# Decompressing recompression chamber attendants during Australian submarine rescue operations

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## Abstract

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**Introduction:** Inside chamber attendants rescuing survivors from a pressurised, distressed submarine may themselves accumulate a decompression obligation which may exceed the limits of Defense and Civil Institute of Environmental Medicine tables presently used by the Royal Australian Navy. This study assessed the probability of decompression sickness ($P_{DCS}$) for medical attendants supervising survivors undergoing oxygen-accelerated saturation decompression according to the National Oceanic and Atmospheric Administration (NOAA) 17.11 table.

**Methods:** Estimated probability of decompression sickness ($P_{DCS}$), the units pulmonary oxygen toxicity dose (UPTD) and the volume of oxygen required were calculated for attendants breathing air during the NOAA table compared with the introduction of various periods of oxygen breathing.

**Results:** The $P_{DCS}$ in medical attendants breathing air whilst supervising survivors receiving NOAA decompression is up to 4.5%. For the longest predicted profile (830 minutes at 253 kPa) oxygen breathing at 30, 60 and 90 minutes at 132 kPa partial pressure of oxygen reduced the air-breathing-associated $P_{DCS}$ to less than 3.1 %, 2.1% and 1.4% respectively.

**Conclusions:** The probability of at least one incident of DCS among attendants, with consequent strain on resources, is high if attendants breathe air throughout their exposure. The introduction of 90 minutes of oxygen breathing greatly reduces the probability of this interruption to rescue operations.

## Introduction

The ambient pressure inside a distressed submarine (DISSUB) may be elevated above 101 kPa due to compression of the remaining gas space by partial flooding or released high-pressure gas supplies.[1] Locating the DISSUB and delivering the rescue system on to the site may take several days resulting in the crew of the DISSUB becoming saturated (inert gas tissue tension equilibration with the inspired inert gas pressures) at elevated pressure. As detailed in a companion paper,[2] the submarine crew may be rescued by a Submersible Rescue Vehicle (SRV) which can mate to the DISSUB's escape hatch.

Survivors can transfer under pressure to a recompression chamber (RCC) at the surface where they undergo saturation decompression from the DISSUB internal pressure.[2] Royal Australian Navy (RAN) DISSUB planning assumes all souls could be rescued from a DISSUB pressure of 253 kPa (2.5 bar). Higher DISSUB pressures are possible, but RAN analysis of Collins Class submarines (classified) has assessed that likely conditions associated with such pressures are not survivable, and would require the crew to escape rather than await rescue.[3–5]

The current RAN rescue system uses the James Fisher Defence 'LR5' SRV which can rescue up to 14 seated survivors per sortie, a transfer under pressure (TUP) compartment, and two RCCs that can accommodate seven survivors and one medical attendant each (see accompanying paper for more details[2]). Separate medical personnel attend survivors inside the SRV, the TUP compartment, and inside each RCC. Decompression of the SRV and TUP medical attendants was the subject of the companion paper.[2] The hyperbaric exposure for RCC medical attendants begins with pressurization of the RCC to DISSUB internal pressure ready for transfer under pressure of survivors. The RCC attendant hyperbaric exposure consists of 60 to 150 minutes (min) at the equivalent to DISSUB internal pressure, while survivors are transferred under pressure from the SRV to the RCCs, plus the time required for saturation decompression.

The National Oceanic and Atmospheric Administration (NOAA) 17.11 standard table is currently favoured by the

RAN for oxygen-accelerated saturation decompression of survivors, owing to its relatively short total decompression time (TDT) of 680 min from a 253 kPa air-saturation depth.[6] The RCC medical attendants may, therefore, be exposed to hyperbaric pressure for a total of 740 to 830 min. Unlike survivors, the RCC medical attendants' duties will prevent them from remaining at rest, and they therefore cannot breathe oxygen ($O_2$) throughout the decompression. These RCC medical attendants will themselves be exposed to the risk of decompression sickness (DCS).

Each cohort of fourteen survivors must be decompressed before the next SRV sortie is completed, and six or more sorties may be required to evacuate the DISSUB of rescue personnel and survivors, particularly if some survivors are immobilised secondary to their injuries. With the current RAN rescue plan, inside chamber attendants assisting survivors will be required to supervise two saturation decompressions separated by a 34-hour (h) surface interval.

