalmann Algorithm schedule and a profile that was for the same depth and bottom time but with decompression schedule being the optimum distribution (minimum P_{DCS}) according to BVM(3) of the VVal-18 Thalmann Algorithm prescribed TST. The P_{DCS} of dive profile pairs was estimated with BVM(3) and NMRI98, the latter of which is a probabilistic gas content model in which the instantaneous risk of DCS is a function of the compartmental gas supersaturations.[12] The ideal characteristics of a test dive profile pair are (1) a large difference in estimated P_{DCS} (deep stops dive profile − shallow stops dive profile) under each probabilistic model; (2) the sign of this P_{DCS} difference being opposite under the BVM(3) and NMRI98 models; and (3) all estimated P_{DCS} being less than 7%. The first requirement was to enhance the likelihood of observing a significant difference in DCS incidence between the two profiles within a practical number of man-dives. The second requirement was to objectively verify that one schedule had distinctively bubble model characteristics and the other had distinctively gas content model characteristics. The final requirement was to limit incidents of severe DCS associated with estimated P_{DCS} higher than 7% under a model similar to NMRI98 for air and N_2-O_2 decompression dives.[13] The dive profile pair selected was to 170 feet sea water (fsw) for 30 minutes bottom time with 174 minutes TST under both schedules. The schedules and estimated P_{DCS} are given in Table 1 and dive profiles represented graphically in Figure 5A.

Table 1 Shallow stops [VVal-18] and deep stops [BVM(3)] test schedules

	Depth BT	Decompression Stops (fsw) Stop Times (min)							P_{DCS} (%)	
	170	70	60	50	40	30	20	10	BVM(3)	NMRI98
Shallow stops	30				9	20	52	93	6.158	4.429
Deep stops	30	12	17	15	18	23	17	72	3.664	5.880

60 fsw/min descent rate; 30 fsw/min ascent rate; stop times do not include travel time to stop

EXPERIMENTAL DESIGN

Ethical considerations require that a manned dive trial with DCS as an end point be designed to limit unnecessary injury to divers. Three hundred and seventy-five dives on each dive profile were planned, with sequential stopping rules to terminate testing of a schedule with a binomial P_{DCS} higher than 7% at 95% confidence (reject-high) or lower than 3% at 95% confidence (reject-low). For safety reasons, testing of a particular dive profile could also be terminated if pre-defined, unacceptably severe DCS resulted. These rules were to limit exposure of divers to the risk of severe DCS and to limit the potentially inconclusive testing of two low-risk dive profiles.

If one dive profile was rejected-high and one dive profile was rejected-low, the trial was to be concluded with declaration that the P_{DCS} of the two profiles are significantly different. The trial was also to be concluded if a midpoint analysis after completion of approximately 188 man-dives on each dive profile found a significantly greater incidence of DCS (Fisher Exact test, one-sided $\alpha = 0.05$) for the deep stops dive profile than for the shallow stops dive profile. Otherwise the trial would continue to 375 man-dives on each dive profile and a one-sided Fisher Exact test ($\alpha = 0.05$, alternative hypothesis DCS incidence lower for the deep stops dive profile than the shallow stop schedule) would determine the outcome. These interim and final analyses were directed by the purpose of this study to select one of two classes of models for development of future air tables. Selection of the bubble model (deep stops) class would represent a departure from current U.S. Navy practice, whereby all decompression procedures are based on gas content models, and would only follow a finding of significantly lower P_{DCS} for the bubble model schedule than the gas content model schedule, a problem for which a one-sided test is appropriate. The “opposite tail” finding at the midpoint analysis would provide strong evidence that the P_{DCS} of the bubble model (deep stops) schedule was not lower than that of the gas content model schedule and would justify early termination of the trial.

For stopping rules, only cases diagnosed as DCS by the duty Diving Medical Officer were counted. Signs and symptoms that the Diving Medical Officer judged not to require recompression therapy (marginal symptoms) were not counted. For subsequent hypothesis testing, all incidents were re-evaluated according to the criteria for inclusion in the U.S. Navy air and N_2-O_2 primary decompression database,[14] and incidents deemed marginal or not to be DCS were excluded.

Venous gas embolism

As a secondary outcome measure (but not as a trial end point) divers were monitored for venous gas emboli (VGE) with trans-thoracic cardiac 2-D echo imaging (Siemens Medical Solutions® Acuson Cypress Portable Colorflow Ultrasound System) at 30 minutes and two hours postdive. While the divers reclined with left side down, the four heart chambers were imaged with the diver at rest and then, in turn, while they flexed each elbow and knee. VGE were graded according to the Table 2 scale, adapted from Eftedal and Brubbak.[15]

Table 2 VGE grading system

Grade	Description
0	No bubble seen
1	Rare (<1/s) bubble seen
2	Several discrete bubbles visible per image
3	Multiple bubbles visible per image but not obscuring image
4	Bubbles dominate image, may blur or obliterate chamber outlines

DIVING PROCEDURES

Subjects

Eighty-one qualified U.S. Navy male divers provided informed consent and participated as diver-subjects in this study. At the time of their first dive in this study, divers mean (SD) age was 37 (8) years, body weight was 192 (24) pounds or 87.2 (10.7) kg, height was 70 (2) inches or 1.79 (0.06) m, BMI was 27 (3), and estimated body fat calculated from body dimensions[16] was 15% (4%). A Diving Medical Officer judged all divers-subjects to be physically qualified for diving on the basis of review of medical records and a physical examination. Details about diver-subjects are given in Appendix A.

Divers participated in multiple experimental dives in this study. However, they refrained from any hyperbaric or hypobaric exposure for a minimum of 60 hours before, and 48 hours following any experimental dive. Divers diagnosed with DCS were not physically qualified for diving and were unable to participate in an experimental dive until a Diving Medical Officer cleared them — typically either seven or 28 days after symptoms resolved depending on DCS classification and treatment.

Immediately before each experimental dive, diver-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 diver-subjects for participating in each experimental dive.

Dives

Dives were conducted in the Ocean Simulation Facility wet pot at the Navy Experimental Diving Unit. The wet pot was pressed 73 times with up to six divers participating in each chamber dive for a total of 390 man-dives. The wet pot was pressed once per day, generally Monday through Thursday. The two test dive profiles were alternated weekly. Diving took place over a nine month period (November 2005 – August 2006) in three phases separated by a break of one month or longer (see Appendix B)

Divers wore an equipment harness and breathed compressed air via an umbilical and full face mask equipped with an oro-nasal mask, demand valve, and diver communications (U.S. Navy MK 20 underwater breathing apparatus). One at a time, divers donned the MK 20, entered the wet pot, and assumed a seated position fully submerged with mid-chest approximately 3 fsw (0.91 cm) below the wet pot water surface. Once all divers were seated, the wet pot air space was compressed to 167 fsw gauge pressure by the introduction of compressed air, so that diver depth at mid chest level was 170 fsw (622.04 kPa absolute).

The target descent rate was 60 fsw/min and the actual mean (SD) descent rate was 57 (3) fsw/min, range 42–61 fsw/min. Upon reaching bottom the divers began exercising on custom-built, hysteresis-braked (model HB210, Magtrol; Buffalo, NY), underwater cycle ergometers. The ergometers were constructed to position the divers in a semi-prone position (approximately 15° head-up inclination) during pedaling to mimic underwater fin swimming. Divers pedaled at a target cadence of 60 rpm with the ergometer hysteresis brake controller (W.E. Collins; Braintree, MA) set at 65 watts so that divers' work rate (incorporating the extra power required due to submersion in this diving dress) was approximately 134 watts.[17] This underwater cycle ergometer work rate requires a diver oxygen consumption of approximately 2.3 L/min.[18] Occasionally, a diver was unable to maintain a power of 130 watts, so the hysteresis brake current was reduced until the diver could maintain 60 rpm pedaling cadence. Pedaling a completely unloaded underwater ergometer at 60 rpm requires approximately 75 watts power and an oxygen consumption of 1.4 L/min.[17,18] Divers exercised until one minute before ascent and then rested for the remainder of the dive in either seated or prone positions with mid chest level 3 fsw below the wet pot water surface.

The wet pot was decompressed according to one of the schedules given in Table 1. Decompression stops were at diver mid chest depth. Target ascent rate to decompression stops was 30 fsw/min and actual mean (SD) ascent rate to the first decompression stop was 29 (1) fsw/min, range 25–30 fsw/min.

Wet pot water temperature was actively controlled with a target of 86 °F. The grand mean wet pot water temperature (the mean of the 73 dive means) was 85.6 °F (29.8 °C), range 85.1–87.4 °F (29.5–30.8 °C). Divers wore neoprene gloves and booties to protect extremities from non-freezing cold injury and abrasion from cycle ergometer pedals. Otherwise, to avoid confounding differences in trunk thermal protection due to wet suit compression between the two dive profiles, divers wore only cotton shorts and t-shirt. Divers were queried about thermal discomfort every 15 minutes throughout the dive and responded on a scale from 0 (no discomfort) to 10 (unbearable).

Wet pot pressure, water temperature, diver pedaling cadence, and cycle ergometer hysteresis break settings were digitized and recorded with a microcomputer based data acquisition system every two seconds throughout the dive.

Following each dive, divers were observed for two hours. Divers were restricted from most work — for instance climbing stairs — during this period. Divers were not restricted from incidental walking, such as to reach the observation area. Most divers undertook two ultrasonic trans-thoracic 2-D echocardiograms with flexion of each limb; otherwise, they generally remained seated at rest during this period. Most divers also ate a meal during this period. Air temperature during this two-hour postdive observation period was recorded following 64 of the 73 chamber runs and ranged from 70 to 77 °F (21 to 25 °C), with a mean (SD) of 74 (2) °F [24 (1) °C]. Divers dressed for comfort.

A Diving Medical Officer interviewed all divers at 10 minutes and two hours after surfacing, and again the following day, generally between 21 and 24 hours after surfacing (mean 22; IQR 21–24; range 16–28, n = 361: five interviews, time not recorded; seven, with mishap intervening; 17, missing). Occasionally, divers reported symptoms of DCS at these interviews, but more commonly these interviews established the last known time a diver was symptom free. More commonly, divers who developed DCS symptoms contacted the duty Diving Medical Officer between interviews.

RESULTS

DIVING

Departures from prescribed dive profile

Twenty-seven man-dives departed slightly from the intended dive profiles (detailed in Appendix C). In most cases (20 man-dives) these departures were interruptions in descent (delay range 16–32 s) for divers experiencing difficulty equalizing sinus or middle ear gas spaces with ambient pressure and, in one case, a chamber operator error. In one chamber dive (six man-dives) the 20 fsw stop was extended by 99 s because of a timekeeping error. In another instance, for operational reasons, a diver ascended into the dry trunk chamber (167 fsw) for three minutes during the bottom time. None of these departures from schedule resulted in substantial difference in estimated P_{DCS} under either NMRI98 or BVM(3) models.

Diving intensity

Fourteen divers participated in only one experimental dive, six on the shallow stops dive profile (one DCS incident) and eight on the deep stops dive profile (one DCS incident and one incident of marginal symptoms). The remaining 67 divers participated in two to 17 (median, 4) experimental dives in this series. Although no mechanism was used to assign divers to specific dive profiles, most of these 67 divers dived each dive profile approximately an equal number of times. However, four divers conducted two dives only (one DCS incident) and one diver conducted three dives only, all on the deep stops dive profile. Diving intensity is detailed in Appendix B.

Thermal status

Whereas divers were thermally comfortable early in the dive, they generally became cold while at rest during the decompression. Median thermal discomfort score just before surfacing was 4 (range 0–7; IQR 3–5). Semantic anchors at these scores were 0 (no discomfort), 3 (moderate), 4 (somewhat severe), 5 (severe/onset shivering), and 7 (very severe/continuous shivering). After exiting the wet pot, most divers shivered during the first few minutes of exposure to the cooler air temperature.

DCS OUTCOME

Narrative descriptions of each DCS case are given in Appendix D. The 192 shallow stops dives resulted in three cases diagnosed as DCS requiring recompression: two late-onset, mild, pain-only cases and one early-onset case with symptoms of spinal involvement. The 198 deep stops dives resulted in 11 cases diagnosed as DCS requiring recompression variously presenting as pain-only, skin bends, and neurogical symptoms. Figure 1 illustrates the cumulative occurrence of DCS on each dive profile as the trial progressed.

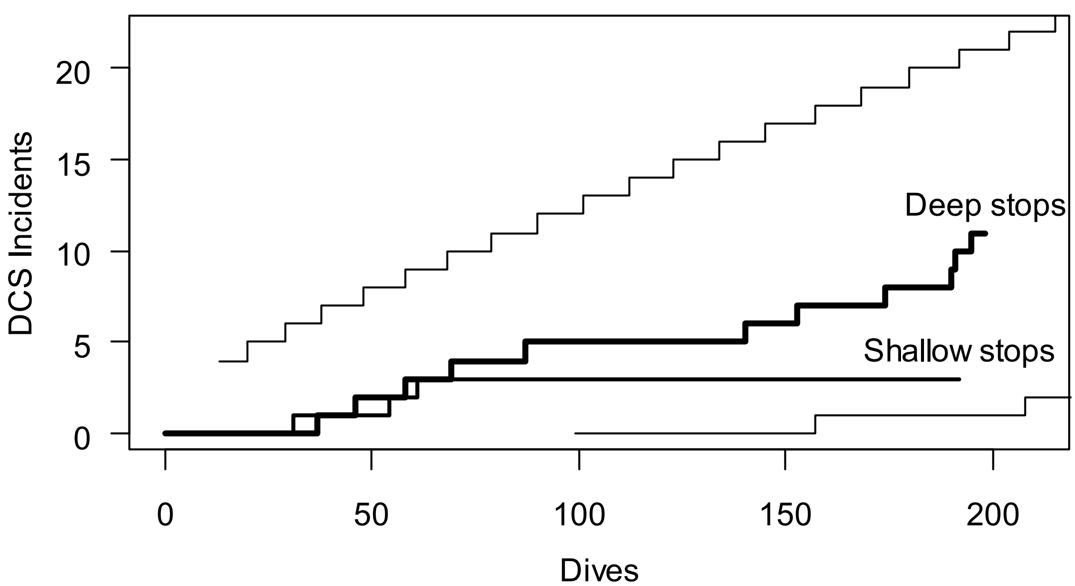


Figure 1. Sequential trial envelope (outer lines) and cumulative incidents of DCS requiring recompression on the shallow stops (light line) and deep stops (heavy line) schedules.

After half the planned number of dives had been conducted, neither dive profile was rejected due to high or low incidence of DCS (touching the trial envelope lines in Figure 1), but the midpoint interim analysis indicated that the deep stops schedule resulted in significantly higher incidence of DCS than the shallow stops schedule (p=0.0324, one-sided Fisher's Exact test), see Figure 2. As a consequence the trial was terminated at this time.

During re-evaluation of the cases according to the criteria described in Temple et al.,[14] (see Appendix D) one case with symptom onset 27 hours after surfacing from the deep stops dive profile was re-classified as not DCS. Despite this re-classification, the deep stops schedule still resulted in a significantly higher incidence of DCS than the shallow stops schedule (p=0.0489, one-sided Fisher's Exact test), see Figure 2.

