Venous and Arterial Bubbles at Rest after No-Decompression Air Dives

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ABSTRACT

LJUBKOVIC, M., Z. DUJIC, A. MØLLERLØKKEN, D. BAKOVIC, A. OBAD, T. BRESKOVIC, and A. O. BRUBAKK. Venous and Arterial Bubbles at Rest after No-Decompression Air Dives. *Med. Sci. Sports Exerc.*, Vol. 43, No. 6, pp. 990–995, 2011. **Purpose**: During SCUBA diving, breathing at increased pressure leads to a greater tissue gas uptake. During ascent, tissues may become supersaturated, and the gas is released in the form of bubbles that typically occur on the venous side of circulation. These venous gas emboli (VGE) are usually eliminated as they pass through the lungs, although their occasional presence in systemic circulation (arterialization) has been reported and it was assumed to be the main cause of the decompression sickness. The aims of the present study were to assess the appearance of VGE after air dives where no stops in coming to the surface are required and to assess their potential occurrence and frequency in the systemic circulation. **Methods**: Twelve male divers performed six dives with 3 d of rest between them following standard no-decompression dive procedures: 18/60, 18/70, 24/30, 24/40, 33/15, and 33/20 (the first value indicates depth in meters of sea water and the second value indicates bottom time in minutes). VGE monitoring was performed ultrasonographically every 20 min for 120 min after surfacing. **Results**: Diving profiles used in this study produced unexpectedly high amounts of gas bubbles, with most dives resulting in grade 4 (55/69 dives) on the bubble scale of 0–5 (no to maximal bubbles). Arterializations of gas bubbles were found in 5 (41.7%) of 12 divers and after 11 (16%) of 69 dives. These VGE crossovers were only observed when a large amount of bubbles was concomitantly present in the right valve of the heart. **Conclusions**: Our findings indicate high amounts of gas bubbles produced after no-decompression air dives based on standardized diving protocols. High bubble loads were frequently associated with the crossover of VGE to the systemic circulation. Despite these findings, no acute decompression-related pathology was detected.
Key Words: SCUBA DIVING, NO-DECOMPRESSION DIVING TABLES, GAS EMBOLI GRADING, LEFT VENTRICULAR GAS EMBOLI

During SCUBA diving, gas supersaturation (total gas tissue tension in excess of environmental pressure) may occur when the ambient pressure is reduced by surfacing. The total tissue tension (composed of all dissolved gases such as O_2, CO_2, inert gases, and water vapor) is the driving force for bubble nucleation and growth. Vascular gas bubble formation occurs at very low levels of supersaturation, and the study of Eckenhoff et al. (10) demonstrated that venous gas bubbles could be observed after air dives at depths as shallow as 3.5 m of seawater.

Most dives result in the formation of gas bubbles that predominantly originate in systemic veins and are carried away by the bloodstream to the right valve of the heart and pulmonary circulation, where they are eliminated. The general conclusion from previously collected data is that the presence of much venous gas emboli (VGE) in the circulation increases the risk for decompression sickness (DCS), a major clinical complication associated with diving. Still, the available data on DCS risk–VGE grades relationship indicate that the probability of DCS predicted from the highest VGE grades is only approximately 13% (16). Thus, even if considerable venous bubbles can be observed, only few divers will experience any symptoms.

Sometimes the VGE can cross from the venous to the arterial side of circulation (VGE arterialization), and these events have usually been linked to the presence of a patent foramen ovale (PFO) (17,25). Factors leading to VGE arterialization in divers with PFO are most probably increased venous return, such as during performance of Valsalva maneuver (13), and increased pulmonary artery pressure (24), which was also observed after a field air dive (8). In the absence of PFO, arterialization of gas emboli was seldom documented (1,14,19).

