Health outcome following multi-day occupational air diving

D. J. DOOLETTE

Anaesthesia & Intensive Care The University of Adelaide, Australia, 5005

Doolette DJ. Health outcome following multi-day occupational air diving. Undersea Hyperb Med 2003; 30(2): 127-134 - Acclimatization to decompression stress has been reported in caisson workers and helium-oxygen divers; however the alternative notion that the risk of decompression sickness increases with successive days of diving is widespread. We examined 201 multi-day series of 2 to 29 diving days identified retrospectively in a database of occupational air dives for evidence of acclimatization or sensitization. Decompression related health status was measured using a self-administered diver health survey; resulting scores were analyzed by linear modelling. Daily diving consisted of 1 - 3 dives each to mean maximum depth of 17.2 (SD 3.9) meters seawater for a mean duration of 23 (SD 17) min. Daily diver health scores increased with calculated daily risk of decompression sickness but were not influenced by the order of dives in multi-day series. Poor health outcome indicated by treated decompression sickness and diver health scores > 8 occurred early in multi-day series. There was no evidence of sensitization to decompression stress whereas the timing of poor health outcomes suggests an element of acclimatization.

Decompression Sickness, risk factors, health surveys, health status, diving, occupational health

INTRODUCTION

Decompression sickness (DCS) is caused by tissue bubble formation from excess dissolved gas during reduction in ambient pressure (decompression), such as occurs in undersea diving. Bubble formation with decompression is common but does not always result in DCS and there is considerable intra- and inter-individual variability in both bubble formation and susceptibility to DCS (1).

Successive daily decompressions appear to reduce DCS risk. In an analysis of 40,000 decompressions of caisson workers, the incidence of DCS drops from approximately 12% to 1% over the first 10 to 15 daily decompressions (5 days per week) and this acclimatization is lost during 2 to 10 days break from compressed air work (2). Similarly extensive analyses of underwater dives have not been reported but four evenly spaced work-up dives in two weeks prior to experimental helium-oxygen dives resulted in much lower incidence of DCS [2/32] compared to non-worked up divers [14/31] (3). Similar acclimatization is suspected for air dives and avoided in acquiring decompression schedule validation data (4, 5).

Despite evidence to the contrary, the notion that the risk of DCS increases (sensitization) with multi-day diving has spread through some diving communities in recent years. The origin of this notion is unclear, but it may be result from the observation that multi-day diving is common among divers treated for DCS (6, 7) although with unknown underlying diving patterns such data do not measure risk. A contrary datum also without denominator is that diving
injuries, mostly DCS, reported to the Divers Alert Network occur most commonly on the first day of diving (8). Multi-day diving remains common practice in some recreational and occupational diving populations and acclimatization or sensitization is not confirmed for air diving. Multi-day diving is examined in occupational tuna farm air divers for evidence of acclimatization or sensitization. Health status is used as the indicator of decompression outcome with the hypothesis that health outcome following decompression does not change during successive days of diving.

METHODS

Decompression related health outcome during extensive multi-day diving was examined in a database of occupational (tuna farm) diving logs and post-decompression health status describing 1376 days of air diving during a three-year period. A portion of this database has been previously analyzed with respect to daily (as opposed to multi-day) decompression outcome and the data collection described in detail (9). The data collection method was approved by the University of Adelaide Human Ethics Committee and conducted in accordance with the National statement on ethical conduct in research involving humans, 1999. Data collection was rotated through different diving operations for typically 1 to 2 month periods and was voluntary and is therefore not a complete record of diving in the industry. Electronic dive log information was uploaded from diver carried depth/time recorders and supplied by their employers. Health status was assessed from self-administered diver health surveys completed and returned by the divers following diving.

The diver health survey has been described in detail elsewhere (10) and is an inventory of 9 standardized items and responses covering 5 symptoms of decompression illness (parasthesia, rash, balance, fatigue, and pain), 5 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 diver health score (DHS) ranges from 0 (well) to 30 and can be analyzed as interval data. DHS > 8 are indicative of decompression illness among divers presenting to recompression facilities.

Either electronic dive log or diver health survey (which contains limited dive log information) alone was considered as sufficient evidence of diving exposure. Diving was considered multi-day if logged on consecutive days (67% of intervals) or two days apart (33% of intervals). This definition of multi-day diving was used to reduce incorrect splitting of multi-day series due to missing dive logs. Multi-day series were only included for analysis if health status was measured on at least 2 days. Using these criteria, 201 multi-day series of dives of 2 to 29 diving-day duration (total of 920 diving days) and conducted by 35 divers were identified. Health status was measured at the end of 820 of these diving days (11% missing health data).

