ARTICLE

Beneficial Role of Exercise on SCUBA Diving

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DUJIC, Z., Z. VALIC, and A.O. BRUBAKK. Beneficial role of exercise on scuba diving. *Exerc. Sport Sci. Rev.*, Vol. 36, No. 1, pp. 38–42, 2008. *Exercising before, during, or after diving is proscribed because of the assumption that it would increase incidence of decompression sickness. Our findings show that exercise performed in a timely fashion before diving or during decompression will reduce the number of venous gas bubbles formed. Exercise after diving did not increase the number of bubbles. Nitric oxide seems to play a protective role.* **Key Words:** decompression sickness, exercise intensity, nitric oxide, venous gas bubbles, ultrasound

INTRODUCTION

SCUBA (self-contained underwater breathing apparatus) diving is growing in popularity every year. It is reported by Divers Alert Network that in 2000, there were more than 9 million registered dives. The population engaged in this activity is also changing. Formerly, diving was reserved mostly for young fit men who remained in good shape by regular exercise. Today, the diving population is often older and includes many individuals who are relatively unfit.

There are several reasons for such change. One is the increased affluence of the population coupled with an increased interest in higher risk sports among the older population, but advancement in diving equipment may also play a role. Along with the increased number of dives, there have been consistent efforts to improve diving safety. New procedures and diving tables have been developed and are now often integrated in diving computers. Pressurized chambers, used to treat divers that show clinical signs of decompression sickness (DCS), are technically improved and decreased in size, so they can fit on boats used for field diving. Most sports divers are tourists visiting popular dive sites (such as in Croatia), which may create special dangers when combined with other vacation-related conditions such as lack of sleep and alcohol consumption.

Diving involves breathing of compressed gas, usually air, which will be taken up during the stay under water. On returning to surface, the diver will have to eliminate the excess gas during decompression (Fig. 1). Decompression sickness, which represents the major health risk in diving, is not a single disease entity but rather a syndrome. It may present not only as minor symptoms such as skin itching and pain in joints (often termed "bends") but also as serious neurological symptoms that can even lead to death of the diver. It is generally acknowledged that gas coming out of solution as bubbles is the main cause for injury; however, the exact mechanism is not known. Venous gas bubbles are regularly observed in divers, and a high number of venous gas bubbles is clearly linked to the high incidence of DCS (13). However, bubbles are observed without any clinical signs of symptoms (18). In the Table, we summarized proposed factors that can positively or negatively influence development of DCS. The precise mode of action for most of these risk factors still remains elusive.

This manuscript highlights recent evidence by our laboratory (6,8,10,11,16,23,24) and others (1,2) that exercise before a dive and during decompression reduces the number of venous gas bubbles formed, perhaps through a nitric oxide (NO) mechanism. Thus, exercise may represent a novel means to reduce the risk for DCS.

Venous gas bubbles can be observed with ultrasound using the Doppler method (18) or echocardiographic scanning (12). A grading system used extensively by our group is composed of the 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 centimeters in all frames; and 5, "whiteout," individual bubbles cannot be seen. Studies have shown that the Doppler and the echocardiographic grading system can be used interchangably (3). Because the grading

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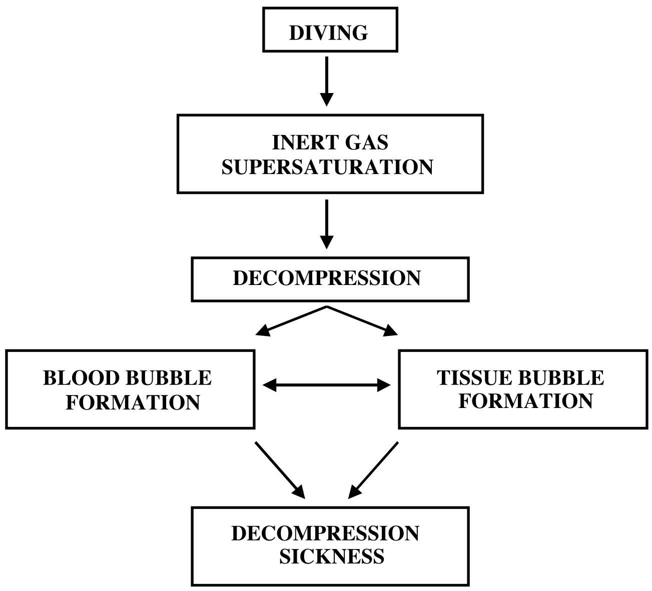

