Decompression procedures for transfer under pressure ('TUP') diving

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Abstract

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Background: There is an increasing interest in 'transfer under pressure' (TUP) decompression in commercial diving, bridging traditional surface-oriented diving and saturation diving. In TUP diving the diver is surfaced in a closed bell and transferred isobarically to a pressure chamber for final decompression to surface pressure.

Methods: Tables for air diving and air and oxygen decompression have been compared for total decompression time (TDT), oxygen breathing time as well as high and low gradient factors (GF high and low). These have been considered surrogate outcome measures of estimated decompression sickness probability (P_{DCS}).

Results: Six decompression tables from DadCoDat (DCD, The Netherlands), Defence and Civil Institute of Environmental Medicine (DCIEM, Canada), Comex MT92 tables (France) and the United States Navy (USN) have been compared. In general, USN and DCD procedures advised longer TDT and oxygen breathing time and had a lower GF high compared to MT92 and DCIEM tables. GF low was significantly higher in USN procedures compared to DCD and one of the MT92 tables due to a shallower first stop in many USN profiles compared to the two others. Allowance and restrictions for repetitive diving varied extensively between the six procedures. While USN procedures have been risk-assessed by probabilistic models, no detailed documentation is available for any of the tables regarding validation in experimental and operational diving.

Conclusions: Absence of experimental testing of the candidate tables precludes firm conclusions regarding differences in P_{DCS}. All candidate tables are recognised internationally as well as within their national jurisdictions, and final decisions on procedure preference may depend on factors other than estimated P_{DCS}. USN and DCD procedures would be expected to have lower P_{DCS} than MT92 and DCIEM procedures, but the magnitude of these differences is not known.

Introduction

Commercial diving is conventionally described as either surface-oriented or saturation. Most diving is surface-oriented: the diver enters and exits the water from a diving platform at surface. The diving depth is typically restricted to 50 metres of seawater (msw), and bottom time is usually restricted to a few hours to avoid excessive decompression time in the water. Surface decompression with oxygen ($SurDO_2$) may extend the bottom time somewhat for surface-oriented diving, but this diving method has faced criticism for a high incidence of decompression sickness (DCS).[1] Surface-oriented diving requires limited resources with respect to manning, training, equipment and breathing gas. For deeper work, saturation diving is used. The saturation diver will stay in a pressure chamber for many days or weeks, pressurised to the approximate ambient pressure at the diving work site. The diver will be transferred from the saturation chamber complex to the worksite by means of a closed diving bell and will typically be 'locked out' for 4–6 h per day. One important benefit of saturation diving is the amount of immersed working time, the drawback is the high cost of equipment and support organisation as well as a prolonged decompression time at the end of the saturation period. Decompression rate for saturation diving is typically in the range of 15–25 $msw \cdot d^{-1}$.

Closed bell no-saturation diving is commonly associated with the term 'bounce diving'. While bounce diving is not clearly defined, it has a historical origin with the 'mini bell' system used in North Sea petroleum related diving in the 1980s.[2] The bottom time for deep bounce dives was limited and the diving procedures were optimised to exploit most of it as in-water diving time. This was achieved by rapid compression with the divers in the closed bell. Decompression was commonly done by a sequence of gas shifts and the final part of the decompression in a deck decompression chamber. The method has later generally been considered unsafe and Hamilton and Thalmann wrote "*DCS incidence has not been reported formally, but it was probably in the range of 10–20% for the more stressful dives*".[3] This quote was stated at a meeting in 1976.[4] Imbert has reported the experience from Comex Services Company with heliox tables.[5] These tables, designed for diving down to 120 msw with bottom times up to 120 min achieved a 3.8% DCS incidence. The divers were decompressed in a closed bell breathing compressed air followed by oxygen. These historical ‘bounce’ decompression procedures were proprietary commercial products and have not been available to us.

Modern no-saturation closed bell diving is commonly termed ‘transfer under pressure’ (TUP) diving. Such diving is usually based on air as the breathing gas in the bottom phase and air or oxygen as the decompression breathing gas. Oxygen breathing during decompression increases the efficiency of the decompression and permits longer bottom times compared to conventional in-water air decompression. Depth is typically limited to 50 msw. Previous bounce decompression procedures as well as modern TUP procedures are based on isobaric transfer from the diving bell to the deck decompression chamber. Beyond this fact the differences are too extensive to allow a meaningful comparison.

To reduce the probability of DCS, the United Kingdom Health and Safety Executive (HSE)[6] has enforced bottom time limitations for surface-oriented diving. Similar restrictions apply in Norwegian waters.[7] These bottom time restrictions are relaxed for TUP decompression compared to in-water and surface decompression. This relaxation is motivated by the observed lower DCS incidence in TUP diving compared to conventional in-water and surface decompression methods.[1] A comparison of allowed[6,7] bottom times for a selected number of table depths is presented in Table 1.

To the best of our knowledge, there has only been a small number of TUP diving systems produced in recent years and TUP diving is not widely used in North Sea petroleum-related diving. However, the interest in TUP diving has been increasing as the diving method may be a cost-effective underwater intervention method bridging conventional surface-oriented diving and saturation diving. In 2019 the Norwegian Oil and Gas Association (NOROG, presently Offshore Norway) approached the editorial team of the Norwegian Diving and Treatment Tables (NDTT)[8] requesting a review of available TUP decompression tables. The editorial team produced an internal report in Norwegian language and presented the conclusions at the Bergen International Diving Seminar the same year. The report has not been published in the open domain. The current manuscript is an extended and restructured version of the original Norwegian report.

The objective of the present study is to review available decompression procedures applicable to TUP diving. Such diving has not been unequivocally defined. We will use the term for diving with a closed bell. After diving is finished, the divers will revert to the bell and be transferred isobarically to a deck decompression chamber without interventing decompression to surface pressure. Decompression after compressed air work shares some commonalities with TUP after immersed diving but falls beyond the scope of this work. For this work, we have limited our search of candidate procedures to those using air or nitrogen-oxygen (nitrox) as the breathing gas during the bottom phase and air, nitrox or oxygen as the breathing gas during decompression. We have not reviewed procedures for air or nitrox saturation diving.