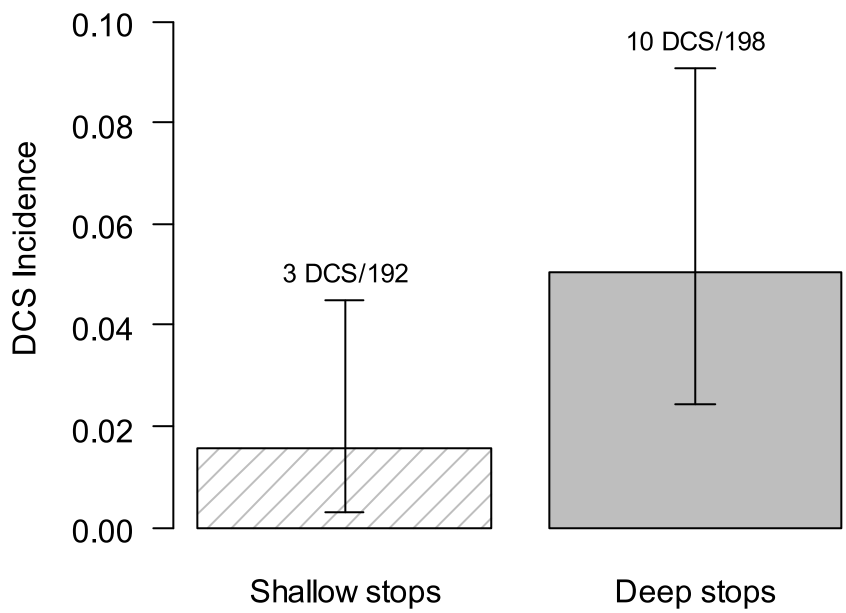


Figure 2. Observed incidences and binomial 95% CI for DCS requiring recompression according to the criteria described in Temple et al.[14] on the two test dive profiles.

This large man-trial had unique potential for response or diagnosis bias because it was not practical to conceal the diverging DCS incidence on the two schedules, not possible to blind diver-subjects to the schedules, and some DCS presented as subjective symptoms only. However, misinterpretation of symptoms is unlikely in experienced professional divers (mean years diving = 13; IRQ 6–17; range 1–23), and VGE grades, which are not subject to these biases, were also higher after the deep stops schedule than after the shallow stops schedule.

VGE OUTCOME

Resting VGE grades and maximum grade of rest or limb flexion were higher following the deep stops schedule than following the shallow stops schedule at both the 30-minute and the two-hour examinations (Wilcoxon rank sum tests, all p<0.001). Raw VGE data are given in Appendix E. Figure 3 summarizes the VGE findings, showing the maximum grade (of rest or any limb flexion) seen at any examination. The maximum VGE grade observed was significantly higher after the deep stops schedule (median=3) than after the shallow stops schedule (median=2, Wilcoxon rank sum test, W=12967, $p<0.0001$). The maximum resting VGE grade at any examination (not shown) was also significantly higher after the deep stops schedule (median=2) than after the shallow stops schedule (median=1, Wilcoxon rank sum test, W=13712, $p<0.0001$). VGE scores at the two-hour exam were increased over those at the 30-minute exam following the deep stops schedule (Wilcoxon rank sum test, W=4418, p=0.0006) but not following the shallow stops schedule (Wilcoxon rank sum test, W=2578, p=0.7340). The ultrasonic testing was not sufficiently frequent to ensure capture of the peak grade and more frequent monitoring may have produced a different result.

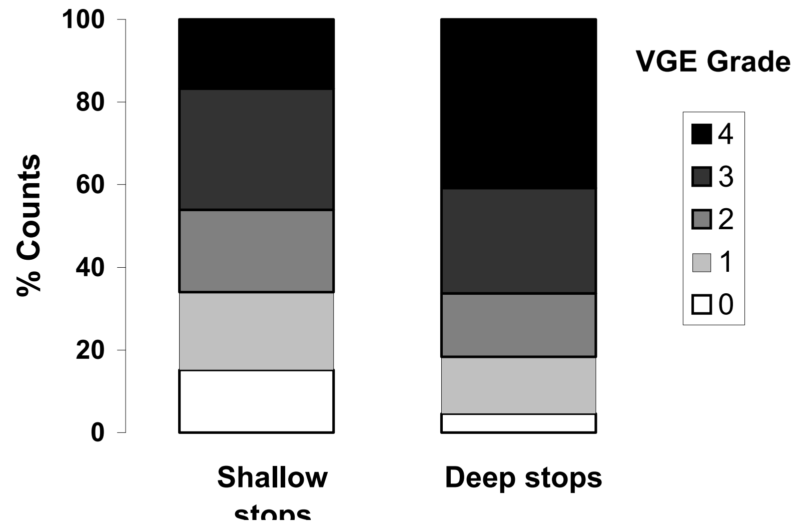


Figure 3. Distribution of VGE grade, maximum of all exams (rest or limb flexion at 30 minutes and two hours)

DISCUSSION

Both DCS incidence and median VGE scores were higher after the deep stops schedule than after the shallow stops schedule. This is the largest man-trial of individual decompression schedules of which we are aware and the only laboratory comparison of deep stops and shallow stops that is not confounded by differences in TST. Present results failed to support any potential benefit of the bubble model schedule over the gas content schedule for air decompression diving. Since the purpose of a decompression stop is to limit the formation of bubbles while allowing washout of gases from tissues, interpreting this result requires a clear picture of the relationship between tissue gas kinetics and bubble formation. For simplicity we will consider a single breathing gas mixture with a fixed fraction of component gases (e.g., air).

Tissue bubbles may form *de novo,* or may grow from pre-existing bubble nuclei, if the sum of all gas partial pressures in the tissue (ΣP_{tis_j}) exceeds the ambient barometric pressure (P_{amb}) by more than the threshold imposed by the increased pressure across the bubble's gas-liquid interface exerted by surface tension (P_{st}) and by displaced tissue (M). Bubbles will grow or shrink due to transfer of gas across the bubble surface according to Fick's First Law

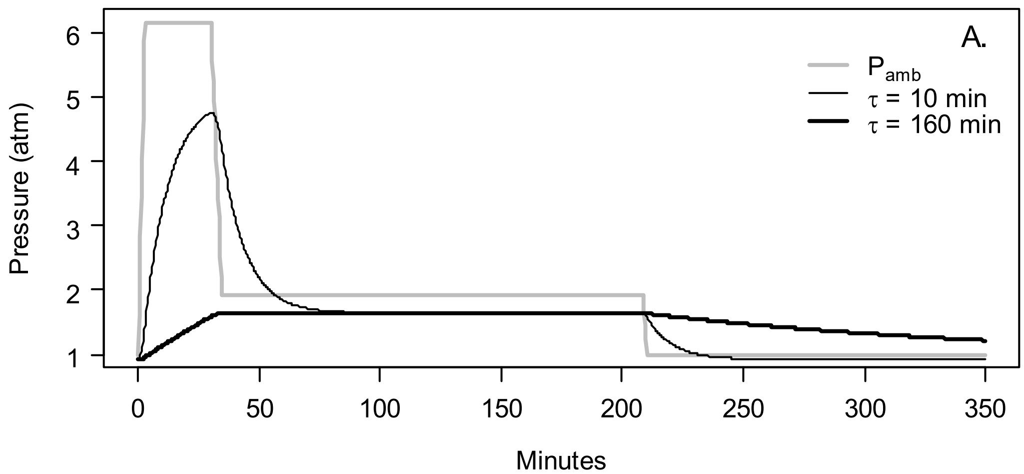
$$\frac{d\left(P_{bub}V_{bub}\right)}{dt} = A\sum_{j=1} \alpha_{tis_j} D_j \left.\frac{dP_{tis_j}}{dr}\right|_{r=r_A} \tag{1}$$

where D_j is the bulk diffusivity of gas j in tissue, A is the bubble surface area, dP_{tis_j}/dr is the partial pressure gradient of gas j in tissue evaluated at the bubble surface, V_{bub} is the bubble volume, and P_{bub} is pressure inside the bubble ($P_{amb} + P_{st} + M$). Bubbles grow only if the tissue gas supersaturation (ΣP_{tis_j} - P_{amb}) exceeds (P_{st} + M). Supersaturated tissue has higher inert gas tension than arterial blood has, so inert gas also diffuses from tissue into the capillary blood and is washed out. Once inert gas washout has reduced inert gas partial pressure in tissue below that inside the bubble, the bubble shrinks.

Upon arrival at a shallow first decompression stop (low P_{amb}), $\Sigma P_{tis_j} - P_{amb}$ is greater than upon arrival at a deeper first decompression stop, and, assuming sufficient gas supersaturation for bubble formation, there will be more bubble formation at the shallower than the deeper stop. According to Boyle's Law, bubbles formed at low P_{amb} will be larger and the partial pressure of each inert gas in these bubbles will be lower than those formed at a deeper first stop, so that, initially, both A and dP_{tis_j}/dr in Equation (1) will be larger and result in faster bubble growth at a shallow than at a deeper first stop. However, inspired and arterial inert gas partial pressures at a shallow first decompression stop are lower than those at a deeper first stop, and the resulting greater inert gas partial pressure gradient between tissue and arterial blood allows faster washout of dissolved inert gas from the supersaturated tissue. Such a benefit is reduced by diffusion of inert gas into bubbles; sequestering gas into bubbles reduces the tissue–blood partial pressure gradient for gas washout from that of tissue where all gas stayed in solution. This reduction will be greater at a shallow first stop than at a deep first stop; the worst case would be one of bubble formation so profuse that inert gas partial pressure across the whole tissue is in equilibrium with bubbles.

Present results indicate that reducing arterial inert gas partial pressure more rapidly by following a shallow stops decompression schedule is more advantageous than following a deep stops schedule to minimize bubble formation and growth. The profusion, size, and lifetime of bubbles that result from any particular decompression schedule depends on the unknown size distribution of bubble nuclei and the physicochemical characteristics of the tissues relevant to DCS, but an argument need not be based on any particular arbitrary selection of such parameters. The gas supersaturation that can be produced in compartments with differing rates of tissue–blood gas exchange during the different schedules can explain the present results.

Figure 4 compares changing gas pressures and development of gas supersaturation in modeled tissue compartments for theoretical air dive profiles with a shallow stops (panel A) and a deep stops (panel B) decompression. The decompression schedules are simplified for clarity but embody these features: the total decompression time is the same for the two schedules, and the ascent is relatively conventionally scheduled to preclude consideration of deep stops that are effectively part of a multi-level bottom time (see dashed line in Figure 4B). Total compartmental gas pressures change with monoexponential uptake and washout of a single inert gas. The exact form of the inert gas exchange function is not important for the following discussion; it simply represents the fact that compartment inert gas partial pressure monotonically approaches that in arterial blood. The fast (time constant, τ = 10 minutes) compartment is representative of all compartments that have comparatively fast gas exchange and in which an ascent to the shallow first decompression stop results in gas supersaturations greater than those produced by an ascent to a deeper first stop. The slow compartment (τ = 160 minutes) is representative of all compartments having comparatively slow gas exchange and which are not gas supersaturated upon ascent to the deep first decompression stop. In such compartments, gas washout is either slower or, as illustrated, gas is taken up rather than washed out at a deep first stop.



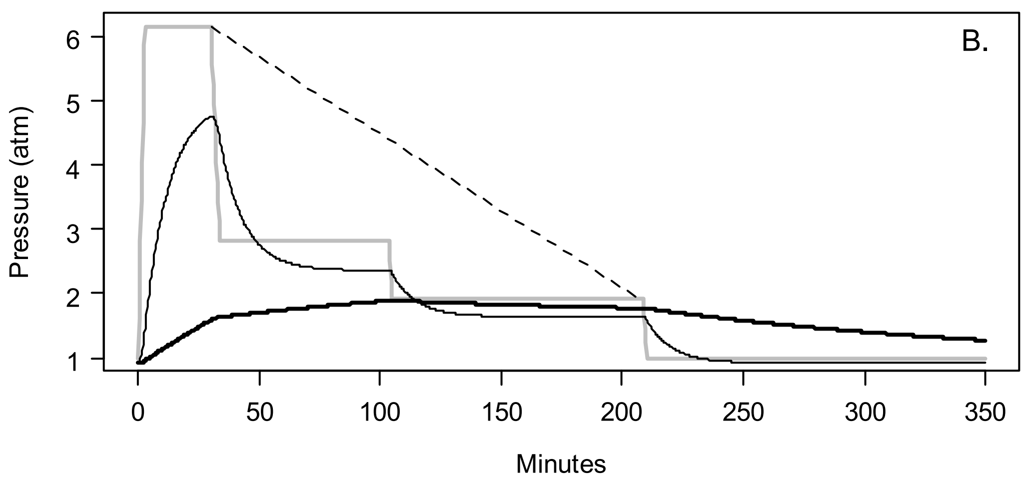


Figure 4. Fast and slow compartments gas pressures in theoretical shallow stops (A) and deep stops (B) schedules. The total decompression time is the same for the two schedules, and the ascent is conventionally scheduled, here defined as having no decompression stop extending beyond the dashed line in panel B — times at depths extending beyond the dashed line are considered part of a multi-level bottom time. Gas pressures (ΣP_{tis_j}) calculated for representative fast (τ = 10 minutes) and slow (τ = 160 minutes) monoexponential inert gas exchange compartments are indicated by the black lines. Compartments are supersaturated whenever a black line is above the gray line (P_{amb}).

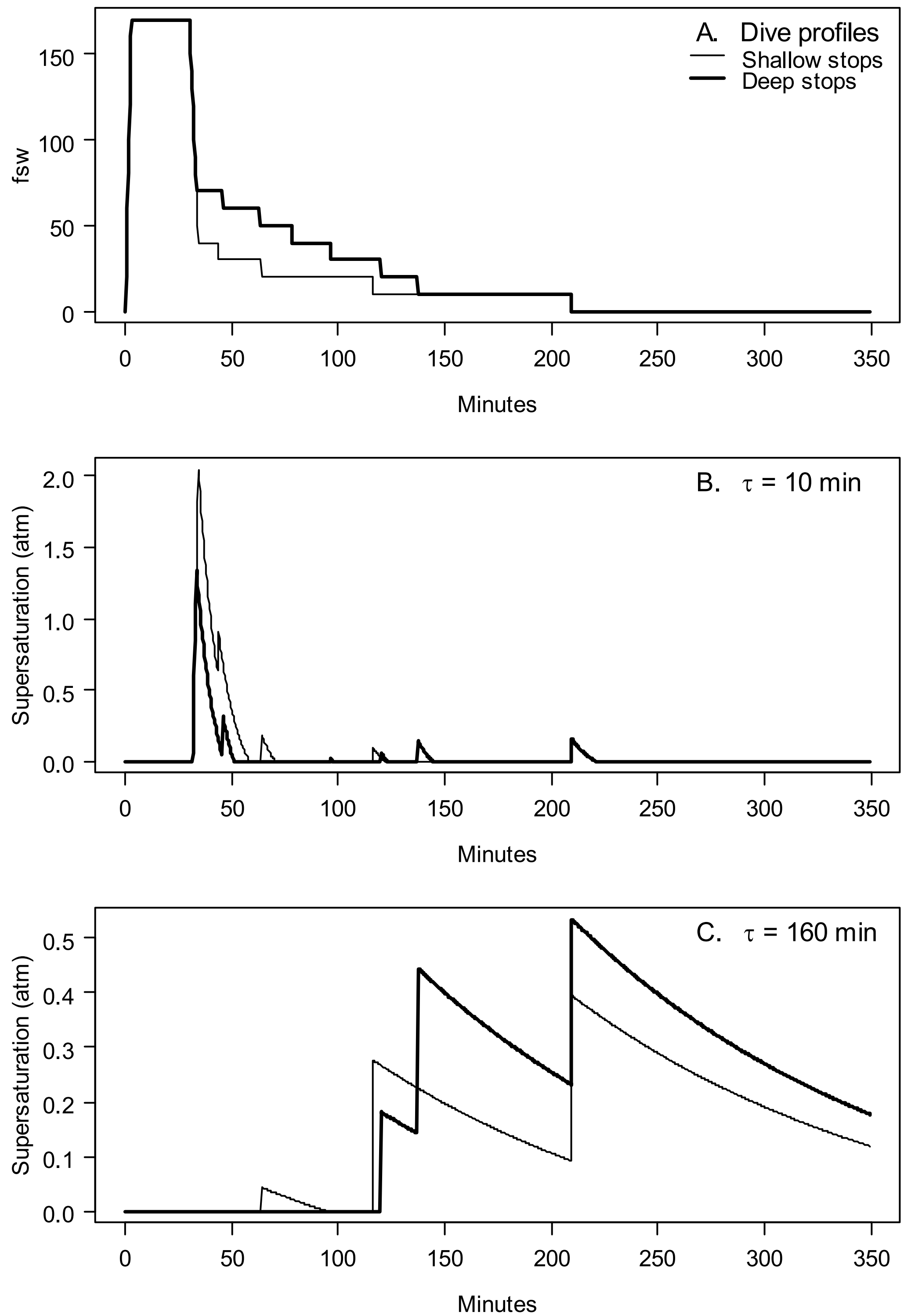


Figure 5. Supersaturation ($\Sigma P_{tis_j} - P_{amb} > 0$) in fast and slow compartments for the tested shallow stops and deep stops schedules. A. Overlay of the two 170 fsw/ 30 minute air decompression dive profiles tested. B. Supersaturation in a modeled compartment with fast (τ = 10 minutes) mono-exponential inert gas exchange. C. Supersaturation in a modeled slow (τ = 160 minutes) compartment.

