Rapid ascent and buoyancy problems among Western Australian certified recreational divers

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Abstract

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Introduction: We investigated risk factors associated with ascending rapidly and/or losing buoyancy control among recreational divers.

Methods: Dive and diver information were collected and depth/time loggers attached to recreational divers. Case dives recording an ascent > 18 m min^{-1} were compared with control dives made at the same dive site and time by divers recording ascents ≤ 18 m min^{-1}. In a second analysis, case dives with reported buoyancy problems were compared with control dives during which no problems were reported. Conditional logistic regression identified factors significantly associated with ascending faster than 18 m min^{-1} or reporting a buoyancy problem.

Results: In total, 1,032 dive profiles were collected. Case dives (n = 71) recording an ascent > 18 m min^{-1} were compared with 282 control dives. The main risk factor for making a rapid ascent was a loss of buoyancy control. Case dives were also shorter. Dives resulting in reported buoyancy problems (n = 68 cases) were compared with 320 control dives. The three main risk factors for buoyancy problems were an inability to describe how to check for neutral buoyancy, reportedly not being in control during the final ascent and maximum ascent rates that were a mean of 20% faster than during control dives.

Conclusions: Further research is necessary to identify if ascending rapidly is the result of a loss of buoyancy control, a lack of ascent rate reference or a failure to appreciate the potential consequences of ascending rapidly. The inability of many divers to describe how to check for neutral buoyancy also deserves attention.

Key words

Ascent, buoyancy, risk factors, recreational diving, scuba diving

Introduction

Recreational scuba diving is enjoyed by tens of thousands in Western Australia (WA).[1] Each year in WA, on average, 40 divers are treated for decompression illness (DCI) in the Fremantle Hospital hyperbaric facility and two divers die.[2,3] In addition, it is likely hundreds of people suffer minor diving-related morbidity such as marine stings, ruptured tympanic membranes and pain-only bends for which treatment is not sought.[4] The most serious forms of diving morbidity are severe DCI and near drowning, and the most common cause of death among recreational divers is drowning.[5] Loss of buoyancy control and/or rapid ascent are known diving problems that may lead to drowning and/or DCI.[6,7] Experienced together they are far more likely to result in injury than either problem alone.[8]

Rapid ascent was among the top ten contributory factors reported in 286 American diving fatalities.[9] Among 34 breath-hold embolisms, 13 involved rapid ascents and an analysis concluded "*rapid ascent is the most frequently reported contributory cause of incident*".[10] These problems are just as prevalent among WA divers as they are among other diving populations.[4] Information on the reasons why divers lose buoyancy control and/or ascend rapidly (i.e., faster than 18 m min^{-1}) is limited.[11] A Delphi survey of diving experts suggested the most likely reasons recreational divers experience these problems. They are shown in order of likelihood in Table 1.[12]

Despite the similarity of reasons suggested for each of these dive problems a recent cross-sectional analysis of 46,801 recreational open-circuit scuba dives made by 4,711 adult divers found that divers ascending faster than 18 m min^{-1} (n = 235 divers) were more likely to be younger, male and have a higher diver certification level, while divers who reported losing buoyancy control (n = 223 divers) were more likely to be older, female and have basic diver certification.[13] Controlling for age and sex by comparing dives involving a

Table 1
Potential reasons for ascending rapidly and losing buoyancy control in order of suspected likelihood; (BCD – buoyancy control device)

Likelihood rank	Potential reasons for: Rapid ascent	Losing buoyancy control
1	Panic/anxiety/stress	Inexperience
2	Fail to release gas	Fail to release gas
3	Inexperience	Poor training/skills
4	Run out of breathing gas	Incorrect weighting
5	Incorrect use of BCD	Panic/anxiety/stress
6	Ignorance of safe ascent rate	Unfamiliar equipment
7	Incorrect body position	Incorrect body position
8	Fail to monitor depth gauge	Incorrect use of BCD
9	Loss of weight system	Loss of weight system

reported rapid ascent (n = 296) with dives made by the same divers with no reported rapid ascent (n = 2,598), rapid ascent dives were shallower, shorter, more likely made from a boat and were perceived as strenuous.[13] Comparing 362 dives with reported buoyancy problems to 3,174 dives without buoyancy problems made by the same group of divers, the study found that buoyancy problem dives were more likely to have been shorter, made from a live-aboard or day-boat and to have involved a higher perceived workload.[13]

