Original articles

Health outcome of hyperbaric-chamber inside attendants following compressed-air exposure and oxygen decompression

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Key words
Decompression sickness, occupational health, health surveys, regression analysis

Abstract

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Multi-place, hyperbaric-chamber inside attendants are at risk of decompression sickness (DCS). Attendant decompression protocols vary between facilities and there has been limited specific development or testing of these procedures. Forty-six attendants completed a health survey designed to measure decompression-related health outcome following both 490 hyperbaric exposures and 26 days of ward work without hyperbaric exposure. The risk of decompression sickness (pDCS) for each different hyperbaric schedule was calculated according to a model for oxygen decompression. The contribution of pDCS to a decompression health survey score (DHS) was assessed by linear regression. DHS was not influenced by the hyperbaric exposures and was not different to non-hyperbaric DHS. Three attendants were treated for DCS in close agreement with the calculated mean pDCS. Despite non-zero incidence of DCS, mean attendant health status was not adversely affected by these occupational hyperbaric exposures.

Introduction

Decompression sickness (DCS) is a significant health risk for compressed-air workers. Gases breathed while at high pressure become dissolved in the body tissues and with reduction in ambient pressure (decompression) excess dissolved gas produces bubbles that may result in DCS. Patient attendants who work inside multi-place hyperbaric chambers are at risk of DCS. This risk is widely considered negligible; however, a survey of North American hyperbaric facilities indicates an overall incidence of 5 per 10,000 decompressions, similar to the 1 to 3 per 10,000 reported for underwater air divers.[1-4] The primary factor influencing the risk of DCS is the pressure/time/breathing gas profile. Following a hyperbaric exposure, the risk of DCS for the attendant can be minimised by a slow decompression and oxygen breathing but these decompression procedures vary widely between facilities. Unlike decompression procedures for divers there has been limited specific development or testing of attendant decompression procedures. Since decompression procedures can fail if applied outside of the range of conditions for which they were developed and tested, some attendant decompression schedules present an unknown risk.

Large-scale decompression schedule development programmes are expensive and a recently developed alternative is to collect health outcome data in the field that can be used to evaluate decompression procedures.[5] We have previously used a method based on prospective collection of objective pressure/time/breathing gas profiles and health status scores using a self-administered decompression health survey to evaluate decompression practice in occupational underwater air divers.[6,7] We have been collecting equivalent attendant health outcome data following routine hyperbaric-chamber compressed-air exposure and oxygen decompression with the long-term goal of fitting decompression models to these data. Here we report a preliminary evaluation of the present attendant decompression protocols used at the Royal Adelaide Hospital Hyperbaric Medicine Unit.

Methods

DATA COLLECTION

The study was approved by the University of Adelaide Human Ethics Committee and the Royal Adelaide Hospital Research Ethics Committee and was conducted in accordance with the National Statement on Ethical Conduct in Research Involving Humans (Commonwealth of Australia. Canberra: AusInfo; 1999). This was an observational study whereby data were collected in the course of routine hyperbaric treatments. Chamber operators submitted paper logs describing the attendants' pressure/time/breathing gas profiles. Attendants voluntarily completed a self-administered health survey several hours following decompression and periodically following non-hyperbaric ward duties.

The health survey used was a minor modification of the one developed for divers that 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 (unwell) and can be analysed as interval data. A DHS value of 2 is typical for a well person. The DHS correlates with diagnosed DCS and following routine occupational underwater diving the DHS increases one unit for every 1% increase in calculated risk of DCS.[6,7] The validated format of the decompression health survey and scoring instructions are available from the authors. The DHS was used as the outcome measure without any attempt to categorise outcome as DCS or not.

Health surveys and chamber logs were returned in confidence by reply-paid mail to one of the investigators. The paper logs describing chamber profiles were converted to machine-readable pressure/time/breathing gas profiles that could be used to calculate the risk of DCS and visually inspected to exclude data errors. Decompression data were managed using purpose-designed, partially automated database and analysis applications programmed in our laboratory (Access 2000 and Visual BASIC, Microsoft Corp., Redmond, WA, USA).