Figure 5B shows gas supersaturation in a representative fast, monoexponential inert gas exchange compartment for the tested shallow and deep stops dive profiles illustrated in Figure 5A. The fast compartment displays markedly less gas supersaturation, and therefore less driving force for bubble formation and growth, during the deep stops than during the comparable period of the shallow stops schedule. The present results indicate that this reduction of initial gas supersaturations in fast compartments does not manifest in reduced DCS incidence. On the contrary, DCS incidence was higher after the tested deep stops schedule than after the shallow stops schedule, an indication that the large ascent to the first stop in classical schedules is not a flaw that warrants "repair" by deeper initial stops. Figure 5C illustrates that deep stops result in greater and more persistent gas supersaturation in relatively slow compartments on subsequent ascent than during the comparable period in the shallow stops schedule. This results from continued uptake of inert gas into these slow compartments during the deep stops. Gas supersaturations in slower gas exchange compartments late in the decompression are in accord with the present results from the tested dive profiles. The observed higher VGE scores and DCS incidence following the deep stops schedule than following the shallow stops schedule must be a manifestation of bubble formation in slower compartments.

Although the tested shallow and deep stops schedules are the optimal distributions of stop time under the VVal-18 Thalmann Algorithm and BVM(3) models, respectively, this does not mean that either schedule is the true optimal distribution of 174 minutes TST. Of present interest is how alternative deep stops schedules might have performed against the classically shaped shallow stops schedule. To further explore this question, we formally define deep stops skew (DSS) to characterize any distribution of TST. DSS is calculated by trapezoidal integration of the area under the trace of P_{amb} from the point of leaving bottom to that of reaching the surface, as illustrated by the hatching in Figure 6. DSS was used to classify alternative schedules created by combinations of five-minute blocks of time at 100 and 90 fsw, 10-minute blocks of time from 80 to 20 fsw, and the remainder of the 174 TST at 10 fsw with the total number of schedules limited as illustrated with the dashed line in Figure 6. Hypothetical dive profiles were created comprising a 170 fsw for 30-minute bottom time followed by each of the resulting 504,271 decompression schedules. The minimum DSS results from a single 174 minute stop at 10 fsw and the maximum DSS results from the schedule that most closely follows the dashed line in Figure 6.

Since bubble formation and growth depends on the magnitude and duration of gas supersaturation, the time integral of gas supersaturation was used as a model-independent index of the contribution of any compartment to the risk of DCS. The integral gas supersaturation is the area under the curve describing the time course of compartmental gas supersaturation, curves such as those of those illustrated in panels B and C of Figure 5. In probabilistic gas content decompression models such as NMRI98, P_{DCS} is a function of the sum of similar risk functions from all relevant compartments. Figure 7A illustrates the integral gas supersaturation for representative fast and slow compartments and their sum for the 504,271 hypothetical dive profiles.

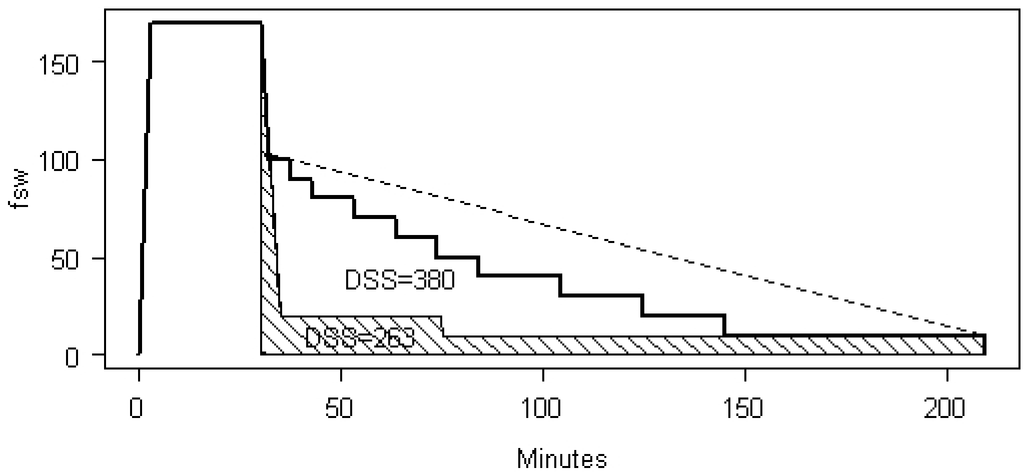


Figure 6. Classification of alternative decompression schedules by their deep stop skew (DSS). Following 170 fsw for 30-minute bottom time air dives, alternative distributions of 174 minutes TST were created by all possible combination of five-minute blocks of time at 100 and 90 fsw, 10-minute blocks of time from 80 to 20 fsw, and the remainder of the 174 TST at 10 fsw with maximum time at any stop limited to not cross the dashed line. This last constraint precludes consideration of stops that are effectively part of a multi-level bottom time. Two of the resulting 504,271 dive profiles are illustrated. The hatching defines the DSS for one of the decompression schedules. Values of DSS for the two illustrated schedules are given in units of (atm min).

In the slow compartment (τ = 160 minutes in Figure 7), increasing DSS generally increases the risk index as more gas is taken up during the deep stops and this results in increased gas supersaturation on subsequent ascent. The integral supersaturation of the fast (τ = 10 minutes) compartment initially declines with increasing DSS but approaches an asymptote (Figure 7). The cause of this asymptote is illustrated in Figure 4B, where inert gas partial pressures in the fast compartment converge with that in arterial blood before the end of the stop, which is therefore longer than necessary for gas washout. For fast compartments, increasing DSS becomes inefficient, but it cannot increase the supersaturation. The analysis illustrated in Figure 7 does not account for the kinetics of bubble dissolution during the period of tissue undersaturation (where the thin line is below the gray line in Figure 4B), and an analysis that used bubble volume as an index of risk would shift the risk asymptote, but the overall picture would be the same. Prolonging deep stops may become inefficient but cannot result in a greater bubble volume in fast compartments than would a more rapid ascent. Such a rapid ascent to shallower stops will cause any bubbles that do persist to expand according to Boyle's Law and then, if the tissue is supersaturated, to grow by diffusion. In unsaturated tissue, bubbles will dissolve more slowly at the shallower than deeper stop because of a reduced tissue−bubble inert gas gradient (a less negative dP_{tis_j}/dr in Equation [1]) that results principally from a reduced oxygen window (illustrated by the difference between ambient and steady-state gas partial pressures in Figure 4).

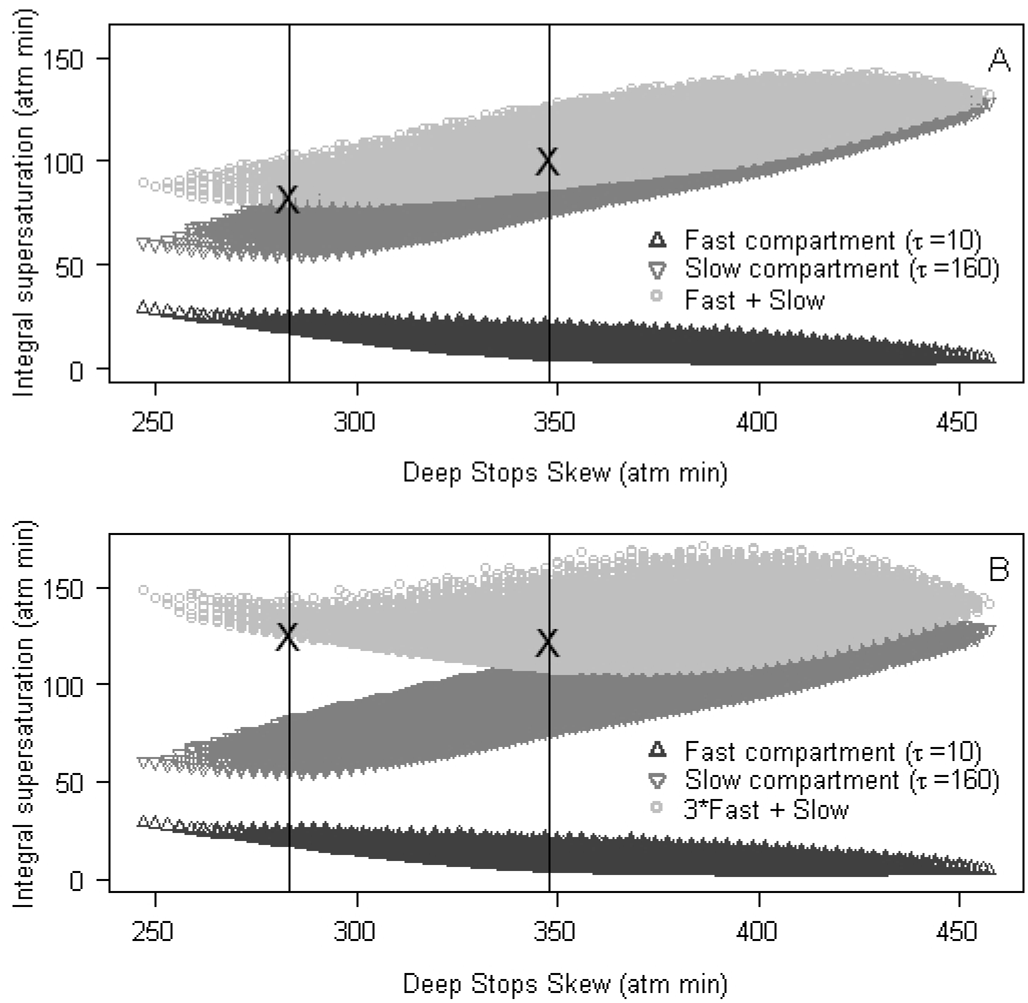


Figure 7. Integral supersaturation as an index of risk resulting from alternative distributions of 174 minutes TST classified by their deep stop skew (DSS) following 170 fsw for 30-minute bottom time air dives. A. Integral supersaturation calculated for representative fast (τ = 10 minutes) and slow (τ = 160 minutes) compartments and their sum for each of 504,271 hypothetical dive profiles. The sum of fast and slow is an index of how both compartments contribute to the risk of DCS. The vertical black lines are at the DSS of the tested shallow stops (left) and deep stops (right) dive profiles and the heavy “X” indicates the respective sum of integral supersaturation for the tested dive profiles. B. Similar illustration to panel A, but in which the fast compartment is weighted more heavily in the combined risk index. Note that the calculated sums of integral supersaturation for the tested dive profiles (X) are inconsistent with the present experimental findings.

The DSS and sum (fast + slow compartments) integral supersaturation of the tested shallow stops and deep stops dive profiles are also indicated on Figure 7A (vertical lines and large “X”). A requirement for the choice of representative fast and slow time constants is that sum integral supersaturation of the tested deep stops dive profile is higher than the tested shallow stops dive profile, in accord with the observed incidence of DCS. All examined pairs of representative time constants showed a similar pattern to that illustrated in Figure 7A. Dive profiles with DSS greater than that of the tested shallow stops dive profile generally had sum integral supersaturation higher than that of the tested shallow stops dive profile. With some pairs of time constants, a few profiles with DSS greater than that of the tested shallow stops dive profile resulted in sum integral supersaturation slightly lower than that of the tested shallow stops. It therefore seems unlikely that any deep stops schedule exists that would result in a P_{DCS} discernibly lower than that resulting from the tested shallow stops schedule.

Figure 7B illustrates ascribing a greater relative contribution of fast compartments than slow compartments to the risk by calculating a weighted sum integral gas supersaturation. Such a calculation can result in some dive profiles with higher DSS and substantially lower risk index than those of the tested shallow stops dive profile. Such behavior would require that compartments with relatively slow time constants contribute little or nothing to the risk of DCS. And if this were true, decompression from a 170 fsw for 30-minute dive could be safely conducted in a small fraction of the TST presently tested — an implication at odds with the weight of evidence from thousands of experimental air dives (see for instance, Temple et al.[14]). Even the modest increase in the relative contribution of fast compartments to the sum integral gas supersaturation illustrated in Figure 7B results in a lower risk index for the tested deep stop dive profile than for the tested shallow stops dive profile and is therefore inconsistent with the present experimental findings.

Although the foregoing analysis is the most parsimonious explanation of the present results, it is worth noting that deep stops may also have impeded gas washout by mechanisms other than unfavorable tissue–arterial inert gas gradient. It is possible that higher inspired oxygen partial pressure at deep stops caused vasoconstriction and reduced tissue gas washout due to reduced tissue blood flow. This seems unlikely because inspired oxygen partial pressures differ relatively little (0.66 and 0.46 atm) between 70 and 40 fsw and vasoconstriction would also have reduced gas uptake into slow compartments during the deep stops. It is also possible that intravascular gas bubbles arising during decompression enhance the inert gas carrying capacity of the blood and accelerate tissue gas washout, as do artificially produced intravascular bubbles at one atmosphere.[19] More intravascular gas bubbles during the greater initial decompression of the tested shallow stops schedule may have enhanced tissue gas washout in comparison to that of the deep stops schedule, a mechanism proposed by Kindwall and colleagues.[20] VGE measurements were not made during decompression, but a greater intravascular bubble load in the shallow stops schedule than in the deep stops schedule during decompression seems unlikely as it is contrary to the VGE findings soon after reaching surface.

CONCLUSIONS

The practical conclusion of this study is that controlling bubble formation in fast compartments with deep stops is unwarranted for air decompression dives.

REFERENCES

1. P. Tikuisis and W. A. Gerth, "Decompression Theory," in *Bennett and Elliott's Physiology and Medicine and Diving*, *5 ed.*, A. O. Brubakk, T. S. Neuman, eds. (Saunders, Edinburgh, 2003), pp. 419-454.

2. Naval Sea Systems Command, *U.S. Navy Diving Manual*, *Revision 6, NAVSEA 0910-LP-106-0957/SS521-AG-PRO-010 ed.* (Arlington (VA): Naval Sea Systems Command, 2008)

3. W. A. Gerth and D. J. Doolette, *VVal-18 and VVal-18M Thalmann Algorithm Air Decompression Tables and Procedures,* Technical Report 07-09, Navy Experimental Diving Unit, May 2007.

4. W. A. Gerth, K. A. Gault, V. L. Ruterbusch, J. L. Melton, D. J. Doolette, *Empirical Evaluation of the Efficacy of Deep Stops in Air Decompression Dives*, NEDU Protocol 05-23/32174, Navy Experimental Diving Unit, Nov 2005.

