Decompression practice and health outcome during a technical diving project

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Key words

Technical diving, cave diving, safety, health surveillance, decompression, air, mixed gas, trimix, nitrox, oxygen

Abstract

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Technical divers use multiple helium/nitrogen/oxygen breathing-gas mixtures to reach depths greater than 40 metres seawater (500 kPa) using scuba. Self-assessment of health outcome by 9 divers using a validated decompression health survey followed a series of 200 technical dives to a maximum of 123 metres of fresh water. Decompression was planned using the ZH-L16 calculation procedure. Although the incidence of treated decompression sickness was only 0.1%-3.4% (95% confidence limits), high health survey scores, possibly marginal symptoms of decompression sickness, were associated with maximum diving depth greater than 90 metres.

Introduction

The practical range of 'recreational' diving is limited by the use of a single-cylinder, nitrogen/oxygen, open-circuit scuba to a maximum depth of 40 metres seawater (msw) (500 kPa) with minimal decompression. 'Technical' diving, although typically conducted for recreational purposes, is scuba diving beyond the practical range of recreational diving. Although technical diving encompasses many types of diving activities, technical diving in the format that is presently common arose from underwater cave exploration in Europe and USA in the 1980s.[1,2] Principally, technical divers use multiple helium/nitrogen/oxygen breathing-gas mixtures to reach depths greater than 40 msw and to accelerate decompression. With the advent of instructional programmes for this style of diving there is a growing 'mainstream' of technical divers conducting brief dives to 100 msw. A smaller core of technical divers is pioneering dives beyond this range.

A principal challenge for technical divers is uncertainty in the safety of decompression procedures. In the past only the military and commercial diving communities have had the resources for large-scale development and validation of decompression schedules, and even where resultant decompression schedules are available they are designed for diving procedures quite different to technical diving. Military and commercial deep-diving procedures include use of heliox mixtures, tethered divers, diving bells, and saturation techniques, whereas many technical dives are helium/nitrogen/oxygen trimix bounce scuba dives.

Technical diving decompression procedures are commonly wholly or partly based on the ZH-L16 decompression calculation method of Bühlmann.[3,4] Although not developed for technical diving there are several reasons for the popularity of this method. Unlike many decompression procedures a full description of the ZH-L16 (or its ZH-L12 predecessor) calculation method was freely available in the mainstream scientific literature at the outset of modern technical diving. The ZH-L16 is a decompression model rather than a set of schedules generated by a model and therefore can be used to calculate decompression requirements for helium/nitrogen/oxygen dives of any complexity. The ZH-L16 calculation method is simple and user-controllable implementations have been developed for microcomputers, palm tops, and mobile phones and it is commonly programmed into decompression computers carried by divers.

Although there are many anecdotes about the safety or otherwise of the ZH-L16 calculation method and its variants, mainly in Internet forums, there does not appear to be any formal evaluation of the ZH-L16 in the specific context of technical diving. This manuscript examines the decompression health outcome following technical dives using the ZH-L16 decompression calculation method during a technical diving project to explore and map an underwater cave called 'The Shaft'.