A high percentage of arterializations were reported previously during deep chamber saturation excursions from 300 to 250 m of seawater (5). Recently, we reported a high incidence of arterializations during a series of deep trimix dives (16). These events mostly occurred in divers without PFO, suggesting some alternate pathway for VGE crossover

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into the systemic circulation, such as pulmonary capillaries or/and intrapulmonary a-v shunts. Furthermore, arterializations were always associated with high bubble grades in the right valve of the heart (grade 4 on the scale 0–5), indicating that, in order for the crossover to take place, the filtering capacity of the pulmonary microcirculation needs to be exceeded. The remarkable observation (16) was that the divers with detected arterialization did not exhibit any clinical signs of DCS after these dives nor had any DCS been recorded in their diving histories. Although it has been generally accepted that the gas emboli on the arterial side pose greater health threats than venous bubbles, our data indicate that factor(s) other then bubble arterialization alone are of importance for decompression-related injury (16).

In the current study, we investigated the formation of VGE following the no-decompression diving procedures based on the established diving tables and at depths commonly used both in commercial and recreational diving (18–33 m of seawater). The tested dive profiles were obtained from the Norwegian no-decompression tables, which are very similar to the diving tables constructed and used by the U.S. Navy.

METHODS

Study population. Twelve experienced male divers aged 38.8 ± 4.8 yr, with average height of 1.83 ± 0.1 m and weight of 90.7 ± 12.8 (body mass index of 27.1 ± 3.1 $kg \cdot m^{-2}$) took part in the study. All participants were healthy nonsmokers and, at the time of the study, had a valid medical certificate for diving. The participating divers were active members of the Croatian navy and had considerable diving experience. All experimental procedures were conducted in accordance with the Declaration of Helsinki and were approved by Ethics Committees of the University of Split School of Medicine and the Norwegian University of Science and Technology. Each method and potential risks were explained to participants in detail, and they gave written informed consent before the experiment.

All procedures tested were well below the limits set by the U.K. Health and Safety Executive for commercial diving. This limit is set at 25 of $p\sqrt{t}$, where p is the absolute pressure in bar and t is the bottom time in minutes, Exceeding this limit was reported to increase the incidence of DCS in air dives significantly (23).

Conditions of the study and tested dive protocols. The diving site was located near the field laboratory, and divers were transported to the site by a powerboat during a 5-min ride. Sea temperature at the bottom was 16°C–18°C. Divers were equipped with 8-mm wet suits and regularly serviced open-circuit breathing equipment. A total of 12 divers were included in the study, and each of them performed either five or six dives (one dive per day) with at least 3 d of rest between the diving procedures. The dive profiles, as displayed in Table 1, were based on the official Norwegian Diving Tables (*Norwegian Diving and Treatment Tables,* 3rd edition, 2008), which are similar to the diving tables regularly used by the Croatian military divers participating in this study. The descent and ascent rates were 10 and 9 m of seawater per minute, respectively, which were monitored by a dive computer (Galileo, Uwatec; Johnson Outdoors, Inc., Racine, WI). The divers did not perform any physical exercise during the bottom phase of the dive, and their HR was continuously monitored. The diving procedures were performed near a recompression chamber facility at the Naval Medical Institute of the Croatian Navy, and a physician specialist in Diving and Hyperbaric medicine was present at the diving site throughout the study. After surfacing, the divers were interviewed and carefully examined by the specialist for any signs or symptoms of DCS or other diving-related pathology.

TABLE 1. Dive profiles performed by 12 male divers.

Dive No.	Depth (m of Seawater)	Bottom Time (min)	Stop	$p\sqrt{t}$
1	18	60	—	21.7
2		70	5 min at 3 m of seawater	23.4
3	24	30	—	18.6
4		40	5 min at 3 m of seawater	21.5
5	33	15	—	16.7
6		20	5 min at 3 m of seawater	19.2

All divers were exposed to the same diving protocols that were conducted with at least 3 d apart. A compressed air was the only breathing gas used.
p, pressure in bars; *t*, time in minutes.