By controlling for environmental factors associated with the dive site and type of dive platform this study aims to further explore potential factors that increase the risk of losing buoyancy control and/or ascending rapidly. The maximum safe rate of ascent recommended by the Professional Association of Diving Instructors is 18 m min^{-1}.[14]

Methods

Adult certified divers attending organised recreational group dives were recruited as previously described.[3,15] Briefly, dive businesses and dive clubs in WA were invited to participate. A researcher (PB) met the divers at popular dive sites around the coast of WA. The study was approved by the Human Research Ethics Committee of the University of Western Australia.

Dive and diver information were collected using a modified Divers Alert Network (DAN) Project Dive Exploration (PDE) questionnaire and Sensus Ultra™ data-loggers (ReefNet, Mississauga, Ontario) were attached to the front of each diver's buoyancy control device (BCD). Depths, (to +/- 0.01 m resolution and 0.3 m accuracy[16]), were recorded every 10 seconds and downloaded from each logger. Diver data collected included sex, age, weight, dive experience, certification level and problems experienced during the dive. Self-reported starting and finishing gas pressures and stamped cylinder volumes were recorded on the dive record. Consumed volume of gas was calculated by multiplying cylinder volume by the difference between starting and ending cylinder pressures, expressed as surface-equivalent air consumption (SAC) per kilogram of body,weight, (L min^{-1} kg^{-1}).

ANALYSIS

Mean depth was calculated by dividing the total of recorded depths from each dive by the number of samples recorded between the time the diver left the surface (depth >1 metre sea water, msw) and the time returned to the surface (depth = 0). This included divers swimming back to the boat underwater but excluded time spent at the surface. For example, when taking a bearing back to the boat near the end of a dive it is assumed that divers at the surface would have temporarily discontinued using scuba and breathed air from the atmosphere. Surface air consumption was calculated by dividing the gas volume used by the number of minutes spent underwater and by the mean ambient pressure in bar at the mean depth, (excluding time at the surface, as described above). Divers were asked "*What is the maximum recommended safe rate of ascent?*" The maximum recorded rate of ascent (m min^{-1}) during each dive was calculated by multiplying the maximum negative difference in depth in msw during any single 10-second sampling period by six.

To control for environmental conditions two case-control analyses were performed. In the first analysis, dives in which a diver recorded an ascent rate > 18 m min^{-1} were classed as rapid ascent 'case' dives and dives made at the same dive site and at the same time without ascending faster than 18 m min^{-1} were classed as 'control' dives. In the second analysis, dives in which a diver reported a buoyancy problem were classed as 'case' dives and dives made at the same dive site and at the same time by at least one other diver without reporting buoyancy problems were classed as 'control' dives. Data were imported into the Statistical Analysis System (SAS) version 9.2 (Cary, North Carolina) and the distribution of variables tested for normality. Bivariate

Table 2
Bivariate associations with ascending faster than 18 m min^{-1}
(* each risk factor modelled as per units indicated in parentheses)

Risk factor*	Cases (n = 71)	Controls (n = 282)	Bivariate OR	95% CI	P value
% with buoyancy problem	23.0	6.0	5.03	2.27 to 11.13	<0.01
% with low certification	76.0	54.0	2.58	1.26 to 5.30	0.03
Mean dive time (per 5 mins)	40.8	48.3	1.33	1.15 to 1.54	<0.01
No of dives in BCD worn (per 100 dives)	44.0	100.0	1.22	0.90 to 1.49	0.14
Years of diving (per 10 years)	6.0	11.5	1.18	0.87 to 1.67	0.26
Dives made in last 5 years (per 100 dives)	75.0	140.0	1.11	0.90 to 1.35	0.47

analyses were conducted for each factor. Variables with expected cell counts of less than five were excluded from further analysis. Remaining factors were fitted to conditional logistic regression models for reporting buoyancy problems and ascending rapidly. This was achieved by numbering each organised dive consecutively and stratifying the regression by dive number. Non-significant associations ($P > 0.05$) were removed by backwards elimination.

