U.S. Navy Dive Computer Validation

David J. Doolette
Keith A. Gault
Wayne A. Gerth
F. Greg Murphy
U.S. Navy Experimental Diving Unit
321 Bullfinch Road
Panama City, FLORIDA 32407-7015 U.S.A.

The U.S. Navy Dive Computer (NDC) is a typical diver-carried dive computer that uses a simple decompression algorithm to provide decompression schedules updated in real time. However, unlike many dive computers, the NDC is based on a well-documented decompression algorithm that is the result of extensive manned test-diving and for which the risk of decompression sickness is well defined. Since this Thalmann Algorithm is itself validated, validation of the NDC involved the relatively simple task of verifying a faithful implementation of the Thalmann Algorithm. The U.S. Navy experience in dive computer validation provides a useful framework for validating a commercial off-the-shelf dive computer, but challenges exist for dive computers that do not implement a well-documented decompression algorithm.

INTRODUCTION

Breathing a gas mixture at elevated ambient pressure (p_{amb}), such as during underwater compressed gas diving, results in tissue uptake of dissolved respired gases. During ascent (or "decompression") to sea level, p_{amb} may decrease to a level less than the sum of the partial pressures of all gases dissolved in tissue, and in this state of gas supersaturation, bubbles can form and potentially cause decompression sickness (DCS). To manage the risk of DCS, dives are conducted according to depth/time/breathing gas decompression schedules derived with decompression algorithms that implicitly or explicitly 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. Instead, practical decompression algorithms balance the probability of DCS (P_{DCS}) against the costs of time spent decompressing. Modern, diver-carried dive computers sample p_{amb} at frequent intervals and use this as input to simple decompression algorithms that provide decompression schedules updated in real time.

The principal requirement for a dive computer is that dives following its decompression guidance will have a target (typically low) incidence of DCS. A corollary to this requirement for dive computers used in occupational (military or commercial) diving - the focus of this workshop - is that the decompressions are efficient, because time spent decompressing is unproductive (costs money) and prolongs exposure to a hostile environment. Requirements will be specific to some range of diving practices and to particular populations of divers because no decompression algorithm is suitable for all types of diving and different diving communities have different risk tolerances. Validation of a system such as a dive computer is

simply a demonstration that it matches its requirements. Validation of a dive computer entails measurement of the incidence of DCS, or estimation of P_{DCS} by some other method, associated with its decompression guidance.

Validation could be accomplished by subjecting a dive computer to many different depth/time dive profiles and evaluating the P_{DCS} of resulting decompression guidance. Such validation could be done without knowledge of the underlying decompression algorithm. Alternatively, the decompression algorithm can be validated separately from the dive computer, by measuring P_{DCS} associated with another implementation of the algorithm. The latter would then be the "gold standard" implementation. In this case, validation of the dive computer would follow from verification that it is a faithful implementation of the decompression algorithm by comparison of the dive computer behavior to the gold standard implementation. In this approach, understanding of the decompression algorithm can guide the validation process. It is this latter approach that is used by the U.S. Navy.

U.S. NAVY DIVE COMPUTER (NDC)

U.S. Navy Dive Computers (NDCs) are built by Cochran Undersea Technologies (Richardson, TX) but implement the Thalmann Algorithm, a decompression algorithm developed at the U.S. Navy Experimental Diving Unit (NEDU). There are now several configurations of the NDC tailored to the requirements of different diving communities within the U.S. Navy and different diving operations breathing open-circuit air or constant pO_2 from the MK 16 MOD 0 or MK 16 MOD 1 closed-circuit, mixed gas underwater breathing apparatus (UBA). In support of different combinations of these UBAs, the various configurations of the NDC for air and N_2-O_2 diving calculate decompression assuming inspired inert gas partial pressures associated with constant $FO_2 = 0.21$, constant $pO_2 = 0.7$ atm, and constant $pO_2 = 1.25$ atm, and make depth-dependent changes between these modes.

