

Early nitrogen wash-out for inside attendants during hyperbaric oxygen therapy: a novel oxygen distribution regimen

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Abstract

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Introduction: Hyperbaric oxygen therapy (HBOT) is widely used as treatment of decompression sickness (DCS). The patient breathes oxygen at an elevated oxygen partial pressure of up to 280 kPa, whereas any inside attendant (IA) normally breathes air. This results in nitrogen uptake and tissue loading in the IA, which must be considered during decompression. The US Navy Treatment Table 6, and its equivalent used by the Swedish Armed Forces, prescribe periods of oxygen breathing prior to and during decompression to reduce the risk of DCS for the IA. However, since these oxygen periods are concentrated toward the latter part of the hyperbaric treatment, they do not account for the possibility of rapid decompression in the event of an earlier emergency.

Methods: We suggest rescheduling the distribution of oxygen for the IA to an earlier stage of the HBOT, which would allow early emergency decompression to a greater extent than the traditional IA oxygen regimen. To verify the duration of oxygen periods and their timing, we used the exponential linear Thalmann decompression algorithm with SWEN21B parameters to analyse compartmental gas load and perform a comparison between the original and our newly proposed regimens.

Results: We identified an alternative oxygen regimen for the inside attendant (IA) that remains within the permissible limits of the decompression algorithm yet allows for emergency decompression to be performed over an extended section of the period of compression.

Conclusions: Based on the decompression model used herein, we can conclude that greater flexibility in emergency decompression is possible if the oxygen regimen for the inside attendant (IA) is administered at an earlier stage of the therapy session.

Introduction

Hyperbaric oxygen therapy (HBOT) is widely recognised as the gold standard for treating decompression sickness (DCS). This treatment has been known for over a century and has shown good results in mitigating symptoms resulting from rapid decompression or arterial gas emboli.¹ HBOT is typically performed at hospitals, military facilities, offshore facilities, ships, or private facilities.

The typical pressure used in HBOT ranges from 240–280 kPa, which corresponds to a depth of 14–18 metres of seawater (msw). The pressurising gas is typically air and the oxygen is normally distributed through a built-in breathing system (BIBS) or a hood. The inside attendants (IA) breathe the chamber air and therefore absorb nitrogen into their tissues in the same way as they would during a dive, but without any submersion, thermal or workload-related issues.^{2–4}

DECOMPRESSION PROTOCOLS: SWAF B6 AND USN TT6

In the Swedish Armed Forces (SwAF), decompression sickness is normally treated using Behandlingstabell 6 (B6), which closely resembles the U.S. Navy Treatment Table 6 (TT6).^{4,5} Both tables involve prolonged oxygen breathing during compression and during decompression, with specific oxygen-breathing periods prescribed for the IA to limit inert gas uptake. While effective, these oxygen periods are largely concentrated in the latter phase of the treatment, limiting the possibility for earlier emergency decompression should the need arise.

USN TT5 AND ALTERNATIVE PROTOCOLS

According to the U.S. Navy Diving Manual, if the patient achieves full recovery after 10 minutes at 280 kPa, it is acceptable to transition to the shorter Treatment Table 5

(TT5).⁴ This table has been evaluated with favourable results.^{6,7} Alternative protocols resembling TT5 have also been proposed for the treatment of DCS and have demonstrated promising outcomes.⁸ Alternative gases such as nitrox with fractions of oxygen (F_{O_2}) 50% and 60.5% have been suggested for the IA.^{9,10}

INSIDE ATTENDANT SAFETY IN EMERGENCY SCENARIOS

The maximum pressure of the TT6 and B6 tables is 280 kPa (2.8 bar, 18 msw equivalent), a pressure/depth at which the maximum allowable duration of air breathing before decompression stops would become mandatory varies between 50–60 minutes, depending on the decompression table used. For instance, the ‘no-decompression time’ for SWEN21-dive table at 18 msw is 59 minutes.¹¹ Emergencies requiring premature termination of HBOT may arise due to patient deterioration or external hazards, necessitating consideration of the IA’s decompression safety.

The safety for IA must always be remembered regardless of situation.¹² According to multiple studies, the risk of DCS for IAs during HBOT is considered low and acceptable, with a reported incidence below 1%.^{13,14} Severe cases of central nervous system (CNS) bends have nevertheless occurred, even when IAs are within limits of compartmental gas load.^{2,15,16} This highlights a critical limitation of ‘decompression models’ as they provide a structured and predictive framework, but cannot fully capture the complex physical, physiological and individual factors involved in DCS.

