Bubble Mechanics: Implications for Safe Ascent

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A typical decompression schedule for divers consists of a series of relatively rapid ascents interspersed with appropriate safety stops at progressively shallower depth. This is a convenient way of approximating, in practical situations, a theoretically more ideal profile, which would be a smooth curve describing a gradual but continuous pressure reduction. The objective of such a profile or schedule is to allow time for gas dissolved in the body to exit through the lungs, thereby avoiding excessive supersaturation, the formation of bubbles, and the onset of decompression sickness.

Previous strategies for decompressing humans have been

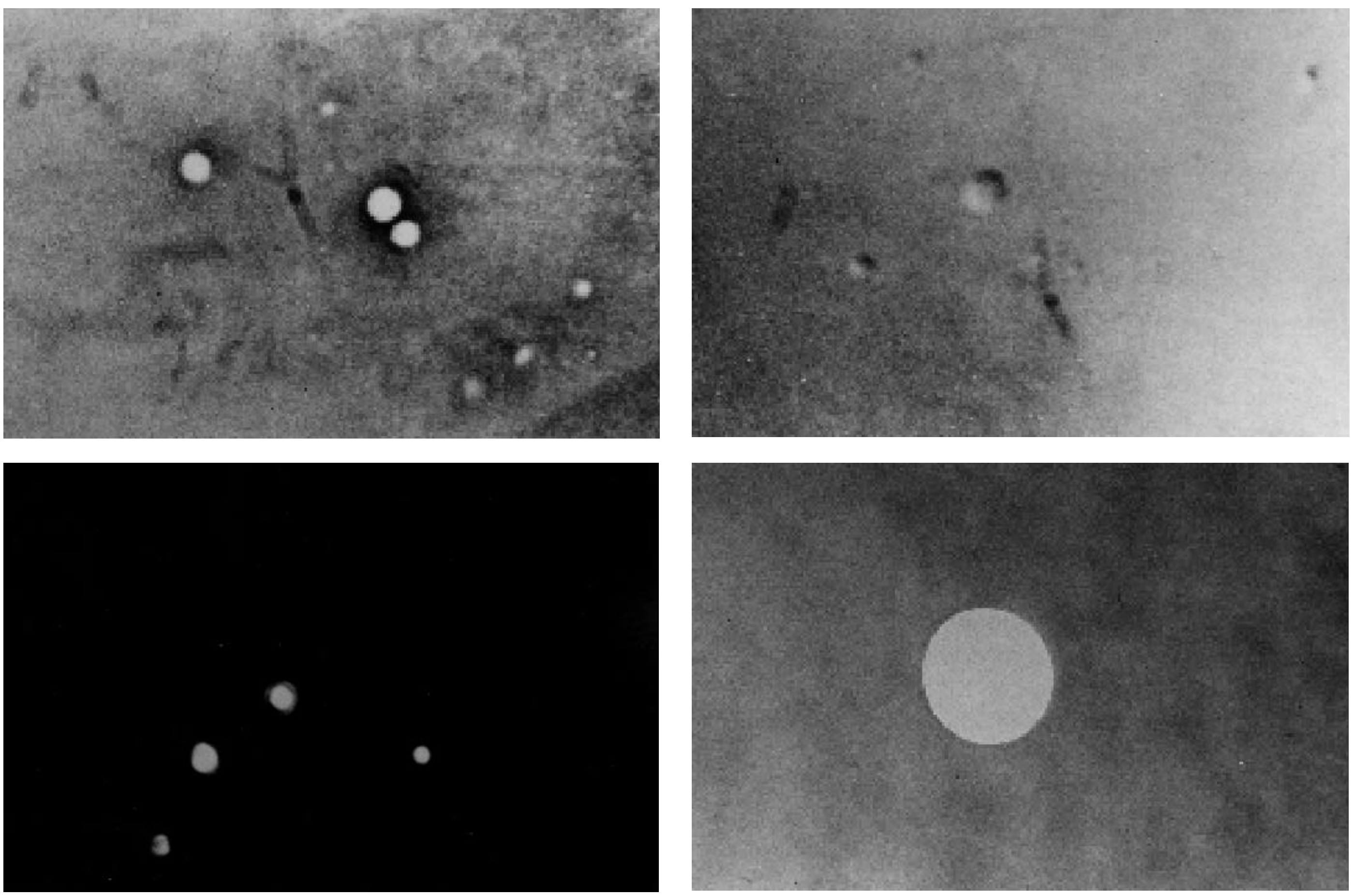

Figure 1 - Candidate nuclei found in agarose gelatin. From left-to-right top-to-bottom are phase-contrast, Nomarsky, dark-field, and transmission electron micrographs.

based mainly on trial-and-error informed by past mistakes as well as by a set of unsupported algorithms and assumptions, some of which are now known to be wrong. Tables differ widely, both in the duration of the stops and in the ascent rates between stops, with no apparent justification. Under these circumstances, it may be useful to try a new approach based on verifiable physical principles and especially on the mechanics of bubble formation.