Diving

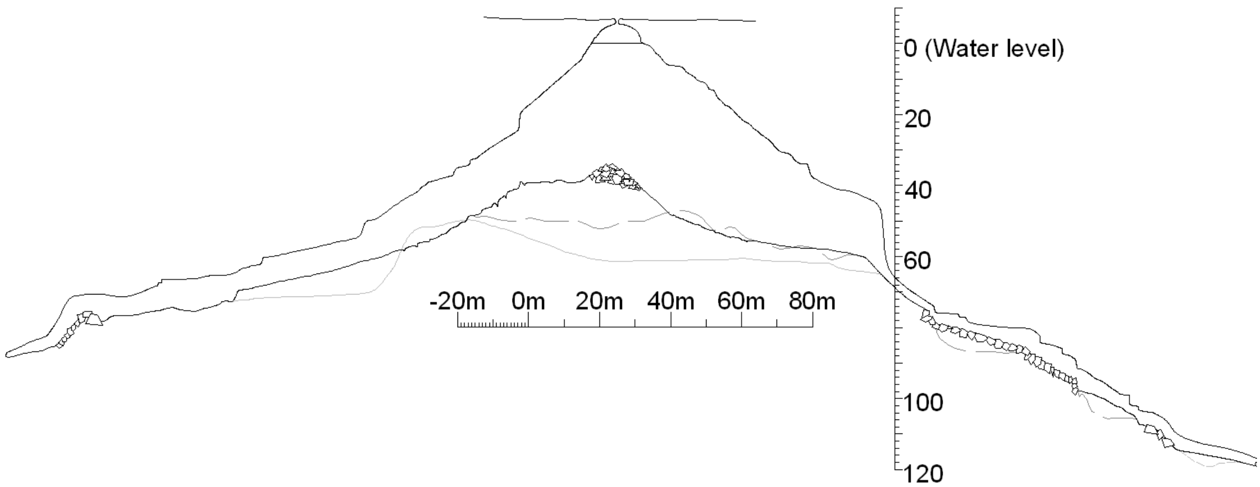
The Shaft is a freshwater cenote near Allendale East in South Australia named for the shaft of sunlight that at times shines through the 1 m wide entrance and tracks across the debris cone below. A brief history of diving in this site has been published.[5] The site has been dived since the 1960s and the first mapping project, using air diving, was undertaken in the early 1980s. The diving since then has been limited to 40 metres fresh water depth (mfw; 494 kPa) at the request of the landowners. After obtaining permission for some preliminary exploratory deep technical dives in the early 1990s a group of divers obtained permission to undertake an extensive exploration and mapping project of The Shaft deeper than 40 mfw under the auspices of the Australian Speleological Federation. This project, which is the subject of the present report, was conducted between October 2000 and January 2004.

Aspects of the earlier map were verified but the majority of the mapping occurred at depths greater than 40 mfw. The survey used knotted line, compass, depth gauge, and clinometer. Survey lines knotted every 5 m were installed throughout the cave in locations chosen to capture the shape of the cave. Each change in direction of the line was designated a survey station and at each station divers recorded the depth of water, distance to walls, floor and roof, the bearing, and the distance to the next station. The inclination along a few steeply sloping line segments was also measured. On a subsequent dive, using the line survey as reference, the significant features of the cave at and between stations were sketched. Eleven divers conducted 225 air and trimix dives during the exploration and survey of this site. The resulting map is a 1:500 scale plan and extended elevation (Australia, The Shaft Cave [speleological map]. Payne T, cartographer. Adelaide, Australia: Australian Speleological Federation - Cave Diving Group; 2004. 1 sheet: black & white, 69x98cm, scale 1:500, ASF grade 33A. Located at: Cave Exploration Group of South Australia archive, Adelaide, Australia; map 1322). A miniature of the extended elevation is shown in Figure 1.

Typically, teams of two or three divers assigned specific mapping or exploration tasks dived once per day. Divers dressed in drysuits with passive insulation provided by air inflation and undergarments; water temperature was 15°C to 16°C. Primary lighting was provided by hand-held halogen or arc lamps with waist-mounted battery canisters. Depth and time were monitored using Uwatec AladinPro™ or Suunto Vyper™ decompression computers. The breathing-gas supply for the deepest portion of the dives was carried in twin 12 l or 15 l 23.2 MPa working pressure steel cylinders; these were back-mounted along with buoyancy wings. To provide redundant scuba, back-mounted cylinders were equipped with dual open-circuit regulators either independently or via a duel outlet manifold. If additional breathing gas and/or different breathing-gas mixtures were required to travel to the maximum distance or depth, these were breathed from separate cylinders with single, open-circuit regulators attached to the divers' left side. These cylinders would be detached and left on the cave floor (staged) either at a planned cylinder pressure or when the maximum operating depth (determined by P_IO_2 or P_IN_2) for that gas was reached. Staged cylinders were retrieved and breathed upon return. Gases breathed only during decompression were contained in separate cylinders left attached to shot-lines from the surface at the appropriate depths. Each cylinder was clearly labelled with its maximum operating depth.