As the NOAA tables were originally designed for decompressing uninjured scientific divers from underwater habitats, there are no accompanying instructions within the NOAA diving manual on how to decompress supervising attendants.[6] At present, the only tables authorized for decompression of RAN medical attendants are the Defense and Civil Institute of Environmental Medicine (DCIEM) tables.[7,8] These tables were designed for underwater diving operations and have a table limit of 280 min at 253 kPa (DCIEM 2 Table).[8] In order to supervise survivors during 830 min in the RCC, it would require a new attendant to be locked-in after each 280-min period, and the previous attendant decompressed according to the DCIEM schedule. This is impractical for supervising the saturation decompression, as it would require three attendants to be rotated through each RCC, or six attendants in total, to supervise survivors from each SRV sortie. These human resource constraints prompted an investigation into the DCS risk for RCC attendants supervising the NOAA 17.11 schedule and whether the introduction of $O_2$ breathing periods could mitigate this risk and avoid the need to decompress with DCIEM tables.

## Methods

The approach was to analyse hypothetical dive profiles (pressure/time/breathing gas histories) representing RCC attendant hyperbaric exposures whilst supervising saturation decompression from 253 kPa. Dive profiles were for either 60 or 150 min exposure at 253 kPa, followed by the 680 min of decompression stops required by the NOAA 17.11 table for a 253 kPa saturation depth. Different dive profiles represented either air breathing throughout the exposure or incorporating periods of $O_2$ breathing.

The methods of analysing the dive profiles are covered in detail in the companion paper in this issue and given here in summary.[2] The instantaneous risk and the probability of DCS ($P_{DCS}$) for each dive profile was calculated using the Navy Medical Research Institute 98 (NMRI-98, Model 2) and Bubble Volume Model 3 [BVM(3)] probabilistic models.[9,10] In the NMRI-98 model, instantaneous risk of DCS is a function of the gas supersaturation in three modelled tissue compartments.[9] In the BVM(3) model, instantaneous risk is a function of the bubble volume in three modelled tissue compartments.[10] The $P_{DCS}$ is a function of the time-integral of these instantaneous risks.[9,10] In this paper the instantaneous risk was used to guide scheduling of $O_2$ breathing periods.

The oxygen consumption and units pulmonary toxicity dose (UPTD) were calculated for each of these dive profiles using an equation derived from the Harabin et al. method.[11] $O_2$ usage per attendant was based on a conservative respiratory minute ventilation rate of 15 litres·min$^{-1}$, adjusted for Boyles Law and body temperature and pressure, saturated (BTPS). This is a deliberate over-estimation, based on a 10 ml·kg$^{-1}$ tidal volume, resting adult respiratory rate of 15 breaths·min$^{-1}$,[12] and a body weight of 100 kg.

## Results

Figure 1 shows the dive profile for 150 min at 253 kPa followed by the NOAA 17.11 decompression stops. The upper panel shows the time course of the BVM(3)-estimated instantaneous risk for this profile if the attendant breathes air throughout. This risk occurs after decompression from 132 to 117 kPa (10 to 5 feet' seawater, fsw) and after decompression to the surface. The lower panel illustrates the effect of introducing attendant $O_2$ breathing for the entirety of the 132 kPa decompression stop (90 min). This $O_2$ breathing eliminates the BVM(3) estimated instantaneous risk at 117 kPa and greatly reduces the magnitude and duration of the risk at the surface. Similarly, NMRI-98 estimated instantaneous risk (not shown) occurred principally after decompression from 132 to 117 kPa and after decompression to the surface. Once again DCS risk was reduced by $O_2$ breathing at 132 kPa. These results prompted evaluation of the $P_{DCS}$ when different periods of oxygen breathing were introduced at 132 kPa.

Figure 2 shows the estimated $P_{DCS}$ (%) for RCC medical attendants supervising survivors during the NOAA 17.11 Table following 60 or 150 min at 253 kPa with total hyperbaric times of 740 and 830 min respectively. It compares air decompression with varying periods of $O_2$ breathing (3 min, 30 min, 60 min and 90 min) at 132 kPa ending just prior to ascent to 117 kPa. $O_2$ breathing at this depth reduced estimated $P_{DCS}$ from between 3.8% to 4.4% using air to 1.2% to 1.3% with 90-min $O_2$ breathing for an 830-min dive.

We did not directly estimate $P_{DCS}$ for repetitive RCC medical attendant exposures under the assumption that the 34-h

**Figure 1**

BVM(3) estimated instantaneous risk of DCS for RCC attendants supervising the NOAA 17.11 table whilst breathing air. Total exposure is 830 min commencing with 150 min at 253 kPa; the secondary y-axis is instantaneous DCS risk in arbitrary units representing bubble volumes in three modelled compartments. The upper panel represents air breathing throughout, the lower panel is air breathing with a single 90 min of $O_2$ breathing at 132 kPa, indicated by the horizontal bar. The recompression just prior to surfacing reflects the origin of these schedules for decompression from sea-floor habitats for which recompression is required to allow divers to exit the habitat into the water

