Decompressing rescue personnel during Australian submarine rescue operations

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Abstract
(Reid MP, Fock A, Doolette DJ. Decompressing rescue personnel during Australian submarine rescue operations. *Diving Hyperbaric Medicine*. 2017 September;47(3):159-167.)
Introduction: Personnel rescuing survivors from a pressurized, distressed Royal Australian Navy (RAN) submarine may themselves accumulate a decompression obligation, which may exceed the bottom time limits of the Defense and Civil Institute of Environmental Medicine (DCIEM) Air and In-Water Oxygen Decompression tables (DCIEM Table 1 and 2) presently used by the RAN. This study compared DCIEM Table 2 with alternative decompression tables with longer bottom times: United States Navy XVALSS_DISSUB 7, VVAL-18M and Royal Navy 14 Modified tables.
Methods: Estimated probability of decompression sickness (P_{DCS}), the units pulmonary oxygen toxicity dose (UPTD), the volume of oxygen required and the total decompression time were calculated for hypothetical single and repetitive exposures to 253 kPa air pressure for various bottom times and prescribed decompression schedules.
Results: Compared to DCIEM Table 2, XVALSS_DISSUB 7 single and repetitive schedules had lower estimated P_{DCS}, which came at the cost of longer oxygen decompressions. For single exposures, DCIEM schedules had P_{DCS} estimates ranging from 1.8% to 6.4% with 0 to 101 UPTD and XVALSS_DISSUB 7 schedules had P_{DCS} of less than 3.1%, with 36 to 350 UPTD.
Conclusions: The XVALSS_DISSUB 7 table was specifically designed for submarine rescue and, unlike DCIEM Table 2, has schedules for the estimated maximum required bottom times at 253 kPa. Adopting these tables may negate the requirement for saturation decompression of rescue personnel exceeding DCIEM limits.