In most scenarios, chamber operators have limited support and flexibility apart from standard decompression tables, even though there are strategies described in US Navy diving manual such as “*Recompression treatment abort procedures*”, however the IA might be confined until the completion of the therapy session.⁴

Methods

The primary aim of this study was to evaluate the oxygen administration regimen for the IA and to assess the feasibility of facilitating emergency decompression over an extended portion of the HBOT session, focusing on the SwAF B6 recompression table.

The secondary aim was to compare the IA inert gas load across different HBOT protocols by introducing the Nitrogen Tension Index (NTI), a normalised measure of compartmental nitrogen tension relative to the maximum permissible tissue tension (MPTT).

We hypothesised that redistributing oxygen periods can reduce the proportion of the treatment during which the IA is unable to perform immediate emergency decompression. An analytical approach was chosen to calculate expected

tissue tension or compartmental gas load, according to the Thalmann decompression algorithm (EL-DCM Thalmann), and to compare these values to other standard exposures for IA’s that are described as safe or associated with a low risk of DCS.

SUGGESTED STRATEGY

The objective of the proposed new oxygen regimen is to start administering oxygen earlier in order to maintain the nitrogen load below the MPTT defined by SWEN21B parameters.¹¹ Breathing oxygen at greater pressures than 2.5 bar (equivalent to ~15 msw depth) carries a risk of CNS oxygen toxicity, including seizures. While the risk is generally low in resting individuals at 2.5 bar (~15 msw) in a hyperbaric chamber, and very unlikely at 1.9 bar (~9 msw), patients with severe Type II DCS or arterial gas embolism may be unusually sensitive and thus at higher risk.⁴ This must be considered when selecting an oxygen administration regimen.

INTRODUCING NITROGEN TENSION INDEX (NTI)

To enable standardised comparison of inert gas loading across tissue compartments and between profiles with differing dive characteristics, we introduce the Nitrogen Tension Index (NTI). This index expresses the current partial pressure of nitrogen (P_{tN_2}) in a given compartment as a normalised percentage of the chosen MPTT. Lower NTI values indicate a greater margin to the maximum permissible tissue tension (MPTT) and should therefore be interpreted as reflecting lower decompression risk for the inside attendant, whereas higher NTI values indicate reduced safety margins. NTI may assume negative values during hyperoxic exposure, when tissue nitrogen tension is reduced below surface equilibrium pressure.

This methodology follows Witucki et al, who employed a similar normalisation approach to evaluate nitrogen load as a fraction of allowable tissue tension limits in the US Navy no-stop diving tables.³ NTI is not intended as a dynamic model of decompression stress during descent or bottom time. It is designed as a surface-referenced metric, most relevant for assessing and comparing nitrogen load after surfacing.

The advantage of this method is that it facilitates comparison between compartments with different MPTT and enables inter-profile comparisons based on a surface-referenced nitrogen pressure ($P_{surf}N_2$), defined as the tissue nitrogen partial pressure corresponding to equilibrium with inspired air at the local surface ambient pressure.

CALCULATION OF NTI

NTI for each compartment is calculated using a piecewise formulation, depending on whether tissue nitrogen tension is above or below surface equilibrium.

For $PtN_2 \geq P_{surf}N_2$:

$$NTI_{pos} = \frac{PtN_2 - P_{surf}N_2}{MPTT - P_{surf}N_2} \quad (1)$$

For $PtN_2 < P_{surf}N_2$:

$$NTI_{neg} = \left(\frac{PtN_2}{P_{surf}N_2} - 1 \right) \quad (2)$$

This yields $NTI = 0\%$ when PtN_2 equals $P_{surf}N_2$. $NTI = 100\%$ when PtN_2 equals $MPTT$. $NTI < 0\%$ when PtN_2 is below $P_{surf}N_2$, indicating nitrogen elimination due to for example hyperoxic exposure. $NTI > 100\%$ represents overloading beyond safe decompression limits.