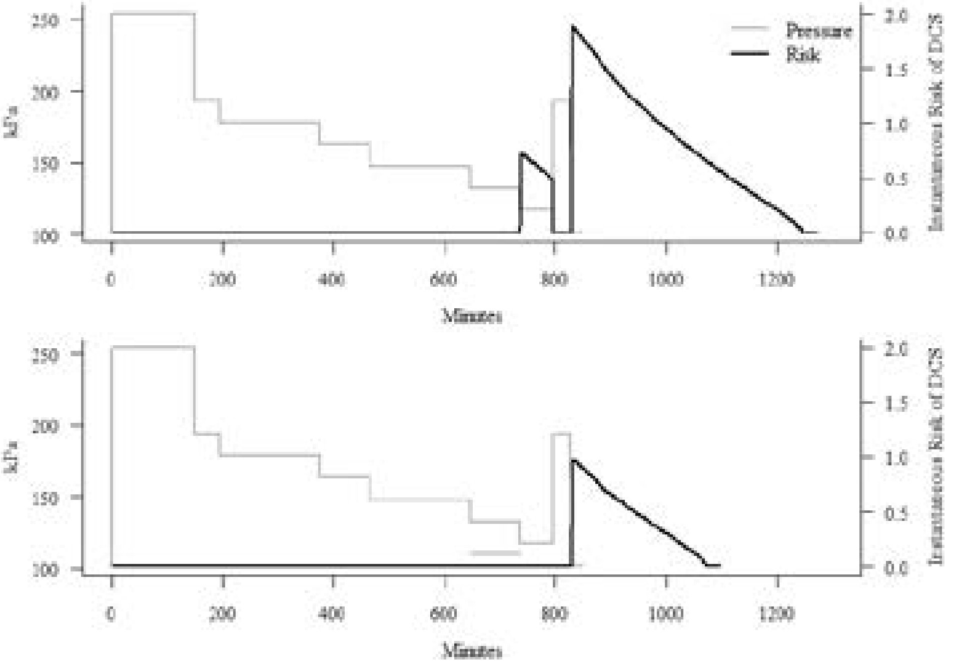

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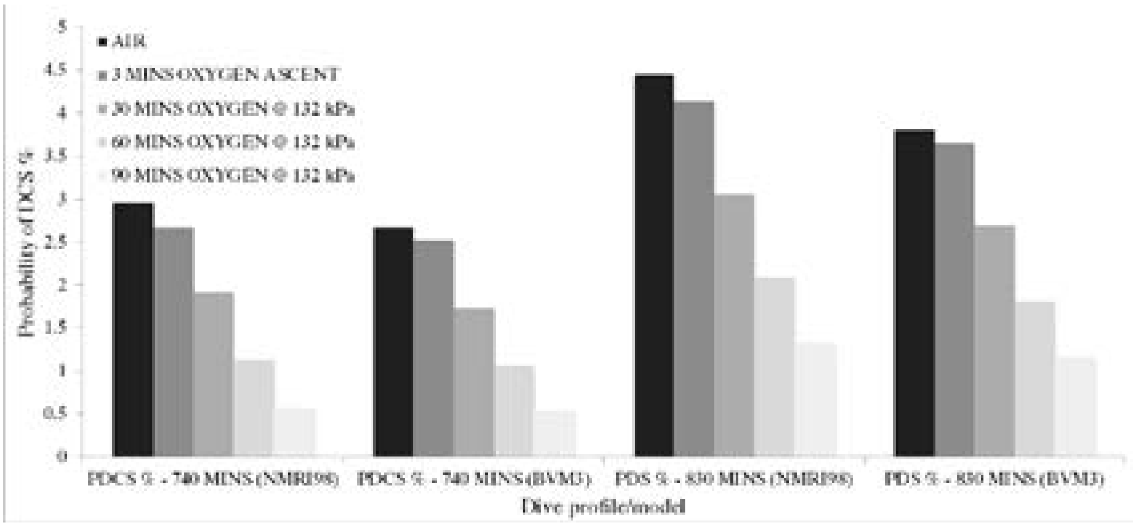
**Figure 2**

$P_{DCS}$ (%) for medical attendants for single dives with bottom times of 740 and 830 min at 253 kPa estimated using the NMRI-98 and BVM3 model for the NOAA standard table; at each bottom time the cluster of bars gives the $P_{DCS}$ for decompression