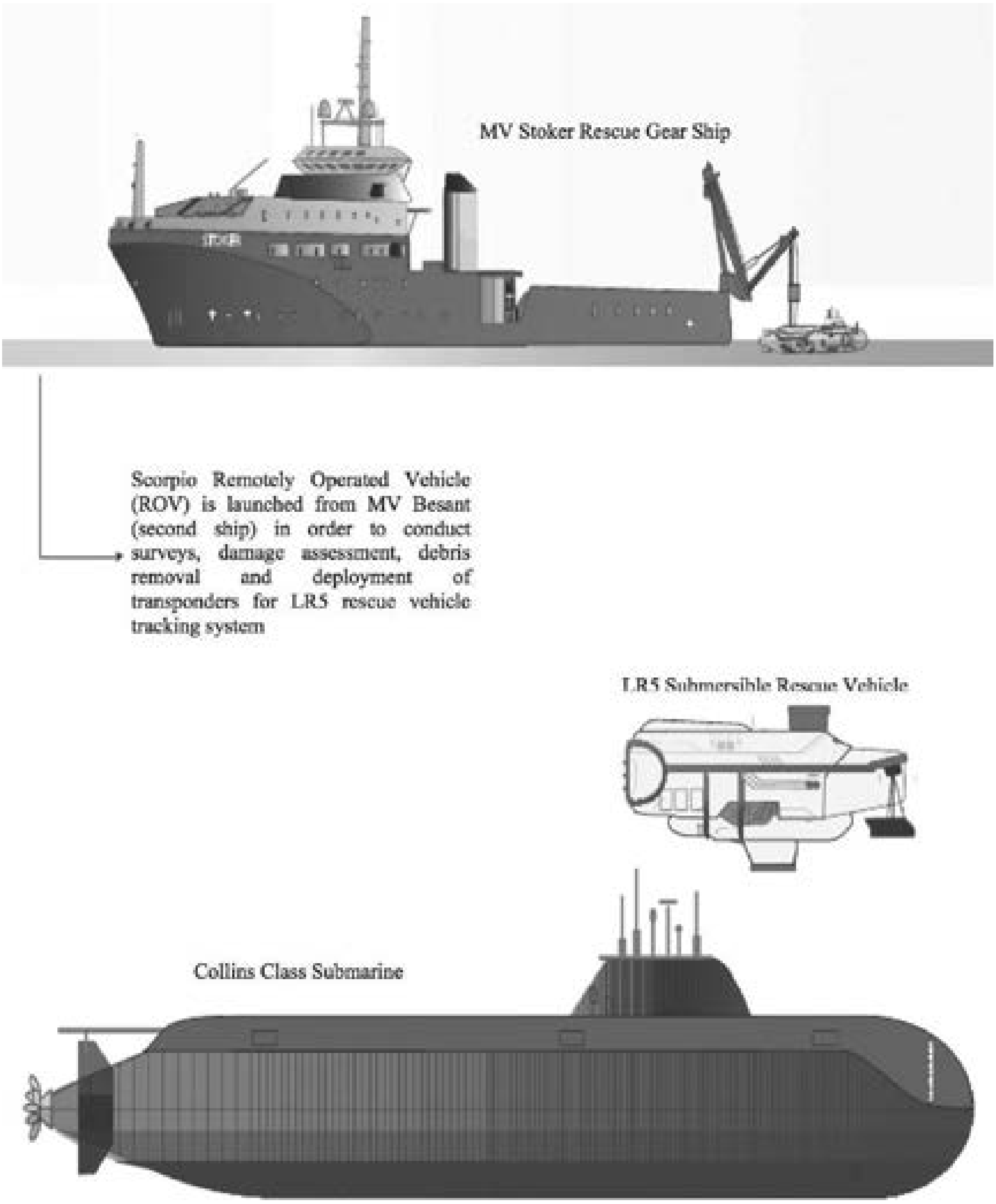
Introduction

The ambient pressure inside a distressed submarine (DISSUB) may become elevated above 101 kPa owing to compression of the remaining gas space by partial flooding or release of high-pressure gas supplies.[1] Locating the DISSUB and delivering the rescue system to the site may take several days resulting in the crew of the DISSUB becoming saturated (inert gas tissue tensions equilibrate with the inspired inert gas pressures) at elevated pressure. A Submersible Rescue Vehicle (SRV) that can mate with the escape hatch of the DISSUB may rescue survivors (Figure 1).[1,2] To accomplish the evacuation, ambient pressure inside the SRV must be equalized with the DISSUB internal pressure.[1] The SRV remains pressurized at the DISSUB pressure during the transit to the surface where the survivors are again transferred under pressure to a recompression chamber (RCC) located on-board a rescue ship in order to complete saturation decompression. Rescue personnel who are exposed to the DISSUB pressure accrue their own decompression obligation.

The current Royal Australian Navy (RAN) DISSUB rescue system uses the James Fisher Defence 'LR5' SRV, which can rescue up to 14 seated, 80 kg survivors per sortie (excluding stretcher cases), a transfer under pressure (TUP) compartment, and two RCCs that can each accommodate seven survivors and one medical attendant (Figure 2). On the surface, the SRV mates to the TUP compartment and survivors are transferred, one at a time, between the TUP compartment and the RCCs using one-man, portable chambers (Figure 2). This process is labour intensive and susceptible to delays owing to inclement weather or the need to transfer immobilised patients. Rescue sorties are separated by a surface interval time (SIT) of many hours, as the SRV can only redeploy to the DISSUB two hours before the previous cohort of survivors are due to complete decompression so that the RCCs are available for the next cohort of survivors.

A Collins class submarine can accommodate 65 people, including crew and other personnel. It is estimated that six SRV sorties will be required to evacuate the DISSUB of rescue personnel and survivors, based on the average

Figure 1
Overview of Royal Australian Navy submarine rescue operations

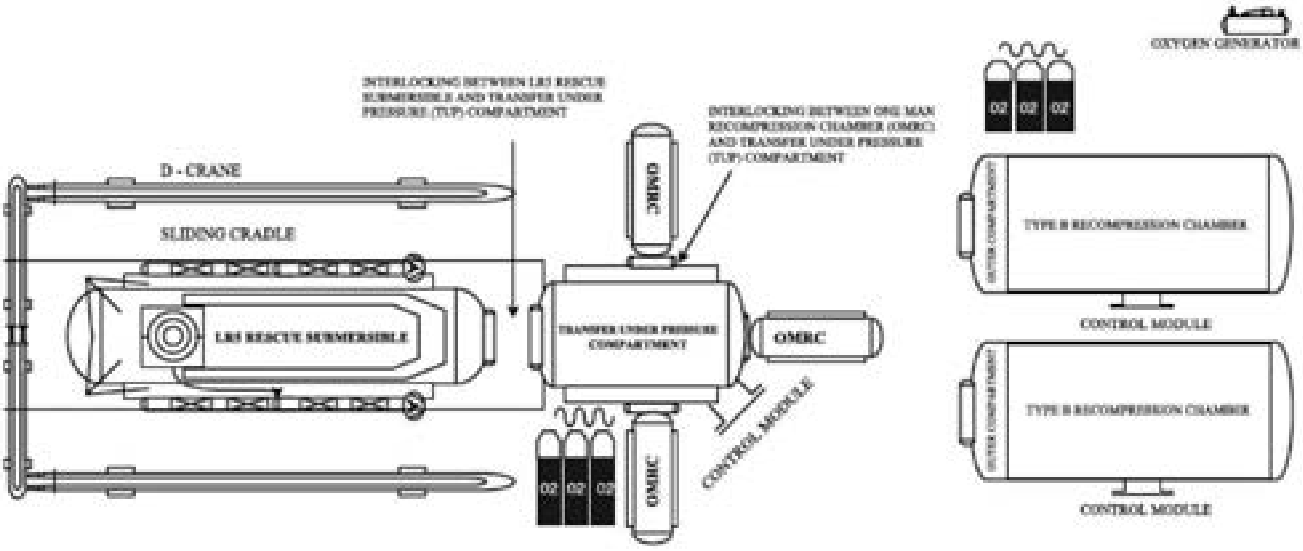


weight of a RAN submariner (96 kg) (Ponton, K, personal communication; 2013) and assuming all personnel can be seated. The number of sorties will increase if patients need to be immobilised on stretchers.