Results

A description of the participants and the range of diving conditions has been reported previously.[3,15] A total of 1,032 dives were recorded. Of these, 71 dives were made with recorded ascents faster than 18 m min^{-1} ('case dives') at the same time as 282 dives were recorded with ascents no faster than 18 m min^{-1} ('control dives'). In a second analytical sub-set from the 1,032 dives recorded, 68 dives were made by divers reporting buoyancy problems ('case dives') at the same time as 320 dives during which no buoyancy problems were reported ('control dives').

RAPID ASCENT SUB-SET

Case dives (n = 71) recorded a mean maximum depth of 21.0 (SD 10.0) msw whilst the mean maximum depth during control dives (n = 282) was 19.7 (9.4) msw (P = 0.30). Case dives ascended at a median maximum rate of 20.1 m min^{-1} (range 18.3 to 39.6) whilst the median maximum ascent rate during control dives was 11.0 m min^{-1} (range 5.5 to 16.5).

During any 10-second period only one dive recorded an ascent faster than 30 m min^{-1}. In the thirty-fifth minute of a dive with a median depth till then of 4.9 msw (maximum 17.9 msw), the diver ascended from 9.0 msw to 2.4 msw, (a difference of 6.6 msw), recording a mean ascent rate over 10 seconds of 39.6 m min^{-1}. The dive was the first in a three-dive series over two days, and the diver reported no adverse effects.

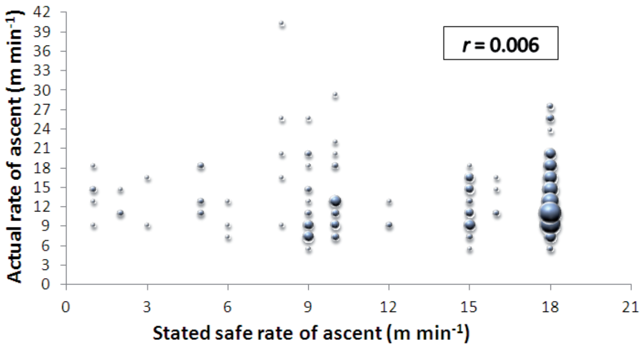
Divers making case dives more often than divers making control dives reported their final ascent to have been uncontrolled (24% versus 10%, $P < 0.01$). Table 2 presents bivariate comparisons between case and control dives.

Divers self-reported their perceived workload for each dive as 'resting/light', 'moderate' or 'severe'. Case dives had a higher SAC rate (0.30 L min^{-1} kg^{-1} versus 0.23 L min^{-1} kg^{-1}, $P < 0.01$). Based on mean values for the sample as a whole (n = 1,032) this equates to SAC for control dives being classed as 'resting/light' while case dives were classed as 'severe' (Table 3).

Table 3
Surface-equivalent air consumption (SAC) by perceived workload overall (n = 1,032)

	Perceived workload		
	Resting/light	**Moderate**	**Severe**
SAC mean (SD) (L min^{-1} kg^{-1})	0.22 (0.07)	0.24 (0.08)	0.28 (0.05)

Figure 1
Actual maximum rate of ascent versus estimated maximum safe rate of ascent during 208 dives; bubble size (area) represents the number of data points (range 1 to 24)



When asked "*What is the maximum recommended safe rate of ascent?*" divers who did not know were more likely to ascend faster than 18 m min^{-1} (35/135, 26%) than divers who provided a numerical rate (36/208, 17%) (P = 0.05). Figure 1 plots the recorded maximum ascent rate versus the estimated maximum safe rate of ascent given by divers (n = 208 dives). In total, 80 dives (38%) exceeded the maximum safe rate of ascent offered by the diver making the dive. As Figure 1 shows, there was no correlation between the stated maximum safe rate of ascent and the actual maximum ascent rate (r = 0.006). The median recorded maximum rate of ascent among the 208 dives made by divers able to offer a numerical maximum safe rate was 11.9 m min^{-1} (range 5.5 to 39.6).