Table 1

Schedules selected from transfer under pressure (TUP) candidate tables for comparison. Three to six bottom times (BT1–BT6) have been selected for each of the six chosen table depths. Schedules were selected to match United Kingdom Health and Safety Executive and Norsok-allowed[6,7] maximum bottom time for a non-TUP dive (BT lim. non-TUP), the longest allowed bottom time for a TUP-dive (BT lim. TUP) and an intermediate bottom time. Schedules printed in all tables are identified by bold typeface. Some tables lack schedules for the preferred bottom times, these have been identified with superscripts as follows: [1]DCD dry or wet bell, [2]DCD TUP, [3]MT92 12 msw O_2, [4]MT92 6 msw O_2, [5]DCIEM. Maximum bottom times for a direct ascent dive (No decompression [NoD] time) according to the US Navy Diving Manual Rev 7[9] are shown for comparison

Table depth (msw)	NoD time (min)	BT lim. Non-TUP (min)	BT lim. TUP (min)	BT 1 (min)	BT 2 (min)	BT 3 (min)	BT 4 (min)	BT 5 (min)	BT 6 (min)
15	92	180	240	180[1]	210[2,5]	**240**			
18	63	120	180	**120**	**140**	**180**			
24	39	70	180	70[2]	**80**	**100**	**140**	160[3,4]	180[1,5]
30	25	50	110	50[2]	**60**	80[2]	**90**	110[2]	
36	15	35	85	30[3]	40[2]	**60**	80[2]	**90**	
42	10	30	65	**30**	40[2]	**60**			

Methods

The study was initiated with a literature review. Searches were designed to identify TUP decompression procedures. Pubmed (https://www.ncbi.nlm.nih.gov/pubmed/) was searched with search terms *TUP* AND *diving* OR *Transfer under pressure*. The Rubicon Research Repository (http://archive.rubicon-foundation.org/xmlui/) was searched (last time 29.10.2019 due to the site subsequently closing) using the indexed term *Transfer under pressure*. Additionally, a Google (https://www.google.com) internet search on combinations of «TUP» «Decompression table» and «Decompression tables» was undertaken.

Independent of these searches the authors have reviewed diving procedures published by the United States (US) Navy,[9] Defence and Civil Institute of Environmental Medicine (DCIEM, Canada),[10] Comex MT92 table (France),[11] DadCoDat (DCD, the Netherlands),[12] National Oceanographic and Atmospheric Administration (NOAA, USA),[13] Norwegian Diving and Treatment Tables[8] and the Royal Navy (United Kingdom)[14] for their applicability for TUP diving. These procedures hold a number of decompression tables applicable for various diving procedures, e.g., air in-water decompression, air and oxygen in-water decompression, and SurDO$_2$. The combination of a specific table depth and bottom time will be termed *schedule*. We will use the term *profile* and *decompression profile* for the staged decompression stops and switches of breathing gas for a given schedule.

Three major diving contractors, operating in the North Sea, were contacted requesting access to decompression tables applicable for TUP diving.

To be considered for detailed review, the procedures should be publicly available, they should be based on compressed air or nitrox as the bottom gas and air, nitrox or oxygen as the breathing gas during decompression. The reason for not including other mixed gases (e.g., helium-oxygen or helium-oxygen-nitrogen) is the assumed limited relevance of these gases in commercial surface-oriented diving to depths not exceeding 50 msw. One of the tables – the DCD TUP tables – did not meet one of these criteria since these tables are commercial products not published in the open domain. This table was nevertheless included in the study for reasons described in the results and discussion sections.

We have included all publicly available decompression procedures intended for use with air or nitrox as the bottom gas and air or nitrox and oxygen as the decompression breathing gas. We expected this search strategy to include procedures developed for in-water decompression as well as closed bell decompression. The consequences of including in-water decompression procedures for TUP diving will be discussed later.

We have reviewed several parameters for each decompression table and summarised the findings in Table 2. A comparison of DCS probability has been assessed based on total decompression time (TDT) and oxygen breathing time. Increasing TDT and oxygen breathing time is expected to reduce the probability of DCS[15] though this reduction cannot be quantified. The distribution of decompression stops will likely influence this probability. Previous studies have reported increased DCS incidence and venous gas embolism when deep decompression stops were introduced.[16,17] However, we have no means of quantifying the effect of changing either TDT, oxygen breathing time or the distribution of decompression stops on DCS probability. Concerning comparison of TDT and oxygen breathing time, a comparison of all depth and bottom time combinations would be ideal. We found this to be too exhaustive and we have therefore compared a limited set of schedules (Table 1). We have chosen the table depths 15, 18, 24, 30, 36 and 42 msw. These table depths were selected due to their operational relevance. These table depths would allow the longest extension of bottom time using TUP compared to conventional surface-oriented diving according to UK and Norwegian regulations.[6,7] Whenever possible we have tried to review schedules for the longest allowed[6,7] bottom time for dives with TUP decompression, the longest allowed bottom time for decompression without TUP and a third bottom time midway between these two limits. The stipulated bottom time limitations as well as the schedules selected for comparison are presented in Table 1. Some of the published decompression tables did not provide schedules for each of the three preferred bottom times for every table depth. In these cases, we have chosen to analyse a schedule for a bottom time as close as possible to the preferred shared by all or a majority of the tables. A total of twenty-five schedules have been reviewed. Thirteen of these schedules were available for comparison across all tables.

We have retrieved TDT for each schedule as they were printed in the original decompression tables. It is common operational practice to breathe compressed air for 5 min after every 20–30 min of hyperbaric oxygen breathing to reduce likelihood of pulmonary and central nervous system (CNS) oxygen toxicity. DCD procedures include these 'air breaks' in the listed TDT in contrast to the other procedures. A 5 min air break after 30 min of oxygen breathing is mandated by USN and is recommended by the DCIEM procedures. MT92 doesn't provide information on air breaks. To facilitate comparison, we have included a 5 min air break for every 20 min of oxygen breathing when calculating TDT, independent of the advice given by the publisher.

We have calculated gradient factors[18] (GF) for the controlling compartment at the deepest stop (GF low) as well as GF at the time of surfacing (GF high) using the software Deco Planner version 4.5.1 (Global Underwater Explorers, High Springs, FL) configured with a descent and ascent rate of 10 msw·min^{-1}. Ascent rate and descent rate varies between

Table 2

Comparison of six TUP decompression table candidates published in four diving procedures; further details are presented in Appendix 1; DCD – DadCoDat; DCS – decompression sickness; msw – metres of seawater; NEDU – Navy Experimental Diving Unit; SurDO$_2$ – surface decompression with oxygen; TUP – transfer under pressure; USN – United Sates Navy; VGE – venous gas emboli

Feature	**DCIEM**	**MT92 12 msw MT92 6 msw**	**DCD dry or wet bell DCD TUP**	**USN**
Latest revision	2009	2012	2014 and 2015	2018
Algorithm/ parameter set	Kidd & Stubbs Serial perfusion	Haldanian	Haldanian	Thalmann E-L VVAL79
Algorithm/ parameter set published in public	No/No	Yes/No	No/No	Yes/Yes
Validation method	Experimental	Field experience	Field experience	Experimental/ probabilistic
Validation criteria	DCS and VGE	DCS	DCS	DCS
DCS estimate available for TUP candidate profiles	No	No	No	Yes
Publisher	Defence R&D Canada	French government	DadCoDat	USN (NEDU)
Deepest decompression stop breathing oxygen (msw)	9	12 (MT92 12 msw) and 6 (MT92 6 msw)	15 (TUP) and 9 (wet and dry bell)	9
Shallowest decompression stop (msw)	9	6	3	6
Air break	Recommended	Not stipulated	Mandatory	Mandatory
Compatibility with air tables	Yes	Yes	Yes	Yes
Compatibility with SurDO$_2$ tables	Yes	???	Yes	Yes

the tables, but changing these to 18 msw·min^{-1} will affect GFs by 2% or less which we consider of no practical consequence. The oxygen fraction (FO$_2$) in air was rounded to 21%. Breathing gas inspired O$_2$ fraction (F$_i$O$_2$) of the built-in breathing system (BIBS) was set to 85% as will be discussed later. The decompression model was ZH-L16B.[19]