Pilots housed in the forward SRV compartment remain at 101 kPa hence do not require decompression, but separate medical personnel attending survivors inside the aft section of the SRV, the TUP compartment, and the RRCs each accrue their own decompression obligation. Each SRV sortie requires approximately 240 minutes (min) and the medical attendant in the aft compartment of the SRV will be at the DISSUB pressure along with the rescued survivors for approximately 180 min after equalization with the DISSUB internal pressure and during the return to the rescue ship. The SRV aft compartment remains pressurized for a further 60–150 min to permit transfer of 14 survivors from one SRV sortie to the deck RCCs. An additional 15 min is required to

Figure 2

Deck layout of the RAN submarine rescue system on-board the rescue vessel. The SRV (LR5) is in position to mate with the TUP compartment, which in turn can mate with three portable, one-man recompression chambers (OMRCs). OMRCs are manually wheeled across the deck to mate with the Type B RCCs



close the RCC inner lock and commence survivor saturation decompression. This frees the RCC outer lock for oxygen (O_2)-accelerated decompression of medical attendants. Since neither the SRV nor the TUP compartments are equipped for O_2-accelerated decompression, the SRV medical attendant transfers to the RCC outer lock for O_2-accelerated decompression, whilst the TUP medical attendant undergoes air decompression in the TUP compartment.

RAN DISSUB planning assumes all souls could be rescued from a DISSUB pressure of 253 kPa. Higher DISSUB pressures are possible, but RAN analysis of Collins Class submarines has assessed that likely conditions associated with such pressures are not survivable, and would require the crew to escape rather than await rescue (classified or restricted access).[3–5] At present, the only decompression tables authorized for decompression of RAN medical attendants are the Defense and Civil Institute of Environmental Medicine Air and In-Water O_2 schedules (DCIEM Tables 1 and 2 respectively).[6,7] Both tables are designed for underwater diving operations and have a maximum bottom time at 253 kPa of 280 min,[7] insufficient to accommodate the 345 min exposure possible for the SRV medical attendant.

Fresh medical attendants could lock-in before the limits of DCIEM tables are exceeded; however, there may not always be sufficient personnel for the longest exposures. Current RAN planning requires medical attendants who have exceeded the limits of the DCIEM tables to be decompressed on the same saturation schedule as survivors (Hissink J, personal communication, 2013).

The National Oceanic and Atmospheric Administration (NOAA) 17.11 standard O_2-accelerated saturation decompression table is currently favoured for saturation decompression of survivors owing to its relatively short total decompression time of 680 min from 253 kPa.[8] Nevertheless, saturation decompression of medical attendants from exposures of 345 min or less is unnecessary and costly in terms of O_2 supply, RCC space, and human resources on-board the rescue ship.

As a result of these constraints, the first author was tasked by the Officer-in-Charge, Submarine Underwater Medicine Unit to investigate alternative decompression tables that would permit decompression of personnel with bottom times up to 345 min at 253 kPa. VVAL-18M is the algorithm underlying the air decompression tables in the United States Navy (USN) Diving Manual, Revision 6, and is intended for diving operations, but has schedules for bottom times up to 420 min at 253 kPa.[9,10] The Royal Navy Table 14 (RN14) was originally a diving table, retrospectively modified for submarine rescue, and has schedules for bottom times up to 350 min at 253 kPa.[11,12] The USN XVALSS_DISSUB 7 Table were specifically designed for submarine rescue and has schedules for bottom times up to 460 min at 253 kPa.[13]

To evaluate the utility of these alternative tables, this paper compares the estimated probability of decompression sickness (P_{DCS}), the units pulmonary toxicity dose (UPTD), volume of oxygen required and the total dive time (TDT) of single and repetitive exposures to 253 kPa followed by O_2-accelerated decompression prescribed by DCIEM, VVAL-18M, XVALSS DISSUB 7, and RN14-Modified tables for exposures relevant to SRV and TUP medical attendants.[6,7,9–13] A companion paper evaluates strategies for decompressing RCC medical attendants.[14]

Methods

The approach was to analyse hypothetical dive profiles (pressure/time/breathing gas histories) representing single or repetitive exposures to a DISSUB ambient pressure of 253 kPa for various bottom times, and followed by decompression prescribed by each of the four candidate decompression tables that had a schedule for that exposure. In all these profiles, an 85% inspired oxygen fraction (F_iO_2) was assumed during O_2 breathing, to account for leakage of chamber atmosphere into a demand-valve oral nasal mask.[15] If higher FiO_2 can be achieved, the actual P_{DCS} will be lower than estimated.