Dives planned at less than 45 mfw were conducted entirely breathing air. For deeper dives air was breathed to approximately 45 mfw, then helium/nitrogen/oxygen trimix was breathed deeper than 45 mfw to reduce the work of breathing, reduce the level of nitrogen narcosis, and reduce the risk of oxygen toxicity. Trimix was produced by mixing helium and air for an equivalent air narcotic depth – [[D/10.33+1]*[1-FHe]-1]*10.33 – of 46 mfw (P_IN_2 = 436 kPa at the planned maximum actual depth, D), although mapping was generally conducted shallower. Trimix was produced by partial pressure mixing of helium and air, and nitrogen/oxygen mixtures by partial pressure mixing of oxygen and air in the cylinders used by the divers. The mixtures were analysed for oxygen content by galvanic and polarographic methods at the time of mixing and all breathing gases were analysed for oxygen content

Figure 1
Extended elevation of 'The Shaft' reduced from the original (Australia, The Shaft Cave [speleological map]. Payne T, cartographer. Adelaide, Australia: Australian Speleological Federation - Cave Diving Group; 2004. 1 sheet: black & white, 69x98cm, scale 1:500, ASF grade 33A. Located at: Cave Exploration Group of South Australia archive, Adelaide, Australia; map 1322) with permission of the cartographer.



immediately prior to use. The commonly used helium fractions were 20%, 30%, 40%, 50%, and 60% for maximum depths of 60, 70, 80, 100, and 120 mfw, resulting in equivalent air narcotic depths of 46, 46, 44, 45, and 42 mfw, respectively. For dives deeper than 100 mfw an intermediate helium-air mixture was breathed between 45 and 70 or 80 mfw. Decompression was accelerated by switching from trimix to air at either 45 mfw or 55 mfw, then to a 50% nitrogen-50% oxygen mixture at 21 mfw, then to 100% oxygen at 6 mfw.

Decompression calculations

Underlying the ZH-L16 calculation method is a mammillary model of helium and nitrogen tissue uptake and washout comprising 16 compartments in communication with a central pool equivalent to arterial blood or alveolar gas. For each compartment, different half-times describe the rate of exchange of nitrogen (4-635 minutes) and helium (1.5-240 minutes) with the central pool. The helium and nitrogen half-times are related by the inverse of the square root of the molecular weight of the two gases according to Graham's law for auto-diffusion of gases, implying diffusion of gas between the compartments and central pool. Decompression is controlled by the maximum of the set of minimum tolerated ambient pressures (P_{amb_tol}) for the compartments:

$$\max\left\{P_{amb\_tol_i} = \left(P_i - a_i\right) \times b_i\right\}$$

where, for the ith compartment, P is the inert gas tension before ascent and a and b are constants. Various ZH-L16 implementations modify the set of a and b constants in a more or less *ad hoc* manner to modify the decompression in line with prevailing folklore; however, the present project used the unmodified ZH-L16 a and b constants as published.[4] Since this original publication a unique set of a and b constants for helium has been promulgated that allows a more accelerated decompression; this was not used.

Decompression calculations for trimix dives were performed using Excel (Version 9.0. Redmond, WA, USA: Microsoft Corp; 1999). Schedules that defined a multi-level bottom time and all decompression stops were generated for specific dives. The ascent always included one-minute stops at each stage bottle collection depth and a three-minute swim across the main chamber at 40 mfw in addition to the decompression stops dictated by the ZH-L16 model. Figure 2 shows an example schedule. Air-diving decompression was not structured but instead followed the prescription of diver-carried decompression computers. Most air dives were conducted using Uwatec AladinPro™ computers, which use an 8-compartment version of the ZHL model; a very few air dives were conducted using Suunto Vyper™ computers which use a 9-compartment ZHL model variant where half-times are reduced for gas washout and a and b constants are reduced for repetitive diving. Divers tended to extend air-dive decompression time beyond that prescribed by the decompression computer.