We have presented the difference in TDT and O$_2$ breathing time by modified Bland-Altman plots and sorted them according to expected exposure severity. We have considered two different parameters describing decompression stress. First, the 'PrT' index (PrT = pressure x square root of time). PrT has been shown in epidemiological surveys[1] as well as statistical probabilistic models[20] to be positively associated with DCS. We have calculated PrT using Bar as the pressure unit (1 Bar = 10 msw) and minutes as the time unit. The second measure of decompression stress would be to use the estimated DCS probability (P$_{DCS}$) calculated by a probabilistic model. The P$_{DCS}$ for schedules based on the USN decompression tables (P$_{DCS\text{-}USN}$) has been retrieved from Appendix E in Navy Experimental Diving Unit (NEDU) report 12-01.[20] We have used P$_{DCS\text{-}USN}$ as listed for 'VVAL-79 air/in-water O$_2$, 20 feet of seawater (fsw) last allowed stop' calculated by the NMRI98 probabilistic model.[15] The NMRI98 model estimates P$_{DCS}$ at any time during or after decompression as a function of supersaturation in three compartments. Probability of DCS is calculated by the integration of this function. The NMRI98 model presumes exponential gas uptake and linear gas elimination, modified by the extent of hyperoxia in the breathing gas. The arguments to use P$_{DCS\text{-}USN}$ as the decompression severity index are further described in Results and Discussion.

We have presented table depths in units of msw although the SI unit Pa would be scientifically correct for a description of ambient pressure. However, most of the published decompression tables use msw as the depth and pressure unit, and comparisons and practical application of this work are facilitated by using the msw unit. The USN Diving Manual (USNDM)[9] has published depth in fsw. We have deliberately rounded 10 fsw = 3 msw to facilitate the comparison of similar table depths. This conversion implies a 2% rounding error since 10 fsw = 3.06 msw[9] and will overestimate the deepest schedule reviewed in this work (140 fsw/42 msw) by

0.3 msw. We consider this rounding error to be substantially less than the accuracy of the DCS estimate[20] of the USNDM and of no practical implication for the interpretation of the data. Metric conversion of USNDM table depths (10 fsw = 3 msw) will tend to give a lower P_{DCS} for USN schedules than stipulated.[20]

STATISTICAL ANALYSES

All six tables were compared pairwise, i.e., for any outcome variable there would be fifteen pairwise comparisons. First, differences in TDT, oxygen breathing time, GF low and GF high were analysed for normality with the Shapiro-Wilk test. If any of the pairwise comparisons didn't meet the requirement for normality distribution all comparisons for that test would be presented with median and interquartile range. Pairwise differences in TDT, oxygen breathing time, GF low and GF high have been statistically analysed with the Wilcoxon signed rank test. The association between $P_{DCS\text{-}USN}$ and the pairwise differences was measured with Pearson's correlation coefficient. As mentioned earlier not all tables have published all the schedules listed in Table 1. The number of comparisons for each of the twenty-five schedules thus range from 15–24. To compensate for familywise alpha inflation and Type I errors, α for each of these fifteen multiple comparison tests has been adjusted according to the Šidák correction. Statistical analysis was completed using Wizard for Mac Version 1.9.4 (www.wizardmac.com). $P < 0.05$ has been considered statistically significant.

Results

SEARCH FOR TUP CANDIDATE TABLES

Among the reviewed public decompression procedures (see Methods) we identified five tables applicable to TUP-Diving: the DCD 'BOX15';[12] DCIEM 'Table 2';[10] MT92 'Table 4';[11] MT92 'Table 5';[11] and the US Navy 'Air/O_2' table.[9] The most authoritative textbook in diving medicine[21] has no reference to TUP-procedures. The PubMed search gave no results. The Rubicon Research Repository search gave one result referring to a presentation by the UK Chief Inspector of Diving relating to North Sea offshore diving in 1979. The presentation discusses how the diving bell should be secured to the deck decompression chamber, but decompression tables were not discussed. The Google search gave references to Wikipedia, International Marine Contractors Association, N-Sea (a Dutch diving contractor), NDTT[8] and others who discuss TUP decompression, but without references to specific decompression tables. Due to the extensive internet references to N-Sea as well as a presentation of their TUP operations at the Bergen International Diving Seminar 2019 the company was approached to learn the details of the decompression tables. We were informed that N-Sea used proprietary tables developed by Prof. Wouter Sterk (Rob Borgonjen, personal communication 2019). Prof. Sterk was contacted in October 2022 requesting permission to review and analyse the decompression procedure for immersed diving with closed bell decompression breathing compressed air in the bottom phase and oxygen and compressed air in decompression. A set of tables designated 'AoxTUP2B' version October 2014 was submitted to the authors under a non-disclosure agreement. The publisher of the tables allowed the authors unrestricted access to read, review and analyse the tables. However, the specific details of individual profiles could not be shared with others. The AoxTUP2B tables are termed 'DCD TUP' in the present work and this is the sixth table included for analyses. Two other major diving contractors operating in the North Sea, Subsea 7 and Technip FMC, were contacted and submitted their decompression tables. Technip FMC had developed TUP procedures using the MT92 Table 5 (without air breaks). Subsea 7 had not developed specific TUP procedures but provided two sets of tables intended for in-water decompression breathing oxygen at 12 or 6 msw. These tables listed decompression schedules identical to or within 2 min of the MT92 Table 4 and Table 5. The decompression procedures from these companies have not been reviewed in further detail since they for all practical purposes are identical to the MT92 tables.

REVIEW OF PUBLISHED DECOMPRESSION TABLES

Details of the individual tables are presented in Appendix 1.We have summarised some of the main characteristics in Table 2. A typical arrangement for a TUP dive would be for the diver to enter the diving bell at the surface, lock the hatch and remain at surface pressure while the bell is lowered to working depth. The bell atmosphere will be compressed to ambient water pressure. United States Navy and DCIEM recommend a maximum descent (compression) rate of 23 and 18 $msw{\cdot}min^{-1}$ respectively, while DCD and MT92 don't provide advice on descent rate. The diver will be locked out of the bell once chamber and ambient pressure is equalised and return to the bell after finishing bottom time. Surfacing takes place with the hatch closed. Decompression may take place in the bell, in a deck (surface) decompression chamber or in a combination. The diver will typically breathe air or nitrox during the bottom phase and the first part of the decompression. At 12, 9 or 6 msw the breathing gas will be changed to oxygen through a built in breathing system (BIBS) with short periodic interruptions for breathing air (air breaks) to reduce the toxic effects of high pO_2. A typical profile is presented in Figure 1.