5. W. A. Gerth, D. J. Doolette, and K. A. Gault, "Deep Stops and Their Efficacy in Decompression: U.S. Navy Research," *Decompression and the Deep Stop, Proceedings of the Undersea and Hyperbaric Medical Society Workshop,* P. B. Bennett, B. R. Wienke, and S. J. Mitchell, eds., 2008 Jun 24-25, Salt Lake City (UT), (Undersea and Hyperbaric Medical Society, Durham (NC), 2009), pp. 165-185.

6. W. A. Gerth, D. J. Doolette, and K. A. Gault, "Deep Stops and Their Efficacy in Decompression," *Technical Diving Conference Proceedings,* R. D. Vann, S. J. Mitchell, P. J. Denoble, and T. G. Anthony, eds., 2008 Jan 18-19, Durham (NC), (Divers Alert Network, Durham (NC), 2009), pp. 138-156.

7. W. A. Gerth, K. A. Gault, V. L. Ruterbusch, J. L. Melton, D. J. Doolette, Empirical Evaluation of the Efficacy of Deep Stops in Air Decompression Dives, NEDU Protocol 05-23/32174, Navy Experimental Diving Unit, Nov 2005.

8. E. D. Thalmann, *Air-N2O2 Decompression Computer Algorithm Development,* Technical Report 8-85, Navy Experimental Diving Unit, Aug 1986.

9. W. A. Gerth and R. D. Vann, *Development of Iso-DCS Risk Air and Nitrox Decompression Tables Using Statistical Bubble Dynamics Models,* Final Report National Oceanic and Atmospheric Administration, Office of Undersea Research, 1996.

10. W. A. Gerth and R. D. Vann, "Probabilistic Gas and Bubble Dynamics Models of Decompression Sickness Occurrence in Air and N_2-O_2 Diving," *Undersea and Hyperbaric Medicine*, Vol. 24, No. 4 (1997), pp. 275-292.

11. P. K. Weathersby, J. R. Hays, S. S. Survanshi, L. D. Homer, B. L. Hart, E. T. Flynn, and M. E. Bradley, *Statistically Based Decompression Tables II. Equal Risk Air*

Diving Decompression, Technical Report 85-17, Naval Medical Research Institute, Mar 1985.

12. E. C. Parker, S. S. Survanshi, P. B. Massell, and P. K. Weathersby, "Probabilistic Models of the Role of Oxygen in Human Decompression Sickness," *Journal of Applied Physiology*, Vol. 84, No. 3 (1998), pp. 1096-1102.

13. E. D. Thalmann, *Suitability of the USN MK 15 (VVAL18) Decompression Algorithm for Air Diving,* Technical Report 03-12, Navy Experimental Diving Unit, Aug 2003.

14. D. J. Temple, R. Ball, P. K. Weathersby, E. C. Parker, and S. S. Survanshi, *The Dive Profiles and Manifestations of Decompression Sickness Cases After Air and Nitrogen-Oxygen Dives,* Technical Report 99-02, Naval Medical Research Center, 1999.

15. O. Eftedal and A. O. Brubakk, "Agreement Between Trained and Untrained Observers in Grading Intravascular Bubble Signals in Ultrasonic Images," *Undersea and Hyperbaric Medicine*, Vol. 24, No. 4 (1997), pp. 293-299.

16. J. A. Hodgdon, "Body Composition in the Military Services: Standards and Methods," in *Body Composition and Physical Performance: Applications for the Military Services*, B. M. Marriott, J. Grumstrup-Scott, eds. (National Academy Press, Washington DC, 1992), Ch. 4, pp. 57-70.

17. B. E. Shykoff, *Underwater Cycle Ergometry: Power Requirements With and Without Diver Thermal Dress,* Technical Report 09-01, Navy Experimental Diving Unit, Jan 2009.

18. B. E. Shykoff, *Oxygen Consumption As a Function of Ergometer Setting in Different Diver's Dress: Regression Equations,* Technical Memorandum 09-06, Navy Experimental Diving Unit, Aug 2009.

19. C. Lundgren, G. Bergoe, A. Olszowka, and I. Tyssebotn, "Tissue Nitrogen Elimination in Oxygen-Breathing Pigs Is Enhanced by Fluorocarbon-Derived Intravascular Micro-Bubbles," *Undersea and Hyperbaric Medicine*, Vol. 32, No. 4 (2005), pp. 215-226.

20. E. P. Kindwall, A. Baz, E. N. Lightfoot, E. H. Lanphier, and A. Seireg, "Nitrogen Elimination in Man During Decompression," *Undersea Biomedical Research*, Vol. 2, No. 4 (1975), pp. 285-297.

21. P. K. Weathersby, S. S. Survanshi, R. Y. Nishi, and E. D. Thalmann, *Statistically Based Decompression Tables - VII: Selection and Treatment of Primary Air and N2O2 Data,* Joint Technical Report NSMRL 1182 and NMRI 92-85, Naval Submarine Medical Research Laboratory and Naval Medical Research Institute, Sep 1992.

APPENDIX A DIVER CHARACTERISTICS

DiverID	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	177	80.3	32	0.81	14.5	0.37	24	13
2	38	68	1.73	238	108.0	39	0.99	19	0.48	36	20
3	45	68	1.73	180	81.6	32	0.81	15.5	0.39	27	13
4	31	74	1.88	200	90.7	34	0.86	16.5	0.42	26	12
5	24	70	1.78	215	97.5	36	0.91	19	0.48	31	13
6	37	71	1.80	212	96.2	36	0.91	15	0.38	30	20
7	39	72	1.83	175	79.4	34	0.86	16	0.41	24	14
8	44	72	1.83	205	93.0	36	0.91	16.5	0.42	28	17
9	43	76	1.93	205	93.0					25	
10	35	68	1.73	190	86.2	36	0.91	17	0.43	29	18
11	43	73	1.85	208	94.3	37	0.94	18	0.46	28	16
12	42	68	1.73	150	68.0	32	0.81	15.5	0.39	23	13
13	46	72	1.83	190	86.2	34	0.86	16	0.41	26	14
14	33	67	1.70	158	71.7	30	0.76	14	0.36	25	12
15	49	68	1.73	160	72.6	32	0.81	16	0.41	24	11
16	38	72	1.83	205	93.0	38	0.97	18.5	0.47	28	18
17	45	72	1.83	192	87.1	35	0.89	15	0.38	26	19
18	36	70	1.78	190	86.2	35	0.89	16	0.41	27	17
19	44	68	1.73	195	88.5	37	0.94	17	0.43	30	20
20	36	71	1.80	200	90.7	34	0.86	17	0.43	28	13
21	35	69	1.75	180	81.6	34	0.86	16.75	0.43	27	14
22	33	68	1.73	195	88.5	32	0.81	17.5	0.44	30	9
23	41	70	1.78	183	83.0	33	0.84	16	0.41	26	13
25	46	70	1.78	200	90.7	35	0.89	17.5	0.44	29	15
26	36	68	1.73	184	83.5	38	0.97	16.5	0.42	28	23
27	38	72	1.83	187	84.8	36	0.91	15	0.38	25	20
28	42	70	1.78	195	88.5	36	0.91	17.5	0.44	28	16
29	44	75	1.90	180	81.6	33	0.84	16	0.41	23	11
30	28	66	1.68	135	61.2	30	0.76	14.5	0.37	22	11
31	30	68	1.73	168	76.2	33	0.84	15.75	0.4	25	15
32	44	72	1.83	180	81.6	34	0.86	18	0.46	24	10
33	44	74	1.88	220	99.8	36	0.91	17.5	0.44	28	15
34	35	69	1.75	170	77.1	33	0.84	15	0.38	25	16
35	37	72	1.83	210	95.3	38	0.97	16.5	0.42	28	21
36	43	71	1.80	210	95.3	36	0.91	15.75	0.4	29	19
37	33	68	1.73	200	90.7	34	0.86	16	0.41	30	16
38	45	72	1.83	245	111.1	40	1.02	20	0.51	33	19
39	22	70	1.78	190	86.2	32	0.81	16	0.41	27	11
40	41	72	1.83	185	83.9	33	0.84	16	0.41	25	12
41	35	70	1.78	205	93.0	36	0.91	16	0.41	29	19
42	34	69	1.75	165	74.8	32	0.81	14.5	0.37	24	14
43	30	69	1.75	155	70.3	30	0.76	16	0.41	23	6
44	35	68	1.73	190	86.2	35	0.89	16.5	0.42	29	17
45	43	71	1.80	235	106.6	38	0.97			33	
46	37	72	1.83	195	88.5	34	0.86	16.5	0.42	26	13
47	37	71	1.80	210	95.3	36	0.91			29	
48	37	70	1.78	230	104.3	37	0.94	17	0.43	33	19
49	35	69	1.75	170	77.1	32	0.81	15.5	0.39	25	13
50	34	73	1.85	214	97.1	34	0.86			28	
52	28	69	1.75	190	86.2					28	

DiverID	Age*	Height (inch)	Height (m)	Weight (lb)	Weight (kg)	Waist (inch)	Waist (m)	Neck (inch)	Neck (m)	BMI	Body Fat (%)†
53	41	68	1.73	190	86.2	35	0.89	17	0.43	29	16
54	34	72	1.83	227	103	36	0.91	18.5	0.47	31	13
55	45	69	1.75	204	92.5	36	0.91	17.25	0.44	30	17
56	36	72	1.83	220	99.8	37	0.94	19	0.48	30	15
57	39	69	1.75	185	83.9	33	0.84	17	0.43	27	12
58	26	69	1.75	170	77.1	32	0.81	16.5	0.42	25	10
59	42	68	1.73	165	74.8	32	0.81	15	0.38	25	14
61	32	74	1.88	195	88.5	34	0.86	16	0.41	25	13
62	41	74	1.88	265	120.2	44	1.12	19	0.48	34	26
63	27	69	1.75	170	77.1					25	
64	34	70	1.78	172	78.0	31	0.79	16.5	0.42	25	8
65	39	70	1.78	175	79.4	34	0.86	15	0.38	25	17
66	47	72	1.83	195	88.5	32	0.81	17	0.43	26	8
67	27	71	1.80	165	74.8					23	
68	34	62	1.57	155	70.3	33	0.84	15.5	0.39	29	18
69	27	72	1.83	215	97.5	36	0.91			29	
70	37	69	1.75	170	77.1	34	0.86	17	0.43	25	14
72	0	70	1.78	158	71.7	32	0.81	15.5	0.39	23	12
73	26	69	1.75	185	83.9					27	
74	25	72	1.83	195	88.5	34	0.86	17	0.43	26	12
75	48	73	1.85	213	96.6	36	0.91	17.5	0.44	28	15
77											
78	39	71	1.80	209	94.8	38	0.97	17.5	0.44	29	20
79	39	68	1.73	185	83.9	34	0.86	15.5	0.39	28	17
80											
81	34	71	1.80	238	108.0	39	0.99	21	0.53	33	15
82											
83	48	70	1.78	184	83.5					26	
84	41	66	1.68	165	74.8	37	0.94	17	0.43	27	21
85	28	75	1.90	205	93.0	34	0.86	16.5	0.42	26	12
86	34	71	1.80	200	90.7	34	0.86	17	0.43	28	13
Mean	37	70	1.79	192	87.2	35	0.88	16.5	0.42	27	15
SD	8	2	0.06	24	10.7	3	0.07	1.25	0.03	3	4

*age at first dive in this study; † calculated from height, waist circumference, and neck circumference according to U.S. Navy method [16]

APPENDIX B DIVING INTENSITY

The following tables show the dates on which each diver-subject participated in the dive trial

NOV 2005-JAN 2006

DiverID	2005-11-21	2005-11-22	2005-11-28	2005-11-29	2005-11-30	2005-12-01	2005-12-05	2005-12-06	2005-12-07	2005-12-08	2005-12-12	2005-12-13	2005-12-14	2005-12-15	2006-01-03	2006-01-04	2006-01-05
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1: A1 VVal-18 shallow stops. 2: A2 BVM(3) deep stops

FEB 2006 – APR 2006

DiverID	2006-02-06	2006-02-08	2006-02-09	2006-02-13	2006-02-14	2006-02-15	2006-02-16	2006-02-21	2006-02-23	2006-02-27	2006-02-28	2006-03-02	2006-03-06	2006-03-07	2006-03-08	2006-03-09	2006-03-21	2006-03-22	2006-03-23	2006-03-27	2006-03-28	2006-03-29	2006-03-30	2006-04-03	2006-04-04	2006-04-05	2006-04-06	2006-04-10	2006-04-11	2006-04-12	2006-04-13
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1: A1 VVal-18 shallow stops. 2: A2 BVM(3) deep stops

JUL 2006 – AUG 2006

DiverID	2006-07-10	2006-07-11	2006-07-12	2006-07-13	2006-07-17	2006-07-18	2006-07-19	2006-07-20	2006-07-24	2006-07-25	2006-07-26	2006-07-27	2006-08-07	2006-08-08	2006-08-09	2006-08-10	2006-08-14	2006-08-15	2006-08-16	2006-08-17	2006-08-21	2006-08-22	2006-08-23	2006-08-24	2006-08-28
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1: A1 VVal-18 shallow stops. 2: A2 BVM(3) deep stops

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APPENDIX C DIVE PROFILES

Dives were conducted in the Ocean Simulation Facility wet pot at the Navy Experimental Diving Unit. The wet pot was pressed 73 times with up to six divers participating in each chamber dive for a total of 390 man-dives. Two additional chamber dives, for a total of 10 man-dives, (DiveDayID 19 on 20060207 and DiveDayID 31 on 20060301) were aborted during the descent, due to divers being unable to equalize sinus or middle ear gas spaces with ambient pressure. Wet pot water temperature was controlled at 86 ± 2 °F.

MODIFIED DIVE PROFILES

Deviation from the planned dive profile occurred on six chamber dives (27 man-dives), as follows:

Shallow stops dive profile, DiveDayID 7 (20051205), one diver in trunk (167 fsw and dry) for three minutes during bottom time while checking regulator manifold in response to diving mishap.

Shallow stops dive profile, DiveDayID 10 (20051208), 6 divers (including 1 DCS), 20 fsw stop 1 min 39 s longer than tabulated due to time keeping error.

Shallow stops dive profile, DiveDayID 23 (20060214), 6 divers, reach bottom 15s late (3 min 17 s, 52 fsw/min), hold at 135 fsw due to ear squeeze.

Deep stops dive profile, DiveDayID 57 (20060718), 4 divers, reach bottom 16 s late (3 min 18 s, 51 fsw/min), chamber operator error.

Deep stops dive profile, DiveDayID 59 (20060720), 4 divers, reach bottom 32 s late (3 min 37 s, 42 fsw/min), hold at 85 due to ear squeeze.

Deep stops dive profile, DiveDayID 74 (20060823), 6 divers, reach bottom 23 s late (3 min 25 s, 49 fsw/min), hold at 147 fsw due to ear squeeze.

The table below summarizes the estimated P_{DCS} of the dive profiles as recorded. Note the narrow range of values estimated under the NMRI98 model, a range indicating that departures from the ideal schedule were trivial. On the contrary, there is a wide range of estimated risks for the deep stops dive profiles under the BVM(3) model. Notably, however, none of the dives listed above departed substantially from the BVM(3) estimated P_{DCS} for the ideal schedule. Four other deep stops dive profiles (DiveDayID 35 on 20060308, DiveDayID 56 on 20060717, DiveDayID 65 on 20060808, DiveDayID 67 on 20060810) had substantial bottom time recorded at 171 fsw resulting in high estimated risk under the BVM(3) model, and it was these dive profiles that caused the wide spread of BVM(3) estimated P_{DCS} seen in Table C1. The BVM(3) model can be very sensitive to slight variations in the dive profile. A sensitivity analysis of BVM(3) with respect to the deep stops dive profile showed a substantial increase in BVM(3)-estimated P_{DCS} with slight increases in bottom depth, bottom time, or ascent time to first stop. All these resulted in a slight increase in supersaturation on arrival at the first decompression stop in comparison to the ideal dive profile and substantially increased bubble growth during subsequent decompression.

