Collection of Narrative Explanations About the Varying Permeability Model (VPM)

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The following excerpts [with some of my own editorializations] are taken from:

Kunkle, Thomas D. 1979. Bubble nucleation in supersaturated fluids. Univ. of Hawaii Sea Grant Technical Report UNIHI-SEAGRANT-TR-80-01. Pp. 108.

Yount, David E. 1979. Skins of varying permeability: a stabilization mechanism for gas cavitation nuclei. J. Acoust. Soc. Am. 65(6): 1429-1439.

Yount, David E. 1982. On the evolution, generation, and regeneration of gas cavitation nuclei. J. Acoust. Soc. Am. 71(6): 1473-1481.

Yount, David E. 1997. On the elastic properties of the interfaces that stabilize gas cavitation nuclei. J. Colloid and Interface Science 193:50-59.

American Heritage Dictionary, 2nd College Edition, 1985.

Narrative Explanations:

Gas nuclei are microscopic, spherical, physical structures that occur naturally in aqueous media including mammalian tissues and fluids. They are gas-filled and have a skin at the liquid-gas interface consisting of one or more layers of insoluble surface-active(surfactant) molecules. The surfactant molecules act to reduce the surface tension of water at the liquid-gas interface and allow for the gas nuclei to exist as stable structures. The skin is of uniform thickness, and this thickness is small compared with the nuclear radius. The skin is ordinarily permeable for the diffusion of gas through the liquid-gas interface.

The surfactant molecules are amphiphilic (or as David Yount called them - amphipathic) monomers with a polar head and a straight or branched non-polar hydrocarbon tail containing 8-18 carbon atoms. If the separation between the polar and non-polar regions of the molecule is more than a few angstroms, each region will be chemically unaffected by the other, and each will independently seek equilibrium with the system (Langmuir's principle of independent action).

Definitions:

amphiphilic - having an affinity or attraction on both ends. In this case, having an appreciable affinity for both polar and non-polar solvents. It is the amphiphilic nature of surface-active molecules that causes them to be adsorbed at interfaces, whether they be liquid-gas or liquid-liquid. Furthermore, in order for the surface-active compound to be concentrated at an interface, it must be properly balanced with water-soluble and oil-soluble groups. If the compound is too hydrophilic, it remains within the body of the aqueous phase and exerts no effect at the interface. If the compound is too lipophilic (attracted to oils, fats, hydrocarbon compounds), it dissolves completely in the oil phase and very little appears at the interface. Thus, the balance between

hydrophilicity and hydrophobicity is important.

amphipathic - having different bonding energies at either ends (or along the length of the molecule). In this case, the energy required for hydrophilic bonding is less than that required for hydrophobic bonding.

monomer - a molecule that can be chemically bound as a unit of a polymer.

polar molecule - molecule that possesses a permanent electric dipole moment (such as water).

It is energetically favorable for the polar end of the surfactant molecule to be immersed in water and the hydrocarbon tail to be immersed in the gas. If the distance between the polar and non-polar regions of the molecule exceeds the thickness of the liquid-gas interface region, then such a molecule residing at the dividing surface will be aligned with its polar head in the water and its hydrocarbon tail in the gas.

Since the surfactant molecules of the skin are bound by strong electro-chemical interactions, work must be done to remove them from the liquid-gas interface. To move a surfactant molecule entirely into the liquid, work must be done to pull its hydrocarbon tail through the interface and into the fluid. Similarly, to move a surfactant molecule into the gas, work is required to move its polar head out of the liquid and through the interfacial region. The potential energy of the surfactant molecules is reduced at the liquid-gas interface and thus the skin tends to be a stable structure. The molecules are "locked into position" and cannot be dislodged without performing a certain amount of work.

Although many materials can serve as the surfactants for gas nuclei, saturated lecithins (carbon-10, carbon-12, carbon-14, carbon-18) and phosphatidylethanolamines (carbon-10, carbon-18) have physical properties that show close correlation with the values determined from gelatin experiments.