Multivariate analysis for rapid ascent

Fifteen dives (4%) were not considered because of missing variables, leaving 338 of 353 dives (96%) in the analysis. The main risk factor for making a rapid ascent (Table 4) was a loss of buoyancy control. Shorter dives were also significantly associated with recording a rapid ascent. Factors removed by backwards elimination included years of diving, number of dives made during the previous five years,

Table 4
Multivariate risk factors for recording a rapid ascent (following backwards elimination)

Risk factor	Adjusted OR	95% CI	P value
Buoyancy problem (Yes versus No)	4.22	1.84 to 9.70	<0.01
Shorter dive (per 5 mins)	1.29	1.12 to 1.50	<0.01

Table 5
Bivariate associations with reporting a buoyancy problem
(* each risk factor modelled as per units indicated in parentheses)

Risk factor*	Cases (n = 68)	Controls (n = 320)	Unadjusted OR	95% CI	P value
% not in control during ascent	48	5	26.75	10.10 to 70.81	<0.01
Low certification (Low vs High)	74:16	52:36	4.36	1.96 to 9.68	<0.01
Unable to check for neutral buoyancy	80	48	4.28	2.18 to 8.43	<0.01
Older age (per 10 years)	45.2	41.6	2.16	1.48 to 3.19	<0.01
Faster max. ascent rate (per m min^{-1})	13.9	11.6	1.17	1.09 to 1.25	<0.01
Fewer years' diving (median; per year)	6.0	12.0	1.03	1.00 to 1.07	0.07

level of certification (low, medium or high) and number of dives conducted wearing the BCD used on those dives.

BUOYANCY PROBLEMS SUB-SET

Of 1,030 dives where the presence of any dive problem was recorded (two were left blank), 68 (6.6%) reported buoyancy problems (cases) during dives made at the same time and place as 320 (31.0%) control dives during which divers did not report a buoyancy problem when asked. Characteristics of case dives and control dives are presented in Table 5.

Case dives had a higher mean SAC rate than control dives (0.27 L min^{-1} kg^{-1} vs 0.22 L min^{-1} kg^{-1}, $P < 0.01$). As found in the rapid ascent case-control analysis, this equates to control dives being classed as 'resting/light' and case dives being classed as 'moderate' or 'severe' (Table 3). Among case dives 24% exceeded the maximum recommended safe rate of ascent of 18 m min^{-1} compared with 7% of control dives ($P < 0.01$). Case dives were also made by divers who had fewer dives' experience with the BCD worn (55.0 versus 125.0, $P < 0.01$), and when asked, were more likely to state they did not know what rate a maximum safe rate of ascent might be (50% versus 35%, $P < 0.01$).

Table 6
Multivariate risk factors for reporting a buoyancy problem (following backwards elimination)

Risk factor	Adjusted OR	95% CI	P value
In control during ascent (No vs. Yes)	30.21	9.93 to 91.88	<0.01
Able to check for neutral buoyancy (No vs. Yes)	7.76	2.95 to 20.41	<0.01
Faster max. ascent rate (per m min^{-1})	1.10	1.00 to 1.21	0.04

Multivariate analysis for buoyancy problems

Twenty-nine dives (7%) were not considered because of missing variables leaving 359 of 388 (93%) in the analysis. The three main risk factors for reporting a buoyancy problem (Table 6) were divers who were unable to describe how to check for neutral buoyancy, who reported not being in control during the final ascent and dives that included maximum ascent rates that were a mean of 20% faster than control dives. Factors removed by backwards elimination included the age of the diver, number of years of experience and certification level.

Discussion

This study explored potential factors that may increase the risk of losing buoyancy control and/or ascending rapidly, based on suggestions from an 'expert' panel.[12] While many of the potential reasons were supported, several were not.

RAPID ASCENT

Ascending rapidly was significantly associated with reporting a buoyancy problem. However, the wide confidence interval suggests an imprecise estimate (Table 4). Whether a rapid ascent followed a buoyancy problem or if rapid ascent was interpreted as a buoyancy problem was not investigated in this study. Ascending faster than 18 m min^{-1} was associated with dives ending sooner (Table 4) though it cannot be stated with certainty whether dives ended prematurely because of unintentional ascents. Also, we found that 38% of the 208 recorded dives exceeded the rate of ascent given by the diver as a maximum safe limit. However, there was no correlation between stated maximum safe ascent rate and actual maximum ascent rate (Figure 1). Faster ascent rates have been found to generate higher Doppler-detected venous bubble counts.[17] Bubbles are, however, present in otherwise uneventful dives and do not necessarily result in DCS.[11]

