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Influence of Repeated Daily Diving on Decompression Stress

Authors
J. Zanchi[1], M. Ljubkovic[2], P. J. Denoble[3], Z. Dujic[2], S. Ranapurwala[3,4], N. W. Pollock[3]

Affiliations
[1] Cardiology, University Hospital Split, Split, Croatia
[2] Department of Integrative Physiology, University of Split School of Medicine, Split, Croatia
[3] Medical Research, Divers Alert Network, Durham, United States
[4] Department of Epidemiology, University of North Carolina, Chapel Hill, NC, USA

Key words
- acclimatization
- air diving
- decompression sickness
- echocardiography
- repetitive
- venous gas emboli

Abstract

Acclimatization (an adaptive change in response to repeated environmental exposure) to diving could reduce decompression stress. A decrease in post-dive circulating venous gas emboli (VGE or bubbles) would represent positive acclimatization. The purpose of this study was to determine whether four days of daily diving alter post-dive bubble grades. 16 male divers performed identical no-decompression air dives on 4 consecutive days to 18 meters of sea water for 47 min bottom times. VGE monitoring was performed with transthoracic echocardiography every 20 min for 120 min post-dive. Completion of identical daily dives resulted in progressively decreasing odds (or logit risk) of having relatively higher grade bubbles on consecutive days. The odds on Day 4 were half that of Day 1 (OR 0.50, 95% CI: 0.34, 0.73). The odds ratio for a >III bubble grade on Day 4 was 0.37 (95% CI: 0.20, 0.70) when compared to Day 1. The current study indicates that repetitive daily diving may reduce bubble formation, representing a positive (protective) acclimatization to diving. Further work is required to evaluate the impact of additional days of diving and multiple dive days and to determine if the effect is sufficient to alter the absolute risk of decompression sickness.

Introduction

Decompression sickness (DCS) is a disease caused by tissue bubble formation from dissolved inert gas due to reduction in barometric pressure. DCS is most commonly observed following inadequate decompression from compressed gas diving, but it is also possible through depressurization potentially encountered in aviation and microgravity exposures. When the total tissue tension (for example, oxygen, carbon dioxide, nitrogen, helium and water vapor) exceeds the local absolute pressure, the relative supersaturation can elicit the formation of free gas phase (bubbles) which can grow and lead to DCS [19]. Venous gas emboli (VGE) are typically monitored ultrasonically in the bloodstream as an indicator of decompression stress, first with audible Doppler capturing blood flow through major vessels [17] and more recently with 2-dimensional echocardiographic imaging capturing blood flow through the heart [16]. More severe dive profiles, individually or in rapid succession, will increase the decompression stress. It remains an open question whether or not the decompression stress associated with repeated diving that does not generate DCS is altered. Adaptation to repetitive natural exposure is known as acclimatization. It is possible that repetitive compression-decompression cycles of frequent diving could confer a protective effect to reduce the risk of DCS (positive acclimatization) or sensitize divers and increase the risk of decompression stress (negative acclimatization). Evidence of positive acclimatization to diving has been reported in animal studies [1, 7, 14]. Work with human subjects is more equivocal, limited to a small number of retrospective studies of caisson workers [4], surveys of occupational divers without physiological monitoring [1] and an inadequately conducted field study of recreational divers [2] using audible Doppler techniques.

The purpose of this study was to determine whether 4 days of daily diving would alter measured post-dive bubble grades.

Methods

Study population

A total of 16 male, experienced divers, a mix of military and civilian (age 37 ± 7 y [mean ± stand-

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Correspondence
Dr. Neal William Pollock, PhD
Divers Alert Network
6 West Colony Place
Durham
United States
27705
Tel.: +1/919/684 2948
Fax: +1/919/493 3040
neal.pollock@duke.edu

ard deviation], height 1.82 ± 0.05 m; weight 90 ± 10 kg, body mass index [BMI] 27.0 ± 2.7 kg · m^{-2}, waist-to-hip ratio 0.92 ± 0.05, and body fat estimated by skinfolds 18 ± 4 % [8]) participated in the study. None of the divers had patent foramen ovale (PFO) when evaluated by contrast transthoracic echocardiography described elsewhere [12].