From August 1999 to December 2001 there were 1531 attendant decompressions, and 591 health surveys and chamber logs were collected. Some data were excluded, 94 health surveys were incorrectly completed, mostly due to ambiguous wording in an unscored item that was subsequently re-worded, and seven health surveys followed unusual chamber dives. The common hyperbaric oxygen treatments used at the Royal Adelaide Hospital are:

- 10 metres of sea water depth (msw) for 90 minutes (10:90:30)
- 14 msw for 90 minutes (14:90:30)
- 18 msw for 60 minutes (18:60:30)
- United States Navy Table 6 (USN 6)

The standard USN 6 comprises 75 minutes at 18 msw, a 30-minute linear decompression to 9 msw, and 150 minutes at 9 msw. The attendant breathes air during all the treatments and oxygen during a 30-minute linear decompression from the final treatment depth to the surface. USN 6 may include additional attendant oxygen breathing at 9 msw.

In addition, 26 non-hyperbaric DHS were collected from 14 of the attendants following normal ward duties or following ‘sham’ (3 msw) exposures conducted as part of a separate randomised controlled clinical trial. In total, 516 health surveys from 46 attendants were analysed.

EVALUATION OF DECOMPRESSION PRACTICE

The relative decompression stress of each of the attendant hyperbaric exposures was estimated from the pressure/time/breathing gas profile using the JAP98–1 model.[8] The JAP98-1 model returns the risk of DCS (pDCS) but was not specifically developed using low-risk attendant hyperbaric exposures. Therefore, the calculated pDCS should be considered a measure of the relative decompression stress rather than an accurate assessment of the risk of DCS for attendants. In brief, in the JAP98–1 model, nitrogen partial pressure in three compartments changes during gas breathing at different pressures, and pDCS increases whenever ambient pressure drops below compartment gas partial pressure by a specific threshold.

Unlike most decompression models JAP98–1 attributes a direct action of oxygen on decompression whereby high inspired oxygen partial pressure can reduce the rate constant for nitrogen wash-out as might be expected if tissue blood flow were reduced. The effect is to partially counteract the benefit of oxygen decompression. The JAP98–1 was calibrated by statistical best fit to a data set of 4335 well-documented experimental dives and DCS outcome, including 1013 dives using oxygen for decompression. The present implementation was written in GNU Fortran (EGCS version 1.1.2. The Free Software Foundation; 1999) and R (R base package version 1.4.1. The R Development Core Team; 2002). The pDCS was tracked over the daily pressure/time profile and subsequent 24 hours.

The DHS has been shown previously to correlate with the risk of DCS in occupational divers.[7] In our study it was used to measure decompression-related health status amongst chamber attendants during normal occupational compressed-air exposure. The contribution of hyperbaric exposure to DHS was evaluated by linear regression. To accommodate possible between-attendant variability we used a linear mixed-effect modelling approach. The full model investigated was of the form:

$$DHS_{ij} = \beta_{0i} + e_i + \beta_1 pDCS_{ij} + \beta_2 DUR_{ij} + \beta_3 MSW_{ij} + e_{ij}$$

which comprised the dependent variable DHS and fixed explanatory variables, pDCS, exposure duration in minutes (DUR), and treatment pressure in metres sea water (MSW). pDCS is included to rank the different hyperbaric exposures and non-hyperbaric data according to their relative decompression stress. DUR and MSW were included in the model to investigate any possible influence of hyperbaric exposure on health outcome other than via pDCS; for instance a longer treatment may cause fatigue not related to decompression stress.

Different subjects may describe their normal health status differently; this manifests as a different intercept (DHS at pDCS, MSW, DUR all equal 0) in the linear model. To accommodate this the 46 attendants were considered a random sample from a population where the intercept ($ß_0$) of the regression on the explanatory variables depends on the attendant. Subscript i denotes attendant, 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. To find the most parsimonious model, explanatory variables with non-significant parameters ($p > 0.05$) that therefore do not contribute to the model fit to the data were removed from the full model and the resulting reduced models again fitted to the data. Significant difference ($p \leq 0.05$) between nested models was evaluated by likelihood ratio test,

$$2(LL_f - LL_r) \approx X^2_{f-r}$$

where LL is the maximised log-likelihood of the model and f and r are the number of parameters in the full and reduced models respectively ($f > r$). For each model the data were examined for influential values (outliers with high leverage). Outliers were data with a 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.

