Exceeding the limits - estimated tissue pressures among Western Australian recreational divers

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Key words
Scuba diving, recreational diving, decompression, models, diving tables, research

Abstract

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Introduction: In Western Australia (WA), approximately 40 divers suffer decompression sickness per year, many after exceeding accepted safe time and depth limits.

Methods: Divers on organised recreational scuba dives wore depth/time loggers. Dives ('case' dives) exceeding the Diving Science and Technology gas-content limits (M-values) were matched to control dives made at the same dive site at the same time during which no M-values were exceeded. Potential risk factors for decompression sickness were evaluated using a conditional logistic regression model.

Results: A total of 1,032 organised recreational dives were recorded. Case dives (n = 38) were more likely made by females, deeper than other divers in the water at the same time. They were also made by divers less likely to have previously dived as deep.

Conclusions: One in 27 recreational dives studied exceeded an M-value during the dive, but none on surfacing. We recommend that dive organisers in WA continue to encourage recreational dive groups to watch their displayed remaining no-stop time and to dive within the limits of their training and experience. This study successfully utilised periodic depth/time dive profile analysis using freely available software.

Introduction

The first reported experimental attempt to reduce the incidence of decompression sickness (DCS) was conducted for the Royal Navy by physiologist JS Haldane.[1] Dive tables were developed based on a gas-content model, where theoretical compartments of varying (parallel) blood perfusion and inert gas solubility were defined by the respective times they would take to half-fill with nitrogen, known as 'half-times'.[2] In 1965, Workman, in developing tables for a wider range of diving exposures for the US Navy, changed the limits of tolerable decompression stress from supersaturation ratios to maximum pressure differentials, known as 'M-values'.[2,3] During ascent, divers are advised not to ascend above the depth at which any half-time compartment reaches its M-value. Once the pressure differential between tissue compartment and environment is reduced, the diver may recommence ascending. By definition, in recreational no-stop diving, a direct ascent to the surface may be made at any time during the dive without exceeding an M-value.[4]

Gas-content limited models based upon M-values have been validated for recreational no-stop dives to 40 metres' sea water (msw) depth with an ascent rate no greater than 18 m min^{-1}.[2,3,5–8] One of these in popular use in Western Australia (WA) is the Diving Science and Technology (DSAT) model, used by the Professional Association of Diving Instructors, responsible for the majority of diver certifications in WA, and incorporated into at least one brand of recreational dive computer. Since their release in 1988, millions of divers have made millions of dives using the DSAT tables.[9] The majority of recreational dives using the DSAT tables are probably made well within prescribed depth/time limits. After two decades, the DSAT model appears to adequately limit no-stop recreational divers to an acceptably low probability of DCS.[10] The model was adapted for dive computer use by reducing the M-values to account for real-time depth estimation and remaining 'no-stop' time calculation, and by an increasingly severe threshold level for reducing surface interval credit to account for multi-day, repetitive diving.[11]

Between 2000 and 2009 inclusive, a mean of 39 divers per year were treated for DCS at the Fremantle Hospital hyperbaric facility in WA (Sakar K, personal communication, 2010). As not all divers carry downloadable personal dive computers, it remains uncertain which injured divers have exceeded accepted, safe time and depth limits. Recreational dives made in WA can be divided into two groups; self-organised dives, where a small group or pair of divers select a site suited to their intended purpose (e.g., to catch crayfish), and organised group dives, where a dive supervisor selects the site to accommodate the range of abilities within a larger group (e.g., a dive club or charter boat). The present study examined organised group dives to determine which potential factors increase the risk of a dive exceeding safe depth-time limits.

Methods

Eighteen dive businesses or dive clubs were invited to participate in the study and to allow a researcher (PB) to accompany their dives to collect data. One dive business declined to participate. The study was approved by the Human Research Ethics Committee of the University of Western Australia.