Methods

DATA COLLECTION

The study was conducted in accordance with the *National statement on ethical conduct in research involving humans* (Commonwealth of Australia. Canberra: AusInfo; 1999) and is an analysis of the records originally devised, maintained, and used by the author to audit all diving and decompression procedures during the mapping project. Subsequently, informed written consent was sought from each diver to use these data for scientific publication. Two divers refused to give consent for reasons unrelated to their health outcome. Exclusion of these data did not alter the conclusions from the unpublished audit of all diving during the project. The consenting nine divers include the author. The centrally maintained records included a workbook of all steps in the mixing and analysis for oxygen content of breathing gases, all decompression schedules used, and paper dive logs. Divers completed a decompression health survey to measure decompression-related health status before commencing on the project and then again following each dive.

The decompression health survey has been described in detail elsewhere.[6] It is an inventory of nine standardised items and responses covering five symptoms of decompression sickness (paraesthesia, rash, balance, fatigue, and pain), five health-status indicators (vitality, pain, physical functioning, role limitation, and health perception), and time of onset of symptoms, plus one free response, each item scored from 0 to 3. The resulting summed decompression health score (DHS) ranges from 0 (well) to 30 and can be analysed as interval data. DHS are correlated with diagnosed decompression sickness (DCS)[6] and following routine occupational air diving the DHS increases with increase in decompression stress in the absence of diagnosed DCS.[7] The validated format of the decompression health survey and scoring instructions are available from the author.

In addition to paper records those divers using decompression computers capable of recording depth/time profiles submitted these profiles. These devices record gauge pressure (as depth of water) at fixed intervals of 10 or 20 seconds. Dive profiles were compared with the corresponding decompression schedules. The difference in area of the allowed time at depths deeper than 40 mfw and the recorded depth/time profile was calculated (area between the solid and dashed line in Figure 2) and divided by the time allowed to give a safety margin index in mfw. The ascent to first decompression stop was determined by visual inspection of a plot of the depth/time profile and the ascent rate in mfw.min^{-1} extracted. A decompression index was calculated in the following manner. First, the depth/time profile was reduced to a smaller number of depth/time nodes by manual selection of nodes during visual inspection and the fraction of helium and nitrogen in the breathing gas at each node assigned. Then the uptake and washout of helium and nitrogen into each of the 16 compartments defined by the ZH-L16 model was tracked for the duration of the dive and the time on the surface up until the diver health survey was completed (^{t}DHS). The decompression index was calculated as the sum across compartments of the time integral of positive values only of supersaturation scaled by ambient pressure (P_{amb}):

$$\sum_{i=1}^{n=16}\left(\int_{0}^{t_{DHS}} \frac{r\left(P_i + 0.19 - P_{amb}\right)}{P_{amb}}\right)$$

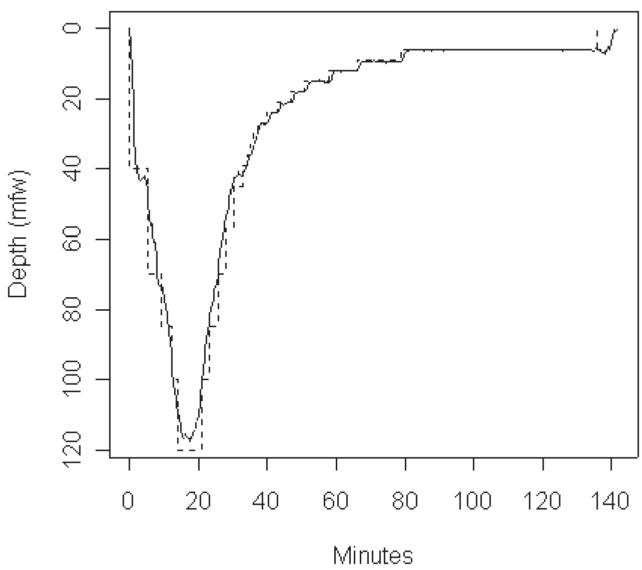
where 0.19 is the contribution of dissolved metabolic gases to the compartment and *r* is the ramp function. Although notionally an indicator of decompression severity, this decompression index is not validated against any measure of decompression stress. These calculations were implemented in GNU Fortran (g77 version GCC-2.95.2 for Mingw. The Free Software Foundation; 1999) and 'R' (R base package version 1.7.0. The R Development Core Team; 2003). For trimix dives, which were rigidly scheduled, if only one team member carried a recording device the other team members were assigned the same values of safety margin, ascent rate and decompression stress unless the dive plan or paper dive log indicated separation of the dive team at any point.