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surface interval was sufficient that attendants would be ‘clean’ for each dive. The probability of at least one incident 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. Using the BVM(3) estimate of 3.8% $P_{DCS}$ (830-min exposure with air decompression), RCC attendants performing two such exposures will have a probability of a DCS case of:

$$1 - (1-0.038)^2 = 7.5\% \qquad (1)$$

Twelve RCC attendant exposures will be required to rescue 65 survivors and the probability of at least one DCS case among all RCC attendants performing such exposures is:

$$1 - (1-0.038)^{12} = 37.2\% \qquad (2)$$

**Table 1**

Cumulative unit pulmonary toxicity dose (CUPTD) for NOAA attendants after 740- and 830-min dives commencing at 253 kPa and total oxygen ($O_2$) usage: breathing air and with 3 min, 30 min, 60 min and 90 min of $O_2$, all at 132 kPa just prior to ascent to 117 kPa pressure

| Oxygen breathing period | CUPTD 740 min | CUPTD 830 min | Oxygen use (L) |
|---|---|---|---|
| None | 2 | 4 | 0 |
| 3 min final ascent | 6 | 8 | 86 |
| 30 min @ 132 kPa | 35 | 37 | 862 |
| 60 min @ 132 kPa | 68 | 71 | 1,723 |
| 90 min @ 132 kPa | 101 | 104 | 2,585 |

The use of 90 min of oxygen breathing reduced the $P_{DCS}$ of the 830-min RCC attendant exposure to 1.2%, and this reduces the probability of at least one case of DCS in two exposures to 2.4% and in twelve exposures to 13.5%. These figures illustrate the advantages of adopting conservative decompression for rescue personnel.

Table 1 shows the UPTD for RCC medical attendants after 740 and 830-min dives commencing at 253 kPa whilst breathing air, and for the four different periods of $O_2$ breathing. Table 1 also shows the estimated $O_2$ usage for a single attendant for these $O_2$ periods. None of these UPTD exceeded Repetitive Excursion (REPEX) recommendations.[13]

## Discussion

Probabilistic decompression model estimates of the $P_{DCS}$ for attendants supervising United States Navy (USN) treatment tables have been reported.[14] The estimated $P_{DCS}$ for Treatment Table 6 ranges from 6.2% to 11.2%, depending on the number of extensions for attendants breathing air throughout.[15,16] The introduction of periods of $O_2$ breathing for the attendant decreases the estimated $P_{DCS}$ to near 0%.[15] Such $O_2$ decompression of attendants has been adopted by many organisations including the RAN,[7] and the same probabilistic modelling was used to investigate $P_{DCS}$ in attendants supervising the NOAA 17.11 table during submarine rescue.

The RAN does not have a policy on acceptable $P_{DCS}$ for diving or DISSUB rescue operations. However, the DCIEM tables, which are approved for RAN use, had a DCS incidence of 3.2% to 3.5% during development and validation.[16–19] Most USN air and nitrox decompression procedures have an upper limit of 5% $P_{DCS}$ for normal exposure diving.[20,21] The highest estimated $P_{DCS}$ for RCC medical attendants breathing air throughout decompression was 4.4%, toward the upper end of the normal exposure air diving range. RCC attendants need to perform at least two dives, separated by a 34-h surface interval, and collectively, twelve RCC attendant exposures will be required to rescue 65 survivors. The probability of a single DCS incident in the course of a series of dives is greater than the $P_{DCS}$ of a single dive and any DCS in rescue personnel will result in a serious strain on resources.

It is neither necessary nor desirable for RCC medical attendants to breathe $O_2$ throughout the decompression, as do the survivors, as attendants have a lower decompression obligation and their duties inside the chamber put them at greater risk of central nervous system (CNS) oxygen toxicity than the survivors. RCC medical attendant $O_2$ breathing should be later in the decompression cycle to minimise the re-uptake of nitrogen during any subsequent hyperbaric air breathing and scheduled at the shallowest decompression stop so as to minimise $O_2$ toxicity and $O_2$ usage. Scheduling $O_2$ breathing to occur at 132 kPa (10 fsw) fulfils these objectives.

The highest UPTD dose of 104 units does not exceed REPEX recommendations.[13] The risk of CNS $O_2$ toxicity is considered low as the deepest decompression stop whilst breathing oxygen is 132 kPa (Table 1). Within a dry environment, the risk of $O_2$ toxicity seizures ranges from 1:1,000 to 1:50,000.[22]

The introduction of 90 min of $O_2$ breathing for RCC medical attendants requires an additional 2,585 litres of $O_2$ per person (Table 1), of which there are sufficient $O_2$ supplies held on-board existing vessels. Assessing the effect of breathing $O_2$ on ascent (3 min) and at 30 and 60 min at 132 kPa provides options in case of critical $O_2$ supply constraints.

## Conclusions

RCC medical attendants supervising saturation decompression of DISSUB survivors are themselves at risk of DCS, and if breathing air for the entirety of their hyperbaric exposure, this risk is considered high. RCC medical attendants are critical to the success of the rescue operation and any DCS occurring within this cohort will place further strain on chamber space availability and human and oxygen supply resources, Introducing 90 min of $O_2$ breathing at 132 kPa greatly reduces the probability of this disruption to the rescue operation.

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## Ethics statements

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