Between February 2008 and March 2009, the researcher met these organised dive groups at popular dive sites in WA and invited divers to participate prior to the commencement of 35 separate dive series. Divers were allowed to participate or decline on multiple occasions. Participants were provided an information sheet, asked to sign a consent form and completed the Diver's Alert Network Project Dive Exploration (PDE) diver data form. A Sensus Ultra data-logger (ReefNet, Ontario) was attached to the front of each participating diver's buoyancy control device and a dive record listing the site details, entry/exit times and cylinder pressures was completed for each dive group. The loggers had a pressure resolution to 1 mbar, with an accuracy equivalent to 30 cm change in depth in seawater. Sampling was at 10-second intervals. Starting and returning air pressure and cylinder volumes were recorded on the dive record. Post-dive recollections regarding warmth and workload were recorded on the PDE dive-data form as the diver exited the water. Lastly, 15 additional questions addressing potential risk factors were asked by the researcher. These recorded familiarity with the dive site and scuba unit worn, pre-dive depth/time planning, previous dives to the same depth and/or with the same dive buddy and personal dive computer use.

After each dive, data from the loggers were downloaded onto a laptop computer. Segmented dives, such as if a diver surfaced momentarily during a dive, were manually cross-checked to the dive record and joined into single dives where appropriate. Once data entry was completed, every twentieth dive ($n = 52$ dives, made by 47 divers) was physically checked for accuracy against the original paper data-collection forms. Of 3,380 items checked, 3,362 (99.5%) were found to have been entered and coded correctly.

To control for environmental conditions, dives in which a diver exceeded a DSAT M-value were classed as 'case' dives, and dives made at the same dive site and at the same time by another diver who did not exceed a DSAT M-value were classed as 'control' dives. Group dives where no diver exceeded an M-value were not considered for further analysis.

Analysis

Dive profile data were exported to the statistics program R and analysed using the package *SCUBA*.[12] For recreational no-stop diving, DSAT uses a 60-minute half-time as the off-gassing rate when estimating the penalty to be applied to no-stop limits for repetitive diving.[3] In this study, however, Henry's law and Fick's first law of diffusion were used to predict gas washout between repetitive dives, with no limiting minimum half time (Baddely A, personal communication, 2008). Theoretical tissue tensions for the original eight DSAT compartments, (5, 10, 20, 30, 40, 60, 80 and 120 minute half-times), were estimated and re-imported into the database. Both ending and maximum compartment pressures were compared with M-values for the DSAT model, using the same conversion factor used by the package *SCUBA* (1 bar = 10.00 msw = 32.646 fsw).[3,12]

Maximum rate of ascent per dive in m min^{-1} was generated by multiplying the largest negative difference in depth over a 10-second interval by six. Diver certification was categorised arbitrarily as low (<10 open-water dives), medium (10–20 dives) and high (≥20 dives).[13]

The data were imported into SAS version 9.1 (Cary, North Carolina) and the distribution of variables tested for normality. Bivariate analyses were conducted for each factor, variables with expected cell counts of less than five were excluded from further analysis. These included rare events such as cigarette use (1/38 cases), ascending faster than 18m min^{-1} (4/38 cases), reported panic (1/38 cases), not making a safety stop (3/38 cases), and not using a dive computer (2/38 cases). Four significant factors were fitted to a conditional logistic regression model.[14] This was achieved by numbering each organised dive consecutively and stratifying the regression by dive number. Non-significant differences ($P > 0.05$) between case-dives and control-dives were removed by backwards elimination.

Results

A total of 1,032 organised recreational dive profiles were collected from sites throughout WA, involving 137 organised group dives with a mean of 7.5 divers per organised group. The opportunity to participate was presented to 503 potential dive-series participants on the first dives of organised dive series and 321 of these 503 dive series (64%) were recorded. Figure 1 illustrates the relationship between dive series, individual divers and group dives.

