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Bubble formation in gelatin: implications for prevention of decompression sickness

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Strauss, R. H. 1974. Bubble formation in gelatin: implications for prevention of decompression sickness. Undersea Biomed. Res. 1(2):169-174.—Gelatin exposed to N_2 at differing pressures was decompressed to form bubbles. Findings are consistent with the existence in gelatin of a spectrum of stable gas nuclei which can be compressed or transformed into bubbles. Results suggest that the number of bubbles and their total volume can be decreased, and decompression time shortened, if the gas supersaturation pressure (i.e. the difference in pressure between dissolved gas and environment) remains constant for decompression of a given tissue.

bubbles	decompression sickness
nitrogen	supersaturation
gas elimination	tissues

Decompression sickness is associated with diving, work at increased pressures in tunnels and caissons, and flying at high altitudes in unpressurized aircraft. The disease follows a reduction in ambient pressure and is generally thought to be a result of bubble formation and growth in blood or tissues (Harvey 1951; Buckles 1968). Manifestations may include paralysis or joint pain (the bends). The object of decompression in diving is to permit a transition from high to low pressures in the least possible time consistent with the avoidance of decompression sickness.

In 1908 J. S. Haldane and coworkers enunciated many of the principles presently utilized to decompress divers and avoid decompression sickness (Boycott, Damant, and Haldane 1908). One hypothesis, sometimes called the Haldane ratio principle, is: "In decompressing men or animals from high pressures the first part should consist in rapidly halving the absolute pressure: subsequently the rate of decompression must become slower and slower, so that the nitrogen pressure in no part of the body ever becomes more than about twice that of the air." Haldane assumed that increasing the ratio (tissue gas pressure)/(ambient pressure) above a critical limit at any time during decompression would lead to bubble formation and growth. This article describes a series of decompression tests in which gelatin is used to simulate animal tissue. The study examines primarily the characteristics of initial bubble formation rather than the growth of existing bubbles by diffusion of gas. The principal finding is that Haldane's method is not optimal for avoiding bubble formation and growth in gelatin.

METHOD

Bubble formation and growth have been studied in various media (Harvey 1951; Buckles 1968; Epstein and Plesset 1950; Bateman and Lang 1944). Nevertheless, the initial process of bubble formation, which could be critical in decompression, is poorly understood. This lack of information is largely a result of the methods of observation and the nature of the systems studied: bubbles which form within liquids generally rise when still too small to be observed; bubbles which form in opaque tissues cannot be seen. The decompression of transparent gelatin avoids these difficulties and yields bubbles which are stationary and can be counted and measured.[1]

A single batch of gelatin was made by dissolving 127 g Knox gelatin crystals in 5 liters (l) of water and then freezing 10 ml aliquots. For each experiment, gelatin was thawed at 40°C and pipetted into two slightly curved glass counting chambers of approximate horizontal cross section 6 mm by 27 mm diameter. The counting chambers were filled to a depth of 4 mm with liquid gelatin and placed in ice water for 10 minutes to speed gelation. Two chambers were then placed in a 21°C water bath within a small pressure chamber. Pressure was increased at 13.6 atm/min to some maximum pressure P_m by adding N_2, and then maintained at P_m for 20 minutes or longer. The gelatin could be viewed and photographed at any pressure with a microscope through a window in the pressure chamber. No bubbles were visible prior to decompression.

Saturation of the gelatin by N_2 took place at pressure P_s, which was set equal to or less than P_m. The time spent at saturation pressure P_s was 5.25 hours unless otherwise noted. According to calculations by the method of Crank (1957), and assuming a diffusion coefficient of N_2 in water of 11×10^{-4} cm^2/min (Bartels 1971), the bottom of a 4-mm gel layer would be greater than 97% saturated after 5.25 hours. Saturation time was also investigated experimentally by varying time at P_s from 1 second to 24 hours ($P_s = 73$ psig). The maximum number of bubbles was reached at saturation times between 5 and 7 hours.

Decompression was achieved by lowering the pressure from P_s to a final pressure P_f in 10 seconds, during which there was little time for diffusion of gas from within the gelatin to the atmosphere. Within seconds after decompression, bubbles became visible and grew rapidly. After a few minutes no additional bubbles appeared, and growth slowed and eventually ceased. The system was then stable for hours. Bubbles occurred throughout the gelatin and were approximately equal in diameter in the lower 3 mm, which corresponded to a gelatin volume of about 0.372 ml/counting chamber. The bubbles in the lower 3 mm were counted using a 7-power microscope. The upper 1 mm and meniscus were disregarded because bubbles near the surface appeared more numerous and smaller than elsewhere.

