Exercise during a 3-Min Decompression Stop Reduces Postdive Venous Gas Bubbles

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ABSTRACT

DUJIĆ, Ž., I. PALADA, A. OBAD, D. DUPLANČIĆ, D. BAKOVIĆ, and Z. VALIC. Exercise during a 3-Min Decompression Stop Reduces Postdive Venous Gas Bubbles. *Med. Sci. Sports Exerc.*, Vol. 37, No. 8, pp. 1319–1323, 2005. **Purpose:** Decompression sickness is initiated by the formation of gas bubbles in tissue and blood if the divers return to surface pressure too fast. The effect of exercise before, during, and after dive on bubble formation is still controversial. We have reported recently that strenuous aerobic exercise 24 h before simulated dive ameliorates venous bubble formation. The objective of this field study was to evaluate whether mild, continuous exercise during decompression has a similar impact. **Methods:** Ten healthy, military male divers performed an open-sea field dive to 30 m of sea water breathing air, remaining at pressure for 30 min. During the bottom and decompression the subjects performed fin underwater swimming at about 30% of maximal oxygen uptake. Each diver underwent two randomly assigned dives, one with and one without exercise during the 3-min decompression period. Monitoring of venous gas emboli was performed in the right heart with ultrasonic scanner every 20 min for 60 min after reaching surface pressure in supine rest and during forced two-cough procedure. **Results:** The study demonstrates that a mild, continuous exercise during decompression significantly reduced the average number of bubbles in the pulmonary artery from 0.9 ± 0.8 to 0.3 ± 0.5 bubbles per square centimeter in supine rest, as well as during two-cough procedure, which decreased from 4.6 ± 4.5 to 0.9 ± 0.9 bubbles per square centimeter. No symptoms of decompression sickness were observed in any subject. **Conclusion:** These results, obtained in the field conditions, indicate that a mild, underwater swimming during a 3-min decompression period reduces postdive gas bubbles formation **Key Words:** COMPRESSED AIR DIVING, OPEN-SEA DIVING, ULTRASOUND, DECOMPRESSION SICKNESS, PHYSICAL ACTIVITY

Decompression sickness (DCS) after sea diving, aviation, and space flights is believed to be initiated with formation of intra and/or extravascular nitrogen gas bubbles, if the return to the surface pressure occurs to rapidly. Nitrogen bubbles cause a variety of symptoms ranging from mild skin rash to serious consequences like seizures, coma, and death (10). Neurological injury is currently the most important decompression-related problem in recreational divers requiring treatment (11). Although venous gas emboli (VGE) after diving have been used as an indicator of decompression stress, in many cases, VGE are observed after the return to surface pressure without association with recurring or delayed DCS symptoms. For example, in 3500 dives, VGE were detected in 56% cases with the incidence of DCS of only 2% (17). However, a single VGE grade III significantly increases the incidence of DCS to 5% (16,18). In addition to pilots and diving professionals who are affected by profession, the number of new recreational SCUBA certifications issued in year 2000 worldwide has been estimated to 854,000 (URL is http://www.padi.com/english/common/padi/statistics/1.asp).

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Exercise is an intrinsic activity during professional diving and has been considered a risk factor for DCS (22). This concept of exercise and bubble formation resulted from the understanding that nitrogen uptake in the tissue and fluids is dependent on the blood flow. Therefore, exercise at depth would increase nitrogen uptake consequently to increased blood flow (9), whereas moderate exercise during decompression will increase gas elimination (9) and reduce the number of venous bubbles detected after diving (13,14). Vigorous exercise immediately before diving may produce microscopic muscular injuries, which could promote bubble formation (21). Recently, we have shown that a single bout of strenuous exercise 24 h before dive significantly reduces the number of bubbles in the right heart of divers (6), and the results are in accordance with previous studies in rats (24). The theoretical explanation for these results is a reduction in the number of preexisting micronuclei from which gas bubbles grow (25). Exercise after diving or shortly before or after decompression to altitude can promote bubble formation (4,13). Webb et al. (23) have recently failed to show that moderate dynamic exercise after altitude exposure resulted in either delayed onset of DCS or recurring DCS. Therefore, no definitive recommendations can be made regarding the effect of exercise before, during, and after decompression. It is apparent that the beneficial effect of exercise on bubble formation is dependent on proper timing, type, and intensity of exercise.