ASSESSMENT OF EXPOSURE SEVERITY

Probabilistic modelling[20] as well as operational experience[1] suggest that there is a positive association between diving exposure severity, expressed as PrT, and the outcome, expressed as P_{DCS}. However, P_{DCS} will depend on the decompression profile for any schedule. Increasing

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Footnote: * Appendix 1 is available on DHM Journal's website: https://www.dhmjournal.com/index.php/journals?id=318

Figure 1

Typical dive profile for a TUP dive to 24 msw for 180 min. The diver breathes air (black line) during the bottom phase and oxygen (red line) at 9 msw and shallower. Oxygen breathing is interrupted for 5 min every 30 min (arrows) when the diver breathes compressed air ('air break'). The diver will be compressed and decompressed in the diving bell and a deck decompression chamber (broken line). This profile corresponds to the USN Diving Manual[9] 80 fsw/180 min in-water oxygen decompression procedure. Comparison of tables in the present work is based on a standardised 5 min air break for every 20 min of oxygen breathing

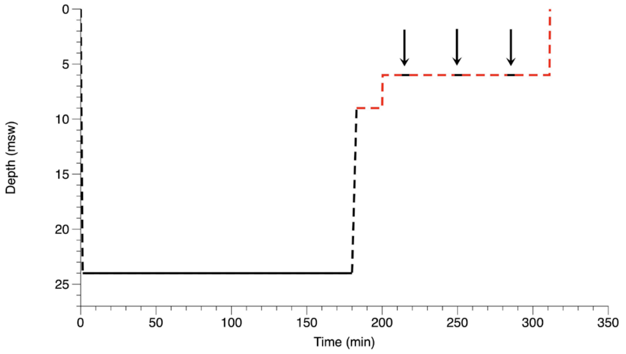


Figure 3

Differences in total decompression time (TDT) for twenty-five different schedules from six different decompression tables presented in a modified Bland-Altman plot. Each symbol represents a schedule with a specified table depth-bottom time combination (see Table 1). The difference between the stipulated TDT for a specific table and the mean TDT for all tables is plotted on the Y-axis. The schedules are sorted (X-axis) according to the expected DCS incidence for the USN schedule[20] ($P_{DCS\text{-}USN}$). Be aware that P_{DCS} will be different for the other tables. Some tables are missing certain schedules. DCD – DadCoDat; DCIEM – Defence and Civil Institute of Environmental Medicine; TUP – transfer under pressure; USN – United States Navy

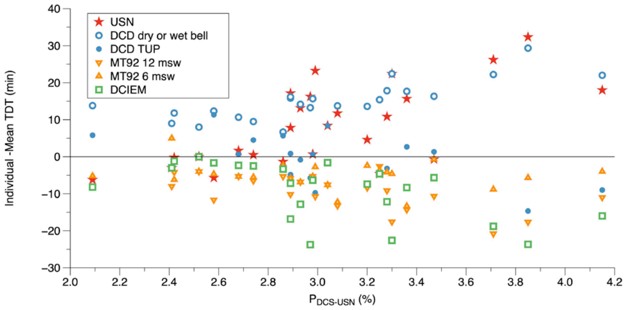


Figure 2

Relationship between PrT (see text) and estimated probability of DCS ($P_{DCS\text{-}USN}$) according to the USN NMRI98 probabilistic model[20] for twenty-five US Navy Diving Manual air/in-water O_2 -schedules[9] compared in the present work (Table 1). Health and Safety Executive[6] and Norsok[7] regulations restrict bottom times for TUP diving to an upper PrT threshold of 42 (vertical broken line)

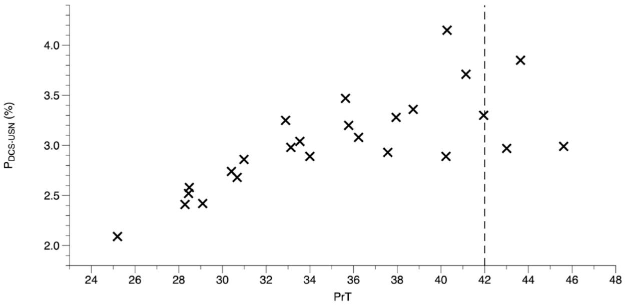
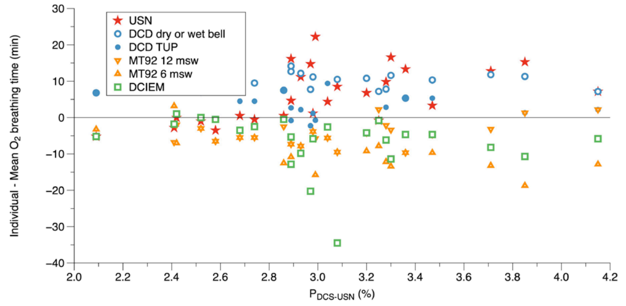


Figure 4

Differences in decompression oxygen breathing time (O_2 breathing time) for twenty-five different schedules from six different decompression tables presented in a modified Bland-Altman plot. Each symbol represents a schedule with a specified table depth-bottom time combination (see Table 1). The difference between the stipulated oxygen breathing time for a specific table and the mean oxygen breathing time for all tables is plotted on the Y-axis. The schedules are sorted (X-axis) according to the expected DCS incidence for the USN schedule[20] ($P_{DCS\text{-}USN}$). Be aware that P_{DCS} will be different for the other tables. Some tables are missing certain schedules. DCD – DadCoDat; DCIEM – Defence and Civil Institute of Environmental Medicine; TUP – transfer under pressure; USN – United States Navy



decompression time or oxygen breathing time will reduce P_{DCS}. We have compared PrT and $P_{DCS\text{-}USN}$ for the twenty-five USN profiles listed in Table 1. As is shown in Figure 2, PrT and $P_{DCS\text{-}USN}$ is highly correlated up to a PrT of 31 ($r = 0.94$, $P < 0.001$). When PrT exceeds 31, the relationship is lost ($r = 0.29$, NS). Accordingly, PrT will not be a valid surrogate measure of the outcome of a dive adhering to USN air/in-water O_2 decompression table, at least not for dives with PrT > 31. We would expect that a decision to prefer a certain procedure in part would depend on the expected P_{DCS}. Given the inaccuracy of using PrT as a surrogate outcome measure, we have decided to present differences in outcome variables (TDT, oxygen breathing time, gradient factors) in increasing order of $P_{DCS\text{-}USN}$ instead. This decision will be discussed later.