RESULTS

Supersaturation pressure P_{ss} is the amount by which dissolved gas pressure exceeds ambient pressure. Thus, immediately following decompression and before significant diffusion occurs, P_{ss} is given by $P_{ss} = P_s - P_f$. It was hypothesized that N_b, the number of bubbles appearing, was a function of P_m, P_s, and P_f. Briefly, the maximum pressure P_m represents a pressure which apparently decreases the size of gas nuclei, making bubble

[1]Cavitation studies in which a glass rod was suddenly torn out of gelatin are mentioned by Harvey (1951). More recently, extensive decompression tests have been carried out on gelatin by LeMessurier (1972). I am grateful to Carl Edmonds, M.D., for calling this work to my attention (private communication of August, 1973).

formation more difficult, and the supersaturation pressure P_{ss} promotes the formation and growth of bubbles.

The dependence of bubble formation upon supersaturation pressure was investigated (Fig. 1). In this experiment $P_m = P_s = 21.4$ atmospheres absolute (ATA), and P_f was allowed to

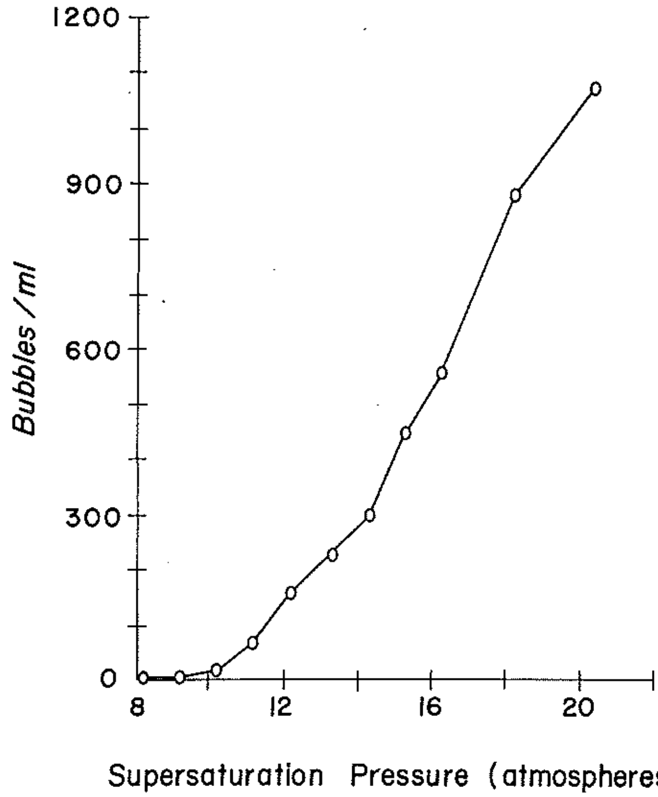

Fig. 1. The number of bubbles appearing in gelatin increased as supersaturation pressure increased. Maximum and saturation pressures were 21.4 ATA. Two chambers were counted at each pressure.

vary, producing P_{ss} of 8.2 to 20.4 atmospheres (atm). The number of bubbles and their size increased with increasing P_{ss}. Similar results have been observed in other media (Hills 1967; Gent and Tompkins 1969).

Bubble formation can be suppressed in water (Hemmingsen 1970) and shrimp (Evans and Walder 1969) by raising the maximum hydrostatic pressure at some time before decompression. This point was confirmed in experiments A and B (Table 1) by varying only the maximum pressure P_m. The greater P_m was maintained for 20 minutes at the beginning of experiment B and resulted in fewer bubbles ($P < 0.001$). Earlier experiments showed that the effect of P_m increased with time and was complete within 20 minutes. Any diffusion of gas into the gelatin during the time spent at the elevated P_m would tend to cause increased bubble formation rather than the decreased bubble formation which was observed. These findings are consistent with the existence in gelatin of nuclei of gas which can be compressed in a manner which is not entirely reversible. The effect of P_m upon bubble formation was not an artifact of the gel state since results were similar when P_m was applied to the sol (liquid) state before it became a gel.