Figure 1. Pathophysiology of decompression sickness (DCS) is presented in this figure. Factors within each step can be responsible for final development of clinically demonstrable DCS.

system is nonlinear when compared with the actual number of bubbles in the pulmonary artery, the bubble grades can be converted to a linear system as bubbles per square centimeters as described by Nishi *et al.* (18).

DIVING AND EXERCISE

Standard recommendations for SCUBA diving usually advise divers to restrain from any kind of exercise before, during, or after diving (5). This practice probably stems from the work of Van der Aue *et al.* (22) who demonstrated the negative effect of exercise on decompression outcome. Before that study, it was common practice in the U.S. Navy to recommend exercise, believing that increase in flow to different tissues will increase the rate of nitrogen elimination. Emerging studies are demonstrating a beneficial role of some sort of exercise protocol on formation of venous gas bubbles (5). Although these results are mostly from animals or a limited number of human volunteers, they might change some of well-established procedures used in diving.

It has been known for approximately 30 yr that endurance training in animals (2,20) or good physical conditioning in divers can lead to less venous bubble formation and decreased incidence of DCS (4). Nevertheless, explanation of such an effect is still elusive. One possible explanation could be that more adipose tissue in sedentary subjects represents a potential site for dissolution of a greater amount of nitrogen during the bottom phase of the dive. Then nitrogen can form venous gas bubbles during ascent to the surface.

We have noticed that in many divers performing relatively shallow dives using accepted decompression procedures, venous gas bubbles can be sonographically observed within the right side of the heart and pulmonary artery. Such observation could be the result of the improved methodology used in bubble detection in recent decade (imaging (two-dimensional ultrasonography) vs sound detection (Doppler)). Furthermore, a high number of venous gas bubbles can be detected in divers without any apparent clinical symptoms (termed "silent bubbles"). However, as mentioned previously, a high venous gas bubble grade is linked to a high risk of DCS (17), and it can also exert various unwanted effects on the heart and vasculature such as reduction in right ventricular function, increase in pulmonary arterial pressure, and reduced flow-mediated dilation response in the brachial artery (7,19).

Exercise Before the Dive

In our recent studies, we extended previous observations and determined the intensity and timing of exercise before diving to achieve a beneficial effect on reduction in formation of venous gas bubbles. Surprisingly, experiments performed on rats showed that one single bout of high-intensity exercise performed 20 h before decompression provided the best protection against venous gas bubble formation and increased survival after decompression (Fig. 2, (24)). Compared with 2 and 6 wk of endurance training, a single bout of exercise tended to show a better protective effect. Results from experiments on rats also demonstrated that exercise before decompression has to be applied in a timely manner. If the rats exercised 48 h before diving, there was a smaller effect than at 20 h; if they exercised 30 min or 5 or 10 h before diving, there was no beneficial effect. So obviously, there is a time window, at least in the rat, during which high-intensity exercise has to

TABLE. Proposed risk factors for development of decompression sickness.

1) Diver specific:
a) Age
b) Gender
c) Body mass index
d) Fitness
e) Dehydration
f) Patent foramen ovale
f) Previous DCS
2) Dive:
a) Duration
b) Depth
c) Ascent protocol
d) Frequency
e) Exercise
f) Temperature
3) Postdive:
a) Exercise
b) Ascent to altitude
c) Surface environment

DCS indicates decompression sickness.

