Ascent Rate and Circulating Venous Bubbles in Recreational Diving

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The aim of this study was to assess the effect of the ascent rate on the production of venous circulating bubbles during the decompression following a recreational dive. Twenty-eight recreational divers performed two open water dives at 35 m during 25 minutes. Ascent rate up to the decompression stop was in one case 9 meter per minute (m/min) and in the other case 17 m/min. Circulating venous bubbles were screened using continuous wave Doppler every 10 minutes during one hour after surfacing. Bubbles Doppler signals were graded according to the Spencer scale (from 0 to IV), and the Kisman integrated severity score (KISS) was calculated. Statistical analysis demonstrated a significantly higher bubbles grade and a significantly higher KISS following the rapid decompression compared to the slow one (respectively p = 0.001 and p = 0.0001). In conclusion, these results demonstrate that a 9 m/min ascent rate is safer than a 17 m/min one.

Key words: Gas emboli, diving, Doppler, decompression.

Introduction

The pathophysiology of decompression sickness (DCS) is usually admitted to be the formation and growth of nitrogen free gas phase, in the form of gas microbubbles, within tissues and blood during exposure to an acute reduction in ambient pressure. Microbubbles develop from pre-existing gas nuclei as a result of supersaturation of the dissolved nitrogen [16]. In fact human and animal experimentation demonstrated a close relationship between bubbles formation and the risk of decompression sickness.

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Animal studies also demonstrated that a rapid decompression rate increases venous bubble production and that a slower decompression rate is associated with a lower DCS incidence [13,14]. These arguments suggest that in humans a rapid decompression may be associated with an increased risk for DCS.

Practically ascent rate up to the decompression stop in the different decompression tables available has been first determined arbitrarily and then modified by empiricism and intuition. The 18 meter per minute (m/min) ascent rate of the USN Air tables was considered as a standard, from which the other decompression tables ascent rates were determined [7].

Referring to the French decompression tables, recommendations vary from 9 m/min (French Labour Ministry decompression table – 1992 or COMEX SA decompression table – 1987) to 17 m/min (Marine Nationale – 1990). Previously in an effort to clarify the problem Marroni and Zannini [9] monitored circulating bubbles every 5 minutes after surfacing during 40 minutes in two populations of divers, who had performed dives with different ascent profiles. They concluded that a 10 m/min ascent rate was associated with a lower circulating bubble grade than a non linear ascent with a mean 14 m/min ascent rate. However, in this preliminary study divers did not perform the two dives, and the conditions and profiles of the dives were not standardised.

To provide a more quantitative understanding of the influence of the ascent rate on bubble production, we designed a prospective study of post-dive ascent rate in recreational divers. We monitored circulating bubbles using continuous wave Doppler in divers who performed two successive standardised dives with different ascent rates, 9 m/min and 17 m/min, which are the extremes in the French decompression tables.

Methods

Dive profiles

Thirty-five male recreational divers, medically fit to dive, were selected for the study. After an initial reference Doppler test seven subjects were excluded because of a poor Doppler signal. Thus 28 divers were finally included in the study (mean age 35.5 ± 10.7 years, mean height 177.0 ± 6.2 cm, mean weight 77.9 ± 12 kg).

Between September 1996 and September 1999 they performed two dives in the open sea, off Marseilles, France, on a 35 m regular flat bottom area. Profiles of the dives were determined prior to the beginning of the study and were the same for all subjects. Divers performed two dives at a depth of 35 m. Descent rate was 30 m/min. The bottom time, including the descent time (70 seconds), was 25 minutes. The ascent was linear, and the ascent rate up to the decompression stop was 9 m/min for one dive and 17 m/min for the other. Decompression stops were determined according to the French Ministry of Labour Table 1992, i. e. 3 minutes at 5 m and 15 minutes at 3 m. Fig. **1** shows the profiles of the two dives. Ascent time to the first stop was 102 s for the 9 m/min ascent rate dive and 195 seconds for the 17 m/min dive. The dive profiles and the ascent rate were strictly controlled by one investigator, who is a diving instructor and who performed the entire dive himself. The ascent rate was controlled using a chronometer and a dive computer (Maestro Pro, Beuchat). Temperature of the sea varied from 15 °C to 20 °C at the surface and from 12 °C and 16 °C at the bottom. Divers were equipped with neoprene suits. During the dive strenuous exercise was avoided. Activity was also reduced before and after the dive.