All statistical calculations were performed using R software base package (version 1.4.1. The R Development Core Team; 2002) and the non-linear mixed effect package (version 3.1–23. Pinheiro J, Bates D, DebRoy S, Sarkar D; 2001).

Results

Daily health status of attendants was not influenced by the standard hyperbaric exposures used at the Royal Adelaide Hospital. During the modelling procedures two influential values were identified in the non-hyperbaric data and removed from all analysis (both DHS = 8). The remaining data are summarised in Table 1. There was no significant difference in DHS between the different treatment schedules or non-hyperbaric activities. The median interval between decompression and DHS was eight hours (interquartile range 5–12, n = 500).

For USN 6 the pDCS was calculated using the JAP98–1 model for each individual exposure as this schedule can be extended for therapeutic reasons and the period of attendant oxygen breathing varied. The lowest value resulted from an extended schedule with 90 minutes of oxygen breathing for the attendant, and the highest risk from a standard duration schedule with only 30 minutes of oxygen breathing. The pDCS for the other schedules were calculated for a typical exposure and do not account for small variations in descent time. The pDCS for all hyperbaric exposures was calculated as the weighted mean of the schedules in the analysed data. Schedules 10:90:30 and 14:90:30 are slightly under- and over-represented, respectively, in the analysed data compared to the actual frequency of their use during the data collection period; the weighted mean pDCS for all hyperbaric exposures calculated for the actual frequency of schedule use is 0.226%.

The results of the modelling of DHS are shown in Table 2. The full model (model 1) shows that the explanatory variables MSW and DUR did not significantly influence DHS. Removal of MSW and DUR produced a simpler model (model 2) that fitted the data equally well. As DHS is a validated measure of decompression-related health outcome we did not expect MSW or DUR to have an influence separately from their contribution to pDCS. However, in model 2 the explanatory variable pDCS did not significantly influence DHS. Removal of pDCS resulted in the null model (model 3) that fitted the data equally well and is preferred as the simplest explanation of the data. In the null model, DHS only varied between attendants and is not different between non-hyperbaric duties or any of the hyperbaric

Table 1. Data summary. Mean DHS, 95% confidence interval (CI), number of surveys (n), number of attendants, and decompression stress index (pDCS: JAP98–1) for each hyperbaric treatment schedule and normal ward duties (non-hyperbaric), and combined means for hyperbaric exposures only and for all data (total)

Schedule	Mean DHS	95% CI	n	Attendants	pDCS (JAP98–1)
Non-hyperbaric	2.4	1.8 – 3.0	24	14	0
10:90:30	2.3	2.0 – 2.5	287	40	0.02%
14:90:30	2.2	1.9 – 2.5	109	20	0.50%
18:60:30	2.0	1.7 – 2.3	78	25	0.87%
USN Table 6	2.3	1.7 – 3.0	16	10	0.46 – 3.27%
All hyperbaric	2.2	2.1 – 2.3	490	45	0.27%
Total	2.2	2.1 – 2.3	514	46	

Table 2. Model comparisons. Estimated value, standard error (SE) and significance (p) of model parameters and log-likelihood (LL) comparison of model fits to the data

Model	Variables	Parameter Estimate	(SE)	p	df	LL	Test	Likelihood Ratio	p
1	**Intercept**	2.8	(0.40)	<0.0001	6	-880.8			
	pDCS	37	(18)	0.0272					
	MSW	-0.04	(0.02)	0.0573					
	DUR	-0.001	(0.002)	0.5800					
2	**Intercept**	2.2	(0.2)	<0.0001	4	-882.7	1 vs 2	3.706	0.1568
	pDCS	14	(11)	0.2143					
3	**Intercept**	2.3	(0.2)	<0.0001	3	-883.5	2 vs 3	1.545	0.2137

exposures. The standard deviation of DHS between attendants was 1.3 (not shown) with 95% CI not including zero, indicating that attendants differed in how they described their normal health status.