Table C1. Estimated P_{DCS} of ideal dive profiles and of actual dive profiles

		P_{DCS}(%)						
Schedule	P_{DCS} model	Ideal	Min	1^{st} Qu	Median	Mean	3^{rd} Qu	Max
Shallow stops	NMRI98	4.429	4.031	4.093	4.104	4.117	4.138	4.245
	BVM(3)	6.158	6.134	6.165	6.182	6.194	6.211	6.299
Deep Stops	NMRI98	5.880	5.733	5.807	5.826	5.843	5.855	6.021
	BVM(3)	3.664	3.644	3.694	3.704	3.984	3.741	6.688

DIVE PROFILE DATA ACQUISITION PROBLEMS

Problems with the primary data acquisition system (DAS) on the Medical Deck resulted in loss of portions of six dive profiles, as outlined in the table below. Lost portions of these dive profiles were reconstructed from data recorded at lower frequency to the Ocean Simulation Facility Control Room DAS and from hand-written logs kept on the Medical Deck and in the Control Room.

Table C2. Reconstructed dive profiles

Date	DiveDayID	Dive Profile	Notes
20051122	2	Shallow stops	Late start of DAS at 8:58::18. Medical Deck manual log indicates left surface at 8:57::55
20060206	18	Deep stops	Medical Deck depth recording bad, pressure transducer line capped inside chamber. Profile reconstructed from Control room DAS depth recording (col 13, no 3 fsw offset, 300s intervals until end of BT, 0.1Hz thereafter) and manual logs.
20060215	24	Shallow stops	Descent portion of dive profile spurious because pressure transducer selector valve diverted to calibration instead of chamber. Manual logs indicate uninterrupted descent of 2 min 43 s (Control Room) and 2 min 47 s (Medical Deck).

Date	DiveDayID	Dive Profile	Notes
20060221	26	Deep stops	Electrical power and UPS failure to DAS at ~11:12am, file saved. Chamber at constant depth throughout ~3 min interruption. DAS restarted with new file name.
20060808	65	Deep stops	Green bike fail, green diver moved to blue bike ~8:55. Transients in recorded pressure trace. DAS failure at 8:58, file saved. Chamber at constant depth throughout 9 min interruption. DAS restarted at 9:07 with new file name. Green diver (DiverID 11) renamed as Blue (same as bike) in DAS files.
20060823	74	Deep stops	DAS failure. Chamber at constant depth throughout 7 min interruption. DAS restarted with new file name.

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APPENDIX D DCS CASE NARRATIVES

The tables below give the case narratives written by the attending Diving Medical Officer for each mishap diagnosed as DCS (Type I, II or marginal). Marginal signs or symptoms are those judged to not require recompression therapy and are typically mild or fleeting. Editorial interventions by one of the authors (DJD) are indicated by <tags>, as follows:

Tag	Meaning
<gap>	material deleted, typically description of dive
<add>…<add>	added in clarification
<corr>…<corr>	correction
<supplied>…<supplied>	material supplied by editor
<reg>…<reg>	regularized expression

Names removed and common short-hand expanded without indication.

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. T1 time was assigned as follows:

T2 reported	T1 assigned
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[21] 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.

DCS FOLLOWING SHALLOW STOPS (A1, VVAL-18)

DiveDay # Date	Dx	T1	T2	Narrative
10 20051208	Type I	118	782	22 year old active duty male USN diver <add>presented 22 hours after<add> participating in <gap> dive (2005-12-08). Patient states he had no problems during or immediately following the dive. The patient complained of some knee "cracking" during the evening of the dive <supplied>(20051209 00:30)<supplied>, but denied any pain. Patient states that upon waking at 0630 the morning following the dive (2005-12-09), he noticed a 1/10 right knee pain. The pain was retropatellar and felt like it was "in the joint". The pain did not radiate, had no relieving or exacerbating factors, and was not reproducible with movement or palpation. The patient played football that morning without difficulty. The patient presented to sick-call at 0900 and mentioned his pain to the duty DMO. After evaluation, it was decided that DCS could not be ruled out as an etiology, and patient was started with recompression

				therapy. Patient had no relief during press to 60 fsw, but experienced complete relief of pain at 6min15s into the first oxygen period. Patient had no further complaints through the rest of the treatment table 6 that was completed. Patient neurological exam was normal both before and after treatment. Patient had no physical exam findings of note. Patient discharged after two hour post-treatment observation. Final diagnosis of DCS type I made based on characteristics of symptoms and response to treatment.
20 20060208	Type II	11	114	34 year old active duty Navy diver presenting with right shoulder pain beginning 2 hours after surfacing from <gap> dive under profile A1. Patient complained of onset of right shoulder pain 1/10 constant, worse with movement. Patient also complained of right arm feeling colder than left arm. Patient denied numbness, tingling, or weakness. Patient exam by DMO before entering chamber showed positive tenderness to palpation at posterior shoulder and a normal neurological exam. After completion of exam, patient complained of increase in pain to 3/10. At that point, the decision was made to press to 60 fsw. In interval between exam and entering chamber, patient noticed increase in cold sensation and onset of weakness. Exam by inside tender showed decrease in right shoulder strength to 4/5 from 5/5 during DMO exam. Patient had no relief at arrival at 60 fsw, but noted improvement 5 minutes into first oxygen period. Patient had complete relief at <reg>12min15s<reg> into first oxygen period. Based on nature of symptoms and time of relief, Patient treated on USN Treatment Table 6. Treatment was uneventful. Patient had no residual symptoms at completion of treatment or at follow-up exam. Neurological exam at both times was normal, including right shoulder strength and right arm sensation. Final diagnosis is Type II DCS. <supplied> Patient admitted to pain/discomfort while seated watching movie, prior to 2 hour interview.<supplied>
21 20060209	Type I	121	156	30 year old, male, active duty diver presenting <add>21 hours after dive<add> with complaint of right knee pain and left eye pain. <gap> Patient states symptoms onset 2.5 hours after surfacing as a dull, achy 1/10 right knee pain with no exacerbating or relieving factors. Patient states pain is not constant, but is usually present. Patient able to sleep w/o difficulty. Patient played basketball and sustained a left corneal abrasion that was evaluated and treated. Patient denied any change in symptoms since onset. Decision made to press Patient to 60 fsw and evaluate at depth. Patient experienced complete relief of symptoms at <reg>6min40s<reg> into first oxygen period. Patient treatment on USN Treatment Table 5 with two 20-minute extensions at 30 fsw. Patient completed treatment without complications. Post-treatment neurological exam was completely normal, unchanged from the initial exam. Patient complained of continued eye pain secondary to corneal abrasion. Patient had not complained of knee pain at follow-up exam. Patient treatment for corneal abrasion continues. Final diagnosis: Type I DCS.

DCS FOLLOWING DEEP STOPS (A2, BVM(3))

DiveDay # Date	Dx	T1	T2	Narrative
11 20051212	Type I	128	1078	37 year old, active duty, male diver with 14 year history of Navy diving and no previous history of DCS injury completed a 170/30 experimental dive (profile A2) on <corr>Monday, December 12th 2005<corr> at 1230 without incident. <gap> Diver noted bilateral wrist pain (2-3/10) of a fleeting nature approximately 1730. Pain “came and went” throughout the evening. Diver woke during the night with a sharp, 7/10, “muscle pull like” pain in his right shoulder at approximately 0200 on the <add>13th<add>, but the pain rapidly subsided and the diver went back to sleep. DMO was first notified at 0620 on the 13th when the diver became concerned regarding a dull, aching pain (1-2/10) on medial aspect of left elbow. The elbow pain remained relatively stable, was present at rest, and was not increased with motion of the elbow joint. Complete neurologic exam revealed no other abnormality except for a previously existing left thumb abduction weakness. The diver was pressed to 60 feet of seawater (fsw) in the NEDU treatment chamber and experienced a pain reduction from 1/10 to 0.5/10 immediately upon reaching 60 fsw. The diver experienced complete relief of symptoms within five minutes of starting the first oxygen period. A treatment table 5 with extensions at 30 fsw was conducted. The diver continued to have complete relief of symptoms post-treatment at the 0, 2 hour, and 24 hour checks. Final Diagnosis: DCS I; pain only, left elbow. Outcome: Complete relief, USN Treatment Table 5, no residual deficits.
18 20060206	Type I	1	115	33 year old, active duty, Navy diver presented <add>2.4 h after dive<add> with progressively, rapidly enlarging pruritic rash over the lower abdomen and left tricep. Symptoms began 01:45 after surfacing from 170/:30 dive<gap>. Upon initial exam, patient had 3cm round erythematous rash at waist line that seemed consistent with traumatic irritation from clothing. Patient instructed to follow and be re-examined in morning. Patient returned to sickbay about 30 minutes later where patient was found to have large area of erythema with purple mottling measuring 30cm by 20cm predominantly over LLQ. Patient also had area of 10cm by 5 cm on left tricep that had similar characteristics. Patient initiated on USN Treatment Table 6 for presumed cutis marmorata. Patient had rapid resolution of rash and itching at arrival at 60 fsw. Patient completed USN Treatment Table 6 without extensions. Exam performed the following morning showed complete resolution of rash with no residual findings. Patient neurological exam was completely normal throughout the entire episode. Final Dx is Type I DCS, cutis marmorata.
25 20060216	Type I	125	220	A 37 year old active duty male diver completed experimental 170/30 "deep stops" decompression dive without incident. Approximately 3.5 hours after surfacing, he noted a 2-3/10 aching, throbbing pain in his left shoulder, including the pectoralis major muscle, lateral and anterior delt muscle. Pain continued unreported for approximately 4 additional hours and

DiveDay # Date	Dx	T1	T2	Narrative
				worsened during this time to a 5/10 level and increased area of involvement, now including his upper arm. The diver called NEDU and the bend's watch team was assembled. Complete neurological examination <add>7.2 hours after dive<add> revealed no additional abnormality except for the noted shoulder/arm pain. Diver was recompressed on air to 60 fsw with no relief of symptoms; diver was started on 100% oxygen by bibs mask with no change in symptoms during the next 20 minutes at 60 fsw on oxygen. DMO advised against compressing the diver to a deeper depth as symptoms were not worsening and DMO believed that additional time breathing 100% oxygen was warranted. By 10 minutes into the second 20-minute oxygen period at 60 fsw, pain had decreased to 4/10. Two 20-minute extensions were completed at 60 fsw, with pain decreasing to 2/10 by end of 3rd period and total resolution of symptoms by end of 4th period. Remaining treatment table 6 was completed without further extension. Tenders were changed after second period at 60 fsw, therefore the inside chamber tender completed the USN Treatment Table 6 with 45 minutes of oxygen breathing at 30 fsw and oxygen breathing during entire travel time to surface. Repeat neurological examination revealed no residual pain, deficit, or symptoms. Patient was observed for standard period post-treatment and driven home for continued observation by trained diver. Final diagnosis: DCS Type I injury (pain only); complete resolution; no residual deficit.
28 20060223	Type II	−1	5	The test diver surfaced from a 170/30 (A-2 profile) research profile at 1223 hrs. The diver was “moving slowly” during his clean time, and when asked how he felt, the diver reported 3/10, dull, bilateral posterior trapezius muscle pain which he attributed to his positioning in the “horns” while riding the cycle ergometer at depth. The DMO did a focused neurological exam at 1228. Diver exhibited normal 11th cranial nerve function, 5/5 trapezius muscle strength bilaterally and sensation of the upper chest and back was completely normal and intact. Because a musculoskeletal cause for the pain was immediately identified (and diver had no other complaints), the decision was made to closely observe the diver over the 2-hour post-dive period. After the 6 research divers had completed their 10-minute clean time, DMO escorted them to the Physiology lab at NEDU for their post-dive observation. During the elevator ride up to the 2nd floor lab, DMO noticed that diver had “slumped” against the wall of the elevator and “didn’t look right”. Upon arrival on the 2nd deck, the other 5 divers were released to the duty Corpsman and DMO started a full neurological exam. Although the diver was alert and oriented x 3, he was having difficulty remaining focused and noted some visual disturbances. During the coordination testing, the diver displayed a “wide gait”, was unable to perform heel-toe walk, had difficulty with all hand-eye coordination tests, and then began to complain of vertigo, followed immediately by ataxia and nausea. Because the diver was rapidly worsening, the neurological exam was halted, the code was called, and the diver was immediately escorted back down to the treatment chamber. Approximately 15 minutes after

DiveDay # Date	Dx	T1	T2	Narrative
				surfacing, the diver’s nausea had worsened and he vomited several times. The patient was then loaded into the chamber and pressed to 60 fsw. The patient reported complete relief of all symptoms (including the bilateral trapezius muscle pain) at 4 min. 43 seconds into the first oxygen period. Dr. Ruterbusch locked into the chamber to perform a full neurological exam during the first air break. The patient’s neurological exam at that time was completely normal, except for a “mild” headache that the patient attributed to the episodes of vomiting. A TT 6 with 2 extensions at 60 fsw was completed. Post treatment neurological was normal, patient reported complete resolution of all symptoms, including the headache. Diagnosis: DCS Type II.
35 20060308	Type I	129	174	Patient is a 33 year old active duty Navy experimental diver who presented with complaint of rash several hours post-surfacing from an 170 feet for 30 minutes dive. <gap> Patient initially surfaced at 1220 without complaint and completed his 10 minute clean time and 2 hour mandatory post dive observation period without complaints. At approximately 1530 patient presented to sickbay with complaint of pruritic rash on abdomen. At that time a Code Yellow was paged and patient was placed on 100% oxygen via non-rebreather mask. The duty dive medical officer arrived on the scene less than 1 minute later and upon arrival patient was sitting calmly in no apparent distress. Patient was alert, responsive, and oriented. Examination revealed a completely intact neurological exam including mental status exam. Examination of skin revealed multiple areas of erythema inter-mixed with non-blanching purple mottling of the skin on areas of abdomen, back, right posterior arm, and bilateral posterior thighs. This was consistent with a diagnosis of Cutis Marmorata, and decision was made to treat patient on a Treatment Table 6. Patient was placed in chamber and pressed to 60 FSW with immediate resolution of purple mottling and approximately 50% resolution of erythema. By the end of the 2nd oxygen period the remainder of erythema had completely resolved. Remainder of treatment table was completed without event. Post treatment neurological exam was normal. Skin examination revealed complete resolution of rash. Diagnosis: Type I DCS (Cutis Marmorata).
56 20060717	Type I	137	337	Patient is a 41 year old male, active duty diver. Patient presented to sickbay at 1200 on 18 July complaining of sharp, non-radiating, constant right shoulder pain that he subjectively rated as a 5/10 in intensity <corr>24 hours<corr> after completion of an experimental dive profile of 170 feet / 30 min. Total in water decompression time was 180 minutes. Patient states that the onset of shoulder pain occurred at approximately 1800 on 17July. This was 6 hours after reaching surface at 1200 on 17July. Initially, the pain was described as a dull ache, rating a 2/10 intensity level that progressed throughout the night to its current level. Neurological exam revealed: normal mental status; cranial nerves II-XII intact; no sensory or motor deficits appreciated; strength to all muscle groups 5/5; reflexes 2+ bilaterally; normal gait. Aside from mild sunburn, the remainder