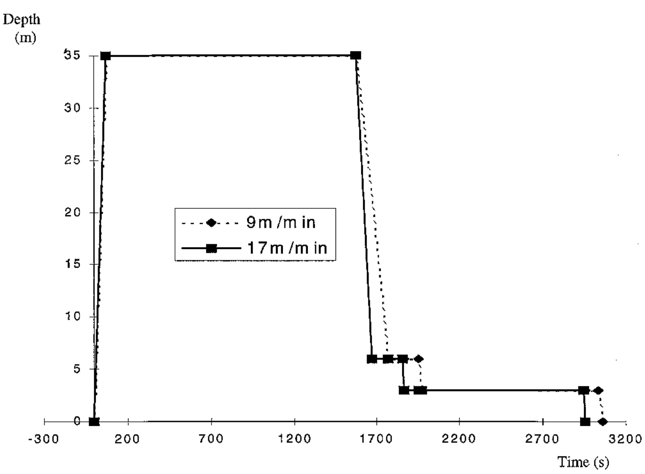

Fig. 1 Profiles of the two dives.

Each diver performed the two dives within a minimal 24 hours interval. In 3 cases the interval between the two dives was 1 day, in the 25 others cases the interval was between 3 and 7 days. Divers were randomly assigned to perform the rapid ascent dive or the slow one first.

Bubbles detection

Circulating bubbles were monitored using a continuous wave Doppler apparatus DUG (Sodelec SA) equipped with a 5 MHz probe. This apparatus allows detection of bubbles > 50 micron diameter. To improve the accuracy of the cardiac signal, subjects were placed in left lateral decubitus. The probe was placed in the precordial region, the ultrasonographic wave being directed onto the pulmonary artery flow. Tests were done every 10 minutes after surfacing and during one hour.

The signals were tape recorded for 2 minutes and graded in a blind manner by two independent investigators according to the Spencer Doppler Scale [15]: grade 0, no bubbles signal; grade I, an occasional bubble signal with the great majority of the cardiac cycles free of bubbles signal; grade II, many but less than half of the cardiac cycles contain bubbles signals; grade III, bubbles in most of the cardiac cycles but not obscuring the heart sounds; grade IV, numerous bubbles obscuring the heart sounds.

Kisman Integrated Severity Score (KISS) calculation

The bubble Doppler grade, from 0 to IV, was used to calculate the Kisman Integrated Severity Score (KISS) [6], according to the following formula:

$$KISS = (100/4^a[t_4 - t_1]) \times ([t_2 - t_1][d_2^a + d_1^a] + [t_3 - t_2][d_3^a + d_2^a] + [t_4 - t_3][d_4^a + d_3^a])/2$$

Where: $a = 3$
t_i = time of observation in minutes after reaching surface
d_i = Doppler score (grade 0 to IV) observed at time t_i

Indeed Doppler scores are often reported using the single maximum bubble grade observed for a subject. This method, unfortunately, does not distinguish between a diver with a single grade III score during a four periods observation (III, 0, 0, 0) conducted over 2 hours (KISS = 7) and another diver with grade III four times (III, III, III, III) during the same period (KISS = 42.2). The KISS was assumed to be a meaningful linearized measure of post-decompression intravascular bubble activity status [12] which may be treated statistically and was used in this investigation to determine the effect of the ascent rate during decompression.

Statistical analysis

Data are expressed as mean ± SEM. Statistical tests were run on the statistical package STATWIEV (Abacus concept Inc, Berkeley USA, 1992). Comparisons between slow and rapid ascent groups were done with non-parametric Wilcoxon rank sign tests. $P < 0.05$ was considered significant.

All divers gave their informed consent. The study was also approved by the local institutional review board (Comité Consultatif de Protection des Personnes dans la Recherche Biomédicale, Marseille 1).

Results

The 28 divers completed the two dives. None of them presented with any clinical sign evocative of DCS symptom. Thirteen divers performed the 17 m/min ascent rate dive first.

Mean bubble Doppler grade was significantly higher following the rapid ascent dive compared to the slow one (2.0 ± 0.3 vs. 1.5 ± 0.3; $p = 0.0001$). Furthermore, in each period the increase of bubble Doppler grade in the rapid ascent group remained significant (Table **1**).

Mean KISS was 26.0 ± 24.5 (ranging 0.6 to 94.2) in the rapid ascent group and 18.7 ± 21.8 in the slow ascent group (ranging 0 to 88.4) (Table **2**) ($p = 0.0001$).