EVALUATION OF HEALTH OUTCOME

The DHS was used to measure decompression-related health status following technical diving and the contribution of the diving exposure was evaluated by linear regression. The full model investigated was of the form:

$DHS_{ij} = \beta_{0i} + e_i + \beta_1 DEPTH_{ij} + e_{ij}$

Figure 2
Dive profile recorded by a diver-carried computer (solid line) and the associated schedule (dashed line) of multi-level bottom times (deeper than 40 mfw) and decompression stops (shallower than 40 mfw)



which comprised the dependent variable DHS and fixed explanatory variable maximum depth (DEPTH in mfw). Bottom time was similar for all dives and total dive time was highly correlated with DEPTH so no indicator of dive duration could be usefully included in the model. In previous studies we have found that different subjects describe their normal health status differently,[7] and a preliminary analysis using factorial regression on divers suggested the same was true here. This is manifest as a different intercept for each diver (DHS at DEPTH = 0) in the linear model; to accommodate this the nine divers were considered a random sample from a population where the intercept (β_0) of the regression on the explanatory variables depends on the attendant. Subscript *i* denotes diver, subscript *j* denotes days, and *e* denotes error.

Parameters of the regression models were estimated by maximising the likelihood. The likelihood is the joint probability density function of the observed values of the dependent variable given the respective regression model. The full model was compared with the null model that includes only the intercept terms and where DHS only varies between divers. Significant difference ($p \leq 0.05$) between these nested models was evaluated by the likelihood ratio test, $2(LL_f - LL_r) \quad X^2_{f-r}$, where LL is the maximised log-likelihood of the model and f and r are the number of parameters in the full and null models respectively ($f > r$). For each model the data were examined for influential values (outliers with high leverage). Outliers were data with standardised residual more than two standard deviations from the mean. Leverage was taken as the diagonal of the hat matrix and values more than twice the mean were considered high.

There was insufficient number of full dive profiles collected to include safety margin, ascent rate, or decompression index in the linear modelling so only descriptive statistics of these variables are presented.

Decompression data were managed using an Access database (Version 9.0. Redmond, WA, USA: Microsoft Corp; 1999). All statistical calculations were performed using 'R' software base package (version 1.7.0. The R Development Core Team; 2003) and the non-linear mixed effect package (version 3.1-39. Pinheiro J, Bates D, DebRoy S, Sarkar D; 2003).

Results

Dive log or DHS was missing for seven dives; Table 1 shows the contribution of the nine divers to the remaining data set of 200 dives and their non-diving DHS from prior to commencing diving on the project. Divers dived once per day for a mean bottom time of 21 minutes (SD = 5, range 9-35), typically two days in succession (range 1-4 days). Dives ranged in depth from 35 mfw to 123 mfw, with total dive durations ranging from 18 to 179 minutes.

Table 1
Data summary for 9 divers for three types of dives; air, trimix <90 mfw depth and trimix >90mfw. DHS – decompression health survey score; median DHS (range); n – number of dives; NA – no data

Diver ID	Pre-diving DHS	Air DHS	Air n	Trimix <90 mfw DHS	Trimix <90 mfw n	Trimix >90 mfw DHS	Trimix >90 mfw n
1	2	0 (0-3)	5	0 (0-5)	20	5 (0-10)	9
2	0	0 (0-6)	6	0 (0-6)	24	1 (0-5)	10
3	7	5 (3-8)	11	5 (3-10)	22	7 (4-12)	7
4	1	2 (1-3)	7	2 (1-4)	15	3 (NA)	2
5	2	0 (0-2)	34	NA	0	NA	0
7	4	NA	0	2 (1-3)	4	7 (3-9)	3
9	1	2 (1-5)	6	NA	0	NA	0
10	1	0 (0-2)	5	NA	0	NA	0
11	5	3	1	3 (2-3)	6	NA	0

Depth/time profiles were available for 44 of the trimix dives and a sample profile along with the decompression schedule is shown in Figure 2. These trimix dives had a mean ascent rate of 5.5 mfw/min (SD = 1.2, range 3.4–7.6), a mean safety margin of 10.2 mfw (SD = 5.4, range 1.0–4.2), and a mean decompression index of 366 (SD = 186, range 47–796). Depth/time profiles were available for 6 of the air dives and showed a mean ascent rate of 5.2 mfw/min (SD = 2.2, range 3.6–8.6) and a mean decompression index of 1540 (SD = 276, range 1104–1956). These high values of the decompression index for air dives are a result of conducting only shallow decompression stops without breathing increased oxygen fraction.