The present study was designed to answer the question of the type and intensity of exercise during decompression that would reduce the number of VGE after field dive. Jankowski et al. (14) have recently reported in the cold wet chamber dive that moderate (50% of maximal oxygen uptake, $\dot{V}O_{2max}$), intermittent (arm or leg) exercise during decompression significantly reduces the number of VGE postdive. In this study we used mild (30% $\dot{V}O_{2max}$), continuous exercise (fin underwater swimming) in field conditions with normal temperature at the bottom. The results of this study are more applicable to real diving conditions, especially in recreational divers, who make up the majority of the diving community worldwide.

METHODS

Study population and dive profile. Ten male military divers, medically fit to dive based on the annual medical examination and without any clinical signs of cardiopulmonary disease, were included in the study. Their mean age was 35.1 $\pm$ 4.3 yr (standard deviation, SD; range 29–41), height 183.3 $\pm$ 4.8 cm (range 174–191), and weight 87.9 $\pm$ 9.4 kg (range 68–98). Their body mass index varied between 22.5 and 29.0 $kg{\cdot}m^{-2}$, and three subjects were smokers (3–35 cigarettes per day). All subjects were military divers experienced in compressed air and oxygen diving. They dived to 400 kPa (30 meters sea water, msw) at a rate of 100 $kPa{\cdot}min^{-1}$ breathing air, remaining at pressure for 30 min. The ascent rate up to the decompression stop at 130 kPa (3 msw) was 90 $kPa{\cdot}min^{-1}$, where they remained for 3 min before they were decompressed to the surface pressure (100 kPa) at the same rate. At the beginning of the decompression period, divers ascended to 3 msw during the period of 3 min. At that decompression stop, divers either rested for 3 min or performed fin swimming for the same duration. About 0.3 min were needed for divers to surface from the decompression stop (20). Each diver performed two dives 3–7 d apart, one with and one without physical exercise during the 3-min decompression period. The succession of the two dives was randomly assigned. The divers used air as breathing gas and measured diving profile with diving computer (Mosquito, Suunto, Finland). The data about the dive profiles were downloaded from the diving computer on the PC with the data acquisition software. The subjects used wet suits. Smoking was prohibited at least 12 h before the experiment. The study was performed at the military base of the Croatian Navy Forces during the 2-wk period. Diving site was located in the vicinity of the base, where the divers were transported by the powerboat during the 10-min ride. The site was chosen because it allowed us to perform dives of the suitable depth and duration. Sea temperature at the surface was 16–18°C, whereas at the bottom it was 14–15°C. The divers were allowed to drink water after diving.

All the experimental procedures complied with Declaration of Helsinki and American Physiological Association's "Ethical Principles in the Conduct of the Research with Human Participants," and were approved by University of Split School of Medicine Ethics committee. Informed written consent was obtained from all the subjects.

Measurement of maximal oxygen uptake. Maximal oxygen uptake ($\dot{V}O_{2max}$) and maximum heart rate were determined in all divers 7 d before the experiments using incremental protocol on the cycle ergometer (Marquette Hellige Medical Systems 900 ERG, Milwaukee, WI). The subjects were initially warmed up during 10 min with cycling at 25 W. The starting load was 50 W, with further 25-W increases each following minute up to exhaustion. This occurred within 10–14 min in all subjects. During the entire test, oxygen uptake and lung ventilation were measured with Quark b^2 breath-by-breath stationary unit (Quark b^2, Cosmed, Italy), and heart rate was registered continuously with Polar S810i HR monitor (Polar Vantage, Finland) and 12-lead electrocardiogram (C12, Cosmed, Italy). Criteria for assessment of $\dot{V}O_{2max}$ included: 1) HR in excess of 90% of age-predicted maximum (220 – age), 2) respiratory exchange ratio (RER) $\geq$ 1.1, and 3) plateau ($\leq$150-mL increase) in $\dot{V}O_2$ with an increase in workload. If at least two of the three criteria were met, the highest $\dot{V}O_2$ measured was chosen as the subject's $\dot{V}O_{2max}$. The mean $\dot{V}O_{2max}$ was 40.9 $\pm$ 2.2 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ and the maximum heart rate at $\dot{V}O_{2max}$ was 177.1 $\pm$ 2.9 beats per minute (bpm).

Exercise during bottom and decompression. During the bottom and decompression phase of the dive, subjects performed exercise at about 13 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ (estimated from the underwater swimming speed with scuba equipment) (1). The divers swam at the bottom for 500 m in 30 min with a speed of 17 $m{\cdot}min^{-1}$. The same speed of fin swimming was used during decompression stop, which resulted with 50-m swim.