Single dive bottom times ranged from 60 to 460 min followed by decompression prescribed by the DCIEM In-Water O_2 Decompression Table (DCIEM Table 2, for dives up to 280 min bottom time),[7] RN14-Modified (for dives up 350 min bottom time),[11,12] VVAL-18M In-Water O_2 Decompression tables (for dives up 420 min bottom time),[9,10] and XVALSS_DISSUB 7 Table (for all dives).[13] Repetitive exposures comprised two identical bottom times of 60 and 150 min at 253 kPa separated by a surface interval time (SIT) of 12.5 hours (h), with decompression from each dive as prescribed by the candidate tables, except for the RN14-Modified tables that do not permit repetitive diving.[11,12]

The 12.5-h SIT was in accord with the time between SRV sorties if survivors must be decompressed from 253 kPa saturation. In addition to examining dive profiles representing the full bottom time of schedules, some dive profiles representing likely medical attendant exposures with decompression schedules selected using standard round-up conventions were also examined. In all, 160 single and 12 repetitive dive profiles were examined.

The P_{DCS} for each complete dive profile was calculated using the Navy Medical Research Institute 98, model 2 (NMRI-98) and Bubble Volume Model 3 [BVM(3)] probabilistic models for DCS incidence and time of occurrence.[16,17] Each of these models uses a dive profile as input and calculates the theoretical time course of gas partial pressures in each of three well-stirred compartments with different half-times. In the NMRI-98 model, the hazard (instantaneous risk) is the sum across compartments of positive values of functions of the gas supersaturation. The P_{DCS} is a function of the time-integral of the hazard from the beginning of a dive profile until the point in time long after the dive when the hazard finally declines to zero.[16]

For repetitive dives, the cumulative P_{DCS} is the sum of the risks of all dives performed and the gas pressures are tracked throughout the repetitive dives and intervening SIT. BVM(3) includes a single bubble in each compartment and the hazard is a function of the calculated bubble volume in the three modelled tissue compartments.[17] The parameters that govern the gas kinetics and bubble dynamics of these models (for instance compartment half-times and gas diffusivities) are selected by a best practicable fit to a large, diverse database of dive profiles (approximately 5% incidence of DCS) from carefully controlled and monitored air and nitrox man dives.[16,17] These two models are fit to similar data sets. Widely dissimilar estimates between these two structurally different models would be considered evidence of inappropriate extrapolation to dives unlike the calibration data.

The oxygen consumption, UPTD, and TDT were calculated for each of these dive profiles. The UPTD concept is based on inspired PO_2 and exposure time (t) isopleths for equivalent decrements in vital capacity (as a marker for pulmonary oxygen toxicity). The UPTD is the exposure time in minutes at 1 atmosphere absolute inspired PO_2 required to produce the equivalent pulmonary oxygen toxicity to any *arbitrary* PO_2 time exposure.[18] The original UPTD was based on the equation:

$$(PO_2 - 0.5)\, t^{1.2} = c \qquad (1)$$

Instead we used the alternative equation:

$$-0.011\, (PO_2 - 0.5)\, t = c \qquad (2)$$

This results in:

$$UPTD = t\left(\frac{PO_2 - 0.5}{0.5}\right) \qquad (3)$$

which is of similar form to the original UPTD derivation.[18,19] We provide UPTD to compare the oxygen exposure of the different profiles without comment on the estimated percentage decrement in vital capacity. Furthermore, cumulative UPTD for repetitive dives does not account for recovery from air breathing.

Oxygen consumption was based on a conservative respiratory minute ventilation of 15 $L \cdot min^{-1}$, adjusted for Boyle's Law and at body temperature and pressure, saturated (BTPS). Fifteen $L \cdot min^{-1}$ was based on a tidal volume of 10 $mL \cdot kg^{-1}$, a resting adult respiratory rate of 15 $breaths \cdot min^{-1}$ and a body weight of 100 kg (the latter based on the 95th percentile for weight in Australian submariners being 96 kg).[20] TDT was calculated using recommended air-breaks. VVAL-18M and RN14-Modified tables recommend a 5-min air-break after every 30 min of oxygen breathing,[9–12] whereas XVALSS_DISSUB 7 tables require a 15-min air-break after every 60 min of oxygen breathing.[13] DCIEM Table 2 does not require air-breaks.[7]

Results

SINGLE DIVES

Figures 3 and 4 give the BVM(3)-estimated P_{DCS} for DCIEM 2, VVAL-18M, XVALSS_DISSUB 7 and RN14-Modified decompression following single dives at a depth of 253 kPa for the full bottom time of the published schedules. NMRI-98-estimated P_{DCS} were not substantially different for any of the dive profiles evaluated, providing confidence that both models were used in their reliable range. Owing to differences in table increments and limits, a direct comparison could not be made between all dive profiles.