Definitions:

lecithin - any of a group of phosphatides found in all plant and animal tissues, produced commercially from egg yolks, soybeans, and corn and used in the processing of foods, pharmaceuticals, cosmetics, paints and inks, and rubber and plastics.

phosphatide - any of a group of lipid compounds, such as lecithin and cephalin, composed mainly of glycerol and phosphoric acid, and found in great abundance in plant and animal tissues with stored fats.

lipid - any of numerous fats and fatlike materials that are generally insoluble in water but soluble in common organic solvents, are related to the fatty esters, and together with carbohydrates and proteins constitute the principal structural material of living cells.

The definitive property of surface-active substances is their ability to reduce the free energy of an interface. In the skins of gas nuclei, these surfactants act to reduce the surface tension of water at the liquid-gas interface. If the surface tension of water is gamma, the addition of a surfactant to the interface will reduce gamma by an amount pi to a final value of gamma-net:

gamma-net = gamma − pi

The parameter pi is commonly referred to as the "surface pressure" of the surfactant, however this is a misnomer because the units are actually those of tension or compression and not pressure. In bubble nucleation terminology, the parameter pi is referred to as the skin compression. The skin compression must be able to assume values larger than gamma in order for a gas nucleus to survive. This is possible because the interface is spherical and the surface area is small.

The skin compression is not constant. It can vary with the concentration of surfactant molecules at the liquid-gas interface. The skin compression increases as the mean distance between surfactant molecules decreases. The most important quantity involved is the functional dependence of the skin compression on the average surface area per surfactant molecule at the liquid-gas interface. This relationship is described by the force-area curve.

The force-area curve has plot coordinates of molecular surface area on the independent axis (x-axis) and skin compression on the dependent axis (y-axis). The general shape of the curve is exponential with the steepness of the curve rising sharply on the left- hand side of the curve towards large values of skin compression when the molecular surface area becomes small. This area of high compression is known as the condensed region of the force-area curve and this is the primary region of interest for decompression modeling.

There is a lower limit for the molecular surface area, A-min, and a dependent upper limit for the skin compression, pi-max. Upon reaching this limit condition, the surfactant molecules are packed so tightly together (near solid) that it becomes energetically favorable for the system to desorb (expel) surfactant molecules into the surrounding liquid rather than to be further compressed. The skin compression, pi-max, at which this occurs is referred to as the maximum skin compression. In the Varying Permeability Model (VPM), this is called the "crumbling compression" and it is denoted by the symbol gamma sub c (gamma-c).

Definitions:

desorb (desorption) - to remove from (an adsorbed substance).

adsorb - to take up by adsorption - the assimilation of gas, vapor, or dissolved matter by the surface of a solid or liquid.

With an increase in ambient pressure when diving, there is work done in compression of gas nuclei. The work done in the compression of the surfactant monolayer skin by an amount equal to the area of single molecule is given by:

delta W = pi (A) * A

If the energy delta W is larger than the desorption energy of a surfactant molecule, then the work done in decreasing the surface area of the skin by an amount A will be less if a molecule leaves the skin than if all molecules were further compressed.

The upper limit, pi-max (or gamma-c), for a stationary surfactant monolayer is determined by

the critical relationship:

pi-max = desorption energy / A-min

where A-min is that area which satisfies the equation:

pi (A-min) = C1 * exp (−A-min / A1) = desorption energy / A-min

C1 = surfactant compression parameter
A1 = surfactant area parameter

Thus, surfactant molecules will leave the skin if and only if the skin compression exceeds pi-max (gamma-c). It is assumed that the rate of molecular loss is sufficiently rapid that the value of the molecular surface area, A, will never be significantly less than A-min, and that the value of the skin compression, pi, will be less than or equal to pi- max (gamma-c) at all times.

The internal parameters that describe a gas nucleus at any given time are the nuclear radius, r, the internal gas pressure, Pin, the mole number of internal gas molecules, Nmol-gas, and the mole number of surfactant molecules in the skin, Nmol-skin. For a gas nucleus to be in stable mechanical equilibrium at constant ambient pressure (no change in radius), the gas inside the nucleus must be in diffusion equilibrium with the dissolved gas in the surrounding liquid, the internal gas pressure must balance with the external ambient pressure, and the skin compression must balance with the surface tension of water at the liquid-gas interface.