REQUIREMENT FOR THE NDC

The history of the development of the original NDC is covered in detail elsewhere (Butler and Southerland, 2001). The U.S. Navy requirement for a diver-carried diver computer arose in the 1970s to support Navy SEAL commandos' conduct of multilevel dives breathing air from an open-circuit supply or constant pO_2-in-nitrogen from the MK 16 MOD 0 UBA (Thalmann et al., 1980). This requirement was the motivation for the development and manned-validation of a new decompression algorithm by CAPT. Ed Thalmann at NEDU (Thalmann et al., 1980; Thalmann, 1984; 1986). Although other options were considered, in 1996 the decision was made to procure and test a modified commercial dive computer for which the principle design requirement was implementation of the Navy-approved VVal-18 Thalmann Algorithm (Butler and Southerland, 2001).

VALIDATION OF THE NDC

1. Development and Validation of the VVal-18 Thalmann Algorithm

The Thalmann Algorithm is a neo-Haldanean decompression algorithm similar to those implemented in many dive computers. Inert gas uptake and washout is modeled for a set of parallel tissue compartments and decompression stops are required to keep the partial pressure of a single inert gas (p_i) in k modeled tissue compartments less than or equal to a depth-dependent maximum permissible value, $p_{i,k} \leq M_k = a_k D + M_{0k}$., where D is p_{amb} at each decompression stop 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.

The Thalmann Algorithm differs from earlier such algorithms in several ways. The principal difference is that compartmental inert gas washout can switch from the normal exponential approach to arterial inert gas partial pressure to a much slower linear approach when a compartment is gas supersaturated (Exponential Linear or EL kinetics). This linear rather than exponential gas washout gives appropriately lengthened decompression times, particularly for repetitive dives, without negatively impacting no-stop limits. Another novelty is that the Thalmann Algorithm was developed specifically with a view to implementation in a dive computer, and was originally called the EL-RTA (real-time algorithm). The EL-RTA running on a minicomputer was used to control most man-dives conducted during the development and testing of the algorithm. The version used to calculate decompression tables, (originally the EL-DCM) calculates gas uptake and washout for finite ascent and descent rates, and therefore printed tables exactly match the EL-RTA if the same travel rates are used. Thalmann published the FORTRAN source code of the original EL-DCM (Thalmann, 1983; 1985), and this original code has been further developed at NEDU to support other diving applications. The structure of this enhanced version of the FORTRAN EL-DCM, renamed the Thalmann Algorithm Decompression Table Generation Software, is documented in detail (Gerth, 2010). This implementation was used to calculate the air and MK 16 decompression tables in the U.S. Navy Diving Manual, Revision 6 (Naval Sea Systems Command, 2008a). A Visual Basic implementation of the Thalmann Algorithm developed at NEDU and called the Navy Dive Planner is also documented in detail (Gerth et al., 2011). Users interact with Navy Dive Planner via a graphical user interface to plan dives or to follow dives in real-time and it is intended primarily as a tool for planning multilevel dives that will be conducted using a NDC. Decompression prescriptions generated by the Navy Dive Planner match those of the table generation software (Gerth et al., 2011).

The Thalmann Algorithm is initialized with a parameter set that includes a table of M-values and different parameter sets exist for different applications. The NDCs for air and N_2-O_2 diving use a parameter set called VVal-18, which is the same parameter set used to calculate the constant 0.7 atm pO_2-in-nitrogen (MK 16 MOD 0; Thalmann, 1984) decompression tables and MK 16 MOD 1 N_2-O_2 decompression tables in the U.S. Navy Diving Manual (Johnson et al., 2000). The Air Decompression Tables in the U.S. Navy Diving Manual, Revision 6 (Naval Sea Systems Command, 2008a) are calculated using a modified parameter set proposed by Flynn and designated VVal-18M which results in shorter air decompression times than VVal-18 (Gerth and Doolette, 2007; 2009). The development and testing that lead to the VVal-18 parameter set was simultaneous with development of the Thalmann Algorithm, and was initially in support of constant 0.7 atm pO_2-in-nitrogen diving with the MK 15 and MK 16 UBAs. This initial development included 1505 air and constant 0.7 atm pO_2-in-nitrogen man-dives (84 cases of DCS) with the algorithm and parameters being adjusted in response to schedules with high incidences of DCS (Thalmann et al., 1980; Thalmann 1984; 1986). In a recent test of VVal-18 Thalmann Algorithm air decompression, 192 dives to 170 feet sea water (fsw) for 30 minutes bottom time resulted in only three cases of DCS (Doolette et al., 2011).