Postdive monitoring and VGE analysis. After surfacing, the divers were transported to the on-shore diving facility by boat and carefully examined by a physician specialist for any adverse effects of decompression. Within 20 min, the subjects were placed in the supine position, a phase-array ultrasonic probe (1.5–3.3 MHz) was positioned to obtain a clear view of the right and left atria and ventricles, and monitoring of the gas bubbles was commenced. The transducer was connected to an S6 and Logic book ultrasonic scanners (GE, Milwaukee, WI), and the echocardiographic recordings were stored for further analysis. The same two experienced cardiologists performed all echocardiographic investigations, and consensus about bubble grading was verified with two additional observers. The monitoring was performed every 20 min after reaching the surface for a period of 2 h, giving a total of six recordings. The gas emboli were observed and recorded, at rest and after performing two coughs, in the pulmonary artery and cardiac cavities as high-intensity echoes and were graded according to method described by Eftedal and Brubakk (11). This scale has been used extensively in several animal species as well as in man. The grading system uses the following definition: 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 squared centimeter in all frames; and 5—"whiteout," individual bubbles cannot be seen. Furthermore, a retrospect analysis of all grade 4 cases was performed, and they were

classified according to the newly proposed subdivision of grade 4 into grades:

4A: Continuous bubbling, one to two bubbles per squared centimeter in all frames (same as the current grade 4)
4B: Continuous bubbling, at least three bubbles per squared centimeter in all frames
4C: Almost complete whiteout in the right valve of the heart, individual bubbles can still be discerned.

Examples for each of the proposed categories are presented in Figure 1.

Assessment of PFO. In all participating divers, the existence of PFO was assessed by a transthoracic echocardiography using an agitated saline as the contrast agent, as previously described (12). A 20-gauge catheter was placed in the left antebrachial vein, and a three-way stopcock was attached with two syringes connected to its ports. One syringe contained 9 mL of saline and 1 mL of blood, and the other contained 1 mL of air. The contrast bubbles, created by alternating the plunger depression six to eight times, were injected as bolus, whereas images were simultaneously obtained in the apical four-chamber view. This procedure ensures rapid delivery of contrast bubbles to the right valve of the heart where they are visualized as echogenic clusters that gradually disappear as they are eliminated in the pulmonary microcirculation. The communication between the right and left cardiac chambers was identified by rapid filling of the left cavities by contrast bubbles within three to four cardiac cycles after the contrast had reached the right valve of the heart. The contrast injections were performed at rest for a maximum of three times and, if the crossover was not evident, once at 3–4 s before a release of a Valsalva maneuver (21). The evaluation stopped at an earlier stage of the protocol if the crossover was identified.

Statistical analysis. Bubble grade data are presented as median (25%–75% quartile range). The χ^2 test was used to compare the incidences of specific bubble grades and occurrences of arterializations between different dive series. Statistical significance was set at $P < 0.05$. All analyses were done using Statistica 7.0 software (Statsoft, Inc., Tulsa, OK).

RESULTS

All 12 divers successfully completed the planned protocol without showing any signs and symptoms of DCS or any other adverse effects for any of the six diving profiles. The dives produced much vascular gas bubbles. The median bubble grade observed at 40 min after surfacing was 3 (range = 1.5–4) for the first, 4 (range = 3.75–4) for the second, 4 (range = 2.5–4) for the third, 4 (range = 4–4) for the fourth, 4 (range = 4–4) for the fifth, and 4 (range = 4–4) for the sixth dive. As displayed in Table 2, a bubble grade of 4 was observed in the right valve of the heart within 2 h in 55 of 69 dives (not including the grade 5 detected in