Bubble Nucleation

Theoretically, bubble formation should not occur in pure water until the driving pressure exceeds 1,000 atm. This is very different from the experimental situation in which ordinary samples of sea water, tap water, or even distilled water begin to bubble at tensile, ultrasonic, or supersaturation pressures as small as one atm. This thousand-fold discrepancy can only be explained by assuming that there are impurities, called "bubble formation nuclei," which are present in nearly all aqueous media including plant and animal tissue.

What is the nature of these nuclei? Numerous experiments have demonstrated that thresholds for bubble formation can be raised by degassing or by a preliminary application of static pressure. Since solid or liquid nuclei would not be affected, these tests show that nuclei must consist mainly of gas.

The existence of stable gas nuclei, like the early onset of bubble formation, is theoretically very surprising. Gas phases larger than one micron in radius should float to the surface of a standing liquid, whereas smaller ones should collapse in less than one second due to surface tension. To resolve this dilemma, a new model, called the varying-permeability or VP model was introduced.

The essence of the VP model is that bubble formation nuclei consist of spherical gas phases (tiny bubbles) that are small enough to remain in solution via Brownian motion and strong enough to resist collapse caused by surface tension. The mechanical strength of these objects is provided by an elastic skin or membrane composed of surface-active molecules, *i.e.*, molecules like those found in soaps and detergents which are attracted to a liquid-gas interface and reduce surface tension. Like the thin films that surround soap bubbles, VP skins are normally permeable to gas, but can become effectively impermeable when subjected to large increases in pressure, typically exceeding eight atm.

Figure 1 is a photomontage of microbubble nuclei found in agarose gelatin. From left to right are phase-contrast, Nomarsky or interference-contrast, dark field, and transmission electron micrographs. The largest nuclei in each case have radii on the order of one micron. The structures identified as nuclei with phase-contrast and Nomarsky micrographs, the shadowing of the nuclei is opposite that of the surrounding gelatin, implying that nuclei are spherical cavities rather than solid or liquid impurities. This inference has been verified by direct microscopic observations that nuclei subjected to changes in pressure expand or contract in the manner expected.

Near the center of the phase-contrast micrograph in Figure 1 are two osculating nuclei, that is, two nuclei that are just barely touching and appear to be spherical in shape at the point of contact. Binary nuclei have also been photographed in distilled water. The fact that there binary nuclei in nature and that binary nuclei are stable provide further evidence that individual nuclei are enclosed in gas-permeable skins.

The idea is that permeable skins allow each nucleus to reach diffusion equilibrium with the gas dissolved in the surrounding liquid. Since both members of a binary configuration are in diffusion equilibrium with the same liquid and one another, they retain their gas contents and relative size. This situation does not hold for binary soap bubbles in air, where it is well-known that the smaller member of the