Figure 1
Relationship between dive series, divers and group dives

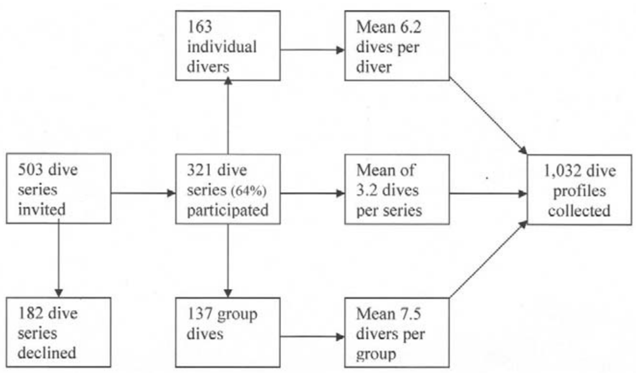
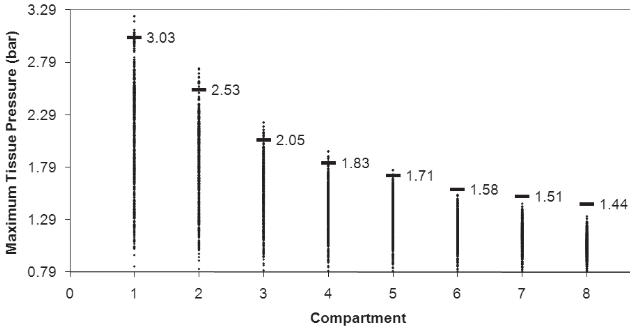


Figure 2
Maximum tissue pressure estimates during 1,032 dives; M-values for each DSAT tisue are shown by the horizontal bars



Recorded depths ranged from one to 45 msw, water temperatures ranged from 15ºC to 29ºC and vertical visibility was to the bottom or at least 20 m at the start of 792 (77%) of the dive profiles. Of the 163 individual divers who participated in one or more dive series, 117 (72%) were male and 46 (28%) female, with mean ages of 42.6 years (range 21–65, sd 10.0) for males and 38.7 years (range 24–58, sd 9.4) for females (Wilcoxon rank sum test $P < 0.01$). As the majority of dives were collected from live-aboard dive boats, bivariate tests were conducted to assess diver heterogeneity across dive platforms. Overall, there were no significant differences between the divers who dived from live-aboard boats (656 dives) and those who made day-trips (376 dives).

Figure 2 shows that the majority of dives resulted in maximum tissue pressures lower than the corresponding recommended M-values. Of the 1,032 recorded dive profiles, at least one DSAT M-value was exceeded during 38 dives (3.7%). These 38 dives were matched to 152 control dives in which divers at the same site on the same occasion recorded depth-time profiles that were estimated to have not exceeded any of the eight DSAT compartment M-values. Table 1 summarises half-times and M-values for the case dives for each of the eight DSAT compartments in the *SCUBA* package, the estimated maximum value reached based on the profiles recorded and the frequency with which each M-value was exceeded.

No shore dives exceeded an M-value. The proportion of dives exceeding an M-value was the same (4%) for both day-boat and live-aboard dives. When comparing case dives with control dives, the difference between the two groups on univariate analysis reached a P-value ≤ 0.01 in 10 of the many variables considered. (Table 2).

On surfacing, none of the case dives exceeded an M-value. As their maximum rates of ascent were actually higher, this suggests decompression was completed in-water before the final ascent.

MULTIVARIATE ANALYSIS

Nine of the 190 dives in the case/control set studied were not considered due to missing variables, leaving 181 dives for analysis. Adjusted odds ratios and confidence intervals for divers exceeding an M-value are given in Table 3. The three main risk factors for exceeding at least one M-value were female divers, diving to deeper average depths and being less likely to have been as deep as the maximum depth before.

Discussion

In this study, it was found that 38 of 1,032 dives exceeded an M-value. After taking into account the stratified nature of the data, these 'case' dives, when compared with 152 'control' dives were more likely made by females; this may have been due to the effect of clustering, as two divers accounted for 21 of the 38 (55%) cases. However, case dives were matched to control dives made in the same location at the same time and not to other dives made by individual divers, as in another recent study.[15] The relatively small sample size should be taken into account when interpreting these results.