DiveDay # Date	Dx	T1	T2	Narrative
				of his physical exam was unremarkable for abnormal objective findings. The patient was diagnosed with pain only Type I DCS and subsequently treated with hyperbaric oxygen. The patient reached bottom (60 fsw) at 1310 and was placed on 100% oxygen. Ten minutes into the first oxygen period the pain was reportedly decreased to 3/10 and by the end of the first oxygen period it was described as “less sharp but still 3/10”. The treatment was extended twice at 60 fsw and at the end of the second extension the patient reported a 2/10 pain scale. Upon reaching 30 fsw pain was reported as a 1/10 and was completely resolved (0/10) by the end of the first 30 fsw period. Treatment table 6 was completed without further extensions and post-treatment observation period was uneventful. The patient was released to home with follow up exam in the AM. <supplied>Patient admitted slight “fullness” in shoulder at end of treatment but complete resolution by morning of 19 July 2006.<supplied> Summary: 41 year old diver with pain only, type 1 DCS of the right shoulder treated on a USN Treatment Table 6 with two extensions at 60 fsw. Complete resolution (0/10) of pain achieved at the end of the first 30 fsw oxygen period.
59 20060720	Marginal	135	1080	Patient is a 46 year old male, active duty diver. Patient presented to the NEDU duty chamber at 1100 on 21July <add>23 hours after dive<add> complaining of swelling of his hands. Patient states that he first noticed the swelling this morning upon waking. This was approximately 18 hours after completing (RS at 1230) an experimental dive profile of 170 feet / 30 min. Total in water decompression time was 180 minutes. Patient states that he experienced transient left shoulder and elbow pain (niggles) yesterday evening but did not think he required treatment. Neurological exam revealed: normal mental status; cranial nerves II-XII intact; no sensory or motor deficits appreciated; strength to all muscle groups 5/5; reflexes 2+ bilaterally; normal gait. Physical exam was remarkable for mild non-pitting edema of the hands with the right hand being slightly more noticeable than the left. The Patient had intact two point discrimination. Hands were warm and pink with capillary refill < 2 seconds and a normal Allen test. The remainder of the physical exam was without abnormal objective findings. Due to the temporal relationship to finishing an experimental decompression dive and no other definitive etiology for the patient’s symptoms, presumptive hyperbaric oxygen therapy will be given. Based on my examination and interview of the patient, I do not feel strongly that this is DCS. However, hyperbaric oxygen treatment will be given to benefit the diver. Summary: 46 year old diver with idiopathic hand edema, possibly related to DCS. USN Treatment Table 5 instituted, LS at 1201, On oxygen at 1205, some relief noted at 1250 prior to leaving 60 fsw. Reached surface at 1420.
59 20060720	Type I	135	285	Patient is a 45 year old male, active duty diver. Patient presented to the NEDU duty chamber at 1920 on 20 July complaining of dull, constant left shoulder pain that radiates with tingling into the left arm and hand. He subjectively rates a 3/10 in intensity 7 hours after completion of an experimental

DiveDay # Date	Dx	T1	T2	Narrative
				dive profile of 170 feet / 30 min. Total in water decompression time was 180 minutes. Patient states that the onset of shoulder pain occurred at approximately 1700. This was 4 ½ hours after reaching surface at 1230. Two hours after surfacing, the patient complained of mild left trapezius pain that was consistent with prior musculoskeletal pain caused by the cycle ergometer shoulder horns. The pain subsequently migrated to the left shoulder joint and began to radiate. Appropriately, the patient then reported for evaluation and treatment. Neurological exam revealed: normal mental status; cranial nerves II-XII intact; no sensory or motor deficits appreciated; strength to all muscle groups 5/5; reflexes 2+ bilaterally; normal gait. Physical exam was remarkable for asymptomatic hypertension. His presenting BP was 178/115. The patient is hypertensive at baseline and was slightly anxious at the time of evaluation. An EKG was obtained and compared to previous EKG demonstrating no changes. During the treatment serial BP checks were performed and the patient's BP was back to baseline 146/90 within one hour. The remainder of the physical exam was without abnormal objective findings. The patient was diagnosed with pain only type I DCS and subsequently treated with hyperbaric oxygen. The patient reached bottom (60 fsw) at 2003 and was placed on 100% oxygen. Upon reaching bottom the tingling sensation had resolved. At 2028 (25 minutes into the first oxygen period) the pain was completely resolved (0/10). Treatment table 6 was completed at 0050 21Jul06 without extensions and post-treatment observation period was uneventful. The patient was released to home with follow up exam scheduled. Summary: 45 year old diver with pain only, Type 1 DCS of the left shoulder treated on a USN Treatment Table 6 with no extensions. Complete resolution of pain achieved with no residual symptoms.
68 20060814	Type I	11	231	Patient is a 36 year old, active duty Navy experimental diver who presents complaining of right shoulder pain after completing the Deep Stops in Air Decompression Protocol 170 feet for 30 minutes Profile A-2 with 180 minutes of total decompression time. Patient reached surface at 1225. Approximately 2 hours after surfacing he began having mild right shoulder pain, that was episodic, and at time thought maybe he was experiencing niggles. At 1615 hours patient states that pain became worse 5/10 <supplied>(pain was shooting, sharp on occasion, no positional relief, and patient couldn't get comfortable)<supplied> and at that point patient presented to chamber. <supplied>Patient arrived at chamber near 17:00.<supplied> Initial neurological exam <supplied>by corpsman<supplied> was normal and patient was given diagnosis of Type 1 DCS. Patient was pressed to 60 feet on Treatment Table 6 at 1725 hours and 18 minutes into first Oxygen period had complete resolution of symptoms. Remainder of treatment was uneventful, and post-treatment neurological exam was normal. Next day follow-up was performed and patient remains pain free without residual symptoms. Diagnosis: Type 1 DCS <supplied>Following treatment, diver mentioned that he had leaned on bar in OSF

DiveDay # Date	Dx	T1	T2	Narrative
				wet pot while watching movie during decompression, armpits on bar supporting weight which might have restricted blood flow.<supplied>
73 20060823	Marginal	137	187	3 hours post surfacing complained of period of sensation of wetness when feeling right hand. Completed full neurological exam with no signs or symptoms of DCS. Sensation did not re-occur. Dx: niggle
75 20060824	Type II	−1	15	35 year old active duty male diver surfaced from a 170/30 air dive at <corr>12:11<corr> on 24AUG06 using MK 20 FFM and following the A-2 “deep stops” experimental decompression profile without reported difficulty. Approximately two minutes into the post dive clean time, the diver reported to the Dive Supervisor that he was feeling “dizzy and weak” and immediately was placed on the deck. Diver later reported losing awareness of his surroundings at this point for a period of 5-30 seconds. The patient was expeditiously placed on a backboard and moved into the Delta chamber of NEDU’s ocean simulation facility for treatment. On reaching 60 fsw in the chamber at 1235, the patient reported complete recovery from all symptoms including a previously unreported loss of his peripheral vision. The patient’s blood pressure upon reaching 60 fsw was 120/80 with a pulse of 80. The patient was placed on 100% oxygen BIBS facemask for a total of 5 20-minute periods at 60 fsw (per Dive Manual V5 for severe DCS II hits). The patient vomited twice during the first air-break at 60 fsw and was given IV saline (1.5 liters) for possible dehydration. The patient completed a USN Treatment Table 6 without extensions at 30 fsw and without further difficulty. Post-dive complete neurologic examination demonstrated no deficits or changes from pre-dive condition. Patient was made NPQ for diving for 28 days. Final DX: DCS II (central) treated with USN Treatment Table 6 with two extensions at 60 fsw, complete resolution of all symptoms within 5 minutes of first treatment period - although this episode was similar to two previous pre-syncopal episodes experienced by this diver during physical training, this episode is not associated with any reported anxiety or excessive physical effort, and this episode responded immediately to pressure. AGE is unlikely due to the experience of the diver, the MK 20 FFM characteristics, and the habit of bringing the OSF from 7 fsw (last decompression stop) to 4 fsw and holding until surfacing due to the difficulty with keeping the hatch sealed at lower pressures. The patient's lungs were clear to auscultation.
75 20060824	Type I	139	949	34 year old active duty male diver surfaced from a 170/30 air dive at <corr>12:11<corr> on 24AUG06 using MK 20 FFM and following the A-2 “deep stops” experimental decompression profile without reported difficulty. The patient reported to NEDU at 0700 the following morning with a report of 2-3/10 right knee pain. <supplied>Woke with pain at approximately 04:00 25 Aug 2006.<supplied> DMO completed a full neurological examination with only abnormality being a constant 2-3/10 dull achy pain within the right knee joint that was unaltered by palpation or movement. No radiation, no change in sensation was noted. The diagnosis of Type I DCS (pain only, right knee)

DiveDay # Date	Dx	T1	T2	Narrative
				was made and treatment initiated. On reaching 60 fsw in the chamber at 0800, the patient reported complete recovery from all symptoms. The patient was placed on 100% oxygen BIBS facemask for a total of 3 20-minute periods at 60 fsw. The patient completed a USN Treatment Table 6 without extensions without difficulty. Post dive complete neurologic examination demonstrated no deficits or changes from pre-dive condition. Patient was made NPQ for diving for 28 days. Final DX: DCS I pain only right knee - treated with USN Treatment Table 6 without extensions, complete resolution of all symptoms within 1 minute of first treatment period. USN Treatment Table 6 used in lieu of USN Treatment Table 5 due to delay to treatment of 20 hours.
76 20060826	Type II*	1185	1584	Member evaluated 1630 30 Aug 06 (approximately 52 hours after deep stops A2 profile on 28 Aug 06) for pain on the top of his left hand and numbness of the ring and middle fingers. Onset of pain symptoms was 1500 29 Aug 06 (27 hours after surfacing), but member did not feel this was related to dive until numbness started about 1600 on 30 Aug 06. He reported no history of mechanical trauma to that hand and no change in pain or numbness with position, elevation, etc. DMO diagnosed with DCS Type 2 and member treated on USN Treatment Table 6 with no extensions. Member had complete relief of numbness within 10 minutes of the first oxygen period at 60 ft. Pain reduced from 3/10 to 1/10 at the same time. Member had incremental improvement of pain throughout treatment and reported 1/2 out of 10 pain at the end of treatment. Neurological exams throughout were normal. Member was observed for 1 hour post treatment and escorted to barracks on base without incident. Follow up at 0800 31 Aug 06 revealed no recurrence of numbness, very mild residual pain on the dorsum of left hand, and an otherwise clean Neurological exam.

*reclassified by authors as not DCS according to criteria in Temple et al. (1999)[14]

DIAGNOSTIC CRITERIA FOR DCS

Diagnostic criteria used for retrospective evaluation of diving incidents for the U.S. Navy air and N_2-O_2 primary decompression database,[14] were used to re-evaluate cases in the present study for hypothesis testing.

<u>DCS requiring recompression</u>

Joint pain persisting at least as long as tabulated below

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[1]
Any inner ear symptoms,[2] unless clearly from barotrauma
Any suspicious symptom leading to and relieved by recompression

Marginal DCS: DCS not requiring recompression[3]

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

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[4]

Not DCS

No signs or symptoms reported
Signs or symptoms reported 24 fours after surfacing[5]
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[6]

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[1] e.g., visual blurring, "mental sluggishness"
[2] e.g., unsteadiness, vertigo, hearing loss
[3] Based on perception that lack of treatment will not result in morbidity
[4] Diver may have gone on to develop DCS if not treated
[5] Signs and symptoms occurring later than 24 hours after a saturation dive may be considered DCS
[6] At which time any DCS should have occurred

APPENDIX E VGE DATA

As a secondary outcome measure, but not used as a trial end point, divers were monitored for venous gas emboli (VGE) with trans-thoracic cardiac 2-D echo imaging at 30 minutes and 2 hours after surfacing. Divers reclined with left side down, and the four heart chambers were imaged with the diver at rest and while, in turn, flexing each elbow and knee. VGE were graded according to the following scale.

Grade	Description
0	No bubble seen
1	Rare (<1/s) bubble seen
2	Several discrete bubbles visible per image
3	Multiple bubbles visible per image but not obscuring image
4	Bubbles dominate image, may blur or obliterate chamber outlines

The following table shows the peak VGE score of either of the two examinations. VGE data were unavailable for three man-dives, including two cases of early onset DCS.

			VGE Grade					
			Rest	Flexion				
DiverID	Dive Day #	Schedule*		R. Arm	L. Arm	R. Leg	L. Leg	DCS
1	6	A2	2	2	2	3	3	
1	12	A2	2	2	2	4	3	
1	21	A1	1	1	2	4	3	Type1
1	34	A2	2	2	2	2	2	
1	38	A1	2	2	2	2	2	
1	45	A1	2	2	1	2	3	
1	51	A2	3	4	4	4	4	
1	63	A1	1	1	1	1	1	
1	65	A2	1	1	1	3	1	
1	71	A1	1	2	2	3	3	
1	75	A2	2	2	2	4	3	
2	9	A1	0	0	0	0	1	
2	11	A2	0	1	0	0	0	Type1
3	1	A1	0	1	0	1	2	
3	6	A2	2	2	2	2	3	
3	17	A1	1	1	2	1	1	
3	21	A1	0	0	1	1	1	
3	25	A2	1	3	3	2	3	
3	38	A1	0	2	1	2	3	
3	43	A2	2	3	3	3	3	
3	47	A1	2	2	1	2	1	
3	55	A1	2	2	2	3	3	
3	59	A2	1	2	2	2	2	Type1
4	1	A1	0	1	2	1	2	
4	5	A2	2	4	3	3	3	
4	9	A1	3	4	3	3	3	
4	11	A2	3	4	4	4	3	
4	32	A1	2	3	1	3	1	
4	33	A2	3	3	4	4	4	
4	39	A1	3	3	3	3	3	

DiverID	Dive Day #	Schedule*	VGE Grade Rest	Flexion R. Arm	L. Arm	R. Leg	L. Leg	DCS
4	42	A2	2	4	2	2	3	
4	44	A1	3	4	2	3	2	
4	48	A2	1	3	2	2	1	
4	74	A2	3	4	2	3	3	
5	5	A2	0	0	1	0	0	
5	7	A1	0	1	0	0	1	
5	13	A2	0	1	1	1	1	
5	16	A1	2	3	3	2	1	
5	29	A1	0	0	0	0	0	
5	37	A1	2	3	2	2	3	
5	51	A2	0	0	0	0	0	
5	54	A1	0	0	0	0	0	
5	73	A2	0	0	1	0	1	
6	4	A2	2	4	3	4	4	
6	8	A1	2	3	2	4	4	
6	12	A2	2	2	2	4	4	
6	18	A2	3	2	3	4	4	
6	21	A1	2	4	2	3	4	
6	22	A2	3	3	4	4	3	
6	28	A2	2	3	2	4	4	
6	32	A1	1	1	2	1	2	
6	36	A2	1	2	2	4	4	
6	39	A1	2	2	2	3	3	
6	53	A1	2	2	4	2	4	
6	56	A2	2	2	2	4	4	
6	61	A1	2	2	2	2	4	
7	12	A2	3	3	3	4	4	
7	15	A1	2	4	4	3	3	
7	26	A2	1	1	2	2	3	
7	38	A1	0	0	0	0	0	
7	45	A1	2	2	2	1	1	
7	50	A2	2	3	3	3	2	
7	71	A1	2	3	3	2	2	
8	12	A2	4	4	4	4	4	
8	29	A1	0	0	0	0	0	
8	36	A2	2	4	4	4	4	
8	49	A2	2	4	4	4	4	
8	62	A1	1	1	1	2	1	
8	74	A2	3	3	3	4	4	
9	4	A2	4	4	4	4	4	
10	5	A2	3	3	3	2	4	
10	7	A1	2	2	2	2	2	
10	16	A1	1	2	1	2	3	
10	30	A1	0	1	0	1	1	
10	33	A2	1	2	1	2	2	
10	46	A1	2	2	2	3	2	
10	48	A2	3	4	3	3	4	
10	54	A1	2	3	2	4	3	
10	58	A2	1	2	2	3	3	
10	60	A1	0	0	0	0	0	
10	66	A2	2	2	2	3	4	
10	70	A1	0	2	1	2	1	