Figure 3

P_{DCS} (%, y-axis) in rescue personnel for single dives with bottom times from 60–280 min (x-axis) at 253 kPa estimated using the BVM(3) model; at each bottom time the cluster of bars gives the P_{DCS} for decompression according to each table that has a schedule for that bottom time; the order in the bar cluster is always the same but not all bars may appear

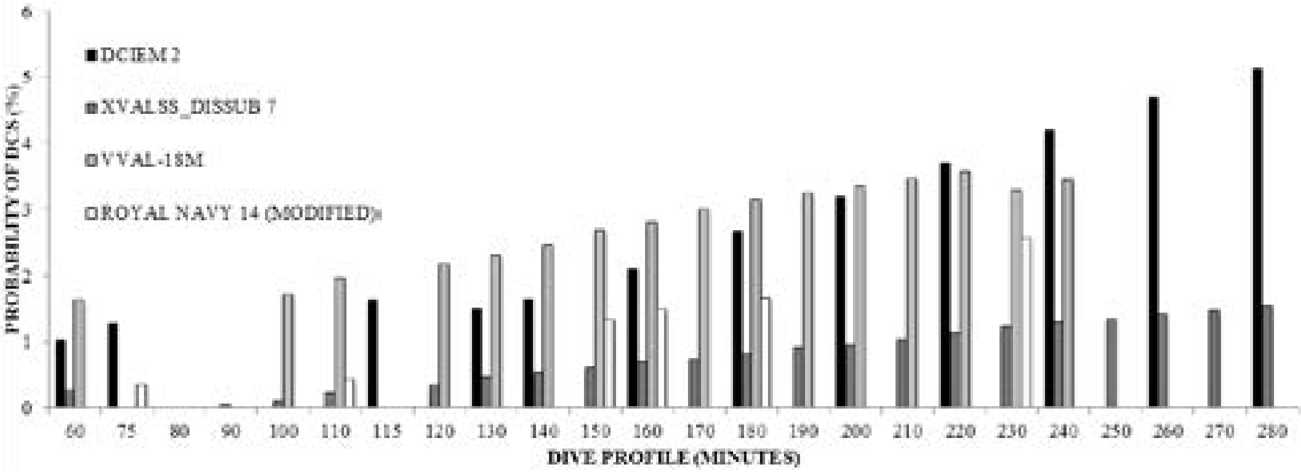
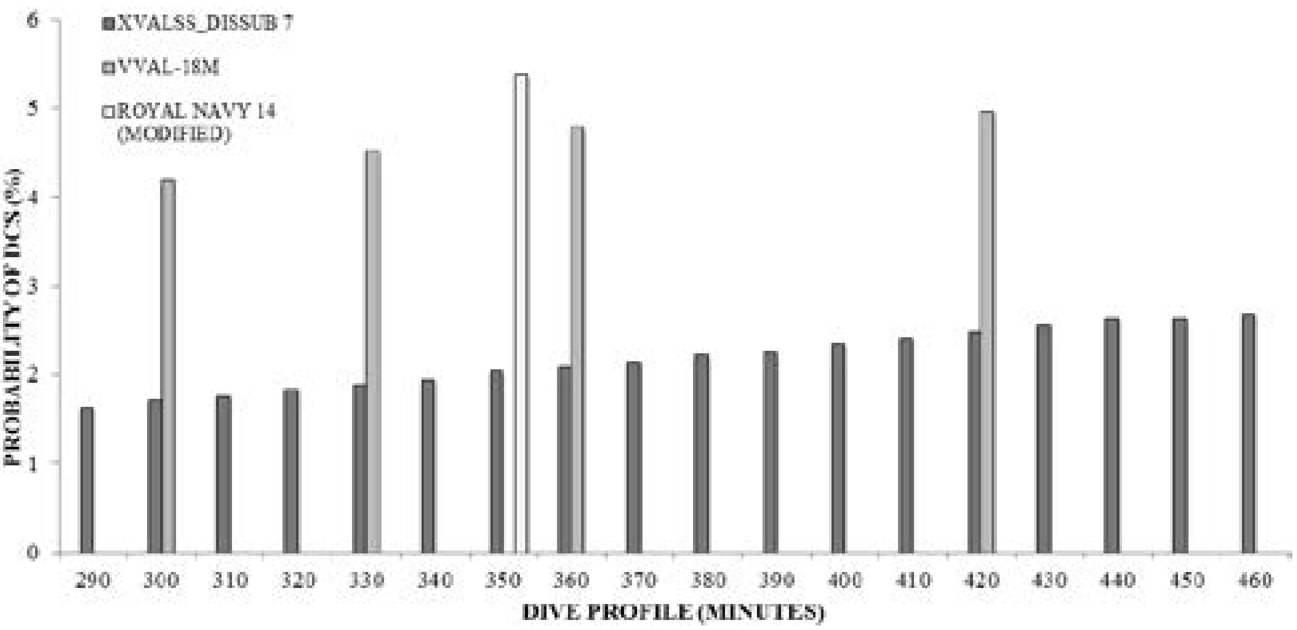