Not accounting for individual variability, a DHS <6 can be considered acceptable for typical diving operations.[6] Figure 3 plots the maximum depth and total decompression time as open circles of all such uneventful dives. There were 12 health surveys that described both DHS = 6 (mean = 9, SD = 2, range 6–12) and occurrence of new symptoms during or following diving; these are plotted as filled circles on Figure 3. The common symptoms were pain (11/12), paraesthesia (9/12), and unusual fatigue (4/12). Pain was described as mild or moderate usually in the left elbow or shoulder and typically appeared during the 9- or 6-metre decompression stop and subsided before or shortly after surfacing. In two cases moderate bilateral joint pain occurred during decompression from 117 and 120 mfw and persisted following diving; these divers were diagnosed with DCS and successfully treated with hyperbaric oxygen.

The influence of maximum diving depth on DHS was examined by linear modelling of all 200 diving and 9 non-diving (DEPTH = 0) data and the results are shown in Table 2. In model 1 there was a significant, approximate unit increase in DHS for DEPTH for every 40 mfw increase in depth. The intercept (DHS at DEPTH = 0) was not significantly different from zero for the fixed component of the model; however, there was a significant inter-individual variation in intercept with a standard deviation of 1.3 (95% confidence interval 0.8, 2.2). This difference in how individuals differently score their normal non-diving health status is evident in Table 1. A strong linear relationship was not evident in a plot of DHS versus DEPTH (not shown), where it was obscured by the between-diver variability. It is evident from Figure 3 that poor health outcomes were associated with the deepest dives and by trial and error it was found that the DHS data were well described by factoring dive depth as =90 mfw or >90 mfw (model 1a). Model 1a had a larger log-likelihood than model 1 but these models are not nested and cannot be formally compared. Both model 1 and model 1a provided a significantly better fit to the data than the null model (model

Figure 3
Plot of maximum depth and total decompression time of air and trimix dives. Uneventful dives (DHS <6 or no new symptoms following diving) are plotted as open circles and dives where DHS =>6 and new symptoms occurred following diving are plotted as filled circles. Mean bottom time was 21 minutes.

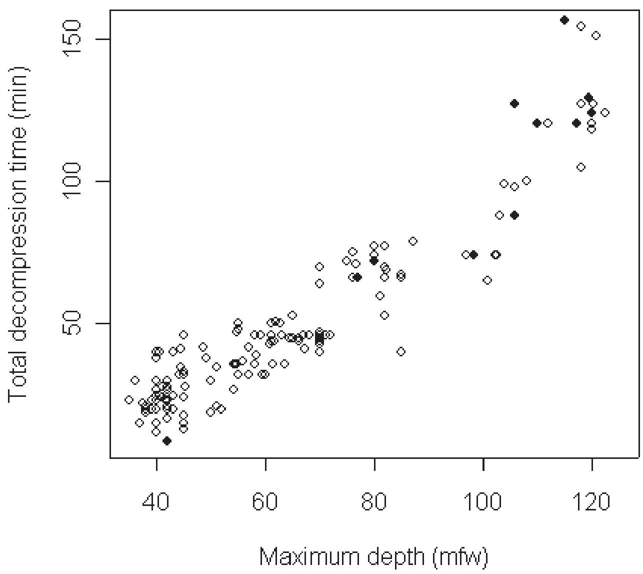


Table 2
Model comparisons (CI = confidence intervals; df = degrees of freedom; LL = maximised log-likelihood)

Model	Variables	Parameter estimate	(95% CI)	P	df	LL	Likelihood ratio test	ratio	P
1	intercept	0.7	(-0.4, 1.8)	0.1856	4	-427	1 vs 2	24	<0.0001
	DEPTH	0.026	(0.016, 0.036)	<0.0001					
1a	intercept	2.0	(1.0, 2.9)	0.0001	4	-417	1a vs 2	44	<0.0001
	DEPTH>90	2.4	(1.7, 3.1)	<0.0001					
2	intercept	2.3	(1.3, 3.2)	<0.0001	3	-439			

2) where only DHS varied between divers.