Bubble analysis. After the dive, subjects were placed in the left supine position and an echocardiographic investigation with a phase array probe (1.5–3.3 MHz) using a Vivid 3 Expert ultrasonic scanner (GE). Echocardiographic investigations were performed by an experienced cardiologist (DD) not aware of the exercise regime during the decompression. High-quality images were obtained in all subjects. Monitoring was performed every 20 min for 60 min after reaching surface pressure. After the dive, the occurrence of gas bubbles in the right heart and the pulmonary artery was determined using ultrasound. Images were graded according to a previously reported method (8). This grading system has been used extensively in several animal species as well as in man. This grading system is composed of following grades: 0, no bubbles; 1, occasional bubbles; 2, at least one bubble/fourth heart cycle; 3, at least one bubble/cycle; 4, continuous bubbling, at least one bubble per square centimeter in all frames; and 5, "white-out," individual bubbles cannot be seen. It has also been demonstrated that the grading system for Doppler (19) coincides with that used for images (2). The grading system is nonlinear when compared with the actual number of bubbles in the pulmonary artery. The bubble grades were converted into bubbles per square centimeter as described by Eftedal and Brubakk (8). The number of bubbles were determined at each of the measurement points and then integrated to give an average bubble number for the whole observation period.

Statistical analysis. Data are expressed as mean $\pm$ SD. The effect of exercise during decompression on the postdive occurrence of venous gas bubbles was evaluated by

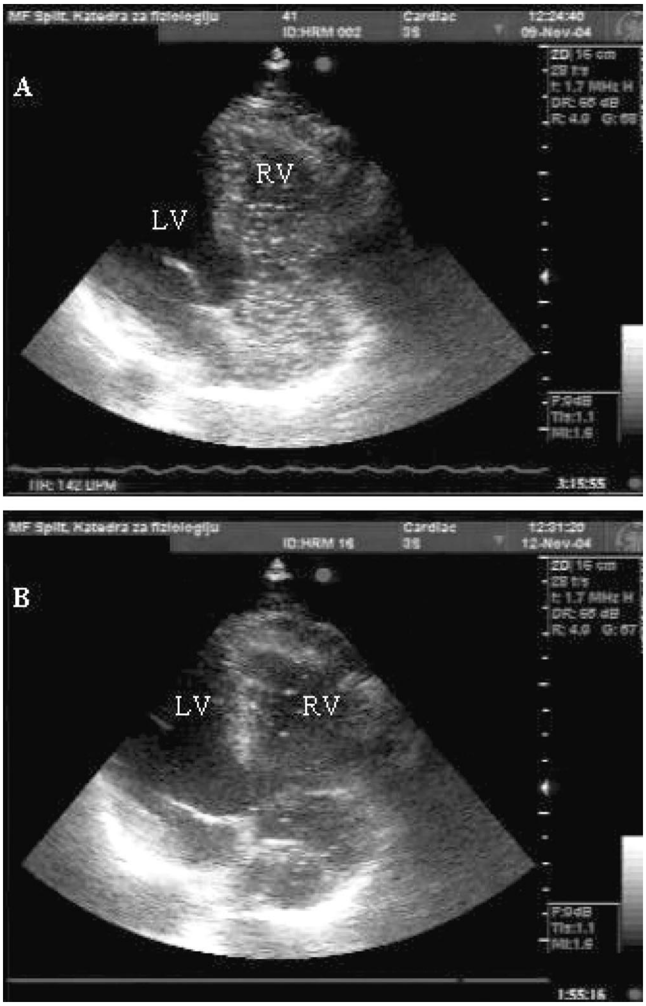

FIGURE 1—Echocardiographic apical four-chamber view of the heart in diver no. 3. The image was obtained 40 min after reaching surface pressure, immediately upon completion of the two-cough procedure, in the control dive (A) and after dive with swimming exercise at the decompression stop (B). The reduction of venous gas bubbles within right heart is clearly visible on panel B.

Wilcoxon matched pair test. Nonparametric tests were used because of the small sample size ($N = 10$). $P < 0.05$ was considered significant. All analyses were done using Statistica 6.0 software (Statsoft, Inc., Tulsa, OK).

RESULTS

All divers successfully completed designed protocol. Average depth during the dive was 30.0 ± 3.8 and 29.6 ± 2.0 m for the dives without and with exercise during decompression, respectively. Corresponding times at the bottom were 22.9 ± 2.3 and 23.4 ± 4.7 min.

The typical reduction in venous gas bubbles occurrence within the right heart in response to performed exercise during the decompression period is presented in Figure 1. Beneficial effect of work out at decompression stop is manifested as reduction in bubble grade 4 to grade 1 in particular diver.