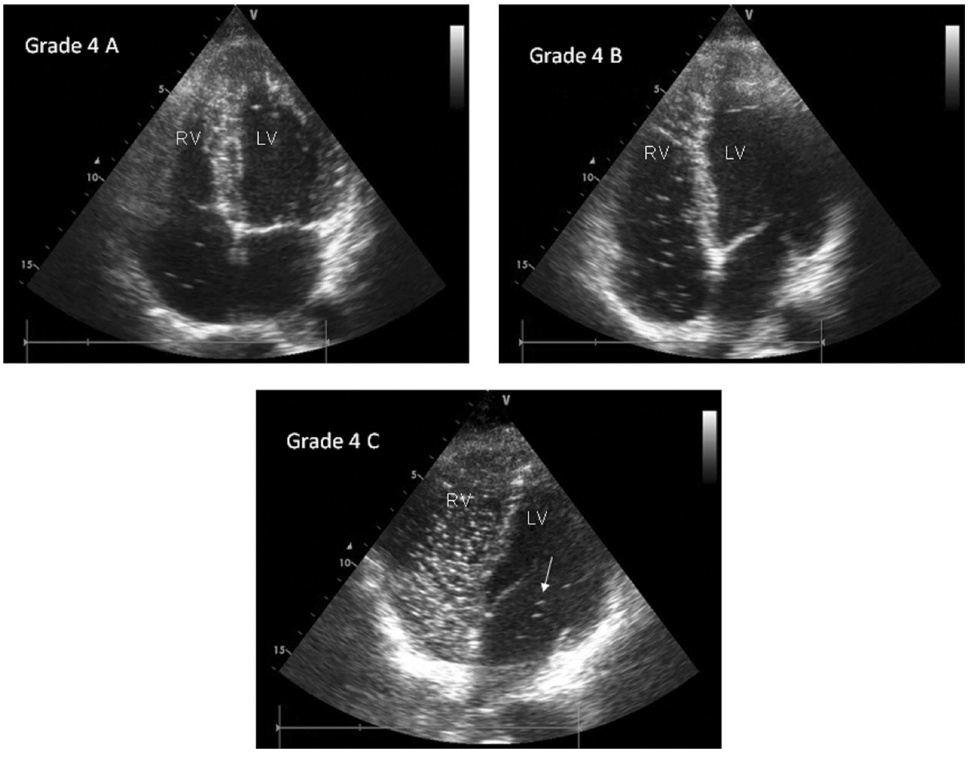

FIGURE 1—Subdivision of the current grade 4 of the vascular gas emboli in the heart. Displayed are echocardiographic images recorded on separate occasions after surfacing with VGE dominantly present in the right cardiac cavities. Although all three cases would be classified as grades 4, we further subdivided them into grades 4A, 4B, and 4C (see text for details). LV, left ventricle; RV, right ventricle. *Arrow* points at gas bubbles present in the left cardiac chambers.

TABLE 2. Occurrence of grade 4 and arterialization in the diving series.

Dive No.	Number of Divers Performing the Dive	Number of Divers with Grade 4 at Any Time Point	Number of Divers Exhibiting Arterialization
1	12	8	0
2	12	10	3
3	11	8	4
4	11	9 (+1 G5)	2
5	11	10	1
6	12	10	1

The presence of gas emboli was assessed in the cardiac cavities by two-dimensional echocardiography every 20 min for up to 120 min after surfacing. The Eftedal and Brubakk scale was used where grade 4 is defined as "At least one bubble/cm^2 in every image." On one occasion, a grade 5 (G5) was observed in the right valve of the heart.

one dive). In the entire dive series, bubble grade of 4 was detected at some point after dive in all but one individual.

During the ultrasonographic imagining of gas emboli in the cardiac chambers, it was observed that grade 4, defined as "continuous bubbling, at least one bubble per cm^2 in all frames" by Eftedal and Brubakk (11), may be more accurately subdivided into three subcategories, as described in the Methods section. Based on these criteria, a retrospect analysis of bubble grade 4 recorded at 40 and 60 min after dive was performed. Of 50 grade 4 dives detected at 40 min after dive throughout the dive series, 10 were classified as 4A, 31 as 4B, and 6 were classified as 4C. In three cases, grade 4 could not be further subdivided because of the insufficient clarity of the echo image. From 38 grade 4 dives detected in all divers at 60 min after dive, 14 fell into 4A category, 13 into 4B, 5 into 4C, and 6 cases remained unsorted.