In these experiments P_s/P_f immediately following decompression corresponds to the Haldane ratio (tissue gas pressure)/(ambient pressure). In order to test the effect of P_s/P_f upon bubble formation it is necessary to hold both P_m and P_{ss} constant because, as has been shown, each greatly affects bubble formation. This was done in experiments B and C (Table 1). P_s and P_f were varied. The larger ratio P_s/P_f resulted in fewer bubbles ($P < 0.05$) which is opposite to the prediction of the Haldane ratio hypothesis. These findings suggest an alternative basis for decompression. In terms of staged decompression (by steps), they imply that if pressure is reduced repeatedly by a constant value following sufficient time at each pressure for gas equilibration, bubbles will form only following the first pressure drop. Such was found to be essentially the case when ambient pressure was reduced successively from 21.4 ATA to 11.2 ATA to 1.0 ATA following 5.25 hours at each pressure for gas equilibration. In 5 trials, using 2 counting chambers in each trial, the first pressure drop of 10.2 atm resulted in a total of 208 bubbles formed. The second pressure drop of 10.2 ATA resulted in the growth of existing bubbles and the formation of a total of 7 additional bubbles. This increment of 3.4% could be due to small technical variations.

TABLE 1
Number of bubbles N_b as a function of pressure variations

Experiment	P_m ATA	P_s ATA	P_f ATA	P_{ss} atm	P_s/P_f	N_b bubbles/ml
A	11.2	11.2	1.0	10.2	11.2	1380.0 ± 40.0
B	21.4	11.2	1.0	10.2	11.2	40.8 ± 2.4
C	21.4	21.4	11.2	10.2	1.9	51.1 ± 4.0

The above results suggest *a.* that the initial pressure drop of decompression should be sufficiently small to prevent or minimize bubble formation; and *b.* that during subsequent decompression, supersaturation pressure could be maintained constant without additional bubble formation. The advantage of maintaining supersaturation pressure is that the diffusion gradient of gas from tissue is maintained, thus speeding decompression. However, the large initial supersaturation pressure of the Haldane method would foster early formation of bubbles into which gas would diffuse during the remaining decompression as long as supersaturation existed. Haldane's method of decreasing the supersaturation pressure as ambient pressure decreases may well be an empirical attempt to control the size of bubbles which formed much earlier. The above principles can be applied to either continuous or staged decompression.

Standard U.S. Navy decompression schedules are based upon the Haldane ratio hypothesis (Workman 1969). In the final experiment a U.S. Navy decompression schedule (U.S. Navy 1970) and an experimental decompression schedule based upon the present results were compared using gelatin 2 mm deep. All bubbles which formed were counted and measured. Figure 2 presents the pressure-time profile for the two schedules. Bubbles became visible following the large initial decompression of the Navy schedule. In the experimental schedule, the initial decompression was considerably less and was followed by linear decompression (which does not necessarily lead to a constant supersaturation pressure).

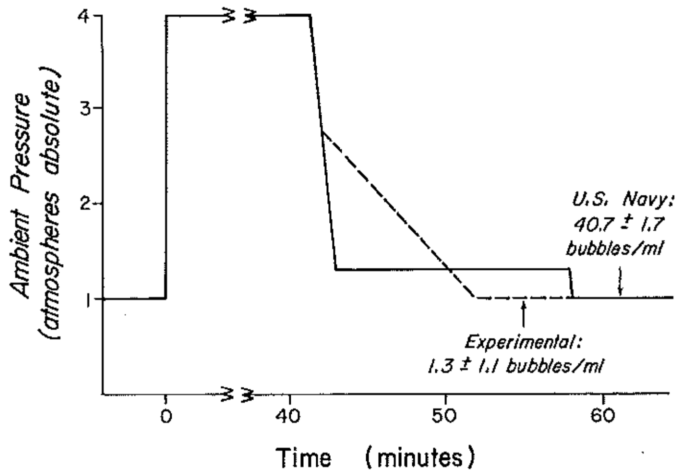

Fig. 2. Comparison in gelatin of a standard U.S. Navy decompression schedule (solid line) (U.S. Navy 1970) and an experimental decompression schedule (broken line). The latter was shorter and resulted in fewer bubbles.

Following decompression in 16 minutes 40 seconds by the U.S. Navy schedule there were 40.7 ± 1.7 bubbles/ml with a total volume of 4.79 ± 0.52 mm^3/ml. Following decompression in 10 minutes 40 seconds by the experimental schedule there were 1.3 ± 1.1 bubbles/ml with a total volume of 0.11 ± 0.04 mm^3/ml. The experimental schedule was shorter than the Navy schedule and resulted in fewer bubbles ($P < 0.001$) with a lesser total gas volume ($P < 0.001$).

The relationship between bubble formation in gelatin and decompression sickness is unknown. The gelatin experiments appear to reflect the response of gas nuclei to pressure changes. Nuclei within animals, either preformed or resulting from motion, have been proposed as a critical factor in bubble formation (Harvey 1951; Evans and Walder 1969). The above findings are consistent with this notion and suggest that the supersaturation pressure of a given tissue may remain constant during decompression. This important result implies that a nontraditional approach is needed to the problem of decompressing persons as safely and quickly as possible.

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