The MK 16 MOD 1 N_2-O_2 VVal-18 Thalmann Algorithm decompression tables were validated with 515 man-dives that resulted in seven cases of DCS (Johnson et al., 2000; Southerland, 1998). All these man dives were conducted in the wet pot of the Ocean Simulation Facility at NEDU under conditions relevant to occupational divers: divers worked

on the bottom and were at rest and cold during decompression - conditions shown to increase the risk of DCS (Van der Aue et al., 1945; Gerth et al., 2007). There has not been extensive manned-testing of air decompression tables calculated using the VVal-18M parameterization of the Thalmann Algorithm, but the P_{DCS} of the each schedule in both VVal-18 and VVal-18M air decompression tables have been estimated using NMRI98 (Parker et al., 1998) and BVM(3) (Gerth and Vann, 1997) probabilistic decompression models (Gerth and Doolette, 2007; 2009).

2. Verification of the NDC and configuration control

As outlined in the preceding paragraphs, the VVal-18 Thalmann Algorithm was already validated with manned diving trials under operationally relevant conditions that demonstrated acceptable P_{DCS}. Testing of the NDC was therefore simply to verify that it was a faithful implementation of the Thalmann Algorithm. This could be done by functional testing of NDCs comparing their behavior to "gold standard" decompression schedules and these gold standards exist in two forms. The gold standard printed VVal-18 Thalmann Algorithm decompression tables are the constant 0.7 atm pO_2-in-nitrogen (MK 16 MOD 0) (Thalmann, 1984) decompression tables and MK 16 Mod 1 N_2-O_2 decompression tables (Johnson et al., 2000) that have appeared in several revisions of the U.S. Navy Diving Manual. The gold standard software implementations are the Thalmann Algorithm Decompression Table Generation Software and the Navy Dive Planner. The latter software package is designed specifically to complement the NDCs and is convenient for generating multilevel dives and decompression schedules of any complexity against which to test the NDC.

A sample of 10 to 30 of each configuration of the NDC has been functionally tested by exposing them to simulated dive profiles in a small, flooded test chamber and comparing NDC prescription to gold standard Navy Dive Planner decompression schedules (Southerland, 2000; Gault and Southerland, 2005; Gault, 2006; Southerland et al., 2010). Schedules differ by no more than can be accounted for by the specified pressure sensor tolerance (maximum ±2 fsw (0.61 msw) deviation at maximum operating depth). This type of functional testing is called "black box" testing because the tester has no access to internal data structures and computer code to guide testing. The agreement between the Cochran Undersea Technologies and the U.S. Navy does not extend to sharing such proprietary information. The outcome of dive computer testing only remains valid while the system remains unchanged and by agreement with the manufacturer, no hardware or software changes are made to any configuration of the NDC after it has passed validation testing at NEDU. Every NDC unit undergoes a simple functional test of pressure sensor accuracy at purchase and subsequently every 18 months.

3. Pitfalls and lessons learned from U.S. Navy experience

Black box testing assumes that the suite of test dive profiles adequately exercise the algorithm so that any errors in the NDC implementation are revealed. Neo-Haldanean decompression algorithms, such as the Thalmann Algorithm, are well behaved and predictable, so that a relatively small test suite of dive profiles would be expected to adequately exercise the algorithm and suffice for verification. An example would be a test of no-stop limits across the range of operational depths, dives requiring decompression stops governed by all relevant compartments, dives to at least the maximum required operating depth and dive duration, and repetitive dives.