COMPARISON OF DECOMPRESSION TABLES

Total decompression time and oxygen breathing time

Total decompression time (TDT) and oxygen breathing time vary between the published tables. Figures 3 and 4 give graphical presentations of this variation in modified Bland-Altman plots. The Bland-Altman plots compare the

Table 3

Pairwise comparison of six tables for differences in total decompression time; the data are median (interquartile range) minutes. A positive sign indicates that the table of the corresponding row has a longer TDT than the intersecting column. Statistically significant differences are indicated in bold ($P < 0.01$). A statistically significant positive correlation (Pearson correlation coefficient) between $P_{DCS\text{-}USN}$ and the difference in TDT between the tables of the intersecting row and column is indicated by * ($P < 0.05$) and ** ($P < 0.01$). DCD – DadCoDat; DCIEM – Defence and Civil Institute of Environmental Medicine; d/w bell – dry or wet bell; TUP – transfer under pressure; USN – United Sates Navy

Table	DCD d/w bell	DCD TUP	MT92 12 msw	MT92 6 msw	DCIEM
USN	**-8 (11)***	7 (24)	**16 (23)****	**11 (20)****	**10 (32)****
DCD d/w bell		15 (11)	22 (10)**	20 (10)*	22 (20)**
DCD TUP			**6 (8)**	6 (9)	**9 (5)**
MT92 12 msw				**-3 (7)**	-2 (9)
MT92 6 msw					3 (11)

Table 4

Pairwise comparison of six tables for differences in decompression oxygen breathing time; the data are median (interquartile range) minutes. A positive sign indicates that the table of the corresponding row has a longer oxygen breathing time than the intersecting column. Statistically significant differences are indicated in bold ($P < 0.01$) or italics ($P < 0.05$). DCD d/w bell: DCD dry or wet bell. Other table abbreviations are as per Table 2. A statistically significant positive correlation (Pearson correlation coefficient) between $P_{DCS\text{-}USN}$ and the difference in oxygen breathing time between the tables of the intersecting row and column indicated by * ($P < 0.05$) and ** ($P < 0.01$). DCD – DadCoDat; DCIEM – Defence and Civil Institute of Environmental Medicine; d/w bell – dry or wet bell; TUP – transfer under pressure; USN – United Sates Navy

Table	DCD d/w bell	DCD TUP	MT92 12 msw	MT92 6 msw	DCIEM
USN	-7 (11)*	2 (14)	**10 (14)**	**13 (17)****	**8 (21)**
DCD d/w bell		*5 (5)*	**15 (5)**	**20 (5)***	**14 (10)**
DCD TUP			10 (5)	15 (5)	**10 (4)**
MT92 12 msw				5 (10)**	*0 (7)***
MT92 6 msw					-4 (4)

stipulated TDT or oxygen breathing time for one profile to the mean of all profiles for each schedule. Each comparison is presented on the Y-axis and ordered in increasing order of expected incidence of DCS according to the USN procedure[9] on the X-axis ($P_{DCS\text{-}USN}$). As an example: for the 36 msw/60 min schedule the USN profile has an estimated DCS incidence of 3.47%. The mean TDT from all profiles for this schedule would be 68 min. MT92 12 msw, DCIEM, MT 6 msw, USN and DCD TUP recommend 57, 62, 67, 67 and 84 min of TDT respectively. The difference between the individual TDTs and the mean TDT (-11, -6, -1, -1 and +16 min respectively) can be seen as vertically stacked symbols at $P_{DCS\text{-}USN}$ 3.47% in Figure 3.

The figures suggest that USN and DCD TUP tables in general stipulates longer TDTs and oxygen breathing times than MT92 and DCIEM. Statistical analyses of these differences confirm this impression (Tables 3 and 4). Other statistical comparisons are summarized in Tables 3 and 4. The difference in TDT comparing either USN or DCD dry or wet bell to the MT92 and DCIEM increase as $P_{DCS\text{-}USN}$ increase (Table 3). Less consistent correlations were present for oxygen breathing time (Table 4). Differences in TDT and oxygen breathing time were not normally distributed for all pairwise comparisons and central location and distribution have been presented with median and interquartile ranges.

Gradient factors

GF low and GF high are measures of supersaturation in the controlling compartment at the deepest planned decompression stop and immediately after surfacing. None of the tested profiles exceeded 100% for GF low or GF high. As shown in Figure 5 and Table 5, USN and MT92 6 msw procedures have significantly higher GF lows than the other four procedures. GF high was significantly lower in USN and the two DCD procedures compared to the two MT92 and DCIEM procedures (Figure 6 and Table 6).

REPETITIVE DIVING

Repetitive diving is probably of limited practical interest for commercial TUP-diving. We will nevertheless provide a short summary comparing table characteristics for such diving.

Independent of depth and bottom time of the preceding dive, the DCIEM and USN tables allow a new single dive after an 18 h surface interval, DCD TUP tables 16 h while MT92 and DCD dry or wet bell tables allow a new single dive after 12 h. The decompression obligation for a repetitive dive is calculated based on a bottom time penalty. MT92 and USN impose a bottom time penalty as a nominal addition to the

Figure 5

Gradient factor low (GF low) for twenty-five different schedules (Table 1) from six TUP candidate tables presented in increasing order of estimated incidence of DCS for USN decompression schedule[20] ($P_{DCS-USN}$). Be aware that P_{DCS} will be different for the other tables. DCD – DadCoDat; DCIEM – Defence and Civil Institute of Environmental Medicine; TUP – transfer under pressure; USN – United States Navy

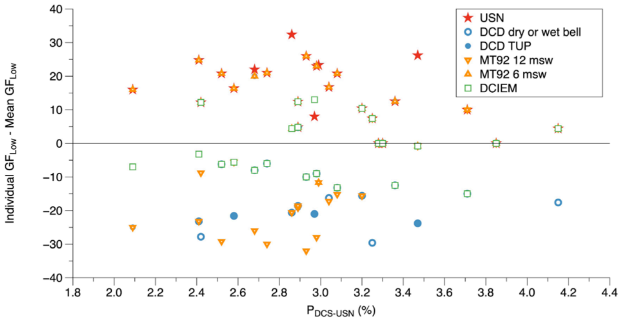


Figure 6

Gradient factor high (GF high) for twenty-five different schedules (Table 1) from six different TUP candidate tables presented in increasing order of estimated DCS incidence for the USN decompression schedules[20] ($P_{DCS-USN}$). Be aware that P_{DCS} will be different for the other tables. DCD – DadCoDat; DCIEM – Defence and Civil Institute of Environmental Medicine; TUP – transfer under pressure; USN – United States Navy

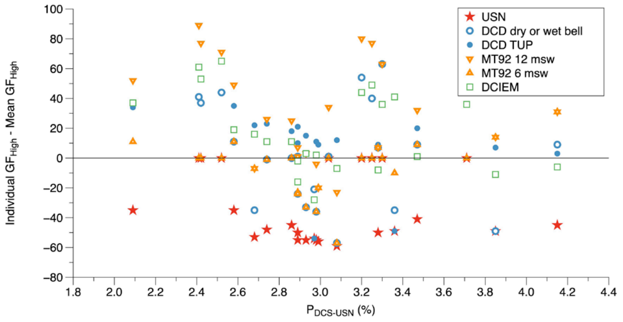


Table 5

Pairwise comparison of six tables for difference in low gradient factor (GF low); the data are median (interquartile range). A positive sign indicates that the table of the corresponding row has a higher GF low than the table of the intersecting column. Statistically significant differences are indicated in bold ($P < 0.01$) or italics ($P < 0.05$). A statistically significant positive ($P < 0.05$) or negative ($P < 0.01$) correlation (Pearson correlation coefficient) between $P_{DCS-USN}$ and the difference between the tables of the intersecting row and column is indicated by * and ## respectively. DCD – DadCoDat; DCIEM – Defence and Civil Institute of Environmental Medicine; d/w bell – dry or wet bell; TUP – transfer under pressure; USN – United Sates Navy