The present modelling does not account for censoring of the data; censored data show only that the event of interest has not occurred at the time of data collection. In the present data, symptoms of DCS (and a resulting higher DHS) may have arisen after the decompression health survey was completed. However, any censoring is probably not severe as symptom onset occurs by eight hours (mean interval between hyperbaric exposure and health self-assessment) in approximately 90% of cases of DCS.[9]

During the period of data collection, three attendants were treated for symptoms of DCS (joint pain, fatigue). In each case the symptoms resolved with a short series of hyperbaric oxygen treatments. Only one of these attendants contributed a decompression health survey following the putative causative chamber dive (DHS = 11). This incidence (3/1531) was the same as the expected incidence of DCS according to the JAP98–1 model calculated from the weighted mean pDCS of all hyperbaric exposures (0.226%). This incidence is not significantly different from the incidence of 5/7197 decompressions during the preceding 12 years using these schedules (Yate's corrected Chi-square, p = 0.31). Of interest, however, is that five of the eight incidents were clustered in an otherwise unremarkable 16-month period.

Discussion

Despite a non-zero incidence of DCS symptoms, mean attendant health status is not adversely affected by the routine compressed-air exposures and oxygen decompressions used at the Royal Adelaide Hospital, being no different from that following non-hyperbaric ward duties. The overall incidence of treated symptoms of DCS amongst attendants at the Royal Adelaide Hospital of eight out of 8724 decompressions (approximately nine per 10,000) is similar to the reported incidence of DCS from other individual hyperbaric facilities, which ranges from eight to 42 per 10,000 decompressions.[1] However, approximately five DCS per 10,000 decompressions (23/49,349) is reported from a survey of 33 North American hyperbaric facilities,[1] suggesting a possible bias towards publication of positive incidence from individual facilities.

Our figures suggest the incidence of DCS in attendants may be higher than generally accepted. It is likely that there is under-reporting of DCS amongst attendants in some facilities, as such under-reporting is commonplace in many diving groups where untreated DCS probably exceeds treated DCS.[7,10] Additionally, there may be some high-risk decompression protocols in use that need to be identified and appropriately modified. For example, later revisions of the US Navy Diving Manual have twice increased the duration of attendant oxygen breathing for decompression following USN 6. All attendant decompression protocols should be subject to this sort of scrutiny.

The DHS reported by attendants was unrelated to the pDCS calculated according to the JAP98–1 model. This is contrary to what has been found for occupational underwater air diving.[7] There are several possible reasons for the present lack of association. The JAP98–1 model may be inappropriate for attendant exposures, the DHS may not be a good measure of outcome in this context or there may be insufficient variation of pDCS in the present data set.

Decompression models, like any models, may fail if applied outside the conditions for which they are tested, and there are no decompression models developed for the specific needs of chamber attendants. The JAP98–1 model was developed for underwater diving, but specifically to explain the effects of breathing high fractions of oxygen during decompression, where other models fail.[8] The JAP98–1 model was chosen since high oxygen fraction breathing is a feature of attendant decompression procedures. The choice seems reasonable since the model predicted the overall incidence of treated symptoms of DCS in these attendants. However, the JAP98–1 model is calibrated against a data set with high incidence of DCS (5.4%) and may not appropriately estimate the very low-risk attendant decompression procedures. It is interesting to note that the USN 93 decompression model,[11] which was not optimised for oxygen breathing decompression and was predictive of occupational underwater air diving outcome,[7] predicted zero incidents of DCS during the present period of data collection. This highlights the need to use appropriate models to plan attendant decompression procedures.

The DHS has been well validated for measuring decompression-related health outcome.[6] Since DCS is rare, it is not possible to validate the DHS for specific occupational groups. However, the DHS correctly identified the one incident of treated DCS amongst the present attendant data. The most likely reason that pDCS was not predictive of DHS in the present data is that the majority of the data were collected following the same three treatment schedules, which have three, low, calculated pDCS. Firstly, this decompression stress may be too low to influence mean attendant health status. Secondly, the DHS can only take integer values, and in occupational divers increased one unit for every 1% increase in pDCS,[7] whereas the majority of the present data spanned less than 1% pDCS.

Data collection is being extended to other hyperbaric facilities with the aim of acquiring data from a larger variety of decompression protocols (and pDCS) and supplementing currently under-represented schedules. More information regarding participation in this multi-centre trial is available from the authors. Such a data set will allow rational design of attendant decompression protocols.

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