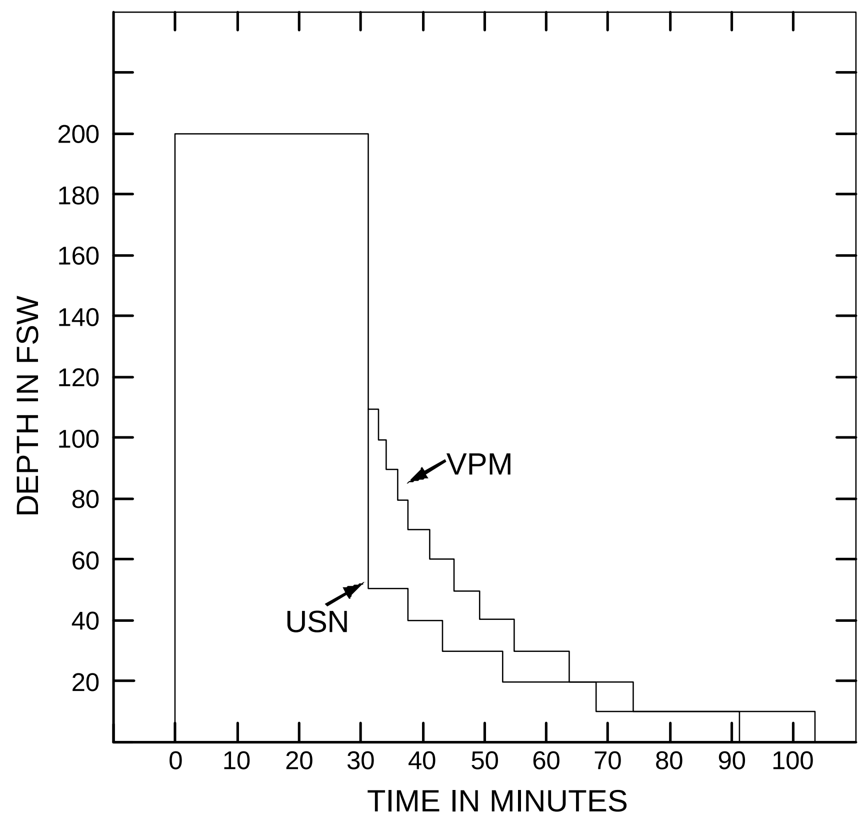

Figure 2 - VPM and USN profiles for a 60-min. dive to 200 fsw. Calculations suggest that the longer "first pull" of conventional tables results in a larger supersaturation, a larger bubble number, and a larger total volume of released gas.

pair will lose its gas to the larger. The fact that nuclei occur in distilled water suggests that they probably can be found in almost any aqueous medium including blood and tissue.

Calculating Diving Tables

Theoretical curves are calculated in the VP model by tracking the changes in nuclear radius that are caused by increases or decreases in ambient pressure. This is facilitated by the "ordering hypothesis" which states that nuclei are neither created nor extinguished by a pressure schedule and the initial ordering according to size is preserved. It follows that each bubble count is determined by the properties of a single critical nucleus, since all nuclei with larger than critical radii will form bubbles and all those with smaller than critical radii will not. The main properties that go into such a calculation are the radius of the nucleus and the crumbling strength of its skin. The main scientific principles are the diffusion equation and Boyle's law.

In the earliest applications of the VP model to decompression sickness, it was assumed that tables which produce the same number of bubbles will yield the same degree of safety, a one percent incidence rate for bends, *e.g.* This hypothesis works very well for that class of dives for which the bottom time is long. For shorter exposures, however, constant bubble number must give way to a "critical volume hypothesis," that is, to the assumption that it is the volume of free gas accumulated in bubbles which must be held constant if the desired degree of safety is to be maintained.

The critical volume hypothesis permits more bubbles to form on the longer ones, because there is less time for them to grow. If the decompression strategy is working correctly, the end result will be the same, namely, the total volume of free gas and the degree of safety will be constant for all of the tables produced in this way.

A feature of this application of the critical volume hypothesis is the assumption that bubbles present in the venous blood are efficiently trapped and dissipated as free gas by the lungs. Meanwhile, dissolved gas in the tissue is continuously coming out of solution. Because gas is simultaneously leaving and entering the gas bubble phase, the term "dynamic critical volume hypothesis" has been used.

With the dynamic critical volume hypothesis, the VP model can serve as the basis for a "global theory" which describes the entire range of decompression experience with the same small set of parameter values. Included among the applications tested so far are no-stop decompressions, saturation dives, repetitive dives, both nitrogen and helium gas mixtures, and altitude bends.

Global theories have the advantage that they can be tested globally, that is, by bringing to bear the full statistical weight of all of the diving lore available, including other tables. Global testing also takes advantage of the principle of leverage; effects which would be difficult to detect over a small range of depths, durations, or dive situations may become quite pronounced when that range is large. One example of this is the increase in bubble number that occurs in going from saturation dives to no-stop decompressions. Another is the wide range of tissue half-times that must be used in any global model, regardless of whether these tissues can be identified with specific organs or sites in the body.

Ascent Rate

In calculating diving tables with the VP model, it is assumed, following the U.S. Navy, that descent and ascent rates are 60 ft./min. As illustrated in Figure 2, the 3.33 minutes required to reach 200 fsw are counted as part of the bottom time. The main difference in these tables is the deeper first stop for VPM, 130 fsw versus 60 fsw for USN. It is believed on the basis of VP model calculations that the longer "first-pull" of conventional tables results in a larger supersaturation, a larger bubble number, and ultimately, in a larger maximum volume of released gas.

Focusing now on the ascent rate used between stages as well as on the first pull, one can ask whether there are any limits on that rate which can be determined from the VP model. The short answer is no. More precisely, one can begin with widely different ascent rates, and the VP model can still be used to calculate a reasonable set of tables. It is no surprise, therefore, that rates of ascent as slow as 20 ft./min. and as fast as 510 ft./min. have been reported.

In summary, the VP Model and the discovery of microbubble nuclei have provided a new way of addressing the problem of safe ascent following exposure to high pressure. With further work, it may someday be possible to describe all decompression experience with a single global theory based on the mechanics of bubble formation.