However, there are pitfalls in assuming the dive computer implementation is well-behaved, even for a simple algorithm. For example, the U.S. Navy is currently procuring a new

configuration of the NDC for use in a new operational scenario. This new configuration passed a relatively small suite of black box verification test profiles, of similar scope as described above, focused on exercising the relevant configuration changes. Subsequently, the NDCs were tested with a simulation of the new operational scenario, a dive profile not considered necessary for the original test suite. On this profile NDCs produced decompression schedules substantially different than those of the gold standard NEDU implementations, a difference that required revision of the NDC algorithm. This test revealed a simplification in the NDC implementation of the Thalmann Algorithm that only manifested substantively following an unusual type of multilevel dive.

The preceding anecdote illustrates that individual dive computer implementations, even of simple neo-Haldanean algorithms, can manifest unanticipated behavior. It is therefore essential that black box testing uses a suite of dive profiles that exemplify all expected operational uses of the dive computer. This requirement is increasingly important if validating dive computers that implement algorithms that are not well-documented, are more complex that neo-Haldanean algorithms, or are unknown.

VALIDATION OF COMMERCIAL-OFF-THE-SHELF DIVE COMPUTERS

The U.S. Navy experience with validating NDCs can serve as general guide for validating a commercial-off-the-shelf (COTS) dive computer as illustrated in Figure 1.

The steps taken by the U.S. Navy were: 1) define requirements; 2) develop and validate the decompression algorithm; and 3) verify the NDC computer implementation of decompression algorithm. For practical purposes argued below, this framework may need to be modified for a COTS dive computer. Validation must occur within a configuration control framework (represented by the diamond in Figure 1) that ensures re-validation if any changes are made to the dive computer software or hardware configuration. In the discussion that follows, “configuration manager” will be used loosely to mean an entity that has oversight of dive computer requirements, validation, and configuration control for a diving community.

1. Requirements for a COTS dive computer

The first step in the selection and validation of a dive computer is to define the requirements. This definition should include the scope of diving applications for which the dive computer must be applicable, for instance: no-stop diving, repetitive diving, multilevel diving, and decompression diving with or without gas switching. This scope will help to define the suite of test dive profiles for validation. The scope of diving application will also suggest specifications, such as depth range, support for multiple breathing gases, and availability of desktop planning software, that may be used to narrow the field of candidate dive computers. Requirements should also include the intended user communities, for instance: scientific, commercial, or military divers. These requirements inform setting of an acceptable range of P_{DCS} for diving operations.[1] The principal requirement for a dive computer is that it provides efficient decompression schedules that meet the target P_{DCS}.

[1] The U.S. Navy decompression schedules that require no or brief total decompression stop time, which are the dives conducted most frequently, have a low estimated P_{DCS}; risk increases with total decompression stop time.[12,13]