DiverID	Dive Day #	Schedule*	VGE Grade Rest	Flexion R. Arm	L. Arm	R. Leg	L. Leg	DCS
10	72	A1	0	2	1	1	1	
11	2	A1	1	1	1	1	1	
11	3	A2	1	1	0	1	0	
11	7	A1	2	2	2	2	3	
11	10	A1	0	0	0	1	1	
11	13	A2	2	4	3	4	2	
11	15	A1	0	0	0	1	0	
11	18	A2	2	2	2	4	3	
11	25	A2	1	3	2	3	3	
11	28	A2	0	1	2	1	1	
11	30	A1	0	0	0	0	0	
11	45	A1	0	0	2	0	2	
11	52	A1	0	0	0	0	0	
11	55	A1	0	0	1	0	1	
11	56	A2	2	2	2	4	2	
11	65	A2	0	0	0	0	0	
12	10	A1	2	2	3	3	3	
12	36	A2	2	4	3	3	3	
12	54	A1	0	0	0	0	0	
12	56	A2	2	3	2	2	2	
13	7	A1	1	1	2	3	2	
13	13	A2	1	4	2	4	3	
13	17	A1	0	2	2	3	3	
13	20	A1	0	0	0	0	0	
13	24	A1	0	1	0	0	0	
13	41	A2	2	2	2	2	2	
13	45	A1	0	0	0	0	0	
13	49	A2	0	1	2	1	2	
13	58	A2	1	2	2	4	3	
13	62	A1	0	1	1	3	2	
13	66	A2	1	1	1	2	1	
13	74	A2	0	0	0	3	1	
14	1	A1	0	0	0	0	0	
14	9	A1	1	1	2	2	1	
14	14	A2	1	1	2	2	3	
14	17	A1	1	0	1	0	1	
15	3	A2	1	1	1	2	1	
15	13	A2	1	4	4	4	2	
15	17	A1	2	3	3	2	2	
15	56	A2	1	2	2	2	2	
16	4	A2	1	2	2	3	1	
16	61	A1	2	2	3	2	2	
17	4	A2	0	1	0	1	0	
17	8	A1	1	1	1	1	1	
17	26	A2	1	3	1	3	1	
17	40	A2	1	2	2	3	2	
18	2	A1	1	2	2	2	2	
18	5	A2	2	3	3	3	3	
18	9	A1	2	2	2	2	3	
18	23	A1	0	0	0	0	0	
18	49	A2	0	3	1	2	2	
19	2	A1	1	2	2	2	2	

DiverID	Dive Day #	Schedule*	VGE Grade Rest	Flexion R. Arm	L. Arm	R. Leg	L. Leg	DCS
19	6	A2	3	3	3	4	3	
19	12	A2	0	4	3	3	3	
19	15	A1	1	3	3	4	3	
19	21	A1	2	3	2	2	2	
19	23	A1	1	2	2	3	3	
19	36	A2	2	3	4	2	2	
19	38	A1	1	2	2	3	2	
19	51	A2	3	3	3	3	3	
19	59	A2	2	3	2	2	2	
19	69	A1	0	1	1	1	1	
20	10	A1	2	4	4	2	2	
20	21	A1	0	3	1	1	2	
20	25	A2	2	4	4	3	3	Type1
20	69	A1	0	2	1	2	2	
21	16	A1	1	2	2	4	3	
21	20	A1	1	4	1	3	2	
21	22	A2	2	4	4	4	4	
22	2	A1	0	2	2	2	2	
22	6	A2	1	3	2	2	2	
22	17	A1	2	4	2	2	2	
22	58	A2	0	0	0	0	0	
22	65	A2	0	0	0	0	0	
23	1	A1	0	0	0	1	0	
23	5	A2	3	3	3	3	3	
23	9	A1	2	3	3	3	3	
23	16	A1	2	4	2	2	2	
23	20	A1	2	2	2	2	2	
23	22	A2	2	2	2	2	2	
23	29	A1	1	1	1	1	1	
23	33	A2	1	2	2	2	2	
23	39	A1	3	4	3	3	3	
23	41	A2	3	4	2	3	2	
23	44	A1	2	2	2	2	2	
23	50	A2	1	1	1	1	1	
23	53	A1	2	3	3	3	3	
23	57	A2	1	2	1	1	1	
23	61	A1	0	0	0	0	0	
23	65	A2	2	2	2	2	2	
23	73	A2	1	1	1	1	1	Marginal
25	14	A2	3	3	4	4	3	
25	23	A1	0	1	2	2	1	
25	34	A2	1	1	1	1	1	
25	47	A1	2	3	3	3	3	
25	55	A1	0	0	0	0	0	
25	69	A1	0	0	1	1	1	
26	2	A1	2	1	1	1	1	
26	4	A2	1	2	1	2	1	
26	8	A1	2	4	2	2	2	
26	15	A1	0	0	0	0	0	
26	20	A1	1	1	1	1	1	
26	24	A1	1	1	1	1	1	
26	26	A2	0	0	1	0	0	

DiverID	Dive Day #	Schedule*	VGE Grade Rest	Flexion R. Arm	L. Arm	R. Leg	L. Leg	DCS
26	37	A1	0	0	1	0	1	
26	40	A2	0	0	0	0	0	
26	46	A1	0	0	0	0	0	
26	48	A2	0	0	0	0	0	
27	1	A1	0	1	1	0	0	
27	3	A2	1	2	2	2	2	
27	8	A1	1	1	1	1	1	
27	11	A2	2	3	2	1	1	
27	30	A1	1	1	1	1	1	
27	35	A2	3	4	3	2	4	
27	41	A2	3	2	2	1	2	
28	10	A1	0	1	0	0	0	
28	23	A1	0	1	0	0	1	
28	28	A2	0	1	1	1	1	
28	30	A1	0	0	0	0	0	
28	34	A2	0	1	0	0	1	
28	45	A1	0	0	0	0	0	
28	49	A2	2	2	1	2	1	
28	53	A1	0	0	0	0	0	
28	60	A1	0	0	0	0	0	
28	70	A1	0	0	0	0	0	
29	2	A1	1	2	2	2	2	
29	5	A2	3	3	4	3	3	
29	8	A1	3	3	3	3	3	
29	14	A2	3	4	4	4	4	
29	15	A1	1	3	2	3	3	
29	18	A2	1	1	1	4	3	
29	26	A2	3	3	4	4	4	
29	40	A2	4	3	3	3	3	
29	63	A1	2	2	2	2	2	
29	64	A1	2	2	3	2	2	
30	12	A2	1	3	1	3	2	
30	24	A1	2	4	2	3	2	
30	32	A1	0	0	0	0	1	
30	66	A2	1	1	1	1	1	
31	7	A1	1	2	1	1	3	
31	11	A2	3	3	3	3	4	
31	15	A1	0	0	2	2	1	
31	22	A2	0	0	1	1	0	
31	35	A2	3	2	3	4	4	
31	41	A2	2	2	2	2	1	
31	44	A1	2	2	2	2	2	
31	48	A2	0	0	1	0	1	
32	6	A2	2	3	2	4	3	
32	23	A1	0	2	0	2	1	
32	34	A2	3	4	4	4	4	
33	4	A2	3	4	4	4	4	
33	25	A2	3	4	3	4	3	
33	38	A1	3	4	3	4	3	
34	7	A1	1	3	2	1	1	
34	11	A2	0	0	1	2	2	
34	33	A2	0	0	1	2	2	

DiverID	Dive Day #	Schedule*	VGE Grade Rest	Flexion R. Arm	L. Arm	R. Leg	L. Leg	DCS
35	30	A1	0	0	0	0	0	
35	36	A2	0	0	0	0	0	
35	47	A1	2	3	2	3	2	
35	53	A1	0	0	1	0	1	
35	67	A2	1	1	1	1	1	
35	71	A1	0	0	0	0	0	
36	3	A2	1	1	1	1	0	
36	11	A2	1	3	1	1	1	
36	35	A2	2	3	2	3	3	
36	46	A1	2	4	3	2	2	
36	54	A1	2	3	2	3	2	
36	66	A2	2	3	3	3	2	
37	1	A1	0	1	1	0	0	
37	6	A2	0	0	1	0	0	
37	13	A2	0	1	1	1	0	
37	18	A2	0	1	1	1	1	
37	22	A2	1	1	1	1	1	
37	42	A2	0	0	0	0	0	
38	3	A2	1	1	1	1	1	
38	8	A1	0	1	0	1	1	
38	46	A1	0	0	0	0	0	
38	57	A2	1	1	1	3	2	
39	10	A1	2	2	1	3	2	Type1
40	3	A2	1	2	1	1	1	
40	9	A1	0	0	1	0	0	
40	16	A1	1	3	1	2	2	
40	18	A2	1	2	1	3	1	
40	35	A2	3	4	3	4	4	
40	40	A2	3	3	2	3	3	
40	44	A1	2	3	1	3	1	
40	50	A2	1	3	1	1	1	
40	54	A1	1	1	2	2	2	
40	62	A1	2	2	2	2	2	
40	66	A2	1	2	1	1	1	
40	70	A1	1	2	2	3	2	
41	14	A2	3	3	3	4	4	
41	41	A2	2	3	4	4	4	
42	16	A1	2	4	3	4	3	
42	18	A2	3	4	3	4	4	Type1
42	35	A2	4	4	4	4	4	Type1
43	10	A1	1	1	1	2	2	
44	17	A1	1	1	0	1	0	
44	20	A1	1	3	3	4	4	
44	28†	A2	1	2	2	2	2	
44	33	A2	1	2	2	3	3	
44	42	A2	2	3	2	4	3	
44	46	A1	0	0	0	0	0	
44	48	A2	1	1	2	1	2	
45	22	A2	2	4	2	3	3	
45	34	A2	2	2	3	2	3	
45	41	A2	3	3	2	3	2	
46	24	A1	1	1	1	1	2	

			VGE Grade					
			Rest	Flexion				
DiverID	Dive Day #	Schedule*		R. Arm	L. Arm	R. Leg	L. Leg	DCS
46	26	A2	1	1	2	2	1	
46	29	A1	1	1	1	1	1	
46	43	A2	2	1	1	3	2	
46	46	A1	1	2	1	1	2	
46	68	A2	1	3	2	3	2	Type1
47	25	A2	2	3	1	3	2	
47	36	A2	2	4	2	4	3	
47	47	A1	2	3	2	3	3	
47	53	A1	1	1	1	2	2	
47	66	A2	2	2	2	2	2	
47	73	A2	1	1	2	2	2	
48	25	A2	2	3	3	3	2	
48	57	A2	2	3	3	4	4	
48	61	A1	2	2	3	2	3	
49	20	A1	2	3	3	3	3	Type2
49	43	A2	3	4	3	4	3	
50	24	A1	1	4	1	1	1	
50	28	A2	2	4	4	3	2	
50	29	A1	3	4	3	3	3	
50	37	A1	2	1	3	2	1	
50	47	A1	4	4	4	4	4	
50	50	A2	1	1	1	2	1	
50	63	A1	2	3	2	3	3	
50	64	A1	1	1	1	1	3	
50	68	A2	2	3	2	3	2	
50	73	A2	0	3	1	1	1	
52	21	A1	0	0	0	0	0	
52	32	A1	1	1	0	0	0	
52	33	A2	0	1	1	1	1	
52	39	A1	2	3	3	3	3	
52	47	A1	3	4	2	4	2	
52	51	A2	0	0	0	0	0	
52	52†	A1	0	1	0	1	1	
52	60	A1	0	0	0	0	0	
52	73	A2	0	0	0	3	0	
53	23	A1	2	4	3	4	3	
53	57	A2	4	4	4	4	4	
54	30	A1	0	1	0	4	1	
54	34	A2	2	2	2	3	3	
55	37	A1	2	3	2	3	2	
55	43	A2	3	4	3	3	3	
55	45	A1	3	3	2	2	3	
55	63	A1	1	3	1	2	2	
55	65	A2	1	4	2	4	3	
55	74	A2	4	4	3	4	3	
56	37	A1	2	3	1	3	3	
56	40	A2	3	4	3	3	3	
56	43	A2	3	3	3	3	3	
57	39	A1	0	1	2	0	1	
57	42	A2	1	0	0	1	1	
58	40	A2	2	3	1	2	2	
58	51	A2	2	4	3	2	2	

DiverID	Dive Day #	Schedule*	VGE Grade Rest	Flexion R. Arm	L. Arm	R. Leg	L. Leg	DCS
59	43	A2	3	4	3	3	3	
59	49	A2	2	3	3	3	3	
59	55	A1	2	3	2	3	3	
59	70	A1	2	3	3	3	2	
61	44	A1	2	3	1	2	1	
62	50	A2	2	4	4	4	4	
62	52	A1	1	2	2	4	3	
62	56	A2	3	3	3	4	4	Type1
62	69	A1	0	1	1	1	1	
63	52	A1	0	0	0	0	0	
64	59	A2	1	3	2	2	1	
65	58	A2	3	4	3	3	3	
65	74	A2	1	1	1	1	1	
66	59	A2	3	4	3	3	3	Marginal
67	55	A1	1	1	2	1	1	
67	67	A2	3	3	3	4	4	
68	61	A1	2	2	3	3	4	
69	61	A1	2	3	2	2	2	
70	63	A1	0	0	0	0	0	
72	64	A1	1	3	2	4	3	
72	67	A2	3	4	4	3	3	
73	64	A1	1	2	1	1	1	
73	67	A2	1	2	1	4	2	
73	68	A2	1	2	2	2	2	
73	71	A1	1	1	1	1	1	
74	64	A1	1	2	2	2	2	
74	67	A2	0	1	1	2	1	
75	64	A1	1	3	1	1	2	
75	67	A2	2	4	2	2	2	
77	68	A2	0	0	1	0	1	
77	71	A1	1	2	1	2	1	
78	68	A2	1	2	2	3	3	
79	69	A1	1	2	2	2	2	
80	72	A1	1	3	1	1	1	
80	75	A2	2	4	2	3	2	
81	72	A1	3	3	2	4	3	
81	75	A2	1	2	2	3	4	Type1
82	72	A1	1	3	1	2	3	
82	75	A2	1	1	1	4	3	
82	76	A2	1	1	1	3	3	
83	72	A1	1	1	1	1	1	
83	76	A2	2	2	2	3	3	
84	74	A2	3	4	3	4	4	
85	76	A2	0	2	1	1	1	Type2‡
86	76	A2	1	1	1	1	1	

*A1: VVal-18 shallow stops. A2: BVM(3) deep stops
†single VGE exam (30 minutes post-dive)
‡reclassified as not DCS according to criteria in Temple et al. (1999)[14]

APPENDIX F WET POT WATER TEMPERATURE SELECTION

INTRODUCTION

Diver thermal status, and in particular diver thermal status during decompression, is an important determinant of decompression sickness (DCS) risk.[1] Since the study reported in the body of this technical report sought to test for a difference in probability of DCS (P_{DCS}) between two dive profiles that differed only in the distribution of total decompression stop time among different stop depths, it was important to eliminate diver thermal status as a confounder. Both tested decompression schedules were of equal length and in a depth range where any difference in respiratory heat loss is negligible. However, because the deep stops schedule includes one hour of deeper stops than the shallow stops schedule, it was important not to use body insulation, such as a wet suit, that was effected by depth. At the deeper stops, the increased wet suit compression and consequent reduced insulation[2] could have resulted in greater cooling during the deep stops schedule than during the shallow stops schedule. To ensure equivalent thermal status on both the deep stops and shallow stops schedules, divers dressed only in cotton shorts and t-shirt and water temperature was held the same for all dives.