Both the US Navy and our implementation of the Thalmann algorithm involves a deliberate limitation as it does not account for inhaled F_{O_2} greater than 80%. As a result, when faced with F_{O_2} greater than 80%, the lowest possible value of NTI is -80% .^{11,17}

COMPARING NTI VALUES AND GAS LOADS ACROSS HBOT PROTOCOLS

To contextualise and compare the derived NTI values, established hyperbaric treatment tables were used as reference, with three HBOT protocols from the University of California San Diego (UCSD) and two from Haukeland, analysed using the Thalmann decompression algorithm.^{3,18} These protocols are used clinically and have demonstrated a low incidence of decompression sickness in IAs. The UCSD and Haukeland reference protocols involve chamber exposures of comparable depth but shorter overall duration than the SwAF B6, and include either no oxygen breathing for the inside attendant or only brief oxygen periods at pressure and/or during decompression.

DECOMPRESSION CEILING

For each time point during the HBOT, tissue nitrogen tension was evaluated across all compartments. The decompression ceiling was determined by identifying the compartment with the greatest exceedance of its maximum permissible tissue tension ($MPTT$) at surface pressure, expressed as $PtN_2 - MPTT$. This compartment represents the leading tissue with respect to ascent limitation at that time point. The red field shown in Figures 1–4 therefore represents the decompression ceiling imposed by the compartment that most restricts ascent, and may shift between compartments over the course of the exposure.

ANALYSIS

Oxygen administration strategies for the inside attendant were evaluated using iterative computer-based simulations of inert gas uptake and elimination. All simulations were

performed under the following desired boundary conditions: (i) no alteration of the treatment table pressure–time profile; (ii) no oxygen administration deeper than 2.5 bar (15 msw); (iii) oxygen administration between 1.9–2.5 bar (9–15 msw) permitted only during ascent; (iv) oxygen administration initiated as early as possible; (v) suppression of nitrogen load during the decompression phase; and (vi) equal or fewer oxygen periods compared with the original schedule, while maintaining synchronisation with the patient's oxygen administration and air breaks. Compartment-level nitrogen tissue tensions relative to the $MPTT$ were calculated for each strategy. The analysis focused on the leading tissue, defined as the compartment with the smallest remaining margin to its $MPTT$, and only the optimal oxygen strategy for each case is presented in the results.

Results

In Figures 1–4, the red field represents the decompression ceiling for the leading tissue and is used as indicator of nitrogen load suppression. When present, ascent must not pass the pressure indicated by this ceiling. If a ceiling is absent, a direct ascent to the surface is permissible. Oxygen distribution protocol is shown as a dashed line, and each period is 20 minutes long followed by a 5-minute air-break. No oxygen administration for the IA is performed at greater pressure than 2.5 bar (15 msw).

The oxygen distribution for our proposed regimen can clearly be seen to suppress the nitrogen gas load for leading compartments indicated by a reduction of the red area in those alternatives.

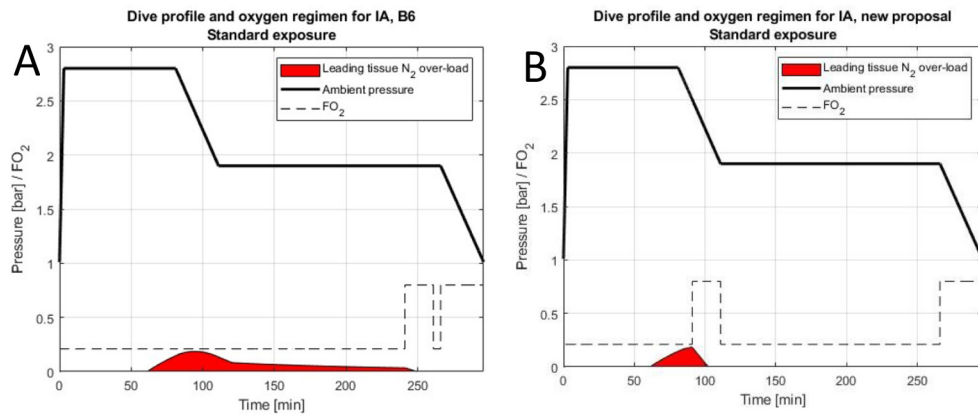
Figure 5 shows the NTI for the IA at surfacing for the TT6 compared to our proposed regimen. Each of the nine compartments are presented along the x-axis and NTI on the y-axis. For reference, 'UCSD 1', 'Haukeland new', and a simulated direct decompression from 2.8 bar (18 msw) after 59 minutes are included as standard protocol comparisons.