Table	DCD d/w bell	DCD TUP	MT92 12 msw	MT92 6 msw	DCIEM
USN	**32 (14)**	**31 (34)**	**28 (48)**##	0 (0)	**23 (28)**
DCD d/w bell		0 (6)	0 (37)	**-30 (12)**	*-18 (31)*
DCD TUP			0 (19)	*-25 (33)*	0 (23)
MT92 12 msw				**-25 (36)***	-15 (22)*
MT92 6 msw					14 (27)

Table 6

Pairwise comparison of six tables for difference in high gradient factor (GF high); the data are median (interquartile range). A positive sign indicates that the table of the corresponding row has a higher GF high than the table of the intersecting column. Statistically significant differences ($P < 0.01$) are indicated in bold. A statistically significant negative correlation (Pearson correlation coefficient) between $P_{DCS-USN}$ and the difference between the tables of the intersecting row and column is indicated by # ($P < 0.05$) and ## ($P < 0.01$). DCD – DadCoDat; DCIEM – Defence and Civil Institute of Environmental Medicine; d/w bell – dry or wet bell; TUP – transfer under pressure; USN – United Sates Navy

Table	DCD d/w bell	DCD TUP	MT92 12 msw	MT92 6 msw	DCIEM
USN	11 (18)	1 (19)	**-17 (14)**	**-20 (16)**#	**-17 (21)**
DCD d/w bell		-7 (6)	-23 (9)	-26 (7)	-24 (8)
DCD TUP			**-15 (11)**	**-18 (5)**	**-19 (4)**
MT92 12 msw				0 (6)#	-1 (12)##
MT92 6 msw					1 (5)

actual bottom time. DCIEM procedures provide ‘repetitive factors’ – a factor by which to multiply the actual bottom time of the repetitive dive to reach an ‘effective bottom time’. Decompression is then calculated based on the effective bottom time. DCD procedures don’t provide guidance on repetitive diving.

The number of possible repetitive dive combinations is too large to allow analysis. We have compared bottom time penalties prescribed for the three tables allowing repetitive dives within a 12 h surface interval. We have arbitrarily chosen three different depth/bottom time combinations. The repetitive dive was presumed to take place to the same depth as the first dive (Table 7). For these three schedules

Table 7

Bottom time (BT) penalty (minutes), that is, time to be added to the actual bottom time of the repetitive dive, for three selected schedules according to DCIEM, MT92 and USN procedures. A large bottom time penalty indicates a conservative procedure. DCIEM – Defence and Civil Institute of Environmental Medicine; SI – Surface interval; USN – United Sates Navy

Depth (msw)	BT first dive (min)	SI (h)	BT repetitive dive	BT penalty (min) for a repetitive dive to the same table depth		
				MT92	DCIEM	USN
15	140	2	120	50	108	109
24	80	8	60	5	18	29
30	55	6	40	5	12	33

Table 8

Maximum allowed bottom time (min) for non-exceptional dives according to United States Navy (USN) and Defence and Civil Institute of Environmental Medicine (DCIEM) decompression tables. Bottom times equal to or exceeding United Kingdom Health and Safety Executive transfer under pressure (TUP) limits are indicated by *

Table depth (msw)	TUP bottom time limit (min)	USN	DCIEM
15	240	*	140
18	180	*	120
21	180	*	100
24	180	170	80
27	130	*	60
30	110	*	55
33	95	*	55
36	85	*	50
39	75	*	45
42	65	*	45
45	60	*	40
48	55	*	35
51	50	*	35

the USN and DCIEM procedures impose a similar bottom time penalty while MT92 imposes less penalty.

OPERATIONAL CONSIDERATIONS

All tables provide decompression schedules for air diving to 50 msw. However, most of the HSE maximum allowed bottom times exceed those permitted for DCIEM non-exceptional dives (Table 8). The USN restricts bottom time for a non-exceptional dive to 24 msw to 170 min (10 min shorter than the HSE limit[6]) (Table 8), for all other table depths the HSE-imposed bottom time limitations are within the non-exceptional dive range. None of the tables detail use of nitrox as the bottom breathing gas. All except the MT92 procedures provide routines for flying after diving.

Discussion

PROBABILITY OF DCS – SINGLE DIVES

All tables presented in this work are recognised as de facto national standards in their originating country. Most of them are additionally applied in commercial diving in foreign jurisdictions. They have been revised for decades. There is no reason to suggest that any of them should be considered unsafe, however one of the objectives of this study was to analyse whether there are systematic differences between them suggesting that one procedure might provide higher protection for DCS compared to others.

Only one of the tables, the DCD TUP tables, has been specifically developed for TUP diving, though the MT92 12 msw is designed for closed bell intervention in addition to surface supplied and wet bell use. Neither the DCD dry or wet bell nor the MT92 tables specifically mention TUP as the diving method but state that they are intended for use with diving bells. The USN Air/Oxygen and DCIEM tables were designed for in-water decompression. The divers' decompression environment may affect DCS incidence. In-water decompression with oxygen will provide the diver with FiO_2 = 100%. When decompressing in a dry environment, leakage from the breathing masks (BIBS-system) will reduce FiO_2 depending on mask fitting as will be discussed later. Immersion, thermal stress and physical activity may also affect DCS probability and validation of decompression profiles should ideally be performed as close as possible to the operational reality.

We have compared the tables with respect to gradient factor low, gradient factor high, TDT and oxygen breathing time. The USN and DCD tables in general stipulate longer TDTs and oxygen breathing times than MT92 and DCIEM (Tables 3 and 4). Longer decompression time and increased FO_2 during decompression is expected to decrease DCS incidence.[15] The difference in TDT between USN and DCD vs MT92 and DCIEM, tended to increase as $P_{DCS\text{-}USN}$ increased (the difference was positively correlated to $P_{DCS\text{-}USN}$ Table 3). The difference between the tables will thus be most pronounced for dives with a high expected DCS incidence. As expected, the increased TDT and oxygen breathing time caused surfacing GF high to be lower for USN and DCD compared to MT92 and DCIEM (Table 6). These results suggest that USN and DCD TUP procedures should give a lower DCS incidence than MT92 and DCIEM tables.

It should be recognised that the stipulated figures for $P_{DCS\text{-}USN}$ are valid for the USN air/in-water O_2 table profiles only. While the longer TDT and oxygen breathing time in USN and DCD procedures would suggest a lower DCS incidence compared to MT92 and DCIEM tables, the distribution of decompression stops may modify this assumption. The GF low was higher in USN profiles than all other procedures except MT92 6 msw. This is due to a shallower first decompression stop in the USN profiles compared to MT92 6 msw. A high GF low implies that the inert gas supersaturation in the controlling compartment is close to the allowed tension threshold. While adding a deep decompression stop, which would reduce GF low, previously was thought to reduce DCS incidence in deeper diving, this has been difficult to confirm. Two studies[16,17] suggested increased venous gas embolism and a negative effect on DCS incidence when deep stops were introduced. Procedures with deep stops may therefore actually have a higher probability of DCS compared to other procedures with similar TDT and oxygen breathing time, but as previously stated, we have no means of quantifying this effect.