Figure 4

P_{DCS} (%, y-axis) in rescue personnel for single dives with bottom times from 290–460 min (x-axis) at 253 kPa estimated using the BVM(3) model; at each bottom time the cluster of bars gives the P_{DCS} for decompression according to each table that has a schedule for that bottom time; the order in the bar cluster is always the same but not all bars may appear



All decompression tables provided reasonably low risk decompression for single dives, with few profiles exceeding 5% P_{DCS}. For single dive profiles XVALSS_DISSUB 7 tables produced the lowest P_{DCS} risk estimates, whereas DCIEM Table 2 produced the highest.

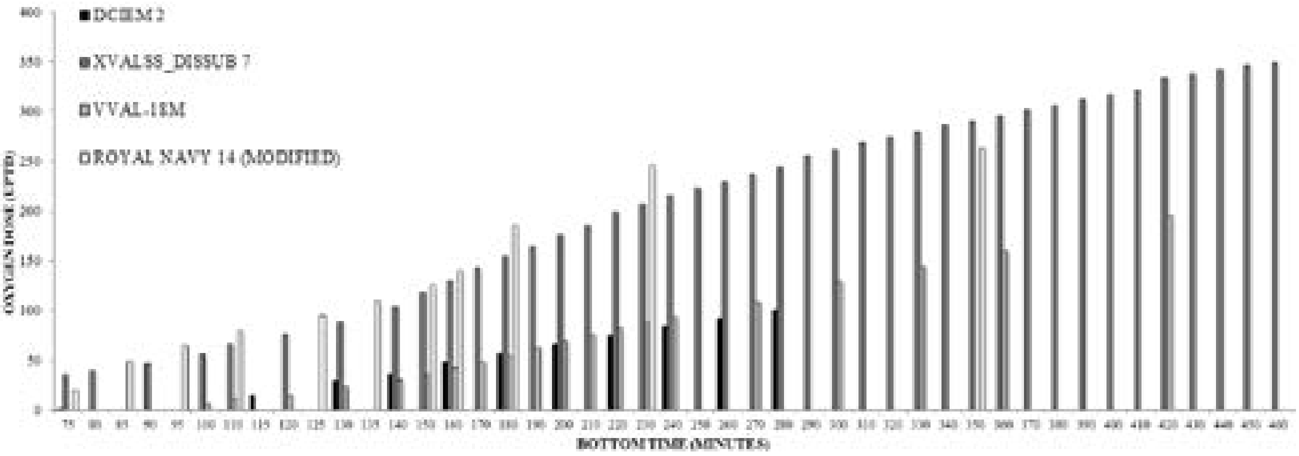
The hyperbaric exposures required of the medical attendant in the SRV aft compartment are too long to allow for repetitive diving and have to be undertaken as single dives by 'clean' personnel (who have not had an hyperbaric exposure in the preceding 18 h). However, medical attendants inside the TUP compartment may have exposures of 150 min or less, which could be undertaken as a repetitive exposure after the 12.5-h SIT imposed by the turn-around time for SRV sorties.

REPETITIVE DIVES

The P_{DCS} of repetitive dives can be increased compared to single dives because of residual inert gas or bubbles from the preceding dive. The BVM(3)-estimated cumulative P_{DCS} for repetitive 60-min dives at 253 kPa with a SIT of

Figure 5

Unit pulmonary toxicity dose (UPTI) in rescue personnel for single dives with bottom times from 75–460 min at 253 kPa; at each bottom time the cluster of bars gives the UPTD for decompression according to each table that has a schedule for that bottom time; the order in the bar cluster is always the same but not all bars may appear



12.5 h using DCIEM 2 was 2.1%, using VVAL-18M was 2.0%, and for XVALSS_DISSUB 7 the cumulative P_{DCS} was 0.6%. Likewise, the NMRI-98-estimated cumulative P_{DCS} for repetitive 60-min dives at 253 kPa with a SIT of 12.5 h using DCIEM 2 was 2.9%, using VVAL-18M was 2.8% and for XVALSS_DISSUB 7 was 1.1%.