Surprisingly, crossover of VGE to the arterial side of circulation was observed after 11 of the 69 dives (16%), and it was found in 5 (41.7%) of 12 divers. On two occasions, it lasted up to 120 min, and the median bubble grade was 1 (range = 1–3.5). In only one individual that a functional PFO was present. The presence of gas emboli in the left cardiac chambers was always accompanied with VGE grade 4 in the right valve of the heart (or grade 5 on one instance). Furthermore, in 7 of 11 dives with arterialization, a subgrade of 4C (according to our proposed scale) was identified in the right valve of the heart simultaneously or at some time point before arterialization (Fig. 1). In the remaining four dives, a retrospect subgrading in the right valve of the heart was hindered because of technical limitations.

DISCUSSION

In the current study, no DCS symptoms were noted in any of the divers; however, a large amount of VGE and their frequent arterialization (16% of all dives and in 41% of all divers) were seen in resting subjects. Right-to-left shunting of VGE lasted in some cases up to 120 min after dive. In only one diver that a functional PFO was detected. The observation that the arterializations were evident only at VGE grade 4 in the right cardiac cavities indicates that the crossover of gas bubbles into the systemic circulation is associated primarily with high bubble grades. A new subdivision of grade 4 into three subgrades was used to categorize the amounts of VGE observed in the heart.

Eftedal and Brubakk (11) have proposed a grading system for ultrasound scanning of gas bubbles. Because we unexpectedly found high bubble grades in the current study, especially grade 4 (found in 55/69 dives), we sought to subdivide this grade further. As stated above, grade 4 is currently defined as continuous bubbling, with at least one bubble per squared centimeter in all frames. However, after retrospect examination of all time points where grade 4 of VGE was detected in the right valve of the heart, we divided the observed cases into three subcategories; 4A, 4B, and 4C, as described in the Methods section and displayed in Figure 1 (A–C). A similar subdivision of grade 4 to grades 4–6 was proposed in 2007 by Pollock (22).

Hennessy and Hempleman (15) proposed a $p\sqrt{t}$ value in their model for evaluating the dive stress and the risk for DCS of the no-decompression dives. The incidence of DCS increased for the $p\sqrt{t}$ values above 25, which has led the U.K. Health and Safety Executive to give a depth/duration limitation of nitrogen/oxygen dives to less than these levels for all professional dives (23), a measure that has resulted in a sharp reduction in the number of incidents. The dives performed as part of the present study had $p\sqrt{t}$ values of 21.7 (18/60), 23.4 (18/70), 18.6 (24/30), 21.5 (24/40), 16.7 (33/15), and 19.2 (33/20). Thus, based on the equation of Hennessy and Hempleman, the lowest risk was associated to two dives to a depth of 33 m of seawater, followed by 24 m of seawater and finally 18 m of seawater profiles.

Norwegian no-decompression diving tables are widely used by both recreational and professional divers and are very similar to the U.S. Navy tables regarding the dive's depth/duration characteristics. According to the traditional view that the occurrence of DCS is related primarily to the large amount of gas bubbles and their appearance in the systemic circulation, the current finding of high VGE formation after no-decompression air dives suggests that divers may be exposed to a much greater risk of DCS than anticipated. These findings may be in agreement with the Divers Alert Network (DAN) data from 2003 (6), which indicate that most of the injured divers with neurological (type II) DCS (75%–90%) have followed dive profiles without performing any procedural error. It is therefore possible that the VGE produced in large quantities after recreational dives and with relatively high incidence of arterialization are at least partially responsible for these acute cases of diving-related injury. Despite that, no DCS or decompression-related disorders were noted in any of the divers. One explanation may be that the number of dives performed here was not sufficient for the probability of DCS to be necessarily realized. Apart from that, an obvious alternative explanation is that high VGE grade and their systemic crossover may not have a high positive predictive power for the incidence of DCS.