Machine-readable depth/time profiles of full diving exposure were available for 444 days. To provide an indication of decompression stress for each unique exposure, the NMRI linear-exponential kinetics probabilistic decompression model (USN93) (11) was used to calculate the probability of DCS (pDCS). An implementation of the USN93 model similar to that previously described (12) and using published parameters (11) was written in the Visual BASIC programming language (Version 6.0. Redmond, WA, USA: Microsoft Corp; 1999). pDCS was tracked over the daily depth/time profile and subsequent 18 h.

The contribution of daily pDCS and order of the dives in the multi-day series (ORDER) to DHS was evaluated using a linear mixed-effect modelling approach to accommodate inter-diver
variability, repeated measures, and design imbalance. The full model investigated was of the form:

\[ \text{DHS}_{ij} = \beta_0 + \beta_1 \text{pDCS}_{ij} + \beta_2 \text{ORDER}_{ij} + \epsilon_{ij} \quad \text{model 1} \]

The 35 divers were considered a random sample from a population where the intercept (\( \beta_0 \)) of the regression on the explanatory variables depends on the diver (random effect), as has been previously shown (9). Subscript i denotes divers, subscript j denotes days, and \( \epsilon \) denotes error.

Regression models were fit to the data and parameters estimated by maximising the likelihood. Non-significant parameters (\( p \geq 0.05 \)) were removed and the resulting reduced models also fit to the data. Significant difference (\( p < 0.05 \)) between nested models was evaluated by likelihood ratio test, \( 2(LL_f - LL_r) \approx \chi^2_{f-r} \), 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 was examined for influential values (outliers with high leverage). Outliers were data with standardised residual more than 2 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.

In another approach, DHS was examined using ANOVA with diving days as a within group (repeated measure) factor. Two balanced data subsets were extracted: the first 5 diving days from multi-day series of 5 or more diving days (66 series) and the first 10 diving days from multi-day series of 10 or more diving days (16 series). Missing DHS values were handled by multiple imputation, a Monte Carlo technique where the missing values are replaced by simulated versions (13). Five simulated complete data subsets were produced using NORM software (Version 2.03. University Park, PA, USA: Shafer JL; 2000), analyzed separately, and F statistics and p values reported as mean (SD). All other 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

Diving exposure. Electronic dive log information was available for 575 days of the 920 days of multi-day diving. Diving was consistent with use of DCIEM standard air diving schedules (14), as is required for all occupational air diving in Australia. One to three dives per day (total of 806 dives) were conducted to a mean maximum depth of 17.2 metres seawater (SD 3.9, range 1.9 - 22.4, \( n = 806 \) dives) for a mean duration of 23 min (SD 17, range 1 - 116, \( n = 806 \) dives). Only uploaded depth/time profiles matched to diver health surveys were used to estimate the mean daily pDCS of 0.48% (SD 0.24%, range 0 – 1.33%, \( n = 444 \) days).

During the 575 days, dives occurred throughout daylight hours but were concentrated between 10:00 am – 12:00 noon (inter-quartile range). The exact surface interval between multi-day dives only could be calculated reliably for 296 days where electronic dive log information was available on consecutive days. The mean multi-day surface interval between dives on consecutive days was 22 h 31 min (SD 2 h 26 min, range 15 h 06 min – 31 h 06 min). There were only 6 intervals less than 18 h and analysis using the USN93 model indicated no residual gas burden at the end of these intervals. It is reasonable to assume that multi-day diving was repetitive within, but not across days, and that the multi-day surface intervals for the full data set followed a bimodal distribution with 616 (67%) centred on approximately 22 h 30 min and 304
(33%) centred on approximately 46 h 30 min. The median number of days without diving prior to a multi-day series of dives was 4 days (range 3 - 347 days, n = 181); values near the median are probably real whereas the few values at the upper end of the range probably represent missing log information.