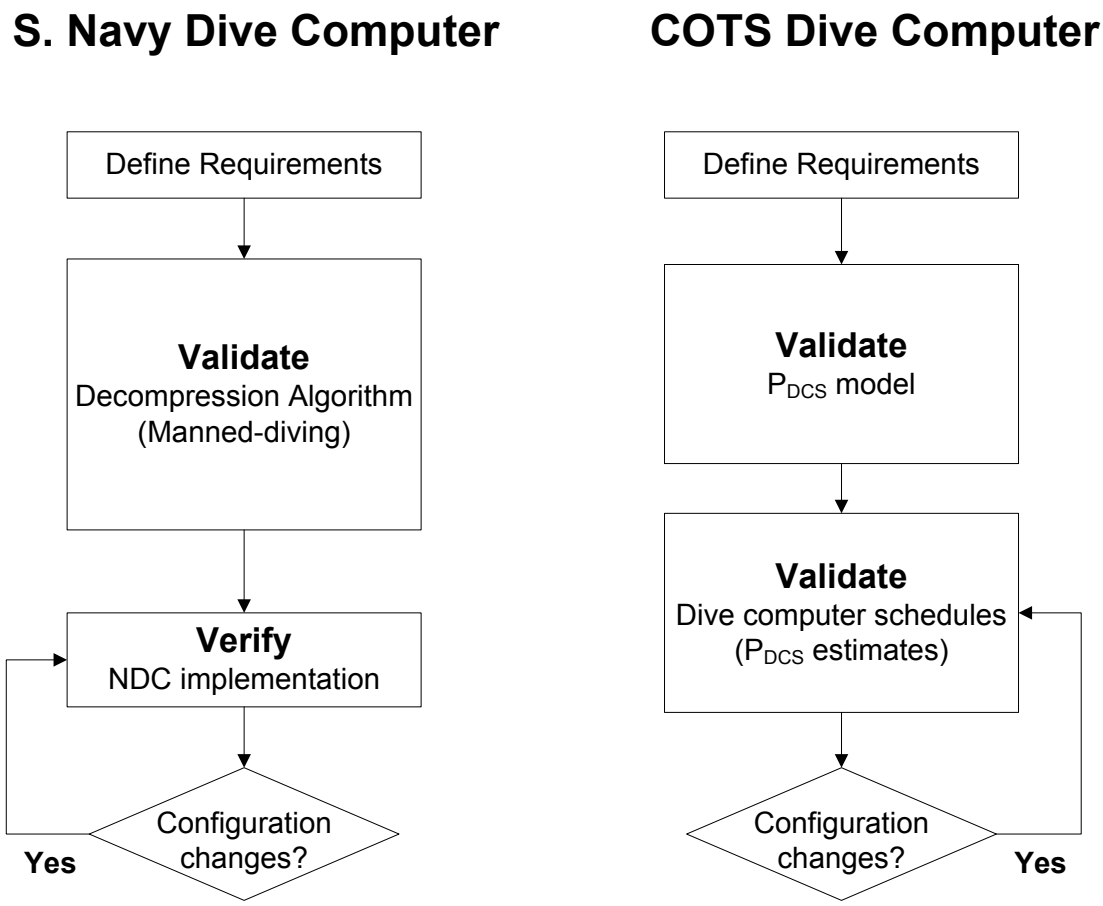

Figure 1. Outline of validation of the U.S. Navy Dive Computer and a proposed framework for validation of a COTS dive computer. The size of the boxes is intended to indicate the level of effort. Development, validation, and documentation of the Navy VVal-18 Thalmann Algorithm was a large effort. Consequently, verification of the NDC implementation of the algorithm can be a substantially smaller effort. Development and validation of a probabilistic decompression model (P_{DCS} model)is a substantial effort, but many already exist. Many dive profiles would need to be generated with an undocumented COTS dive computer decompression algorithm and then evaluated using the probabilistic decompression model.

2. Validating a COTS dive computer

After defining the requirements, there are two paths for validating a COTS dive computer. One path, similar to that used by the U.S. Navy, is to choose a dive computer that implements a well-documented, validated decompression algorithm that the configuration manager considers acceptable, and verify that the dive computer is a faithful implementation of that algorithm. The second path is to demonstrate that decompression guidance provided by the dive computer is acceptable, by some measure, without reference to the underlying algorithm. Each of these will be discussed in turn.

3. Verifying a dive computer implementation of a validated algorithm

If a dive computer implementation of a well-documented, validated decompression algorithm can be identified, a substantial portion of the validation effort is complete at no further cost to the configuration manager. A difficulty with this approach is that, often, scant detail of the decompression algorithms implemented in COTS dive computers is available (Huggins, 2006). Some dive computer implement variants of the "ZH" family of decompression algorithms developed by Bühlmann (2005), which, after military decompression algorithms, is probably the decompression algorithm with the best documentation available in the public

domain. It is not the purpose of this paper to recommend any particular decompression algorithm, that is a policy decision for the configuration manager, but we will use the ZH algorithm as an example of the challenges in validating a COTS dive computer implementation of an algorithm.

