Recompression During Decompression and Effects on Bubble Formation in the Pig

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Møllerløkken A, Gutvik C, Berge VJ, Jørgensen A, Løset A, Brubakk AO. ***Recompression during decompression and effects on bubble formation in the pig.*** **Aviat Space Environ Med 2007; 78: 557–60.**

Introduction: There is a relationship between gas bubble formation in the vascular system and serious decompression sickness. Hence, control of the formation of vascular bubbles should allow safer decompression procedures. ***Methods:*** There were 12 pigs that were randomly divided into an experimental group (EXP) and a control group (CTR) of 6 animals each. The pigs were compressed to 500 kPa (5 ATA) in a dry hyperbaric chamber and held for 90 min bottom time breathing air. CTR animals were decompressed according to a modified USN dive profile requiring four stops. EXP followed the same profile except that a 5-min recompression of 50 kPa (0.5 ATA) was added at the end of each of the last three decompression stops before ascending to the next stop depth. ***Results:*** All CTR animals developed bubbles, compared with only one animal in EXP. The number of bubbles detected during and after the dive was 0.02 ± 0.02 bubbles · cm^{-2} in CTR, while the number of bubbles detected in EXP were 0.0009 ± 0.005 bubbles · cm^{-2}; the difference was highly significant. ***Conclusion:*** By brief recompression during late decompression stops, the amount of bubbles was reduced. Our findings give further support for a gas phase model of decompression.
Keywords: diving, DCS, vascular gas bubbles.

DECOMPRESSION FROM a dive can produce supersaturation of dissolved gas in tissues and subsequent formation of inert gas bubbles. Such bubbles are associated with the development of decompression sickness (DCS). Though their presence is not sufficient to induce DCS, the risk of its development is linked to the volume of gas in bubbles (10). Most decompression schedules used in both commercial and in recreational diving are based on the principles first described by Boycott et al. (1). They aimed at producing a sufficiently large gradient for the elimination of gas, assuming that a rather large supersaturation could be safely tolerated without significant bubble formation. Later studies have shown that this assumption is not correct and that considerable bubble formation is associated with these profiles (8).

Vascular gas bubble formation will probably occur in most if not all decompressions (4) and these bubbles will grow during decompression even when the rate of growth is controlled by decompression procedures. The rate of growth of these bubbles will be influenced by their initial size. Hence the present study was initiated to determine whether recompression during decompression from a standard air dive could affect vascular bubble formation.

METHODS

All experimental procedures conformed to the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes, and the protocol was approved by the Norwegian Council for Animal Research. The animals were maintained under the supervision of a veterinarian.

A total of 12 pigs (*Sus scrofa domestica*), both male and female, were used in this study. The pigs were 12 wk old, weighing 23.3 ± 3.7 kg. All animals arrived at the center for experimental animals at St. Olavs Hospital in Trondheim, and had one week of acclimatization before start of the study. They were kept in housing facilities with free access to water, and were fed a pellet diet once a day. The light was controlled at a 12-h dark/12-h light cycle. Temperature was 21 ± 1°C and the humidity was 55 ± 5%. The pigs were randomly divided into two groups; an experimental group (EXP) and a control group (CTR) with six animals in each.

Surgical Procedures

Before the experiment, the pigs were fasted for 16 h with free access to water. On the day of the experiment, they received premedication with 10 ml Stresnil (azaperon, Janssen-Cilag Pharma, Wien, Austria) and 2 ml Stesolid (diazepam 5 mg · kg^{-1}, Dumex-Alpharma AS, Copenhagen, Denmark). After 20 min, atropinesulfate (atropin, 1 mg iv; Nycomed Pharma, Asker, Norway) was given via an ear vein. Anesthesia was induced by

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This manuscript was received for review in September 2006. It was accepted for publication in March 2007.

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thiopental sodium (5 mg · kg^{-1} Pentothal Natrium, Abbott Scandinavia, Solna, Sweden) and ketamine (20 mg · kg^{-1} Ketalar; Pfizer, Lysaker, Norway). The anesthesia was maintained by a continuous iv infusion of ketamine in 0.9% NaCl (30 mg · kg^{-1} · h^{-1}) together with bolus doses of α-chloralose in 0.9% NaCl (10–15 mg · kg^{-1} injected iv; 0.25% solution). A tracheotomy was performed to allow the pigs to breathe spontaneously through an endotracheal tube. Throughout the experiments, the pigs were in a supine position. The depth of anesthesia was maintained at an even level, as judged by clinical observation and the various measured physiological variables.