**Health outcome:** The regression analysis summarized in Table 1 shows that DHS increases with the explanatory variable pDCS but is not influenced by the order of dives in the multi-day series (ORDER). Models 1 to 3 were fit to a data subset comprising those days with pDCS values with one influential value omitted (443 days, 28 divers). In models 1 and 2 the explanatory variable pDCS makes a significant contribution to the regression with the parameter estimate indicating an approximate 0.9 DHS unit increase for each 1% increase in pDCS. In model 1 the parameter estimate for explanatory variable ORDER indicates a small decline in DHS for each successive day diving, but this parameter failed to reach significance. In addition, this trend towards better health status during successive days diving is not of practical importance; Figure 1 shows the mean DHS during the multi-day diving series, the confidence intervals all fall within the envelope of acceptable health outcome for operational dives in this population described by DHS ≤ 5 (10) and the overall change in mean DHS is less than one unit, the resolution of the diver health survey instrument. Removal of the variable ORDER (model 2) produced similar fit to the data as model 1 and was a significantly better fit than the null model (model 3). Models 4 and 5 examine ORDER but not pDCS in the larger data subset comprising all DHS values (820 days, 35 divers); there were no influential values. Similarly, the parameter estimate for explanatory variable ORDER (model 4) is not significant and the null model (model 5) where DHS only depends on the diver fits the data equally well. DHS varied between divers; the between-diver standard deviation of intercept (random effect, not shown) was approximately 1 DHS unit with 95% confidence intervals not including zero in all models. pDCS did not vary with the order in the multi-day series (not shown).

Repeated measure ANOVA of the imputed data subsets indicated no significant change in DHS during 5 days of multi-day diving F = 1.94 (SD 1.33), p = 0.28 (SD 0.33) or during 10 days of multi-day diving F = 0.814 (SD 0.32), p = 0.60 (SD 0.25). Similar analysis was performed on only consecutive days of diving, data not shown, and also indicated no change in mean DHS.

DHS > 8 is indicative of DCS in divers presenting to recompression facilities (10). There were 10 days with DHS > 8, occurring during 9 multi-day series. All these high DHS occurred in the first 4 days of diving: day 1 (n = 5), day 2 (n = 2), day 3 (n = 1), and day 4 (n = 2). Most common reported symptoms were fatigue (n = 9), difficulty concentrating (n = 6), joint pain (n = 6), difficulty with balance (n = 3), and parasthesia (n = 3). Although the diver health survey is not sufficiently reliable to make definitive diagnosis of DCS in individuals, it is possible some of these high score represent untreated DCS.

There were no treated incidents of DCS among multi-day series included in the analysis, but there were two treated incidents of DCS amongst this group of divers during the period of data collection. One diver was treated for DCS (DHS = 10) following the second dive of the season after several months without diving. Although this diver had dived the previous day, DHS was not available for that day and the series was therefore not included in the analysis. Another diver was treated for DCS (DHS = 11) following the first dive after a 6-day break without diving.
Table 1. Model Comparisons

<table>
<thead>
<tr>
<th>model</th>
<th>variables</th>
<th>parameter</th>
<th>estimate(95% C.I.)</th>
<th>d.f</th>
<th>LL</th>
<th>Likelihood ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>intercept</td>
<td></td>
<td>2.0 (1.4, 2.6)</td>
<td>&lt;0.0001</td>
<td>5</td>
<td>-781.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pDCS</td>
<td>90 (33, 147)</td>
<td>0.0022</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ORDER</td>
<td>-0.03 (-0.07, 0.00)</td>
<td>0.0640</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>intercept</td>
<td></td>
<td>1.9 (1.3, 2.5)</td>
<td>&lt;0.0001</td>
<td>4</td>
<td>-783.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pDCS</td>
<td>90 (32, 147)</td>
<td>0.0025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>intercept</td>
<td></td>
<td>2.3 (1.8, 2.8)</td>
<td>&lt;0.0001</td>
<td>3</td>
<td>-788.0</td>
</tr>
<tr>
<td>4</td>
<td>intercept</td>
<td></td>
<td>2.5 (2.0, 3.0)</td>
<td>&lt;0.0001</td>
<td>4</td>
<td>-1521.8</td>
</tr>
<tr>
<td></td>
<td>ORDER</td>
<td></td>
<td>-0.02 (-0.04, 0.01)</td>
<td>0.2186</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>intercept</td>
<td></td>
<td>2.5 (2.0, 2.9)</td>
<td>&lt;0.0001</td>
<td>3</td>
<td>-1522.6</td>
</tr>
</tbody>
</table>