All divers performed single no-decompression air dives on 4 consecutive days to 18 meters of sea water (msw) with a bottom time of 47 min. No diver showed signs of acute or chronic illness at the time of the study dives. All experimental procedures were conducted in accordance with the Declaration of Helsinki and were approved by the ethics committee of the University of Split School of Medicine and the institutional review board of Divers Alert Network (US Federal Office of Human Research Protections Registration: IORG0006687, IRB00008021). The study meets the ethical standards described for this journal [5]. All methods and potential risks were explained to the participants in detail, and each provided written informed consent before the commencement of experiments.

Location of the study and dive protocols

Study dives were performed at a single military installation of the Croatian Navy Forces. The dives were conducted in open water adjacent to a shore laboratory. The water temperature was 16 °C for all dives. Divers did not participate in any diving activities for a minimum of 7 days before the start of the study. The subject-divers were equipped with wetsuits, buoyancy compensators, open-circuit breathing equipment and Galileo dive computers (Uwatec, Johnson Outdoors Inc., Racine, WI, USA). Divers completed each dive in groups led by highly experienced divers along a depth contour to standardize the exposure. The dive profile and subject heart rate were continuously recorded by the Galileo computers. The air dive was selected as a profile that we have found to reliably generate substantial bubble loads with minimal risk of DCS [12]; important characteristics for a study goal of assessing relative decompression stress through repeated exposures and ultrasonic assessment. Each dive profile included a direct descent to 18 meters and ascent rate of 9 msw · min^{-1}. During the dive, divers performed moderate swimming exercise.

Bubble grade assessment

Subjects were monitored ultrasonically with 2-dimensional GE Vivid q ultrasonic scanners with phase-array cardiac transducer (1.5–3.3 MHz) (GE, Milwaukee, WI, USA). Subjects were positioned left laterally on cots for scanning to obtain a clear four chamber view from the apical axis. Ultrasonic monitoring was conducted at planned 20 min intervals for 2 h, with the first scan completed approximately 15 min after surfacing. Bubble grades were assessed by 2 trained and experienced observers through consensus. The same pair of observers monitored the same divers throughout the study to the extent practical. The pair-monitoring strategy encouraged rapid review of captured images when controversy existed. The echo imaging devices used captured a high fidelity record in short- and/or long-term memory, allowing most disputes to be resolved to the satisfaction of both reviewers. Each scan included bubble grades recorded at rest and followed prescribed sequential movement for each of one arm and one leg. The 'movement' case consisted of effort to contract every muscle and move every joint of the target limb through the full flexion/extension range 3 times in 5–7 s before returning to a neutral resting position. Echocardiographic monitoring was maintained throughout rest and movement periods and continued until a return to baseline conditions was confirmed. Movements were employed to mobilize gas bubbles presumably lodged or generated in the venous pathway. The bubbles were graded on a scale modified from Eftedal and Brubbak [11]. The non-linear ordinal grading system was as follows: 0 – no bubbles; I – occasional bubbles; II – at least one bubble every 4 cardiac cycles; III – at least one bubble every cardiac cycle; IV – continuous bubbling with modifiers [(a = at least one bubble.cm^{-2} in all frames), (b = at least 3 Ibid. in all frames), or (c = almost complete whiteout but individual bubbles can still be discerned)] and V – 'whiteout' where individual bubbles cannot be discerned. The highest score for each rest/arm movement/leg movement cycle was used in the analysis as the peak grade for the cycle.

Statistical analysis

Descriptive data are expressed as mean ± standard deviation (SD). Bubble grade differences were evaluated with cumulative logistic proportional odds model for multinomial data. Bubble grades by study day (1 vs. 4) were compared on a diver-to-diver and time-to-time basis using generalized estimating equations (GEE) to account for repeated measures (16 divers with 6 post-dive monitoring points). The assumption of the analysis is that the odds for the comparison of bubble grades on consecutive days is the same between any 2 consecutive levels of bubble grade (0-V). This is not saying that the difference between one grade and the next is the same. The initial comparison was made for each of the 4 days of diving. Using the odds of having a higher bubble grade from Day 1 as reference, the odds from all 4 days were compared. The odds ratio for Day 4 vs. Day 1 was then computed separately (without inclusion of data from Day 2 or Day 3) to allow better visual comparison to support the statistical analyses.