While the results suggest that DCS incidence would be lower in USN and DCD procedures than MT92 or DCIEM, we have no access to a probabilistic model allowing us to assess the effect size of this difference. However, consideration should be given when decompressing with shorter TDT or oxygen-breathing time than USN unless a higher DCS probability is acceptable. The USN air/in-water O_2 procedure is based on the Thalmann E-L probabilistic model.[20] The VVAL79 parameter set used assumes $FiO_2 = 99.5\%$ during in-water decompression at 9 and 6 msw. The same parameter set assumes $FiO_2 = 85\%$ when breathing 100% O_2 during surface decompression with oxygen accounting for some leakage in the BIBS masks. A somewhat higher DCS probability than that stipulated by $P_{DCS\text{-}USN}$[20] (Figure 2) would thus be expected when USN air/in-water O_2 procedures are used in a TUP setting when divers breathe O_2 through BIBS in the diving bell or chamber.

The assessment of the safety performance of various decompression procedures should ideally be based on experimental studies with many subjects testing all possible profiles. Table revision should be based on large epidemiological studies documenting table performance in operational diving.[22] In practice this is impossible due to logistical constraints and tables are tested with a limited number of experimental dives followed by monitoring of operational dives. Reports from operational dives have several limitations. Data on depths, bottom time and decompression times may be inaccurate since these values previously were registered manually rather than based on electronic depth monitoring. Even more importantly, operational diving will not reflect a homogenous distribution of diving depths and bottom times. It seems likely that diving to bottom times not requiring staged in-water decompression stops (‘no-decompression dives) would predominate. Epidemiological studies[23] as well as the outcome of probabilistic models of USN decompression tables[20] strongly suggest that DCS incidence will increase as a function of diving depth and bottom time. Unless the profiles are presented, caution should be taken in interpreting reports of DCS incidence in operational diving. Assessment of the safety of these tables is challenged by the fact that publicly available data on experimental testing or robust epidemiological data are scarce or non-existent. This is further discussed below.

DCS PROBABILITY – REPETITIVE DIVES

Comparing repetitive dive procedures is complicated by the fact that the tables have different procedures for such diving as well as a difference in minimum surface interval to allow a new single dive. For repetitive dives with a surface interval shorter than 12 h the MT92 procedures will advise shorter bottom time penalties than DCIEM and USN (Table 7) and we would presume that this would affect DCS incidence.

The procedures may be compared with respect to minimum surface interval allowing new dives and bottom time penalties for repetitive dives. For a given surface interval a procedure not allowing new dives would be considered more conservative than those allowing repetitive dives. Similarly, a long bottom time penalty would be considered more conservative than a short bottom time penalty. A broad summary, listing the procedures and repetitive schedules (Table 7) in decreasing order of conservatism, may be presented such:

- Surface Interval > 18 h: all procedures will accept the following dive as a new single dive
- Surface interval 12–18 h: DCD TUP>>USN >DCIEM>>MT92 and DCD dry or wet bell
- Surface interval 0–12 h: DCD>>USN>DCIEM>MT92

DOCUMENTATION AND VERIFICATION OF ALGORITHMS AND PARAMETER SETS

The USN decompression tables have been developed based on a publicly accessible algorithm (Thalmann E-L[24]) and parameter set.[20] Acceptance criteria and verification have been clearly described.[20] USN tables have been revised recently (2018) by NEDU scientists. These tables are expected to be continuously developed and improved due to the institutional commitment backed up by a recognised team of scientists. A large database has allowed USN to develop probabilistic models that may predict the outcome of any decompression schedule. The present study investigated the USN Diving Manual Rev 7 air/in-water O_2 decompression schedule as one of the candidates for TUP models. The schedules in this procedure were developed using the Thalmann E-L deterministic model with VVAL79 parameter set.[20] The NEDU has developed this parameter set to allow DCS probability to stay within USN acceptable limits. The $P_{DCS\text{-}USN}$ has been assessed with two models, one of them being NMRI98[15] calibrated with 4,335 dives. The schedules reviewed in the present manuscript have $P_{DCS\text{-}USN}$ ranging from 2.1–4.2% (Figure 2). While this is the prediction of the NMRI98 probabilistic model,[15] we are not aware of any experimental verification of the air/in-water O_2 decompression schedules published in the USN Diving manual.

The DCD procedures were initially published in 1988, but revised 2015. They are edited by two experienced physicians. The details of the underlying algorithms and parameter sets have not been published in the public domain. Operational experience with DCD tables has been reported in a proceedings document published 1990.[25] A total of eleven cases of DCS had been reported in 25,902 dives (0.04%). About 50% of all dives were 'no-decompression dives. The details of DCS cases were not described. The Dutch NDC diving school experienced ten cases of DCS during 1,091 $SurDO_2$ dives adhering to the DCD procedures during 1998–1998.[26] A later publication[27] reported experience with 1,607 helium-oxygen-nitrogen (trimix) dives in the North Sea during 2005 and 2006. Seven cases of DCS were reported, six of these were skin DCS occurring during a four-week period. The cluster of skin DCS was believed to be caused by insufficient heating of the diving bell and surface decompression chamber. Heating and isolation were provided and though a single neurological DCS occurred later, no further incidents of skin DCS were experienced. However, we have not been able to find reports detailing DCS incidence related to testing or operational use of either of the two DCD tables reviewed in this work.

The DCIEM air decompression tables were updated regularly until 1986. There were some minor changes in 2009, but the tables have for all practical purposes been unchanged since 1986. The algorithm has been described in general terms, but the parameter set has not been published. These tables have been extensively tested in strictly controlled experiments using DCS as well as venous gas emboli as the outcome measure.[10] However, there is no information available presenting how the tables have been adjusted based on the result of these experiments. Nishi et al.[28] claim that high bubble grades (Grade III to IV in more than 50% of the subjects) will predict a DCS incidence of more than 5%. The narrative describing the latest Canadian tables don't specify whether this has been used as an acceptance criterion. The 'Introduction' chapter in these tables states that the tables were used in 5,000 dives up to 1967, 2,000 dives during 1967–1971, more than 1,200 dives during 1983–1986 and more than 1,500 dives during 1986–1991. In total, the Canadian tables have been tested in approximately 10,000 dives. However, details are absent regarding which profiles have been tested. Accordingly, it is impossible to know the safety of individual diving methods, depths or bottom times. Sawatzky[29] reported in his thesis that 73 nitrox dives with in-water oxygen decompression were monitored with Doppler for venous gas emboli (VGE). Another report noted that 27 profiles had been tested with 276 exposures.[30] However, neither the profiles nor the DCS incidence was reported.

The MT92 tables were first published in 1974, revised in 1992 and last published 2012.[11] The underlying principles of the algorithm have been published[31] but not with sufficient details to allow an independent review. Data describing the incidence of DCS has not been published for most of the diving methods except air decompression. However, Imbert et al.[31] reported a significant reduction in DCS incidence when the 1992 tables were introduced – in particular for dives with high inert gas load (PrT > 35). Imbert and Bontoux[32] reported that the Comex database in 1987 held data for 573 man-dives from 40 different table profiles with oxygen breathing from 12 msw during decompression. Similarly, a total of 814 man-dives using 55 profiles were logged using the decompression procedures of breathing oxygen from 6 msw. However, neither the profiles used nor the number of DCS experienced are described. We are unaware of other data describing DCS incidence for dives adhering to MT92 in-water oxygen decompression procedures.