Therefore, for reasons that remain unclear and warrant further research, educating recreational divers about a numerical recommended safe ascent rate limit appears to be ineffective among a substantial proportion of them. Almost one quarter of the divers in the current study commented that they relied upon the speed of their exhaled bubbles as a marker for ascending safely. However, there is no published guideline specifying what size of bubble ascends slower than 18 m min^{-1} and bubble ascent rate may be affected by salinity and water temperature. Coupled with the difficulty associated with magnification of bubbles due to the differing refractive indices of water-to-glass and glass-to-air, bubbles are likely to be an unreliable gauge of ascent rate.[11]

BUOYANCY PROBLEMS

Self-reported buoyancy problems were found in this study to be significantly associated with being unable to describe how to check for neutral buoyancy, though once again, the wide confidence intervals suggest an imprecise estimate of the added risk. In the Delphi study (Table 1), poor training/skill level was considered the third most likely cause of divers losing buoyancy control.[12] Insufficient knowledge or training was identified as early as 1964 as a risk factor in 50% (n = 83) of British diving fatalities.[18] Explanations for why dives made by divers who were unable to describe how to check for neutral buoyancy were more likely to involve buoyancy problems include that they may have begun the dive incorrectly weighted, as also suggested in the Delphi study, or that they may not have known how to establish neutral buoyancy during the dive. However, the exact reasons why divers who were unable to describe how to check for neutral buoyancy were also more likely to self-report a buoyancy problem remain undetermined and require further research.

At the bivariate level, case dives were also made by divers with less dive experience with the BCD worn, as suggested in the Delphi study (Table 1), where unfamiliar equipment was ranked the sixth most likely reason divers lose buoyancy control.[12] Case dives recorded a higher mean SAC rate. Referring back to Table 3, this equates to control dives being classed as 'resting/light' and case dives classed as 'moderate' or 'severe', suggesting that buoyancy problems were associated with the workload of a dive, as has been reported elsewhere.[13] After adjusting for potential risk factors, reporting a buoyancy problem was associated with reporting being out of control during the final ascent and recording a faster maximum mean ascent rate over at least 10 seconds. In the Delphi study, failing to release air during ascent was listed as the second most likely cause of divers losing buoyancy control.[12] However, while failing to release air during ascent may explain reporting of both a buoyancy problem and an out-of-control ascent in the current study, the exact causes of these problems were not identified nor the volume of air released during ascent measured.

Limitations of this study include that it remains uncertain how non-participants may have differed to participants. How self-organised dives may differ to professionally organised dives was also not explored. Therefore, caution is needed in generalising these findings beyond the population sampled.

The 10-second sampling rate was selected for data-loggers to capture sustained ascents whilst ignoring lesser vertical fluctuations, for example, caused by overhead swell or a diver's breathing. No physiological consequences were measured following each ascent, and this study does not establish a clear link between risk factors for rapid ascent over ten seconds and actual diving morbidity. It remains possible, likely even, that diving morbidity is more strongly associated with ascents sustained beyond 10 seconds' duration. It is also possible that rapid ascent for at least 10 seconds carries greater risk of injury in the shallows than ascent from deeper depths and when it occurs at the end of a dive rather than earlier. In this study, however, any ascent over 10 seconds was included regardless of when it occurred during the dive. In short, it is likely that not all ascents carry equal risk but all were treated equally in this study, in keeping with the advice of diver training agencies to not exceed a linear ascent rate of 18 m min^{-1}.[14]

Conclusions

Despite the widespread availability and use of personal dive computers with in-built audible and/or visual ascent-rate alarms, (and despite many divers stating a maximum safe rate of ascent of 18 m min^{-1} or less), many divers in this study ascended faster than 18 m min^{-1}. Additional research is necessary to explore why divers ascend so rapidly. Key issues that need identifying include whether ascending rapidly is linked to a loss of buoyancy control, a lack of ascent-rate reference or a failure to appreciate the potential consequences of ascending rapidly. The inability of many divers to describe how to check for neutral buoyancy at the start of the dive is concerning and deserving of further attention.

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