Discussion

Since technical diving is not regulated there are no records of the number, nature, or outcome of technical dives conducted worldwide with which to compare the present series. For the same reasons it is not possible to define typical technical diving. However, the training agencies provide technical diving training to a typical maximum depth of 100 msw, which could be considered the present status of mainstream technical diving. At the pioneering fringe, this author is aware of a handful of depth-record-setting scuba dives briefly reaching the vicinity of 300 msw, exploration dives with substantial bottom time in the vicinity of 180 and 260 msw, and two-hour bottom times in the vicinity of 70 msw. By these latter standards the present series of dives is not extreme.

To the author's knowledge this small series of dives is the only published analysis of health outcome following technical diving. Based on the two treated cases of DCS in the present series, the probability of DCS using the described protocols is between 0.1% and 3.4% (95% confidence limits). A zero risk of DCS is neither possible nor was expected and the measured risk of DCS seems reasonable. However, inclusion of all poor health scores indicates a probability of poor outcome of between 3.1% and 10.2% (95% confidence limits). Nine of these incidents occurred during 33 dives deeper than 90 mfw, indicating a probability of poor outcome during these deeper dives of between 13.3% and 45.5% (95% confidence limits).

Health outcome was measured by diver self-assessment using the decompression health survey. Extensive validation of the survey against medical assessment shows that high DHS correlates with diagnosed DCS.[6] Two of the poor health scores were confirmed as DCS by subsequent medical diagnosis. It seems likely that some of the remaining poor health scores were 'niggles' or marginal DCS. In occupational air diving the DHS correlates with calculated decompression stress in the absence of DCS.[7] No attempt was made to establish a similar correlation in the present series because there was an insufficient number of recorded dive profiles and no validated decompression-stress-calculation method for trimix dives. High DHS was associated with dives deeper than 90 mfw; although the data must be interpreted cautiously, it appears that the ZH-L16 decompression calculation method provided inadequate decompression for these deeper dives.

There was a trend towards a decreased safety margin with deeper dives; in order to minimise total decompression time, maximum use was made of limited scheduled bottom times to complete survey tasks. Nevertheless, all dives were conducted within limits prescribed by the ZH-L16 model. Inaccuracies in any decompression model as well as execution errors will accumulate with deeper diving: there is more opportunity for failure of a decompression schedule requiring 14 decompression stops than with five stops. Examination of depth/time profiles showed that decompression schedules were well executed. The data used to develop the ZH-L16 model include 211 simulated heliox dives up to 5.1 MPa (490 msw) but the majority of the development is based on dives to a maximum of 450 kPa (34 msw).[3,4] In the present series of dives, as is the case for much technical diving, the ZH-L16 model was used to plan dives that are quite different from the dives used to develop and test the model. It is not surprising that such extrapolation of the ZH-L16 model is not always successful.

During the last several years there appears to have been a shift in the technical diving community away from using the ZH-L16 model and towards using calculation procedures based on the varying permeability model of bubble formation and its derivatives.[8] These models calculate a theoretical number of bubbles formed during decompression and schedules are designed to limit this bubble formation. Implementations of the varying permeability model are now widely available, usually with the bubble model overlaying a ZH-L16 mammillary compartment structure. There are anecdotal reports of both the success and failure of decompression schedules based on these bubble models but there is apparently no published human testing or field validation.

Recreational diving has developed with existing, relevant decompression procedures, such as the standard air diving tables of various navies. More recently, diver-carried electronic decompression computers have been programmed with variants of the ZH-L16 model, which is well tested in the range of recreational diving. There has even been specific development of recreational no-stop decompression procedures. No such basis exists for technical-diving decompression procedures. Decompression safety remains a principal challenge for technical divers.

Acknowledgements

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