Since high bubble grades have a stronger association with DCS than lower grades [3], we wanted to see if the odds of having a relatively higher bubble grade on Day 4 vs. Day 1 differ for bubble grades > III. We created a dataset where we kept all grade IVa, IVb and IVc (there were no grade V bubbles observed) from Day 1 and included their corresponding findings for Day 4 with respect to the diver and time of recording. Then we included all the remaining Day 4 observations of bubble grades > III and included their corresponding findings for Day 1 with respect to the diver and time of recording. Thus, this new data set did not have any observations (with respect to diver and time of recording) where both Day 1 and Day 4 bubble grades were simultaneously < IV. We then subjected this dataset to a similar statistical model as above to evaluate bubble grade difference between Day 1 and Day 4.

Results

The Galileo dive computer records indicated no substantial deviations from the planned experimental dive for any diver. The moderate work rate was confirmed by heart rates during the fully immersed experimental dives of 84 ± 7 beats per minute.

The odds ratio for having a higher bubble grade on Day 2 (vs. Day 1) was 0.85 (95 % CI: 0.63, 1.14), the odds ratio for having a higher bubble grade on Day 3 (vs. Day 1) was 0.61 (95 % CI: 0.39, 0.94) and the odds ratio for having a higher bubble grade on Day 4 (vs. Day 1) was 0.52 (95 % CI: 0.36, 0.74). **Fig. 1** suggests that the odds (or logit risk) for consecutive days of diving have a linear dose-response relationship when compared with the reference category. In other words, daily no-decompression air dives to 18 msw with a bottom time of 47 min led to progressively

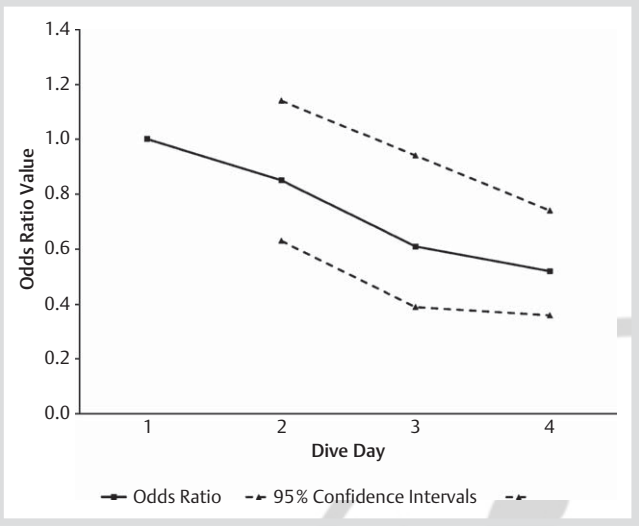

Fig. 1 Assessment of a linear dose-response relationship for the odds (logit-risks) of having a higher-grade bubble over 4 consecutive days of diving referent to Day 1.

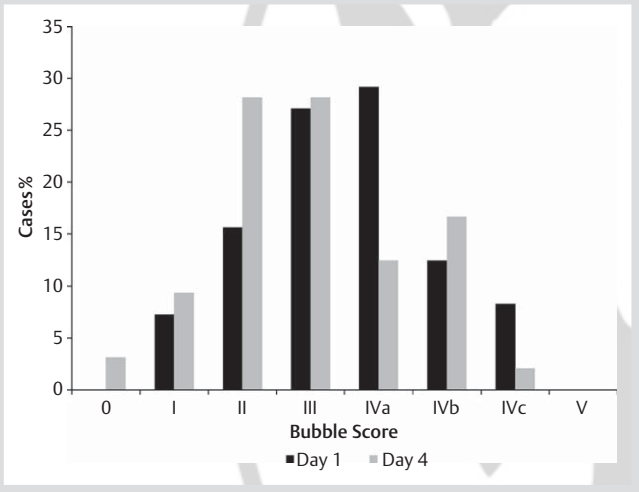

Fig. 2 Distribution of bubble grades on Day 1 and Day 4 of air repetitive diving series, pooled for 6 sample points.

decreasing odds (or logit risk) of having relatively higher-grade bubbles on consecutive days of diving.