Venous gas bubbles per square centimeter for all divers at 20, 40, and 60 min after the dive in supine resting position and after performing two-cough procedure are presented in Table 1. Only one diver (no. 5) showed no advantageous effect of exercise during decompression on bubble formation; moreover, during supine rest in 60 min after the dive, he exhibited increase in venous gas bubble formation (from grade 2 to 3).

Maximal occurrence of venous gas bubbles toke place at 20 and 40 min after the dive (grades 2.5 and 4 during supine rest and forced-cough procedure, respectively), with the greatest reduction in bubble presentation at 40 min after the dive (from grade 2.5 to 1 and from grade 4 to 2.5 for supine rest and forced-cough procedure, respectively).

Figure 2 shows summarized data for all divers at 20, 40, and 60 min of observation during supine rest (A) and during forced two-cough procedure (B). Exercise during decompression period decreased number of venous gas bubbles per square centimeter in rest and during cough conditions at 20 and 40 min of observation ($P < 0.05$). Sixty minutes after the dive, the difference in venous gas bubbles per square centimeter still remained different during cough procedure ($P < 0.05$) but became indistinguishable during the supine rest condition.

DISCUSSION

The present study demonstrates that the mild fin underwater swimming performed during decompression reduces postdive nitrogen gas bubbles and provides another means, together with oxygen breathing and reduction of ascent rate, for amelioration of formation of bubbles upon decompression in humans.

The positive effect of intermittent, moderate exercise during decompression on VGE formation was recently reported by Jankowski et al. (14). In their study, the main emphasis was on the difference between the intermittent arm or leg exercise (50% of specific $\dot{V}O_{2max}$) on VGE formation after the dive. The observed VGE activity was the same in either type of exercise due to higher ventilatory equivalent for oxygen during arm exercise. Strenuous and vigorous exercise was avoided in their study as well as in our because this type of activity is related with increased risk for DCS (5,21,22). In the study of Jankowski et al. (14), diving was done in the water-filled hyperbaric chamber with rather cold temperature (8°C) exposure and the measurement of VGE was performed with precordial Doppler.

We have decided to complement their study by investigating more physiological, continuous leg exercise during decompression in the open-sea conditions, such as fin underwater swimming with scuba equipment, which is more relevant for the professional and recreational divers. Besides different types of exercise, we have tested the effect of the lower exercise intensity (relative $\dot{V}O_{2max}$ 13 $mL \cdot kg^{-1} \cdot min^{-1}$), which is more representative for recreational diving. An average recreational diver may expend 2 or 3 METs (metabolic equivalent: 1 MET = 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ of oxygen consumption), but the energy expenditure might acutely increase up to 11–12 METs under adverse conditions (underwater currents) (1). The method for bubble detection in our study was high-resolution ultrasound

TABLE 1. The effect of exercise during decompression on venous gas bubbles formation in divers represent in Eftedal–Brubbak grading for images.

Diver No.	$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	20 min Postdive				40 min Postdive				60 min Postdive			
		Rest		Cough		Rest		Cough		Rest		Cough	
		Cont.	Exerc.	Cont.	Exerc.	Cont.	Exerc.	Cont.	Exerc.	Cont.	Exerc.	Cont.	Exerc.
1	51.2	3	2	4	3	3	2	5	4	3	2	4	3
2	33.6	4	3	5	4	4	3	4	3	2	1	3	2
3	36.4	4	4	5	5	4	3	5	4	3	2	5	3
4	44.0	2	1	3	3	2	1	4	2	2	1	3	2
5	30.3	3	3	4	4	3	3	4	4	2	3	3	3
6	42.3	3	1	4	3	3	1	5	3	1	0	3	1
7	43.6	0	0	1	0	0	1	0	2	0	0	1	1
8	40.2	2	2	4	3	2	1	3	2	1	1	1	2
9	43.5	1	0	2	1	2	0	3	1	2	0	3	0
10	47.0	1	0	2	0	1	0	1	0	0	0	1	0
Median ± range		2.5 ± 4	1.5 ± 4* P = 0.028	4 ± 4	3 ± 5* P = 0.018	2.5 ± 4	1 ± 3* P = 0.028	4 ± 5	2.5 ± 4 P = 0.076	2 ± 3	1 ± 3 P = 0.076	3 ± 4	2 ± 3* P = 0.012

Cont., subjects performing dive with standing still during 3-min decompression period; Exerc., subjects performing dive with swimming during 3-min decompression period.
* Statistically significant from control, $P < 0.05$.