The most commonly exceeded M-values were for the 10- and 20-minute half-time compartments (Table 1), which

Table 1
Theoretical compartment M-values and frequency and maximum values exceeded on 1,032 dives

Compartment	Half-time (mins)	Max. DSAT M-value (bar)	Divers exceeding M-value	Maximum estimated tissue pressure (bar)	Difference
1	5	3.03	14 (1.4%)	3.23	(+0.19)
2	10	2.53	34 (3.3%)	2.73	(+0.20)
3	20	2.05	29 (2.8%)	2.21	(+0.17)
4	30	1.83	14 (1.4%)	1.94	(+0.11)
5	40	1.71	6 (0.6%)	1.76	(+0.05)
6	60	1.58	0	1.52	(-0.05)
7	80	1.51	0	1.44	(-0.07)
8	120	1.44	0	1.32	(-0.12)

Table 2
Univariate differences between case and control dives

Variable	Case dives (*n* = 38)	Control dives (*n* = 152)	*P*-value
Sex ratio (female:male)	23:15	46:106	<0.01
Median weeks since previous dive	1.0	2.6	<0.01
Median years since certification	10.0	5.0	0.08
Number of dives in own scuba unit	80	48	<0.01
Deeper maximum depth (msw)	30.0	25.1	<0.01
Deeper average depth (msw)	16.0	12.3	<0.01
Not been as deep before	16/38 (42%)	23/152 (15%)	<0.01
Maximum depth planned pre-dive	6/38 (14%)	86/152 (53%)	<0.01
End dive with <50 bar gas	2/38 (5%)	36/152 (24%)	0.01
Felt cold during dive	13/38 (34%)	12/152 (8%)	<0.01
Maximum ascent rate (m min^{-1})	12.6	11.3	0.07
Able to state a 'safe' ascent rate	18/38 (47%)	110/152 (73%)	<0.01

would be relatively fast to equalise if they off-gassed at an exponential rate, as predicted by Haldane and assumed in the package *SCUBA*.[1,12] These tissues have also been found to be associated with higher post-dive bubble scores.[16] The exponential off-gassing rate used in this study to predict repetitive dive penalties may explain why no cases were estimated to have surfaced with tissue pressures in excess of an M-value (i.e., with omitted decompression). If a 60-minute limiting half-time had been used in our study, as is used by DSAT, then it is possible more of the repetitive case dives may have exceeded an M-value at the surface. There is, however, no evidence that any diver ignored the advice offered by a dive computer worn during this study.

That case dives were made by divers who had not been as deep before was a novel finding. No shore dives exceeded an M-value, which may have been due to the shallower depths associated with diving close to shore. This suggests dive organisers may be effective in preventing divers exceeding an M-value by carefully selecting dive sites.

Table 3
Overall risk factors for exceeding an M-value

Risk factor	Adjusted OR	(95% CI)	*P*-value
Female vs. male	5.63	(1.86, 17.03)	<0.01
Deeper av. depth	10.45	(3.02, 36.12)	<0.01
Not as deep before	14.49	(3.11, 66.67)	<0.01

The limitations of this nested case-control study include that no data were collected from non-participants. Therefore, it is unknown if non-participants differed to participants, nor if they declined (or participated) at more than one dive series. How organised recreational dives might differ from self-organised dives was also not explored, and caution is advised before generalising these findings to all recreational divers.

In conclusion, the majority of recreational divers in this study appeared to stay within accepted recreational diving depth/time limits and none are thought to have surfaced with omitted decompression obligations. This should be reassuring to the recreational diving industry in WA. Naturally, we nevertheless recommend dive organisers in WA encourage recreational dive groups to watch their displayed remaining no-stop time and to dive within the limits of their training and experience, even though this study did not find evidence of divers doing otherwise. Furthermore, this study successfully utilised stepwise depth/time dive profile analysis software with finer resolution than traditional table-based depth/time analysis methods, which may be of interest to other researchers.

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