Because the skin compression is a function of the molecular surface area, mechanical equilibrium requires that the surface area of the nucleus be equal to the product of the number of surfactant molecules and the particular molecular area which results in the value of the skin compression being equal to the surface tension of water. Based on mechanical equilibrium considerations, the equilibrium size of a surfactant-stabilized nucleus is uniquely determined by the chemical nature of the surfactant material and by the number of such molecules in the nuclear skin.

The Varying Permeability Model (VPM) of Yount simplifies some of the detailed physics of gas nuclei in order to achieve closed-form expressions and serve as an analytic approximation model. The two main simplifications are:

1) The force-area curve is modeled as a step function. All "large scale" processes take place at the maximum skin compression, gamma-c. An equation of state for skin compression, pi, versus molecular surface area, A, is not specifically employed to track "small scale" changes in which the skin compression varies between zero and pi-max (gamma-c) and in which the molecular surface area varies between larger values and A-min. Rather, the value of the skin compression, pi, is allowed to assume whatever values are required to maintain the mechanical equilibrium of the system. In other words, although the "small scale" changes are not specifically calculated in the VPM, they are acknowledged because they permit a stable mechanical equilibrium near the calculated large-scale radius with the fixed number of skin molecules appropriate to that radius.

In a typical compression-decompression schedule (ref. Fig. 3 in Yount, 1979), the value of the skin compression starts out at an initial value pi-o with initial radius r-o. It then increases to a

value less than or equal to pi-max (gamma-c) during compression while the radius is reduced to a minimum value of r-m (large scale change). While the ambient pressure is held constant at the higher pressure, the value of the radius, r-m, remains unchanged but the value of the skin compression relaxes towards its initial value, pi-o, as the gas tension inside the nucleus is equilibrated at the higher ambient pressure (small scale change). Upon decompression to a lower final ambient pressure with a supersaturation gradient, the radius increases to a final value r-f (large scale change) and the value of the skin compression further relaxes and can fall off to zero. If the final ambient pressure is held constant and the gas nucleus re-stabilizes at the new final radius, r-f, then the value of the skin compression may have to increase again to maintain equilibrium (small scale change).

2) The permeability of the skin is considered to be either fully- permeable or fully-impermeable. This change in permeability is attributed physically to the change in area per surfactant molecule and impermeability occurs when the skin compression reaches its maximum value, gamma-c, and is held constant. This results due to a rapid increase in ambient pressure with a corresponding magnitude of crushing pressure (Pcrush) equal to approximately 8.2 atmospheres. In reality, there is likely variable resistance to diffusion across the nuclear skin, but the resistance is of significant magnitude for calculation purposes only when the surfactant molecules are packed tightly together at values of molecular surface area approaching A- min and values of skin compression approaching pi-max (gamma-c).

One interesting result from the gelatin experiments was that for a series of rapid compressions to a high magnitude pressure ("pressure spike dives"), there was a time delay of up to two minutes for the full effect of the crushing pressure to be realized in terms of reducing the nuclear radius and producing a lower bubble count upon decompression. This indicates that there is in fact a certain degree of resistance to diffusion across the nuclear skin at high pressures. For divers wanting to "pre-compress" their nuclei with "pressure spike dives", the implication is that a bottom time of at least a few minutes should be included with the pressure spike in order to realize full advantage of the crushing pressure.

The Varying Permeability Model (VPM) of Yount evolved to include certain extensions that were not included in the Surfactant Stabilized (SS) model described by Kunkle. Primary among these was the thermodynamic or chemical derivation of the VPM which gave explanation to the "large scale" changes in gas nuclei. This was later supported by a third derivation of the model that applied the thermodynamic methods of Kozlov et al. to describe strongly curved interfaces with low surface tension (a.k.a. the elastic membrane model).

Definitions:

"large scale" changes - those associated with the accretion or deletion of skin molecules and for which the change in nuclear radius is actually calculated. Large scale changes are caused by changes in the ambient pressure.

"small scale" changes - those associated with variations in the spacing of a fixed number of skin molecules. These changes are not calculated but are necessary for the nucleus to maintain mechanical equilibrium at constant ambient pressures. In this regime, the internal and external gases are in diffusion equilibrium and the net surface tension (pi – gamma) is near zero.