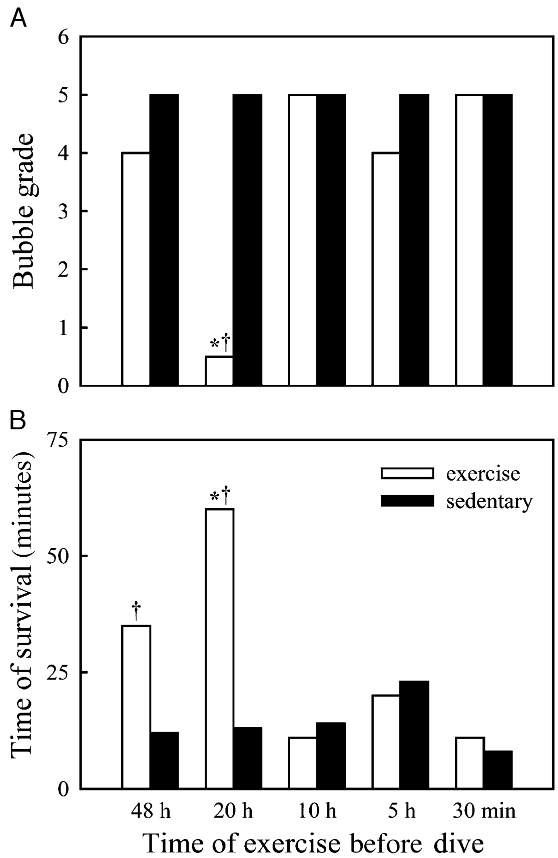

Figure 2. The figure depicts effects of single bout of intense exercise on median values of venous gas bubble formation in rats (A) detected by ultrasonic scanner performed at five different time points before onset of simulated dive. Only exercise bout executed 20 h before the dive produced statistically significant decrease in bubble grade. Time of survival (B) was longer if exercise was performed 48 or 20 h before diving, with more pronounced effect for 20 h. Note that 60 min represents euthanasia of the animal by the investigator rather than survival time. *Significantly different from all other groups, $P < 0.001$; †Significantly different from respective control group, $P < 0.001$. Data from (24).

be performed to get this benefit. Experiments in professional divers showed that high-intensity exercise performed 24 h before the dive had the same salutary effects (Fig. 3, (8)). In comparison with the experiments performed on rats, it seems that, in humans, the time frame in which exercise has to be performed before diving is less important. Blatteau *et al.* (1) have recently shown in 16 trained military divers that a single bout of submaximal exercise followed 2 h later by simulated diving in a hyperbaric chamber (30 m, 30-min duration) significantly reduces the number of venous gas bubbles found in the right side of the heart.

The mechanism by which venous gas bubbles are formed and presented in circulating blood is still controversial. However, many investigators believe that bubbles grow from preformed nuclei composed of small (~1 μm) stable gas bubbles (25). Since the same authors (25) proposed 10- to 100-h time course for regeneration of a depleted nucleus population that might explain the difference in bubble formation between dives in rats that are performed 20 or 48 h after exercise.

Several different theories are proposed to explain how exercise can lead to a reduction in bubble formation and in the incidence of DCS. One is based on the notion that nitrogen elimination might be increased in endurance-trained subjects that may reduce the amount of nitrogen available for diffusion into bubbles. However, a recent study has shown that endurance training does not increase nitrogen elimination at rest (15).

An alternate explanation is still more hypothetical. The endothelium is known to exhibit hydrophobic characteristics due to a coating of surface-acting substances. During exercise, NO is released from endothelial cells via action of endothelial NO synthase. Such NO inhibits blood cell adhesion and aggregation, so it is conceivable that it can also reduce the hydrophobicity of the endothelial wall. Endothelial NO synthase and other molecules in the NO signaling pathway have been localized to small invaginations of the cell membrane called caveolae. It is possible that changing the hydrophobicity of the endothelium NO decreases number of preexisting nuclei, especially if the nuclei themselves are colocalized in the caveolae.