Figure 1. Mean DHS (y-axis) following decompression during multi-day diving series, the maximum acceptable DHS for diving operations is 5 and the maximum possible DHS is 30. Diving days (x-axis) are either consecutive or one day apart. The error bars are 95% confidence intervals and above the bars are number of DHS scores and (number of cases). The inset graph shows the mean or single DHS for later days of long multi-day series (1 to 5 cases).
DISCUSSION

The present results show that mean decompression related health status did not change significantly during this large number of long multi-day series of occupational, working, underwater air dives. These dives were recorded from a relatively stable population of frequent, occupational air divers. In the context of these diving practices multi-day diving does not appear to pose an additional health risk in the form of sensitization to decompression stress. A limitation of this finding is that owing to infrequent occurrence of DCS the evidence is based on an indirect outcome measure (DHS). Additionally, whereas DHS increased with decompression stress, in the absence of an alternative this latter was calculated using a model that is not calibrated against multi-day diving data.

A possible explanation of lack of acclimatization effect in the mean DHS is that these divers may remain substantially acclimatized to decompression stress even after 3 to 4 days without diving. This same diving break is considered to minimize but perhaps not eliminate the effect of acclimatization in US Navy decompression validation data (4, 5). Alternatively, both the mean decompression stress and mean DHS in the present report were relatively low and acclimatization may not be evident in such exposures. There was some evidence of acclimatization in poor health outcomes as the few incidents of treated DCS and of DHS suggestive of untreated DCS occurred early in multi-day series. Such evidence of acclimatization is consistent with reports of reduced incidence of DCS with multi-day experimental helium-oxygen dives (3, 5) caisson work (2), and large animal experiments (15). A physiological basis of acclimatization is not known but could involve reduced bubble formation or reduced host response to bubbles; neither of these processes is as yet well defined. Ultrasonic Doppler detected central venous gas bubbles do not necessarily cause DCS but are an accessible indicator of bubble formation (16). There was no change in Doppler scores in 14 divers conducting 12 consecutive days of single air dives (17) or in 20 divers conducting 6 consecutive days of 4 repetitive air dives per day (18). One diver was excluded from the former study as a result of DCS on the first dive and the remaining divers reported minor symptoms of DCS (pruritis and fatigue) that diminished with successive days (17,19). The daily cumulative decompression stress (USN93 model, calculated by this author) in these previous studies is 8 fold or greater than that in the present report. The Doppler studies were of dry, chamber exposures with variable or no exercise whereas the present report comprised actual working dives in 11°C to 23°C water. Doppler scores are highly variable and in small studies a considerable proportion of individuals had no Doppler detectable bubbles on any day. A recent report of Doppler scores collected in the field during 101 days of underwater recreational diving (67 divers) found that the occurrence of high Doppler scores declined 20 to 30% over 6 to 8 days of multi-day diving (20).

In view of evidence in support of acclimatization, the perception by some that risk of DCS increases with multi-day diving seems puzzling, but a theoretical argument may be analogy with repetitive diving. A dive is repetitive if begun while the body retains excess dissolved or free gas resulting from a previous dive. This biophysical status is approximated within decompression planning methods by defined surface intervals between dives, typically between 15 min and 18 h. Animal studies show that repetitive dives have greater risk of DCS than a combined duration single dive (21). This increased risk is thought to be due to growth or perhaps redistribution of pre-existing bubbles during subsequent compressions-decompressions.
Frequent dives during several days may represent a continuous repetitive dive series across days and risk of DCS may increase over successive days. However, the simulated recreational dives described above approach an across days repetitive pattern without incident (18). The reported incidence of DCS is impressively low in other large series of repetitive, multi-day open water dives, although these are not studies of acclimatization per se, and the depth/time profiles are not fully described. Five dives per day for 4 days resulted in 7 incidents of DCS out of 77680 dives, although all occurred on day 3 or 4 of these short multi-day series (22). Two 20 min dives per day, 5 to 6 days per week, for an unknown number of weeks, resulted in only 3 incidents of DCS out of 7523 dives (23).

The evidence of the present and previous studies suggest that multi-day air diving using established decompression schedules does not cause an increased risk of DCS. Moreover, the majority of the evidence points to acclimatization to DCS with successive days of air diving. Divers may be at highest risk of DCS upon return to diving following a break of several days.

ACKNOWLEDGMENTS

This work was supported in part by WorkCover Corporation, South Australia and the Health Science Research Committee, the University of Adelaide.

REFERENCES