However, it was desirable that diver thermal status in the present dives be comparable to existing decompression data in the USN N_2-O_2 primary data set. This data set is used to calibrate probabilistic decompression models for air and N_2-O_2 diving. Such models were used to design the study in the body of this technical report, and the data collected in that study will be added to the N_2-O_2 primary data set. The USN N_2-O_2 primary data set comprises machine-readable dive profiles and decompression outcomes of experimental manned dives conducted by the U.S. Navy, Royal Navy, and Canadian Forces. A large fraction of these dives was undertaken by divers wearing wet suits in cold water. For instance, the “big292” subset of the USN N_2-O_2 primary data set used to calibrate the USN93 and BVM(3) probabilistic models comprises 3322 man-dives, of which 2601 can be identified as having been conducted by wet-suited divers immersed in water at a dive-weighted mean temperature of 61 °F (see Table F1). There were no objective measures of diver thermal status in these earlier studies. This appendix describes a preliminary study designed to identify a water temperature for divers wearing only cotton shorts and t-shirt that would approximate thermal exposures for wet-suited divers in these earlier trials.

Table F1. Water temperatures in “big292” calibration data set

Data file	Water Temp. °F	# man-dives	Dress	Data file	Water Temp. °F	# man-dives	Dress
Single (Air)				**Single (Non-air)**			
885A	50	112	wet suit	NMR8697	71	477	wet suit
	55	177	wet suit	EDU1180 S	76	120	wet suit
	60	48	wet suit	EDU885M	50	19	wet suit
	65	146	wet suit		55	53	wet suit
DC4W	40	54	wet suit		65	9	wet suit
	50	2	wet suit	**Repetitive & Multi-level (Non-air)**			
	60	4	wet suit	EDU184	45	40	wet suit
	70	55	wet suit		50	80	wet suit
	80	2	wet suit		55	79	wet suit
	40	8	dry suit		60	10	wet suit
	50	25	dry suit		65	30	wet suit
	40	5	unknown	EDU885S	55	37	wet suit
	45	6	unknown		60	19	wet suit
	50	4	unknown		65	38	wet suit
	55	2	unknown	PAMLAOS	70	28	wet suit
	60	5	unknown		75	112	wet suit
	70	9	unknown	PAMLAOD	70	59	wet suit
NMRNSW2	60	48	wet suit		75	75	wet suit
	65	18	wet suit	**Sub-saturation**			
	70	25	wet suit	NSM6HR	dry	57	N/A
PASA	60	67	wet suit	**Saturation**			
	55	5	wet suit	ASATEDU	dry	120	N/A
Repetitive & Multi-level (Air)				ASATNSM	dry	132	N/A
EDU885AR	50	150	wet suit	ASATNMR	dry	50	N/A
	55	32	wet suit	ASATARE	dry	165	N/A
DC4WR	48	12	dry suit				
PARA	55	112	wet suit				
	60	23	wet suit				
PAMLA	65	49	wet suit				
	70	158	wet suit				
	75	29	wet suit				

METHODS

The general procedure was to replicate the thermal conditions of a typical dive from the existing calibration data set in a test dive conducted in cold water, at depth, with divers wearing wet suits. Diver subjective thermal status and mean skin temperatures were recorded and used to guide water temperature selection for a 210-minute experimental dive in which divers wore cotton shorts and t-shirt.

Twelve divers wearing 5–7mm neoprene full wet suits, breathing surface-supplied air via U.S. Navy MK 20 underwater breathing apparatus, and immersed in 60 °F (16 °C) water in the NEDU Ocean Simulation Facility wet pot were compressed at 60 fsw/min to 100 fsw for 30 minutes bottom time. Upon reaching bottom, divers performed intermittent (6 minutes work/6 minutes rest) cycle ergometer work, until one minute before decompression, then rested during 99 minutes of ensuing decompression (see Figure F1). During cycle ergometer work, divers pedaled at a target cadence of 60 rpm with the ergometer hysteresis brake controller (W.E. Collins; Braintree, MA) set at 75 watts so that divers' work rate (incorporating the extra power required by submersion in this diving dress) was approximately 144 watts.

Skin temperatures at chest ($T_{sk,chest}$), back ($T_{sk,back}$), forearm ($T_{sk,forearm}$), and calf ($T_{sk,calf}$), were recorded continuously. Temperatures at the four sites were approximately equally weighted for calculation of mean skin temperature ($T_{sk,mean}$) according to[3]

$$T_{sk,\text{mean}} = \left(T_{sk,\text{chest}} \cdot 0.29425\right) + \left(T_{sk,back} \cdot 0.22425\right) + \left(T_{sk,forearm} \cdot 0.22425\right) + \left(T_{sk,\text{calf}} \cdot 0.25625\right)$$

Subjective thermal status scores were elicited every 15 minutes. The thermal status score is 0–10 scale of thermal discomfort with semantic anchors at 0 (no discomfort), 5 (severe/occasional shivering), 7 (very severe/continuous shivering), and 10 (unbearably cold).

The present wet suit dive was similar to a dive profile tested in an earlier NEDU decompression trial[4] that contributes a substantial portion of the probabilistic model calibration data set but differed in two ways. The present dive was conducted to 100 fsw instead of 190 fsw, to minimize the risk of decompression sickness. This was reasonable because the decline in wetsuit insulation due to compression is greatest at depths shallower than 100 fsw.[2] Also, a water temperature of 60 °F was used instead of 55 °F. This 60 °F temperature was chosen as being more representative of the full calibration data set.

Two days later, 11 of the same divers wearing shorts and t-shirts completed a dive simulating the thermal conditions of an experimental 170 fsw/30-minute air dive with 180 minutes of decompression. While immersed to 3 fsw (mid chest depth) in 85 °F (29 °C) water, breathing surface-supplied air via MK 20 underwater breathing apparatus, the divers rested for 3 minutes, then performed cycle ergometer work for 26 minutes. Divers pedalled at a target cadence of 60 rpm with the ergometer hysteresis brake controller set at 65 watts so that divers' actual work rate was approximately 134 watts. Divers then rested for 181 minutes. Thermal status scores were elicited every 15 minutes. Skin temperature was not measured because unclothed skin temperature rapidly approaches within 1 °C of water temperature.[5]

Significant differences between end-of-dive thermal status scores were evaluated with the Wilcoxon matched pair signed-rank test.

RESULTS

Typical data for wet-suited divers during the 100 fsw/30-minute air decompression dives are shown in Figure F1. Mean skin temperatures stabilized between 80 and 85 °F after ergometer work, while thermal status scores, shown for all divers in the top panel of Figure F2, rose from an initial median of 1 and stabilized at 5 (occasional shivering).

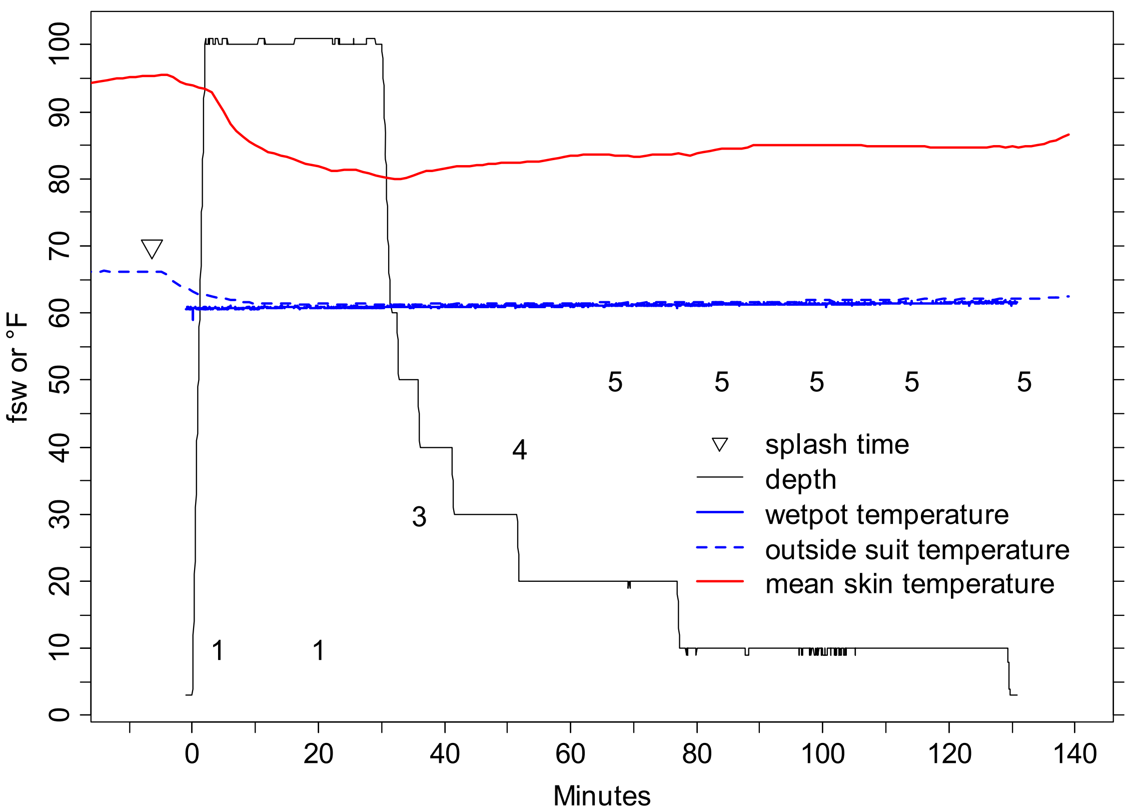

Figure F1. Typical depth-temperature-time record for wet-suited diver (Blue Diver, Team 2). Plotted numerals are the thermal status scores.

In divers wearing shorts and t-shirts in 85 °F water, thermal status scores, shown for all divers in the bottom panel of Figure F2, also rose from an initial median of 1 and stabilized at 5. Thermal status scores under the different dive conditions were not significantly different during the final 75 minutes of immersion (paired Wilcoxon signed rank test, $p > 0.05$).

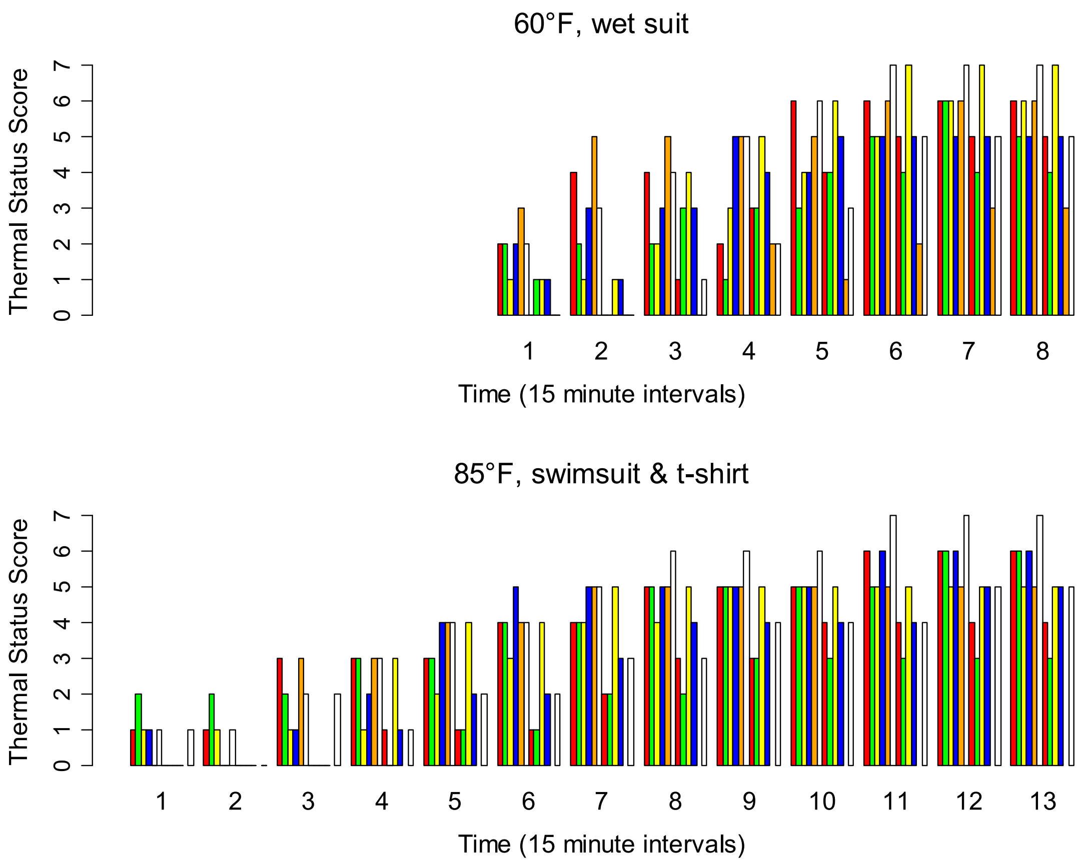

Figure F2. Self-reported thermal status scores from divers each 15 minutes. The two dives were of different duration and are aligned at reach-surface time. There is no significant difference between the two dive conditions in the thermal status scores for the final five intervals (paired Wilcoxon signed rank test, $p > 0.05$).

DISCUSSION

The present wet suit dive was chosen to typify the cold stress of decompression dives in the USN N_2-O_2 primary data set. The reports of the dive trials that comprise this calibration data rarely quantify diver thermal status. The degree of cold stress in water-immersed divers depends on water temperature, duration of immersion, and insulation. The dive was conducted to 100 fsw to result in nearly maximal decrease in wet suit insulation due to compression.[2] The bottom time and decompression schedule for a deeper dive were selected from an earlier NEDU decompression trial[4] that contributes a substantial portion of the probabilistic model calibration data. The water temperature was representative of dives of this duration in the calibration data. Divers surfaced from the present wet suited dive in the same "visibly chilled and shivering" condition as reported for divers in the earlier trial.[4] Upon surfacing, divers wearing only shorts and t-shirts during the longer dive in 85 °F water also appeared chilled and shivering.

CONCLUSIONS

During prolonged decompression dives, cold stress for divers without wetsuits in 85 °F water is similar to that for divers wearing wetsuits in 60 °F water.

REFERENCES

1. W.A. Gerth , V.L. Ruterbusch, and E.T. Long, *The Influence of Thermal Exposure on Diver Susceptibility To Decompression Sickness*, NEDU TR 06-07, Navy Experimental Diving Unit, Nov 2007.

2. K. Monji, K. Nakashima, Y. Sogabe, K. Miki, F. Tajima, and K. Shiraki. “Changes in Insulation of Wetsuits During Repetitive Exposure to Pressure,” *Undersea Biomed Res*, Vol. 16, No. 2 (1989) pp. 313-9. Published erratum appears in *Undersea Biomed Res*, Vol. 16, No. 6 (1989) preceding p. 413.

3. International Standards Organization, *ISO 9886: Evaluation of Thermal Strain by Physiological Measurements* (ISO, Geneva, Switzerland, 1992).

4. E.D. Thalmann, *Air-N_2O_2 Decompression Computer Algorithm Development*, NEDU TR 8-85, Navy Experimental Diving Unit, Aug 1986.

5. G.D. Bynum, R.F. Goldman, and J. Stewart, *Whole Body Cooling With Protective Clothing During Cold Water Immersion*, Report No. 1/80, U. S. Army Research Institute of Environmental Medicine, Natick MA, 1980.