The development of the ZH algorithm is described in several scientific papers and most recently summarized in a monograph (Bühlmann, 1995). In addition to many mixed-gas dives, 813 dry, chamber air dives were conducted in the development of the algorithm (Bühlmann, 1995). This is a substantial number of man-dives, but any validation of the algorithm under the immersed, working conditions relevant to occupational divers appear to be open-water dives that are less well characterized than laboratory dives. In its most recent form, the ZH algorithm comprises 16 compartments with different half times for nitrogen uptake and washout and different pairs of coefficients equivalent to the a and M_0 parameters used to generate M-values. Two different parameter sets are proposed: ZH-L16B for calculation of printed decompression tables and ZH-L16C for use real-time applications. Although the conceptual model is described, there is no documentation of a gold standard ZH decompression algorithm implementation against which a dive computer could be verified. Desktop dive planning software provided with a COTS dive computer, without documented provenance, structure, and verification, is not a gold standard. Published schedules against which a dive computer might be validated exist, but these present challenges. First, the most recently published schedules are of the 1986 ZH-86 tables (Bühlmann, 1995) which appear to be calculated using the ZH-L16B parameter set. On the other hand, most dive computers purport to use the ZH-L16C parameter set, often use a reduced number of compartments (e.g., ZH-L8C), use an "adaptive" variant of the algorithm that adjusts values of the parameters under certain conditions, or use undocumented, proprietary modifications. Second, the methods by which the ZH-86 tables were produced are not clearly documented, but they appear to be calculated using inert gas kinetic equations that handle only instantaneous ascent and descent rates, something that cannot be replicated in dive computer testing. Therefore, no real-time implementation of ZH-L16 will exactly replicate the published schedules.

4. Validating a dive computer implementation of an unvalidated algorithm

Since there are substantial challenges to verifying the implementation of an algorithm in a COTS dive computer, a more practical approach would be to validate such a dive computer without reference to the underlying algorithm. This is illustrated on the right-hand side of Figure 1. This procedure involves generating a large number of validation dive profiles representing a range of depth/time combinations and decompression according to the dive computer prescriptions. The P_{DCS} associated with these validation dive profiles would then be evaluated. This decompression algorithm may be unknown and cannot be assumed to be well-behaved. Many dive profiles would be required to characterize the entire expected operational range of depths, bottom times, and decompression stop depths, as well as multilevel and repetitive diving. It may be possible, by negotiation with the manufacturer, to obtain access to simulation software that executes the exact source code as the dive computer. This simulation software could be run on a larger computer and automated to generate the large number of dive profiles required for validation. In this case the dive computer implementation could be verified in a test chamber with a smaller test suite as described for the NDC. Otherwise, all the validation dive profiles would need to be generated manually. Candidate dive computers would be subjected to the validation range of depth/time combinations in a test chamber. The decompression prescriptions indicated on the dive computers would be recorded as they evolve during the bottom time and during manual

decompression of the test chamber according to these prescriptions to verify consistency with the displayed prescriptions and actual behavior. The P_{DCS} of manually generated dive profiles would be evaluated.

It would be expensive to evaluate all the resulting dive profiles with man-dives. Instead, the dive profiles could be evaluated with decompression models that themselves have been validated as providing accurate estimates of P_{DCS}. For instance, the P_{DCS} of each dive profile could be estimated using probabilistic decompression models such as NMRI98 (Parker et al., 1998) and BVM(3) (Gerth and Vann, 1997). The parameters of these models were found by fit to data comprising thousands of carefully controlled and documented experimental air and N_2-O_2 dives with known depth/time/breathing gas history and time of onset of any DCS. These models therefore embody the experience contained in these large data sets. These models were then validated by their ability to predict the incidence of DCS in data sets of dives not used for calibration but conducted under similar conditions (Parker et al., 1998; Gerth and Vann, 1997). In these probabilistic decompression models, instantaneous risk of DCS is a function of either modeled compartmental supersaturation or bubble volumes and P_{DCS} is the time integral of instantaneous risk during and following the dive. Such models can therefore be used to evaluate dive profiles of arbitrary complexity, as would be required to evaluate dive profiles produced in black box validation of dive computers.