Repetitive 150-min dives with a 12.5-h SIT decompressed using VVAL-18M tables have a cumulative BVM(3)-estimated P_{DCS} of 5.6%. Cumulative NMRI-98-estimated P_{DCS} for VVAL-18M tables was 6.0%. DCIEM 2 and XVALSS_DISSUB 7 tables do not permit a repetitive 150-min dive at 253 kPa with a SIT of 12.5 hours.[7,13] The RN14-Modified table does not support any repetitive diving.[11,12]

The cumulative P_{DCS} for these repetitive dives gives a sense of the overall risk to an individual TUP operator. However, another consideration is the probability of any DCS occurring in the rescue cohort, even if conducting single-dives. Depending on which decompression tables are selected, between 12 to 18 SRV/TUP hyperbaric personnel-exposures will be required to rescue 65 survivors. The probability of a single DCS incident in the course of a diving operation is greater than the P_{DCS} of a single or repetitive dive. The probability of at least one incidence of DCS in a series of identical dives can be determined using binomial theorem, and is one minus the probability of no DCS in all dives.

For illustrative purposes, consider that all rescue sorties were for a 345-min bottom time at 253 kPa. For decompression according to the closest VVAL-18M schedule (360 min), which results in a BVM(3)-estimated P_{DCS} of 4.8%, the probability of at least one case of DCS among all SRV and TUP medical attendants performing 18 hyperbaric exposures is $1-(1-0.048)^{18} = 58.7\%$. If instead decompression is conducted according to the closest XVALSS_DISSUB 7 schedule (350 minutes), which has a BVM(3)-estimated P_{DCS} of 2.0%, the probability of at least one case of DCS among all SRV and TUP medical attendants is $1-(1-0.02)^{18} = 30.4\%$.

OXYGEN EXPOSURE AND REQUIREMENTS

Figure 5 summarizes the UPTD units for single dive profiles at 253 kPa following decompression with each of the XVALSS_DISSUB 7, DCIEM 2, RN14-Modified and VVAL-18M tables. XVALSS_DISSUB 7 tables delivered the highest UPTD, whereas DCIEM Table 2 delivered the lowest. No UPTD exceeded repetitive excursion (REPEX) recommendations for daily UPTD dose limits.[21] For example, medical attendants performing a single dive are permitted a daily and total cumulative dose of 850 units, whereas personnel performing two dives during the rescue operation are restricted to a daily and total pulmonary toxicity dose of 700 and 1400 units respectively.[21]

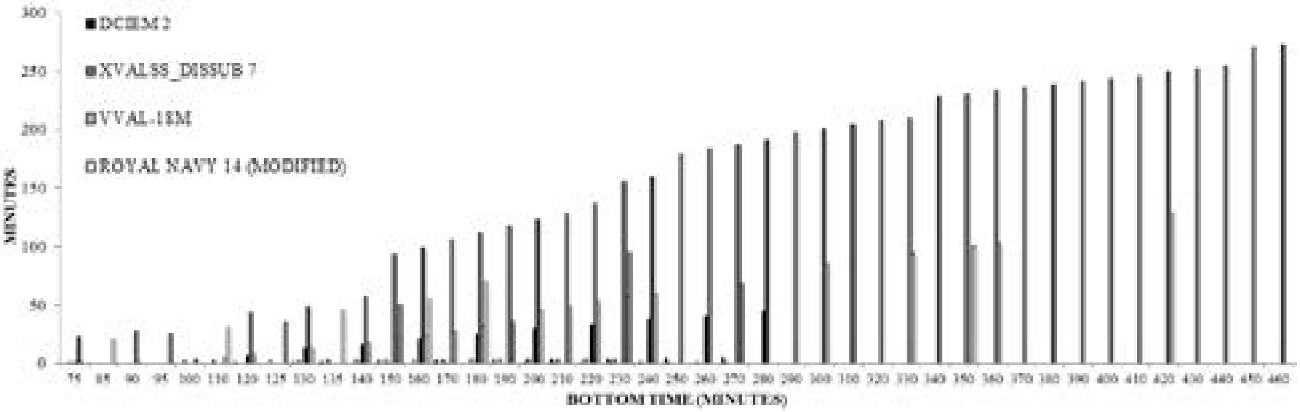
XVALSS_DISSUB 7 and RN14-Modified had higher oxygen requirements in comparison to VVAL-18M and DCIEM Table 2. For the longest predicted bottom time of 345 min (at 253 kPa and adjusted for Boyles Law/BTPS) XVALSS_DISSUB 7, VVAL-18M and RN14-Modified required 4689, 2221 and 3033 litres respectively. Figure 6 compares TDTs for DCIEM 2, VVAL-18M, XVALSS_DISSUB 7 and RN14-Modified tables. XVALSS_DISSUB 7 tables had the longest TDTs whereas DCIEM Table 2 had the shortest.