In Figure 5 it is apparent that the half-time (HT) 40 min compartment is the leading tissue for the 2.8 bar (18 msw) / 59 min profile as it has reached its $MPTT$ revealing an NTI of 100%. It can also be observed that the NTI when decompressing is higher in the slower compartments with half-time $HT \geq 120$ min for TT6 and our proposal compared to 'UCSD 1', 'Haukeland new' and 18 msw / 59 min.

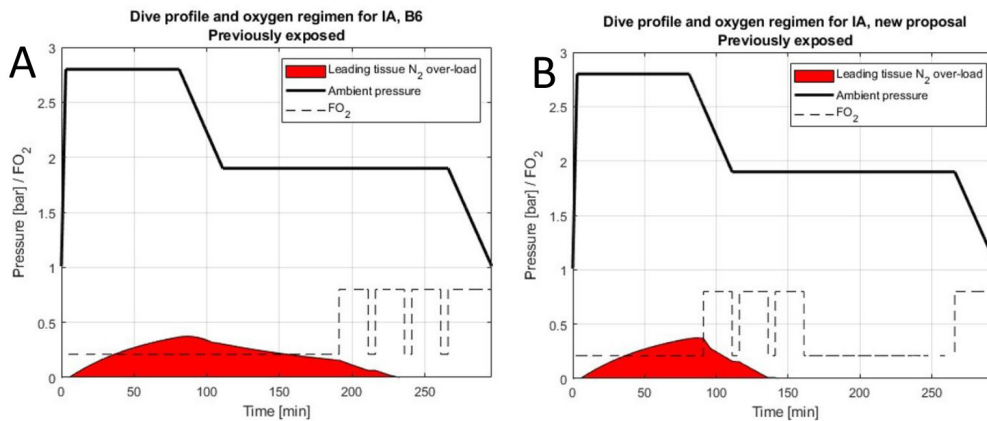
While NTI is typically interpreted based on the maximum value per compartment, the average NTI for all compartments at completion of decompression is presented in Figure 6 as a descriptive metric to illustrate overall nitrogen load. This is not intended as a decision metric in a deterministic model, but rather as a comparative tool to highlight differences in decompression stress distribution among treatment strategies.

Figure 1

The decompression ceiling defined by the leading tissue compartment is shown in red for the original B6 (A), compared with the proposed oxygen regimen for the inside attendant (IA) (B)

**Figure 2**

The decompression ceiling defined by the leading tissue compartment is shown in red for the original B6 (A) and the proposed oxygen regimen for the inside attendant (IA) (B), following a previous exposure of 18 msw for 59 minutes

**Figure 3**

The red field represents the decompression ceiling imposed by the leading tissue compartment for the original extended B6 (A) and the proposed oxygen regimen for the inside attendant (IA) (B). This scenario requires additional oxygen periods

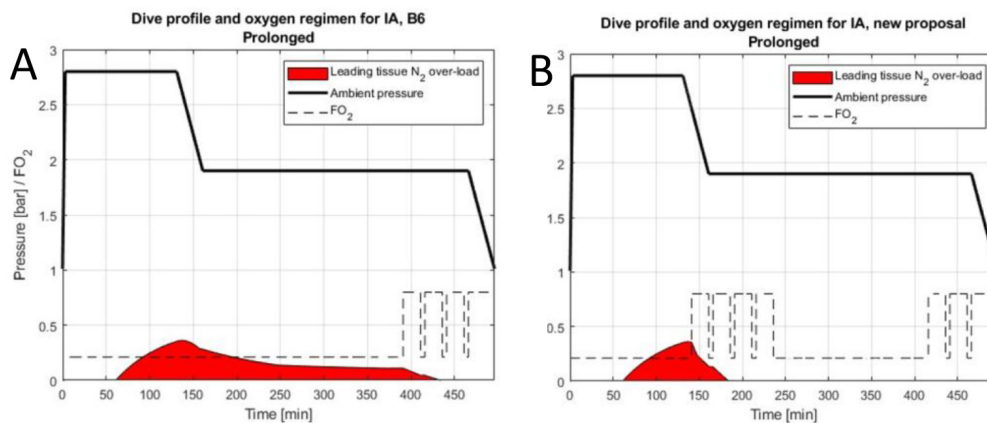
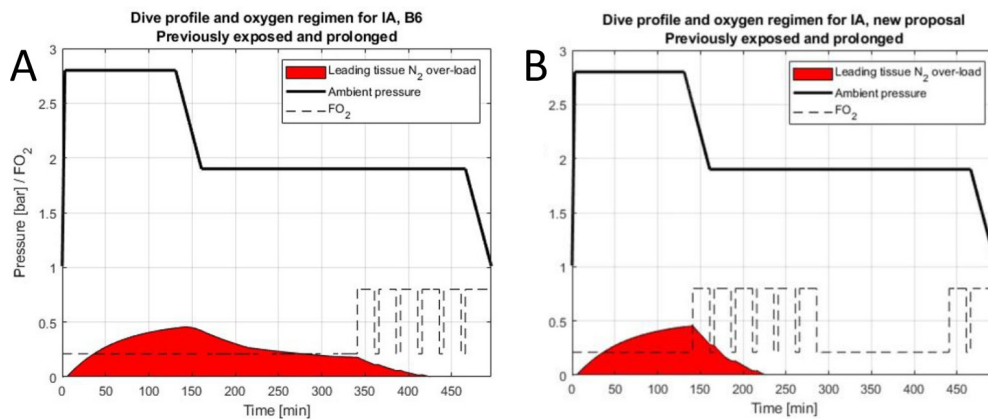