A polyethylene catheter was introduced into the left jugular vein for obtaining venous blood samples for blood gas analysis. Another catheter was introduced into the right femoral artery and advanced into the abdominal aorta to obtain arterial blood samples for blood gas analysis. Deep body temperature was measured continuously throughout the experiments by a rectal thermometer, and was adjusted through regulation of the chamber temperature. Body temperature was kept between 38.0°C and 39.0°C.

Pressure Profiles

All animals were compressed on air to 500 kPa (5 ATA; 39.6 msw) in 2 min in a dry hyperbaric chamber were they stayed for 88 min while breathing air. Decompression was then performed at a rate of 90 kPa · min^{-1} (0.9 ATA · min^{-1}). The control profile was a modification of a USN standard air profile for 90 min at 39.6 msw (12). Pilot studies showed that this profile produced very few bubbles, so it was modified to provoke bubbles in CTR by cutting the normal stop times in half, yielding a profile with stops of 4 min at 12 msw, 9 min at 9 msw, 23 min at 6 msw, and 40 min at 3 msw (**Fig. 1A**). EXP animals followed the same profile with the addition of a 5-min recompression of 50 kPa (0.5 ATA) at the end of each of the last three decompression stops (**Fig. 1B**). The total decompression period was identical in the two groups.

Bubble Detection and Statistical Analysis

A transesophageal echocardiograpic probe was introduced through the mouth and positioned to provide a clear image of the right ventricle and the pulmonary artery as described by Reinertsen et al. (11). The transducer was connected to an ultrasonic scanner (CFM 750; Vingmed Sound, Horten, Norway). The bubbles could be seen as white spots and were graded according to a method described by Eftedal and Brubakk (5). This grading system has been used extensively in several animal species as well as in man, and is nonlinear when compared with the actual number of bubbles in the pulmonary artery. The transesophageal echocardiograpic probe was left in place for the entire experiment, but bubble counting started with the initiation of decompression. A VHS recording was made from each animal, allowing repeated evaluation. The images were also transferred to a Macintosh computer where the number of bubbles in the sample volume located in the right ventricle was continuously measured using a specially developed program (5). The bubble grades were transformed into a linear scale as described by Nishi et al. (10). The number of bubbles is given as bubbles · cm^{-2}. The maximum bubble number was the highest value for each animal regardless of timing. Data were expressed as mean ± SD. A Student's *t*-test was used to compare the number of bubbles during the observation period. A level of $p < 0.05$ was considered as statistically significant.

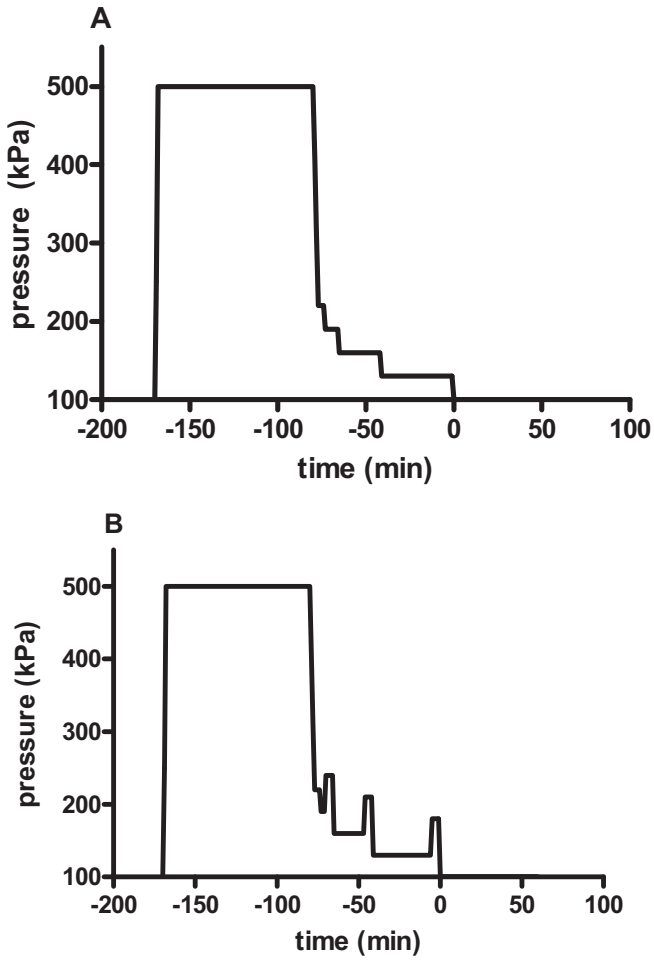

Fig. 1. Pressure profiles for both A) the control and B) the experimental group. Time = 0 is at surface after decompression.