The distribution of bubble scores pooled for all post-dive sampling on Day 1 and Day 4 of the repetitive air diving series appears in **Fig. 2**. The odds ratio for having a higher bubble grade on Day 4 was 0.50 (95 % CI: 0.34, 0.73) in comparison with Day 1. In other words, the odds of having a relatively higher bubble grade on Day 4 were half that of having a relatively higher bubble grade on Day 1.

The visual distribution of non-zero bubble scores across the 6 sampling periods on Day 1 and Day 4 of the repetitive air diving series appears in **Fig. 3a, b**. These figures show the preponderance of higher bubble grades (> III) in the first and second sampling points (15 and 35 min post-dive) on both diving days, with greater numbers of high grade bubbles observed in that time interval on Day 1 than on Day 4. The odds ratio for a > III bubble grade on Day 4 was 0.37 (95 % CI: 0.20, 0.70) when compared to Day 1; thus, that the odds of having a bubble grade > III on Day 4 were 0.37 times (close to one-third) that of having a bubble grade > III on Day 1.

Discussion

It is accepted that VGE do not equate to DCS, but they do represent an indicator of decompression stress [13]. The main finding of this study is that 4 consecutive days of daily diving did result in a progressive reduction in measured post-dive bubble grades consistent with positive acclimatization. This effect held true when considering all bubble grades or only bubble grades > III, the latter having the strongest association with DCS. We believe that the controlled nature of the dive series was important to identify the pattern of change. The effect may be less evident in less controlled dive series since daily exposures are rarely identical. It is common for divers to begin multiday trips with conservative dive profiles and then gradually shift to more aggressive profiles as comfort with the routine increases. While acclimatization may still offer some protective benefit, any such benefit may be masked by exposure differences.

Our results provide evidence supporting positive acclimatization to repeated daily diving. They are consistent with the findings of Dunford et al. [2], although their study was highly limited by the fact that their ultrasonic monitoring (audible Doppler) was restricted to a single sample taken at fairly inconsistent post-dive times. Repetitive monitoring on a structured basis is important to minimize the risk of missing both peak and patterns of post-dive grades. Our sampling at 20 min intervals over a 2 h post-dive period is much more likely to identify both peaks and patterns.

Doolette [1] reported a non-significant – and potentially clinically insignificant – improvement in diver health scores over multi-day air diving series. A modest improvement could reflect either an increase in general comfort as the rhythm of daily diving is established or possibly a reduction in decompression stress. Our results indicating increased odds of observing lower bubble grades on the fourth day of daily diving are consistent with the possibility of reduced decompression stress.

The mechanism of acclimatization to decompression stress is unknown. It could involve reduced bubble formation or reduced host response to bubbles formed [1]. It has been suggested that asymptomatic, or 'silent,' bubbles produced in tissues after decompression are responsible for diving acclimatization [18]. It is possible that silent bubbles produce a subsymptomatic stress that, with repetition, produces a form of preconditioning [6]. Huang et al. [7] proposed the induction theory in 2003, hypothesizing that repetitive daily diving provides preconditioning that reduces the tissue injury caused by subsequent exposure to intravascular bubbles. It has been postulated that repeated dives result in elimination of bubble-precursor micronuclei and reduce the number of bubbles produced in response to a given decompression stress [14]. Interestingly, if fewer bubbles do form as part of the acclimatization, the pressure for further acclimatization would be reduced.

Changes in the host response to bubble formation may include different reactions in tissues activating plasma proteins (clotting factors, enzymes and immunoglobulins) [10]. It is known that the complement system, polymorphonuclear leukocytes and oxygen metabolites mediate bubble-induced tissue injury [15]. The protective mechanism of tissue injury might be associated with induction of different cytokines [9]. It has been reported in animal studies that prior induction of expressing such protective factors reduces the incidence or severity of DCS [7, 18]. Huang et al. [7] showed that increased expression of HSP70 with heat shock pretreatment before diving resulted in protection of rats from air embolism-induced lung injury.