Figure 4

The red field represents the decompression ceiling imposed by the leading tissue compartment for the original extended B6 (A) and the proposed oxygen regimen for the inside attendant (IA) (B), following a previous exposure of 18 msw for 59 minutes. This scenario requires additional oxygen periods

**Figure 5**

A comparison of different treatment tables and dive profiles with correlating Nitrogen Tension Index NTI when surfacing/completion of decompression for each of the nine compartments presented as half-time between 5 and 240 min. Panel 1 includes the B6 and our proposal, 'UCSD 1', 'Haukeland new' and the direct ascent dive profile 18 msw 59 min. Panel 2–4 includes a comparison for the cases where previously exposed IA and extended treatment tables are present

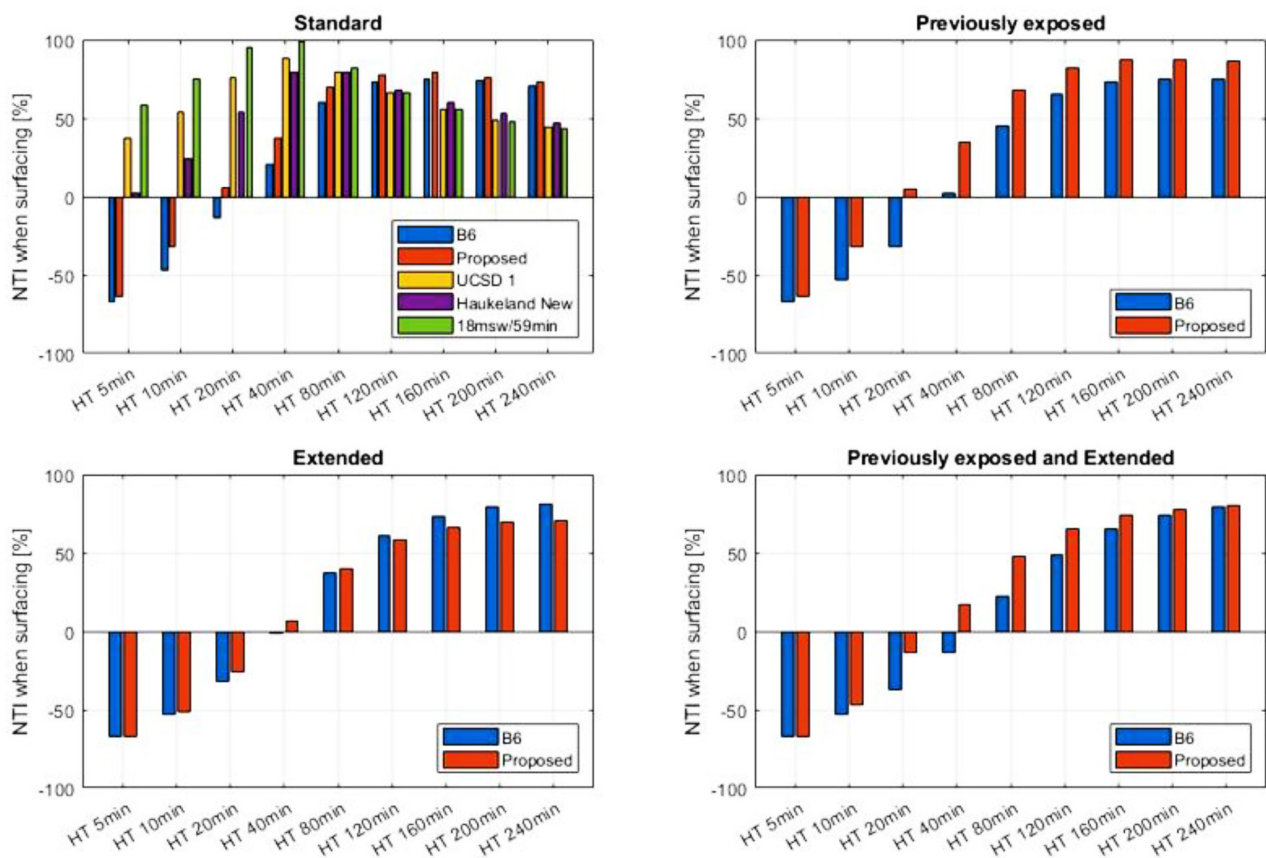
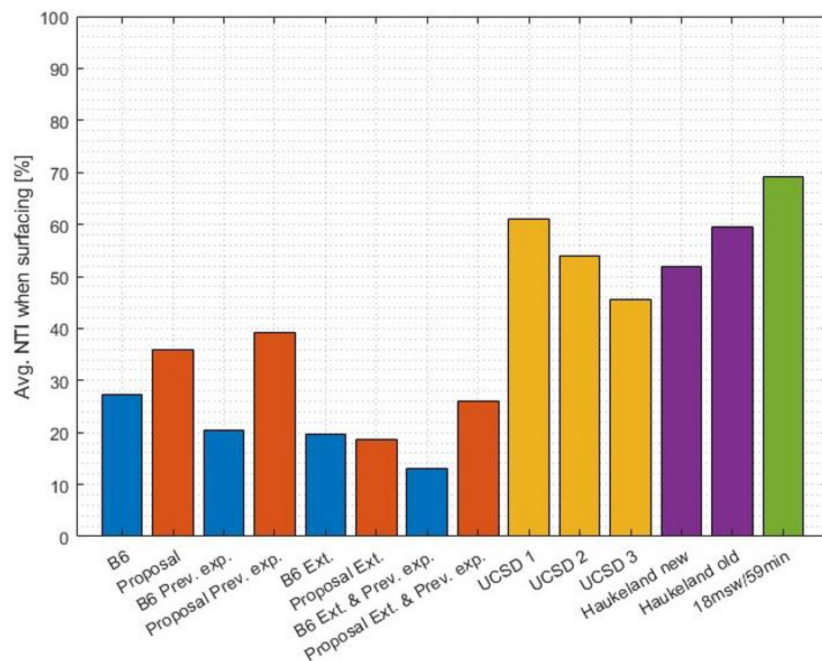


Figure 6

The average nitrogen tissue index (NTI) when surfacing in comparison of the analysed HBOT regimens and an 18 msw / 59 min dive profile



Our analysis indicates that the average NTI at completion of decompression is lower with our proposed regimen compared to the UCSD case, the Haukeland profile, and the 2.8 bar (18 msw) / 59 min dive profile. However, it remains higher or similar than that of the original B6, whether extended or not, and regardless of prior exposure.

Discussion

This study proposes a modification to the current SwAF Treatment Table B6 protocol for the IA. In the revised protocol, oxygen breathing is initiated earlier during the decompression from 2.5 to 1.9 bar (15 to 9 msw). This contrasts with the original B6, where the IA begins oxygen breathing only during the final part at 1.9 bar (9 msw). The goal of this modification is to reduce the IA decompression obligation early during the treatment table, thereby increasing operational flexibility and enabling safe emergency decompression if required.

In high-risk situations or environments such as on a warship in a conflict zone, or any situation where the treatment may need to be abruptly terminated, it can be more appropriate to adopt this alternative oxygen regimen for the attendant during HBOT. Moreover, in the event of an unexpected deterioration in the patient's condition, it may be imperative to promptly evacuate them from the chamber while avoiding DCS in the attendant. This may also be an important property if chamber is small and transportable.

