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On the Use of a Bubble Formation Model to Calculate Nitrogen and Helium Diving Tables

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Introduction

Decompression sickness is caused by a reduction in ambient pressure which results in supersaturation and the formation of gas bubbles in blood or tissue. This well-known disease syndrome, often called "the bends," is associated with such modern-day activities as deep-sea diving, working in pressurized tunnels and caissons, flying at high altitudes in unpressurized aircraft, and flying EVA excursions from spacecraft. A striking feature is that almost any body part, organ, or fluid can be affected, including skin, muscle, brain and nervous tissue, the vitreous humor of the eye, tendon sheath, and bone. Medical signs and symptoms range from itching and mild tingling sensations to crippling bone necrosis, permanent paralysis, and death.

The generality of the symptoms of decompression sickness and the fact that humans consist mainly of water suggest that the problem of bubble formation in the body may have a simple physical solution. Furthermore, since bubble formation occurs in almost any aqueous medium, the phenomenon can be studied in whatever substance is most convenient. A frequent choice in the series of experiments carried out at the University of Hawaii has been unflavored Knox gelatin, which is transparent and holds bubbles in place so that they can be counted and measured (Strauss 1974; Strauss and Kunkle 1974; Yount and Strauss 1976; Yount et al. 1979; Yount and Yeung 1981). Distilled water, seawater, agarose gelatin (D'Arrigo 1978), and infertile hen's eggs (Paganelli et al. 1977) have also been used.

The main outcome of this line of investigation has been the development of the varying-permeability model (VPM), in which cavitation nuclei consist of spherical gas phases that are small enough to remain in solution and strong enough to resist collapse, their stability being provided by elastic skins or membranes consisting of surface-active molecules (Yount 1979b). Ordinarily VPM skins are permeable to gas, but they can become effectively impermeable when subjected to large compressions, typically exceeding 8 atm.

By tracking the changes in the nuclear radius that are caused by

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increases or decreases in ambient pressure, the varying-permeability model has provided precise quantitative descriptions of several of the bubble-counting experiments carried out in supersaturated gelatin (Yount and Strauss 1976; Yount et al. 1979; Yount and Yeung 1981). The model has also been used to trace levels of incidence for decompression sickness in a variety of animal species, including salmon, rats, and humans (Yount 1979a, 1981). Finally, microscopic evidence has recently been obtained (Yount et al. 1984) which indicates that spherical gas nuclei—the persistent microbubbles hypothesized by the varying-permeability model—actually do exist and have physical properties consistent with those previously assigned to them (Yount 1979b; Yount and Strauss 1976; Yount and Yeung 1981; Yount et al. 1979). Nuclear radii, for example, are on the order of 1 μm or less, and the number density decreases exponentially with increasing radius (Yount 1979b; Yount and Strauss 1976; Young and Yeung 1981; Yount et al. 1979). The exponential radial distribution is believed to be characteristic of a system of VPM nuclei in thermodynamic equilibrium, and it can be derived from statistical-mechanical considerations (Yount 1982).

The most recent step in applying the varying-permeability model to decompression sickness has been to calculate a comprehensive set of nitrogen and helium diving tables and compare them with other tables now in use. The work on nitrogen has been reported already at scientific meetings (Yount and Hoffman 1983, 1984) and in a journal article (Yount and Hoffman 1986); the results for helium are being given for the first time here.

The Decompression Criterion

Early applications of the varying-permeability model to decompression sickness (Yount 1979a, 1981) involved rudimentary pressure schedules in which the subjects were first saturated with gas at some elevated pressure P_1 and then supersaturated by reducing the pressure from P_1 to the final setting P_2. The data in such experiments are most easily presented by plotting the combinations of supersaturation vs. exposure pressure ($P_{ss} \simeq P_1 - P_2$ vs. P_1), which yield a given morbidity, for example, a 50% probability of contracting decompression sickness. In order to describe these data, it was assumed that lines of constant morbidity were also lines of constant bubble number N (Yount 1979a, 1981). The bubble number, in turn, was assumed to be equal to the number of spherical gas nuclei with initial radii r_0 larger than some minimum radius $r_0^{\min}$ (Yount 1979b). This approach was remarkably successful, partly because the schedules involved were so simple—representing, as it were, a type of controlled experiment in which most of the variables in the problem were fixed.

The naive assumption of constant nucleation or constant bubble