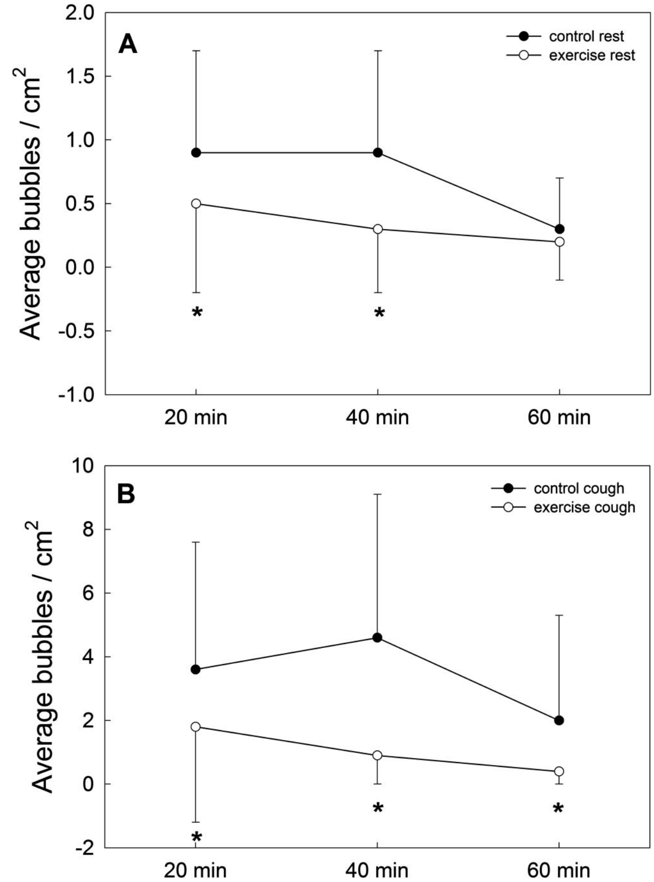

FIGURE 2—Mean venous gas bubbles per square centimeter for all 10 divers in the control dive and in the dive with exercise during decompression period. Mean venous gas bubbles per square centimeter during supine rest are presented in panel A, whereas panel B shows number of bubbles during forced-cough procedure. Values are mean ± SE; *statistically different from the control dive, P < 0.05.

scanner. The main disadvantage of precordial Doppler ultrasonic bubble detection used in the study of Jankowski et al. (14) is its time consumption and requirement for highly trained observer. There have been relatively fewer studies with ultrasonic scanning than those using Doppler. Carturan et al. (3) have found that the combined use of Doppler and scanning methods significantly increased the sensitivity for bubble detection. Training process for untrained observers in grading intravascular bubbles signals in ultrasonic images is rather short (8).

Exposure to cold has been often cited as an additional risk factor for DCS, although the relationship between cold and DCS is complex and depends on proper timing, as was previously stated for the exercise. Dunford and Hayward (7) have reported that if the diver is exposed to cold during the whole duration of the dive, reduced peripheral blood flow and inert gas uptake occur, with resulting beneficial effect on VGE formation postdive. However, if the diver is initially warm during the dive and peripherally well perfused, and the cooling occurs only during decompression, the number of VGE increases after dive (12,15). Jankowski et al. (14) have observed wet chamber divers with cold exposure (8°C) during the whole dive; thereby, this should reduce bubble grade. We have done open-sea field dives during the month of November, when the Adriatic Sea temperature at the bottom is around 14–15°C and at the surface between 16 and 18°C.

We have found in the present study that the fin underwater swimming during decompression significantly reduces the number of bubbles in the right heart of divers. This applies both to the maximum number of bubbles and the total bubble load. These results are in accordance with other studies suggesting protective effect of exercise during decompression (13,14,21). The observed positive effect of rather short continuous exercise (only 3 min) during decompression on VGE formation in this study indicated that a nitrogen pool for bubble formation is coming from the "faster" tissues, which are supersaturated with nitrogen during 30 min of bottom time, even without exercise. There is a likelihood that safety stops, as well as mandatory decompression stops, could also contribute to a decrease in VGE formation.

Study limitation. We were not able to measure the oxygen consumption during the 30-min dive and during the 3 min of exercise while at 3 m, but we used the published report correlating the swimming speed underwater with scuba equipment and O_2 consumption to estimate the level of exercise at the bottom and decompression phases of the dive (1). The work was done in the present study in field conditions that cannot be ideally controlled. The better controlled conditions could be the dive in a 30-m pool and the exercise done on an underwater ergometer. However, these technical capabilities were not available to us.

Conclusion. This study has demonstrated that performing continuous, mild exercise during decompression in the open-sea dives could be additional measure for the reduction of venous gas bubble formation. Potentially, this can be beneficial for divers' safety.

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