"statistical" regime - for the generation and regeneration of gas nuclei (at constant ambient pressure), the number of skin molecules fluctuates slowly and randomly. Eventually the initial "primordial' radial distribution of gas nuclei is generated or re-generated.

The essence of Yount's thermodynamic derivation(s) for "large scale" changes is that surfactant molecules move from the skin to a reservoir just outside the skin during compressions, and that surfactant molecules move from the reservoir back to the skin during decompressions. This movement of molecules is required for the system to maintain thermodynamic or electrochemical potential equilibrium. The transition time constants for large scale changes are the order of one thousandth to one millionth of a second.

On a molecular level, a constant value for skin compression, gamma-c, implies a constant energy per exposed skin molecule, just as a constant surface tension, gamma, implies a constant energy per surface water molecule. This is at the heart of the large scale, thermodynamic approximation in which the forces between surfactant molecules are assumed to be attractive, short-range, and essentially constant, and in which the work done in changing the spacing between a fixed number of skin molecules is neglected in the calculations.

As explained above, during compression the magnitude of the skin compression increases as the molecular surface area decreases. The spacing between the molecules is reduced. Eventually, the skin compression reaches a limiting value and further reductions in the surface area can be accommodated only by expelling surfactant molecules from the interface.

The molecules contained in the reservoir (liquid just outside the liquid-gas interface) are not aligned and hence cannot support a pressure gradient.

During decompressions, when the internal gas pressure of the nucleus exceeds the external ambient pressure, the skin compression is expected to partially counteract the surface tension of water and thus reduce the amount of work necessary to increase the size of the nucleus. As the molecular surface area of the skin increases, the skin compression falls off toward zero. Presumably, a "potential well" is made available to "attract' surfactant molecules back into the skin in order to re-establish equilibrium.

As David Yount described in his 1997 paper using the elastic membrane model, a basic underlying concept is that amphiphilic molecules have a tendency to migrate to an interface, not primarily because their polar heads are seeking an aqueous environment, but mainly because their carbon tails prefer a hydrocarbon environment. The transport of a surfactant molecule from the reservoir to the skin can be visualized as a two-step process in which the tail of an incoming monomer first pushes aside the polar heads of several neighboring skin molecules and exposes a certain area of the liquid-gas interface. The work done in the first step is large, but fleeting, since the change in membrane surface energy is immediately canceled by a corresponding change in the microbubble volume energy. In the second step, the incoming monomer moves an additional radial distance to become situated in the skin. The amount of work done in the second step is small but long-lasting since the incoming monomer is now locked into position and cannot be dislodged from the skin without changing the ambient pressure.

Application of the VPM to predict bubble formation is based on the "ordering hypothesis". This

assumes that a diver starts out with a "pristine" radial distribution of gas nuclei across the body. The number of bubbles that will be formed is equal to the number of nuclei larger than some minimum initial radius that have exceeded the Laplace condition for bubble formation after having been subjected to a compression and decompression schedule. The Laplace condition for bubble formation is simply when the supersaturation pressure (the internal gas pressure in the nucleus minus the external ambient pressure) exceeds 2*gamma/r (the surface pressure caused by the surface tension of water).

The ordering hypothesis states that nuclei are neither created nor extinguished when subjected to a pressure schedule and that the initial ordering of nuclei according to size is preserved. It follows that each bubble count is determined by the properties of a single critical nucleus and that a family of pressure schedules yielding the same bubble count, N, is characterized by the same critical minimum initial radius and by the same maximum skin compression, gamma-c.

Under ordinary pressure schedules undertaken by divers, it is important to point out that gas nuclei are generally neither created nor destroyed. This is apparently an area of some confusion in the deco community because the terms "crushing" and "denucleation" have been used. Some have interpreted them literally to mean that nuclei are physically destroyed or otherwise inactivated with regard to bubble formation. The reality is that nuclei are only "destroyed" under extreme compression schedules that reduce the size of a gas nucleus to the point that the skin thickness is on the order of the nuclear radius. In this instance the nucleus is literally "crushed" to the point of destruction. In general, compressions only cause gas nuclei to become smaller when "crushing" gradients are involved, and decompressions cause gas nuclei to become larger when supersaturation gradients are involved.