Table 1 Venous bubbles Doppler detection

	Mean bubble Doppler grade 9 m/min	17 m/min	p
10 minutes	1.07	1.5	0.01
20 minutes	1.5	1.96	0.1
30 minutes	2.04	2.36	0.02
40 minutes	1.96	2.29	0.02
50 minutes	1.54	2.11	0.002
60 minutes	1	1.68	0.001
mean	*2.0 ± 0.3*	*1.5 ± 0.3*	*0.001*

Table 2 Severity index

Divers	KISS 9 m/min	17 m/min
1	3.3	11.4
2	0.6	5.6
3	3.4	5.9
4	22	30.3
5	39.2	42.2
6	88.4	94.2
7	0	0.6
8	26.9	39.2
9	36.3	42.2
10	3.1	5.8
11	0.6	3.6
12	1.1	7.8
13	0.6	3.1
14	1.1	7.8
15	0.3	0.9
16	36.3	39.2
17	29.2	33.3
18	20	38.1
19	53.8	82.7
20	0.6	5.9
21	42.2	42.2
22	8	20.9
23	42.2	42.2
24	29.2	42.2
25	26.3	39.2
26	0.6	1.1
27	1.4	39.2
28	6.9	0.8
Mean	18.7 ± 21.8	26.0 ± 24.5

Discussion

In the present work we screened circulating bubbles Doppler signals in the normal conditions of diving. Our divers equipped themselves, swam, came back to the boat, took off, and tidied their equipment. They underwent effects of cold water and immersion, all factors reported to modify the desaturation process [5,11]. As a result we consider that our observations are closely representative of what usually happens during recreational diving.

Formation of venous gas emboli as a result of decompression from a SCUBA (self-contained underwater breathing apparatus) dive is well known [16]. During a dive the exposure to high barometric pressure induces dissolution of nitrogen in the tissues as a consequence of an increased alveolar nitrogen pressure. During the ascent nitrogen pressure gradient from tissues to venous circulation and from blood to alveolar gas reverse and nitrogen is eliminated through the ventilation. This desaturation may be monophasic, dissolved nitrogen being eliminated directly through the ventilation or biphasic when blood supersaturates with formation of nitrogen bubbles. Human studies have shown that venous nitrogen bubbles formation is a common situation and bubbles are often detected after a SCUBA dive from all but the most trivial pressure exposure [2]. Nitrogen bubbles formation and growth, from gas nuclei, depend strongly on the ambient pressure reduction, volume modifications being closely related to pressure modifications, but also on bubbles surfacing factors, on gas diffusion rate across the bubble boundary, or on gas partial pressure in fluid immediately surrounding the bubble [8,17]. Bubble growth during decreasing pressure is hyperbolic.

In this study we demonstrate a relationship between the reduction of the ascent rate and the decrease of venous bubble count following a standardised dive at 35 m. When the ascent rate increases, ambient pressure reduces faster and nitrogen gradient between tissues and blood increases as well. It may then reach the critical ratio for nucleation and promote bubble formation. Rapid pressure reduction may also alter the balance between the rate of pulmonary gas elimination and bubble volume growth due to pressure reduction. However, the profiles of our two dives differ in the total decompression time, which may also play a role. In our study ascent time was 93 seconds longer in the slow ascent rate group, which may have been sufficient to promote a better desaturation process.

Further studies are needed to try and differentiate between the effects of the ascent rate and those of the total decompression time.

There are some limitations to this study. Firstly, we performed Doppler tests every 10 minutes post dive for one hour. This gives us better information on bubble production when compared to a single detection. However, we did not monitor the bubbles production after these 60 minutes. In fact Masurel et al. [10] observed, following a 36 m dive of 55 minutes, a first bubbles peak 60 minutes after surfacing but also a second one after 240 minutes. Although Masurel's dive was much longer than ours, it would have been of interest to complete the present study with a prolonged monitoring. Secondly, the statistical analysis could be questioned, which we used for the comparison of Doppler bubble grades, which are categorical data. In fact Fienberg [3] in his statistical handbook focused on analysis of cross-classified data and emphasized that integer-valued (discrete) data might also be treated as continuous data. However, in order to improve our analysis, we also calculated the severity index proposed by Masurel et al., which confirmed that a lower ascent rate was associated with a lower bubble grade.

As many studies have reported a correlation between bubble grade and risk of DCS [1,4,15], our study strongly suggests that a linear 9 m/min ascent rate up to decompression stop decreases DCS risk compared to a linear 17 m/min ascent rate.

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