In summary, the USN procedures seem to be the best documented and validated tables published. The NEDU is staffed by scientists continuously developing the tables. We would nevertheless underscore that none of the published procedures, including those of USN, have reported DCS incidence with TUP-diving using air as the bottom gas and air and oxygen as the decompression breathing gas.

PRACTICAL AND OPERATIONAL DIFFERENCES

A selection of table characteristics is presented in Table 2. The MT92 12 msw and DCD TUP tables are the only tables specifically designed for closed-bell decompression. The DCD TUP tables contain provision for transfer from the diving bell to the surface decompression chamber with bell and chamber pressurised to 15 msw. A maximum of 15 min is allowed for such transfer without the need for extension of table bottom time. No other procedure allows flexibility for such personnel transfer.

The procedures differ for handling a situation in which oxygen-breathing must be interrupted, e.g., due to acute oxygen toxicity or BIBS failure. The DCD TUP procedures contain highly specific air decompression procedures for such cases while the DCD dry or wet bell air diving procedures don't detail emergency air decompression. The DCIEM and MT92 procedures state that air decompression should follow the conventional air decompression procedure. USN have a detailed, but complicated, procedure for conversion from oxygen-breathing to air-breathing decompression stops.

Oxygen breathing at raised ambient pressure involves a risk for acute and chronic oxygen toxicity. The details of this are beyond the scope of the present work, but the probability of oxygen toxicity will rise as PO_2 and exposure time increases. On the other hand, resting state, non-immersed exposure and air breaks will delay toxicity onset. We believe that differences in pulmonary oxygen toxicity will mainly depend on total oxygen breathing time rather than maximum PO_2 since most of the oxygen exposure takes place at 6 and 3 msw for all but DCIEM procedures. The probability for clinically relevant pulmonary oxygen toxicity should nevertheless be small as long as air is used as the bottom breathing gas and bottom time is limited to HSE/Norsok regulations. Risberg and van Ooij[33] recommended the daily hyperoxic exposure, calculated as 'K', not to exceed 50 for multiday diving. The longest oxygen breathing time identified in this work is 113 min in the USN 24 msw/180 min profile. This profile has K = 33, significantly less than the proposed limit. However, consideration should be taken when oxygen enriched gas is breathed during the bottom phase since this may significantly enhance pulmonary oxygen toxicity.

The DCIEM advice for bottom time limitations is more restrictive than those imposed by UK and Norwegian regulators (Table 8). We would presume that this would make DCIEM procedures less relevant for commercial diving than the others.

LIMITATIONS

This study has several limitations. Most importantly we don't have the methods to assess the effect size on expected DCS incidence of a given difference in decompression time or oxygen breathing time. While we have presented these differences for some schedules, we are unable to quantify to what extent a given difference will make a relevant difference in DCS incidence. To compensate for this, we have presented the differences in increasing order of $P_{DCS\text{-}USN}$ (Figure 3 and Figure 4). For schedules with a high $P_{DCS\text{-}USN}$ we advise careful consideration if alternative procedures suggest a significant reduction in TDT or oxygen breathing time than those prescribed by USN. Secondly, we have not compared all schedules. Given the fact that we have compared at least three bottom times for each of the selected table depths, we nevertheless would presume that we have disclosed the general performance of each procedure concerning the analysed parameters.

We have standardised air breaks to 5 min for every 20 min of oxygen breathing in our calculation of TDT and total air breathing time. The reason for this is that recommendations for air breaks vary significantly between the procedures. However, we expect that most users will include an air break to reduce pulmonary and CNS oxygen toxicity. A 5 min air break is mandated for every 20 min of oxygen breathing in the DCD tables except for the 3 msw stop. Our standardisation will extend TDT marginally by 0–5 min for these tables. The USN requires a 5 min air break for every 30 min of oxygen breathing, while the DCIEM tables recommend similarly. The MT92 tables do not stipulate air breaks. Our standardisation has thus extended TDT by a maximum of 20, 15 and 10 min of air-breathing time relative to the original published decompression schedules in the MT92, DCIEM and USN tables respectively. Without standardisation of air breaks the TDT of DCIEM and MT92 will be shortened by 15–20 min for profiles with the longest oxygen breathing times. Without standardisation of air breaks the contrasts in TDT between MT92 and DCIEM tables on one side and USN and DCD tables on the other side would increase compared to those presented in Table 3.

The DCD TUP tables have been provided to the authors under a commercial-in-confidence and non-disclosure agreement. The reason for this restriction is the commercial value of the product for the publisher. The non-disclosure term is an evident concern since it will prevent independent control of the results presented in this manuscript. However, the authors recognise that N-Sea has been the single largest operator of North Sea offshore TUP diving operations in recent years, and the inclusion of the tables would be highly relevant for individuals, organisations, companies and regulators interested in developing TUP diving capacity. We believe that the benefit of including the DCD TUP tables outweighs the disadvantages. The DCD TUP tables illustrate a concern related to proprietary and confidential decompression tables. Such proprietary tables were common in the past, particularly in offshore saturation and mixed gas diving, but are less common in diving in developed countries today. There may exist TUP-tables we are unaware of since our search strategy has been based on open sources. We strongly support sharing the contents of decompression tables in the open domain. In addition, there is a need for better epidemiological data on DCS occurrence in occupational diving. Electronic monitoring of dives is comparatively inexpensive. Sharing exposure and outcome data from commercial diving would allow future studies to compare performance of decompression tables.

We have compared the relative safety of different TUP candidate decompression tables. However, we have no method to assess the absolute DCS risk of these tables when applied for closed bell decompression. We have compared decompression time and oxygen breathing time of candidate tables to those of USN air/in-water oxygen decompression tables. Even though we have referred to the expected DCS probability of USN air/in-water oxygen tables, we would like to reiterate that these estimates are valid for in-water decompression only. TUP decompression will usually avoid the thermal stress, hydrostatic forces and work related to in-water decompression. On the other hand, it is possible that leaks of the BIBS masks may give a lower inspiratory oxygen fraction compared to that of the immersed diver's breathing equipment. The direction and effect size of these factors remain to be studied.

Finally, the focus of this work has been a comparison of parameters related to DCS probability. Economic, practical, legislative and standardisation factors will, in the end, have an important impact on table selection. Assessment of these factors is beyond the scope of this work.

Conclusions

This is a published systematic approach to the evaluation of decompression tables applicable to TUP diving. The present work has identified six candidate tables from DCD (the Netherlands), DCIEM (Canada), MT92 (France) and the US Navy. They are all recognised by their national authorities and widely used in commercial air and SurDO$_2$ diving. When compared with respect to TDT and oxygen breathing time, the USN and DCD tables are more conservative than DCIEM and MT92 tables. However, detailed safety records from experimental or field diving are not available for any of these tables. It is thus not possible to claim that they have been satisfactorily validated. The probabilistic model of the USN suggests that their air/O$_2$ decompression table should perform with a DCS incidence comparable to air diving.

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