A recently published model of ultrasonically detectable venous gas bubbles (Gutvik et al., 2010) can also be used to evaluate dive profiles of arbitrary complexity, and assign each profile a peak bubble score. Peak venous gas bubble scores are weakly associated with incidence of DCS and are used as a surrogate measure of decompression stress (Sawatzky, 1991; Eftedal et al., 2007). Although this model has yet to be validated, once it has, it could be used to evaluate dive computer prescriptions. Care is needed with this approach to evaluating decompression procedures to choose target bubbles scores based on their association with a target P_{DCS} and not seek to minimize venous gas bubbles *per se*, as the latter results in inefficient decompression schedules.

RISK OF DCS USING THE NDC

Conducting dives using printed decompression tables requires that schedules are selected on the maximum depth obtained at any time during the dive and may require round-up to the next deeper depth and longer bottom time. Avoiding this costly round-up procedure is a principal motivation for using dive computers. As a result, however, diving to the no-stop limits or conducting decompression dives using dive computer guidance are expected to generally present greater risk of DCS than divers using printed tables calculated using the same decompression algorithm.

The U.S. Navy has not collated data on the incidence of DCS using NDCs. Indeed, to date, the NDCs have been used principally to keep dives within no-stop limits, and little DCS is expected and none has been reported. Going forward, NDCs will be used to conduct dives to no-stop limits and to conduct decompression dives. Recently, 92 decompression dives were conducted in open water using NDC guidance and no DCS was reported. However, this is a small sample and the U.S. Navy relies on probabilistic model estimates and the outcome of laboratory trials of the VVal-18 Thalmann Algorithm to quantify the expected incidence of DCS when NDCs are used to conduct dives to no-stop limits and to conduct decompression dives.

1. Air no-stop diving

The U.S. Navy Dive Computer (NDC) used for air scuba diving is designated the AIR III. Only no-stop diving is conducted using air scuba in the U.S. Navy. The AIR III is functionally equivalent to the original NSW III configuration of the NDC and assumes air breathing shallower than 78 fsw and constant 0.7 atm pO_2-in-nitrogen at 78 fsw and deeper. The NSW III is used for operations where both MK 16 MOD 0 UBA (constant pO_2 = 0.75 atm) and open-circuit air may be breathed, since a constant pO_2 = 0.7 atm results in a lower pN_2 than air shallower than 78 fsw and a higher pN_2 than air at 78 fsw or deeper. This same configuration was chosen for the AIR III to shorten the no-stop limits deeper than 78 fsw compared to those calculated for air (Doolette et al., 2009; Naval Sea Systems Command, 2008b).

The no-stop limits obtained using the AIR III are close to the no-stop limits printed in the U.S. Navy Air Decompression Table in the U.S. Navy Diving Manual, Revision 6 (Naval Sea Systems Command, 2008a). The discrepancies arise due to different assumptions in the calculations but also to substitution of the no-stop limits in the printed Air Decompression Table with no-stop limits from the Standard Air Decompression Tables that appeared in all earlier versions of the U.S. Navy Diving Manual since 1959, where these latter are shorter (Gerth and Doolette, 2009). The motivation for these substitutions and for the choice of AIR III configuration is that a laboratory test of no-stop limits longer than the those of the Standard Air Decompression Tables resulted in a lower than predicted incidence of DCS, but all the DCS that occurred manifested as unacceptably severe symptoms involving the central nervous system (Doolette et al., 2009).

Table 1 shows that the AIR III no-stop limits for the range 30-190 fsw have a mean estimated P_{DCS} of 2.02% (range 1.32–4.96%) according to the NMRI98 probabilistic model, slightly higher than the U.S. Navy Diving Manual, Revision 6 air no-stop limits which have a mean estimated P_{DCS} of 1.83% (range 1.01–4.96%). Table 1 also shows the probability of severe central nervous system DCS (P_{CNSDCS}) estimated using a logistic model calibrated with 1629 laboratory no-stop man-dives (Doolette et al., 2009). AIR III no-stop limits have a mean estimated P_{CNSDCS} of 0.24% (range 0.11–0.36%), slightly higher than the U.S. Navy Diving Manual, Revision 6 air no-stop limits which have a mean estimated P_{CNSDCS} of 0.13% (range 0.01–0.36%).