Experiments With NO Administration or Blockade of NO Synthesis

Experiments in both animals and humans have shown that NO may indeed play a role in bubble formation. In experiment in rats, Wisloff *et al.* (23) administred N^{ω}-nitro-l-arginine methyl ester (L-NAME, a blocker of NO synthase) in the drinking water of normal weight sedentary rats for a period of 6 d. They found a dramatic increase in detected venous gas bubbles and a decrease in survival time after decompression from the dive, compared with control animals (Fig. 4). However, a single bout of exercise protected NOS-inhibited rats from severe bubble formation and death. They speculated that administration of L-NAME makes the endothelium more hydrophobic and increases the adherence of bubble precursors. Short bouts of exercise either wash out the preexisting nuclei and/or override the effects of NOS inhibition and makes endothelium less hydrophobic.

The next set of experiments (24) showed that prolonged (5 d) or immediate (30 min) administration of NO-releasing agent (isosorbid mononitrate) before simulated diving protects rats against bubble formation and death. Similar results (16) were obtained when NO donor (glyceryl nitrate) was given during simulated saturation dive 30 min before the start of decompression in pigs. The average number of bubbles seen during the observation period decreased 10 fold (from 0.2 bubbles per square centimeters in the control group to 0.02 bubbles per square centimeters in the experimental group). For both studies (16,24), one of the possible explanations for the observed decreased venous gas bubble formation is that administered NO donor changed adherence of preexisting nuclei on the endothelium, presumably by making endothelium less hydrophobic.

Finally, we performed experiments on volunteer human divers (11). As expected from data obtained on animals, application of short-acting NO donor (0.4 mg of nitroglycerine by oral spray, 30 min before the dive) reduced the number of venous gas bubbles observed in the right side of

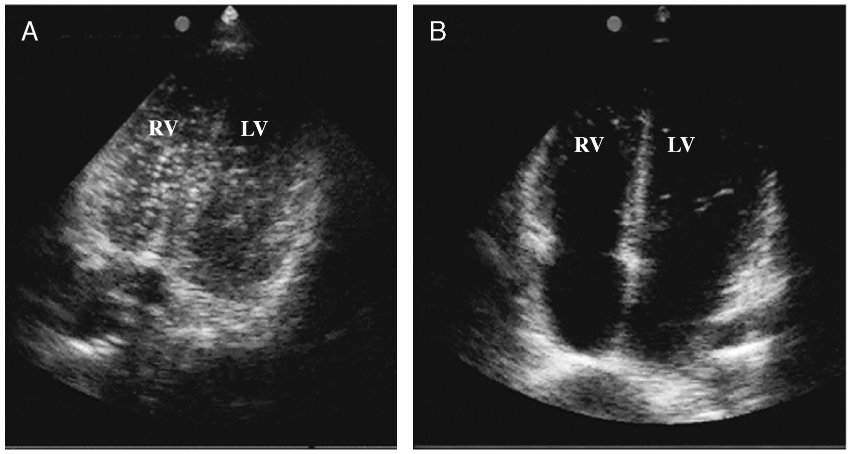

Figure 3. Ultrasound of right ventricle (RV) and left ventricle (LV) indicating a decrease in number of venous gas bubbles in dive 18 meters with strenuous exercise bout (B) in a human volunteer. (Reprinted from Dujic, Z., D. Duplancic, I. Marinovic-Terzic, D. Bakovic, V. Ivancev, Z. Valic, D. Eterovic, N. M. Petri, U. Wisloff, and A. O. Brubakk. Aerobic exercise before diving reduces venous gas bubble formation in humans. *J. Physiol.* 555:637–642, 2004. Copyright © 2004 Blackwell Publishing. Used with permission.)

the heart of the divers. These experiments were performed under field conditions and in a hyperbaric chamber, and NO donor was proven effective in both settings. Diving in open seawater produced more bubbles than diving in simulated dry conditions. Nitric oxide does not only reduce bubble formation in short air dives. In a near saturation dive in pigs, after a bottom time of 3 h of breathing nitrox (30% oxygen tension), bubble formation was significantly reduced during decompression (16).