The first limitation of our study is that it represented only 4 days of single daily diving. It remains to be seen if a prolonged pattern

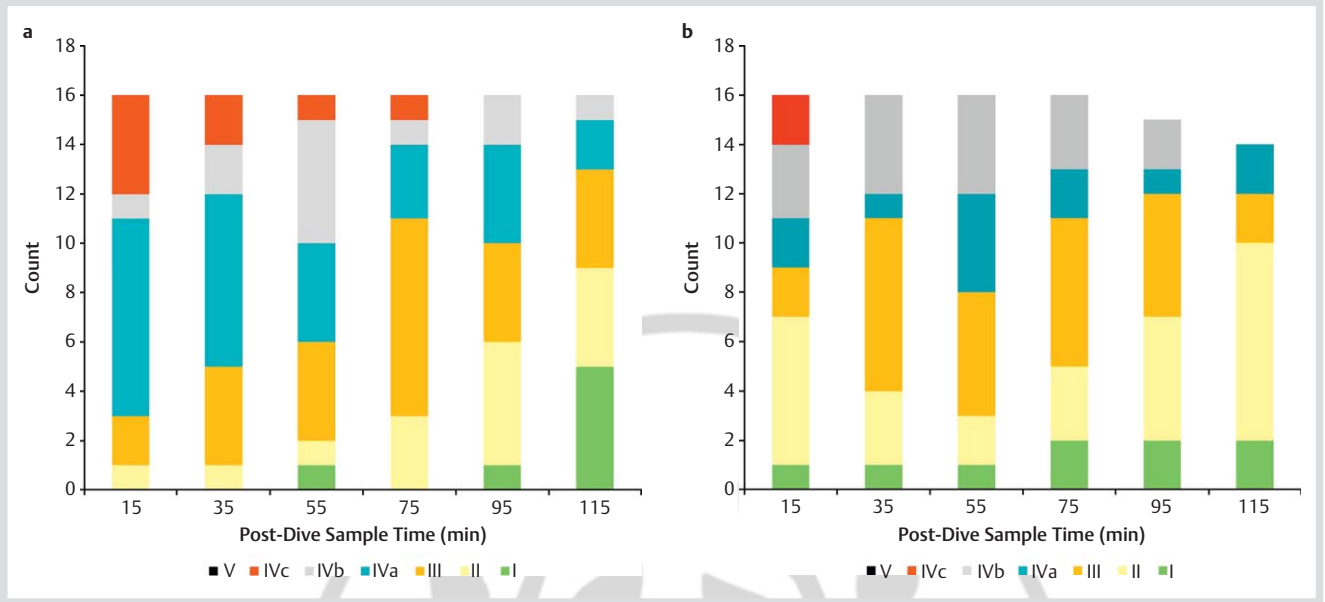

Fig. 3 Distribution of bubble scores across six 20-min interval post-dive sampling points for air dives on Day 1 **a** and Day 4 **b** of 4-day dive series.

of daily exposure and/or prolonged patterns including multiple dive days result in sustained or additional reductions in post-dive bubble grades. The second limitation of our study is the inability to correlate the change in decompression stress indicated by intravascular bubbles with a change in the absolute risk of decompression sickness. The scale used to grade bubbles is semi-quantitative; it effectively discriminates gross differences in bubble counts, but not in a linear manner. The incremental difference between grade levels is not fixed, making it important to cautiously interpret measured differences.

In summary, our results show that daily diving on 4 consecutive days results in reduced odds of higher grade bubbles being evident at the end of the series. This is consistent with the hypothesis that repetitive diving reduces bubble formation, representing what is likely a positive acclimatization to diving. Further work is required to determine if the pattern of acclimatization holds true with additional days of diving and with multiple dive days and if the magnitude of the effect is sufficient to alter the absolute risk of decompression sickness.

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