While this alternative oxygen regimen reduces the amount of time the chamber attendant must undergo a decompression

stop, it is important to consider some potential criticisms. Firstly, instances of emergencies during this type of treatment are rare. Secondly, the attendant could instead undergo recompression using a surface decompression strategy if considered necessary. Thirdly, the increased partial pressure of oxygen (PO_2) during the initial oxygen period (2.5 to 1.9 bar [15 msw to 9 msw] decompression) could pose a risk for oxygen convulsions. Fourthly, the attendant must sometimes assist the patient and equipment during decompression, potentially compromising their ability to administer oxygen to themselves. Fifthly, the oxygen regimen for the chamber attendant outlined in TT6 has been widely recognised as effective in reducing DCS. Lastly, an alternative solution to achieve the desired ability to decompress the IA at any time, could be to have several IAs alternating prior to their no-decompression time expiring.

To address the potential drawbacks previously described, we recommend separating a traditional hospital setting from a military environment where this new oxygen regimen may be more appropriate. In an emergency there may not be access to a pressure chamber for surface decompression for the IA. It is uncommon for convulsions to occur in a dry hyperbaric environment with pure oxygen breathing at pressures less than 2.5 bar (~15 msw), especially if there has been no prior oxygen exposure or if the workload is low.⁴ Any concern for oxygen convulsions during decompression between 2.5 to 1.9 bar (15 to 9 msw) can be mitigated by allowing the IA to hold the oxygen mask rather than having it securely fastened, as this will avoid continued breathing from the mask if unexpected convulsions occur. This certain period still poses a low risk, as the time and decompression are

favorable to avoid convulsions and, referring to experiences from UCSD and Haukeland, no cases of oxygen convulsions have been reported during > 20,000 of treatments with up to 30 minutes of oxygen exposure at a pressure of 2.4 bar (14 msw).^{2,3} During decompression, there may be multiple tasks to attend to, which is similar to the situation during decompression from 1.9 bar (9 msw) to the surface. According to the decompression algorithm used, there are similarly low NTI with this oxygen decompression regimen compared to the TT6 regimen. Lastly, it may not always be possible to have multiple available and unexposed IAs.

When deciding the best treatment option for the patient, it is relevant to highlight the advantages of shorter treatment tables, such as the USN Treatment Table 5 or the Fremantle Hospital Hyperbaric Medicine Unit FH01. They have demonstrated equal or better resolution than the longer TT6 for a range of conditions, including mild neurological symptoms, pain, lymphatic/skin and constitutional/non-specific symptoms which often resolved within 10 minutes at treatment pressure.⁶⁻⁸ By using a shorter treatment table it may lower the threshold for initiating HBOT, especially in the case where only a smaller (transportable) hyperbaric chamber is available. For these treatments it is also possible to decompress the IA at any time avoiding DCS, according to our mathematical analysis.

Among the few reported cases of central nervous system decompression sickness in IA referenced in this study, one case occurred in the absence of a patent foramen ovale (PFO), one was associated with a large PFO, and in one case PFO status was not reported.^{2,15,16} As PFO is a recognised risk factor for decompression sickness, particularly for neurological manifestations, this variability may contribute to outcome heterogeneity in reported cases.^{19,20} However, this does not alter the compartmental gas-load analysis presented herein. Furthermore, hyperbaric chamber operation at altitude has not been shown to increase decompression risk for IAs.²¹

Conclusions

Our main finding is that an alternative oxygen regimen for the IA, compared to the Swedish Armed Forces Treatment Table 6 (B6) with extensions and previous exposure, is feasible and allows for the option of emergency decompression over a longer period. For example, the total time fraction of the IA's decompression obligation decreased from 75% with the original B6 to just 17% with our newly proposed protocol. This analysis is based on the compartmental gas load according to the exponential-linear Thalmann algorithm with SWEN21B parameters. We also found that the average Nitrogen Tension Index (NTI) on completion of decompression is slightly higher or similar for our protocol compared to the standard B6, however lower compared to other uneventful HBOT regimens and the diving profile

18 msw/59 min. The slower compartment's half-time ≥ 120 min has a higher NTI when surfacing for B6 and our proposal compared to reference dive profile and HBOTs.

Our proposed oxygen regimen for IA is believed to be particularly beneficial for handling unforeseen situations such as emergency decompressions. The traditional oxygen regimen, however, has been extensively verified and does not pose any increased risk of oxygen convulsions due to high partial pressures of oxygen or substantial risk for decompression sickness. After human evaluations it can be warranted to switch to this new protocol as the standard method for the distribution of IA oxygen breathing time.

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