Exercise During Decompression

In most dives performed today, decompression to surface includes decompression stops to allow enough time for elimination of inert gas that has accumulated in the body during the bottom phase of the dive and to prevent venous gas bubbles formation. We designed a study to answer the question of what divers should do during those stops by comparing divers who randomly performed or did not perform exercise during decompression stops after a dive to 30 m (10). The results showed that moderate swimming performed during decompression reduces postdive venous gas bubbles. In contrast to the experiments in which NO donor was used, this procedure represents another means (beside oxygen breathing and reducing the ascent rate) for nonpharmacological amelioration of venous gas bubbles formation.

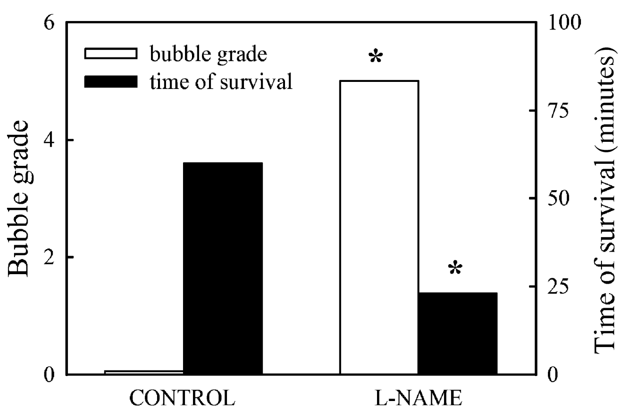

Figure 4. The figure shows the detrimental effect of nitric oxide syntheses blockade and beneficial effect of exercise on venous bubble formation detected by ultrasonic scanner and survival time. Note that 60 minutes represents euthanasia of the animal by the investigator, rather than survival time. *Significantly different between exercise and sedentary group, $P < 0.03$. Data from (23). L-NAME indicates N^{ω}-nitro-L-arginine methyl ester.

Intrapulmonary Shunting

Recently, in the studies by Eldridge *et al.* (14) and Stickland *et al.* (21), significant intrapulmonary shunting of echographic contrast has been shown to occur at submaximal levels of exercise. Moreover, in the study by Stickland *et al.* (21), two of the subjects showed intrapulmonary shunting even during supine rest. To investigate whether venous gas bubbles that are formed during ascent from 30-m-deep dive will pass through intrapulmonary shunts and cause paradoxical arterialization of the bubbles (9), a study was carried out on 12 Croatian Navy divers that did not show a patent foramen ovale during regular transthoracic sonography of the heart. Forty minutes after surfacing, divers were transferred to a cycle ergometer and performed a graded exercise protocol up to approximately 85% of their VO_{2max}. None of the divers had intrapulmonary passage of the venous gas bubbles even at the highest level of exercise. Such a striking difference between our results and previous reports could be explained by the difference in the bubble density and the size of the injected contrast and endogenous bubbles. However, we believe that the most likely explanation is lower prolonged bubble load that is occurring in our divers. Bolus application of agitated contrast may overwhelm the filtering capacity of pulmonary circulation and open existing intrapulmonary shunts (14,21). A short bout of strenuous exercise did not cause any visible intrapulmonary shunting of venous gas bubbles; moreover, it decreased the number of venous gas bubbles arriving in the right side of the heart of the divers (6).

SUMMARY

In conclusion, we believe that our recent findings, admittedly in a limited number of divers, give new insight into the role of exercise in diving. In contrast to being harmful, exercise performed 24 h before diving and during decompression stops seem to decrease the number of venous gas bubbles observed in the postdive period. A reduction in the number of venous gas bubbles probably reduces the risk for DCS. However, if these observations can be the basis of recommendations to the diving population, they should be validated on a larger number of divers. Administration of a NO donor seems to reduce the occurrence of venous gas bubbles. Further studies are needed before use of this drug can be recommended to divers.

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