Although the finding of high venous bubble grades was not anticipated, we used this unique data set to compare

this dive series with our previous study of deep dives using trimix (a mixture of oxygen, helium, and nitrogen) (16). Despite the apparent differences between the two sets of diving procedures, as the depth, duration, number of dives, equipment, and composition of breathing gases were different, on both instances a significant amount of VGE were produced and recorded in the postdive period. Furthermore, the crossover of VGE was detected in both studies only if the grade 4 (or 5 on one instance) was simultaneously observed in the right cardiac cavities. Although grades 4 and 5 were detected in the current study more frequently than in the trimix study (56/69 air dives vs 10/21 trimix dives, $\chi^2 = 9.26$, $P = 0.002$), an incidence of gas bubbles arterialization was greater with trimix (9/10 trimix dives with grade 4 or higher vs 11/56 air dives resulting with grade 4 or higher, $\chi^2 = 19.89$, $P < 0.001$). This may indicate that the crossover of VGE to the arterial side of circulation occurs more readily when diving with helium mixes. However, this hypothesis requires further investigation owing to the substantial differences in diving conditions between the two diving procedures. Moreover, an interindividual susceptibility to arterialization cannot be excluded because different individuals participated in these two studies. Furthermore, the retrospect analysis of arterialization events observed in this study revealed that, in most instances, the arterialization was detected only if "high" grades 4 were present in the right valve of the heart. This notion corroborates the necessity for more sensitive subdivision of the grade 4, which, according to the currently used scale, covers a wide range of bubble amounts starting at one bubble per squared centimeter to almost a complete whiteout of the cardiac cavities. The application of a more sensitive scale might enable researchers to more accurately assess the bubble load threshold at which the VGE crossover occurs.

Even when a large number of vascular bubbles is observed, its importance in the development of DCS is widely debated. However, studies in both animals and men have shown that vascular gas bubbles can lead to endothelial dysfunction both on the venous and on the arterial side (18). Predive administration of antioxidants may partially prevent acute endothelial dysfunction (20). The long-term effects of high VGE exposure on either side of circulation are unknown, but development of procedures resulting in as low levels of vascular bubble formation as possible seems appropriate (4).

The amount of VGE observed in this dive series is surprising. We have shown in two separate studies after air dives to 18 m of seawater with 70 min of bottom time considerable differences in bubble formation in young, healthy male divers (3,7). In both of these studies, considerably less bubble was seen than in the 18 m of seawater dive for 60 and 70 min seen in this study. One is reminded of the comment made by Behnke (2), who stated that, "There are sharply demarcate limits of perhaps 5 feet in diving depth … separating injury from a state of well-being." It is tempting to speculate that, at high levels of dive stress, i.e., after dives that produce a large number of venous gas bubbles, the system behaves very nonlinearly and that even small environmental changes may have a major effect.

Previously, we have shown that submaximal exercise after a single air dive to 30 m of seawater for 30 min was not associated with right-to-left shunting of VGE (9). However, in comparison to the measurements performed after the current dives, significantly lower bubble grades were found in the previous study (9) (2/12 dives resulting with grade 4, $\chi^2 = 20.91$, $P < 0.001$). Therefore, the absence of arterializations in our previous study with air diving was likely due to the substantially lower bubble load that, even with increased pulmonary artery pressure developing during submaximal exercise, did not lead to the VGE crossover. More detailed discussion about the possible mechanisms of right-to-left shunting of VGE through pulmonary circulation is presented elsewhere (16). Our trimix and air data suggest that VGE in the systemic circulation do not necessarily elicit acute neurological symptoms, although the long-term effects cannot be excluded.

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