RESULTS

Mean bubble densities for each group during decompression are shown in **Fig. 2**. All six CTR animals produced bubbles during and after decompression with a mean value of 0.02 ± 0.02 bubbles · cm^{-2} for the entire observation period. By contrast, only one animal in EXP had detectable bubbles, giving a mean value of 0.0009 ± 0.005 bubbles · cm^{-2} during the observation period. This difference was highly significant ($p < 0.0001$).

Once an animal in CTR began bubbling, the condition persisted throughout the rest of the observation period, with a peak at around 30 min after reaching the surface (Fig. 2A). As shown in Fig. 2B, the bubbles in the single EXP case appeared briefly after reaching surface pressure, with a small recurrence after approximately

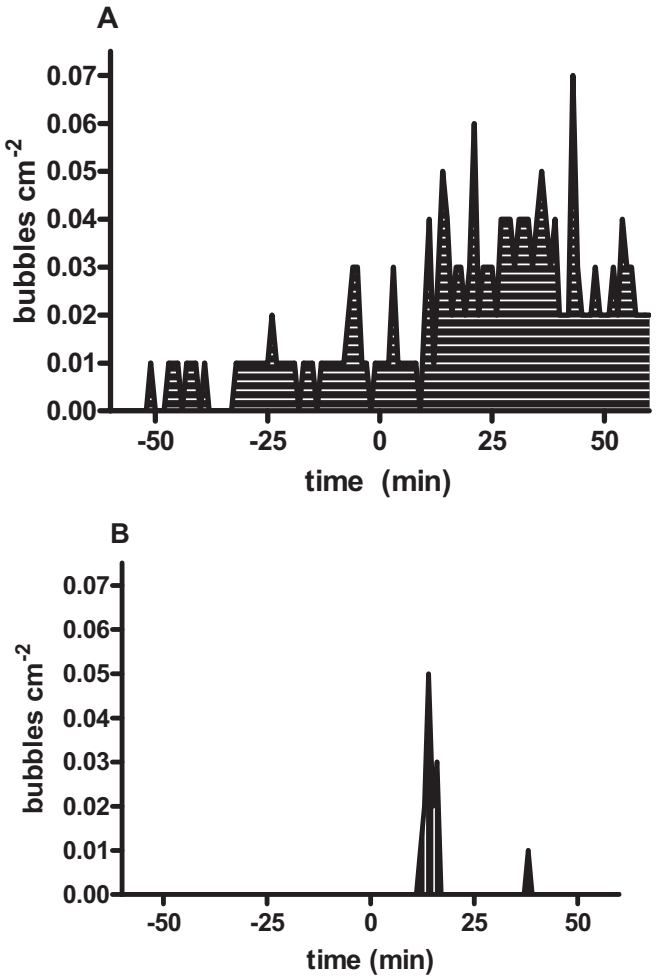

Fig. 2. The mean amount of bubbles detected in the pulmonary artery from start of decompression in both A) the control and B) the experimental group. Time = 0 is at surface after decompression. In both groups, n = 6.

40 min on the surface. The observations ended 60 min after reaching the surface, even though there still were some remaining bubbles detectable in the pulmonary artery, and the animals were then sacrificed.

DISCUSSION

Gas tension inside a bubble is inversely proportional to bubble size. Thus, the larger the bubble, the larger the gradient for bubble growth, and consequently the smaller the gradient for bubble decay. If bubble size can be reduced, bubble growth can be inhibited. During recompression the bubble size will be reduced, inert gas tension starts to increase, and gas will diffuse out of the bubble. This will increase gas tension in the tissue, which again reduces the uptake of gas. Furthermore, as gas tension in the tissues is low because of the effect of bubbles (13), an increase in gas tension will increase the elimination of gas. Hence, even if bubbles increase in size on subsequent ascent, they will do so at a slower rate and from a smaller size than before. Our observation that the bubbles in the control group appeared earlier than in EXP supports this theory.