Discussion

The NMRI-98 and BVM(3) probabilistic decompression models were selected to evaluate candidate decompression

Figure 6

Total decompression time (min) in rescue personnel for single dives with bottom times from 75–460 min at 253 kPa, calculated using recommended, minimum air-breaks; at each bottom time, the cluster of bars gives the total decompression time for each table that has a schedule for that bottom time; the order in the bar cluster is always the same but not all bars may appear



tables for use in DISSUB rescue operations. Both of these models were used in the original development and evaluation of the XVALSS_DISSUB 7 tables.[13] These tables were calculated using the deterministic Thalmann algorithm, but with a parameter set (XVALSS_DISSUB 7) developed to produce schedules with a low NMRI-98 estimated P_{DCS}. The man-tested schedules were evaluated with both NMRI-98 and BVM(3).[13] The present work differs in that it evaluates schedules relevant to a RAN DISSUB scenario. It must be acknowledged that the results presented are model-estimated P_{DCS} and not the result of actual man-trials of the schedules likely in the RAN DISSUB scenario. However, these probabilistic models have been used extensively and provide credible estimates of P_{DCS}. A similar estimate from the two structurally different models provides additional confidence in the results.

The RAN does not have a policy on acceptable P_{DCS} for diving or DISSUB rescue operations. The DCIEM Table 2, which is approved for RAN use, had DCS incidence of 3.2–3.5% during development and validation.[22–24] Most US Navy air and nitrox decompression procedures have an upper limit of 5% P_{DCS} for normal exposure diving.[25] Severe central nervous system DCS is uncommon in air dives with less than about 7% estimated P_{DCS}.[26] These figures provide some objective criteria for evaluation of P_{DCS} estimates. However, any DCS in medical attendants will result in serious strain on resources and, therefore, the lowest practicable P_{DCS} is desirable. Nevertheless, low P_{DCS} must be balanced against TDT, UPTD and oxygen use.

For single dives, the major advantage of using XVALSS_DISSUB 7, VVAL-18M and RN14-Modified over DCIEM Table 2 is their longer table limits,[7,9–13] which covers the worst case, 345-min dive profile for SRV medical attendant and, therefore, obviates the need for these attendants to undergo saturation decompression with the survivors. For single dives XVALSS_DISSUB 7 tables provided the lowest P_{DCS} for dive profiles up to 420 min at 253 kPa (Figures 3 and 4).

The advantages of these lower P_{DCS} become particularly evident when assessing the probability of having at least one DCS among the medical attendants in the course of the rescue operation. It was specifically to mitigate this risk of DCS over the course of multiple dives during submarine rescue, that the XVASS_DISSUB 7 Table was developed. Human validation trials of XVALSS_DISSUB 7 for repetitive diving were tested under dry hyperbaric conditions relevant to submarine rescue personnel. Eight two-dive, repetitive profiles at depths between 193 to 284 kPa, were tested with a total of three cases of DCS during 125 dives.[13]

One DCS case occurred after each of the three repetitive 284 kPa schedules: two 180-min exposures separated by a 56-minute SIT; two 240-min exposures separated by a 66-min SIT and two 360-min exposures separated by a 126-min SIT.[13] It is notable that these DCS occurred after repetitive dives to greater pressure and with shorter SIT than the RAN requirement and it is possible that a lower incidence of DCS would result in the RAN DISSUB scenario.

The risks of oxygen toxicity with these procedures are acceptable as no estimated UPTD exceeded REPEX recommendations.[21] The risk of central nervous system (CNS) oxygen toxicity is considered low as the deepest decompression stops for RN14-Modified, XVALSS_DISSUB 7, DCIEM 2 and VVAL-18M tables are 243, 223, 193 and 162 kPa respectively[7,9–13] and within a dry environment, the risk of oxygen toxicity seizures ranges from 1:1,000 to 1:50,000.[27]

The lower oxygen requirements and shorter TDT for the DCIEM Table 2 and VVAL-18M Table justifies their retention and/or introduction for Australian submarine rescue (Figure 6). Although decompressing personnel with either DCIEM Table 2 or VVAL-18M tables carries a higher risk of DCS, there may be exceptional circumstances such as severe limitation of oxygen supply or time constraints where one must tolerate higher DCS risks in order to preserve oxygen for patients or expedite the rescue.

Conclusion

The introduction of candidate tables will enable decompression of medical attendants with bottom times up to 460 min at 253 kPa, thus negating the previous RAN requirement to decompress personnel exceeding the 280-min DCIEM Table 2 limit (at 253 kPa) with schedules designed for saturation divers. The XVALSS_DISSUB 7 Table provides acceptable P_{DCS} limits of less than 3.1% for single dive profiles up to 460 min at 253 kPa. The VVAL-18M Table allows decompression up to 420-min at 253 kPa with shorter TDT and lower oxygen requirements, albeit with higher P_{DCS} estimates (up to 5.9%). The RN14-Modified Table has little utility for Australian submarine rescue owing to an inability to plan repetitive diving.

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