2. MK 16 MOD 1 decompression diving

There are several NDC configurations used to support diving with the MK 16 MOD 1 UBA, which makes depth-dependent transitions between constant pO_2s of 0.75 and 1.30 atm. The EOD III configuration of the NDC begins with constant pO_2 = 0.7 atm at the surface, transitions to constant pO_2 = 1.25 atm upon any descent to 34 fsw or deeper and subsequently transitions back constant pO_2 = 0.7 atm on ascent to 12 fsw or shallower. The EOD III is an alternative to the MK 16 MOD 1 N_2-O_2 decompression tables in the U.S. Navy Diving Manual, which were developed for Explosive Ordinance Disposal (EOD) diving which involves repetitive dives to the no-stop limits and repetitive decompression dives (Johnson et al., 2000).

Like all neo-Haldanean decompression algorithms, VVal-18 Thalmann Algorithm schedules are not iso-risk. The MK 16 MOD 1 N_2-O_2 no-stop limits have probabilistic model estimated P_{DCS} in the vicinity of 2% and the estimated P_{DCS} increases with increasing total decompression time (Johnson et al., 2000). In the U.S. Navy Diving Manual, Revision 6, routine risk of DCS is capped by limit lines that make all schedules with estimated P_{DCS}

greater than 5% exceptional exposure dives (Navy Experimental Diving Unit, 2007). Conduct of exceptional exposure dives is prohibited for routine diving and requires permission of the Chief of Naval Operations. Dives conducted using NDCs are planned using the Navy Dive Planner. The Navy Dive Planner has a risk monitor that displays red when dives are planned with estimated P_{DCS} of 5% or greater, indicating the dive should not be conducted and serving the same purpose as the limit lines in the printed tables (Gerth et al., 2011). Laboratory validation of the MK 16 MOD 1 N_2-O_2 decompression tables consisted of dives relevant to EOD operations and with repetitive dives calculated in real-time mode, analogous to the operation of an NDC, and resulted in 3 DCS in 325 dives (95% C.L. 0.2%, 2.7%) (Johnson et al., 2000). Since NDCs enable diving to the limits of the decompression algorithm, it is expected that routine MK 16 MOD 1 N_2-O_2 dives conducted using the EOD III will have similar incidence of DCS as the laboratory trials.

Table 1. Air no-stop bottom time (BT) limits and estimated P_{DCS} and P_{CNSDCS}

fsw	U.S.N. Diving Manual, Rev 6			AIR III		
	BT	P_{DCS} %	P_{CNSDCS} %	BT*	P_{DCS} %	P_{CNSDCS} %
30	371	4.96	0.36	371	4.96	0.36
40	163	2.95	0.35	164	2.95	0.17
50	92	2.20	0.16	92	2.20	0.11
60	60	1.96	0.10	63	2.06	0.12
70	48	2.05	0.17	48	2.05	0.15
80	39	2.06	0.22	39	2.06	0.20
90	30	1.86	0.19	32	2.01	0.24
100	25	1.80	0.23	27	1.97	0.30
110	20	1.63	0.21	23	1.91	0.36
120	15	2.17	0.14	19	1.82	0.35
130	10	1.12	0.06	16	1.75	0.35
140	10	1.25	0.11	13	1.60	0.29
150	5	0.88	0.01	11	1.53	0.27
160	5	0.94	0.02	9	1.41	0.21
170	5	1.01	0.04	8	1.40	0.22
180	5	1.08	0.06	7	1.37	0.21
190	5	1.16	0.09	6	1.32	0.18

*BT assuming 60 fsw/min descent rate and 30 fsw/min ascent rate

CONCLUSION

The principal requirement of the NDC is implementation of the U.S. Navy-approved VVal-18 Thalmann Algorithm. The U.S. Navy maintains gold standard software implementations of the Thalmann Algorithm. VVal-18 Thalmann Algorithm decompression schedules produced by these gold standard implementations have acceptable P_{DCS} as demonstrated in manned dive trials and estimation of P_{DCS} using probabilistic models. The NDCs are validated by faithful replication of gold standard decompression schedules when exposed to simulated dives.

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