The recompression and the following shrinkage of the bubbles can be a potential pathway for right to left shunting of bubbles through the pulmonary vessels. Crossing of venous gas from the venous to the arterial side of the circulation can lead to neurological damage after diving. The usual reasoning is that the lungs function as a sponge-type filter through which microbubbles below a certain diameter will pass, whereas larger bubbles are trapped and dissolve in the lung. Infusion experiments have shown that if the volume rate of gas infusion is large enough, microbubbles will appear in the left atrium (14).

After pilot studies, it became evident that the standard U.S. Navy table produced only few vascular bubbles in the pig. Hence we halved the decompression time by halving the stop time at each depth. This increased bubble production sufficiently in the control group. Both in animals and in man a slow ascent induces fewer venous gas bubbles than a fast one, (3,11). However, in a previous study we showed that bubble formation could be significantly reduced by changing the ascent profile in spite of increasing decompression speed (2).Together with our new findings, these data show that a gas phase model is needed to explain the results and hence support the use of gas phase models when designing decompression procedures.

Given that there is no validated mathematical model, both the timing and the duration of the recompression used in our experiments could not be based on theoretical calculations. The recompression used in our study was similar to that suggested by Gernhardt (7). He suggested that intermittent recompression during a saturation decompression would be effective in controlling gas phase growth and decompression stress. The recompressions he simulated were at times of peak bubble growth rates, recompressing 160 kPa (1.6 ATA) for a period of 2 h during a saturation decompression. In our study, the first decompression stop at 12.1 msw lasted only 4 min, and hence we did not perform any recompression at this stage. At all the other decompression stops [at 190, 160, and 130 kPa (1.9 ATA, 1.6 ATA, and 1.3 ATA, respectively)], however, we performed a 5-min recompression to 240, 210, and 180 kPa (2.4 ATA, 2.1 ATA, and 1.8 ATA), respectively. From a Haldanian point of view, such a recompression would not give any advantage; on the contrary, increasing pressure during decompression will only increase tissue gas tensions and hence the risk of exceeding the critical tension values. Even with a simple bubble model like the varying permeability model (16), the immediate effect would be an increase in inert gas uptake, followed by an enhanced bubble growth when ascending back to an even shallower stage. However, a bubble model taking size reduction and surface tension into account may explain the results. Obviously, both the timing and duration of recompression are critical, as is the relative pressure increase. We might end up with increased bubble formation if the increased tissue tension dominates over the positive effect of bubble shrinkage. In such a case, the increased tissue tension would lead to an even greater bubble formation when ascending to the next stage.

In EXP we had only one animal which had detectable bubbles, and five with no bubbles. It is always a di-

lemma how to treat the data, whether one should look at the one animal with bubbles as an outlier, or treat all six animals with mean values. In Fig. 2 the amount of detected bubbles from start of decompression in both groups is shown. The figure represents a mean number of bubbles as a function of time for all the animals in each group, respectively. For all practical purposes, the present study is not to be seen as a new decompression method. The present study is a scientific approach trying to uncover some more of the secrets behind decompression-related problems, and as such it points out some new thoughts and ideas.

There is an increased risk of developing serious DCS when a large number of bubbles can be detected in the vascular system (9). Together with the fact that there is a relationship between neurological DCS and an open foramen ovale (15), and that gas bubbles may pass through intrapulmonary arteriovenous shunts (6), this would support the hypothesis that vascular gas bubbles are the main problem in serious DCS. By reducing the amount developed during and after a decompression, the risk of serious injury may be reduced. Our findings and observations in this study show clearly that there is a need for new ideas in the field of decompression procedures, and that a gas phase model of decompression is needed for designing new decompression procedures.

ACKNOWLEDGMENTS

This study was supported by the Norwegian Petroleum Directorate, Norsk Hydro, Esso Norge and Statoil under the "dive contingency contract" (No 4600002328) with Norwegian Underwater Intervention (NUI). Arnfinn Sira is acknowledged for excellent technical assistance, and the personnel at the Centre for Experimental Animals at St Olavs Hospital in Trondheim for their professional handling of the animals.

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