The term "denucleation" should be replaced by "pre-compression" or a similar term when referring to the practice of reducing the overall size distribution of gas nuclei by compression in order to permit larger supersaturation gradients upon decompression. To "denucleate" implies that gas nuclei have been temporarily removed from the system by the application of extreme "terminal" crushing pressures, centrifuging, micro-filtration, or some other process.

The generation and re-generation of gas nuclei occurs within the VPM "statistical' regime ("small scale" changes). Applying the theory of probability, Yount showed that it is likely that the initial ("primordial" or "pristine") radial distribution of gas nuclei in a system is the result of random fluctuations in the number of skin molecules and that eventually the initial distribution will be regenerated within some period of time after it has been disrupted. The initial radial distribution (continuous distribution function) is an exponential of the general form, N = No exp (-b/r) where N is the number of gas nuclei per unit volume, b is a constant slope parameter, and r is the minimum initial radius of gas nuclei. The transition time constants for "statistical" changes are the order of 10 to 100 hours (or longer?).

It is postulated that gas nuclei can originate from collapsing bubbles that have accumulated on their surfaces a store of various surfactants (the human body is loaded with them). The process of collapse is selective, and weakly bound surfactant molecules are sloughed off. At a certain critical radius, r-o, the surfactant molecules at the liquid-gas interface successfully resist the collapse of the bubble by opposing it with a skin compression that is greater than or equal to the surface tension of water.

If nuclei begin by a process of random accretion, then the probability of finding nuclei with a particular radius would depend upon the total number of skin molecules involved.

Implications of bubble nucleation for decompression schedules:

The threshold pressure for bubble formation is defined to be the maximum reduction in pressure to which a stable gas nucleus may be subjected without growing into a gross bubble. In practice, a useful definition of a "gross bubble" is a gas phase larger than twice the initial radius of the nucleus. Because of the exponential shape of the force-area curve, particularly in the "expanded" region with large values of molecular surface area and low values of skin compression, a quadrupling of the skin surface area is usually sufficient to reduce the skin compression to a very small value. At this point, the gas nucleus acts much like a true bubble, free of surfactant constituents, and the classic equation for a bubble,

$$Pin - Pamb > 2*gamma/r$$

may be evaluated to determine if the bubble will grow.

In experimental results, it was found in all cases that by rapidly increasing the radius of a gas nucleus by a factor of 2, the nuclear radius was larger than the critical radius for bubble growth. Thus, this is a satisfactory "rule-of-thumb" regarding bubble formation for rapid decompressions.

Decompression threshold limits for bubble formation depend only on the magnitudes of the crushing (compression) and supersaturation pressures [gradients].

Decompression threshold limits for bubble formation are inversely proportional to the initial radius of the gas nucleus.

Pressure reduction limits for bubble formation do not depend on the initial ambient pressure or the initial saturation pressure of the gas nucleus.

The area for diffusion per surfactant molecule has little or no effect on decompression thresholds for bubble formation. This is because during decompressions, the molecular surface area is never close to the minimum value, A-min.

Decompression sickness is caused by the formation of bubbles in the tissues and fluids of the body. Evidently, the bubbles that cause the bends originate from gas cavitation nuclei, and any detailed understanding of decompression sickness must therefore include in its foundation a knowledge of the nature of the cavitation nuclei present in living animals.

Bubbles induced by supersaturation form in many parts of the mammalian body. Upon post-mortem examination they have been found throughout the vascular system in both veins and arteries; in the lymph of the thoracic duct; in the aqueous and vitreous humor; in cerebro-spinal, synovial, amniotic, pericardial, and peritoneal fluids; in bile and urine; in liver, lungs, and spinal cord; in the spleen; in the adrenal cortex, the myelin sheath of nerve fibers, and hepatic cells; and in tendon sheath and bone. Evidently, the formation of bubbles is a general phenomenon not limited to a few structures of the body.

Numerous studies using Doppler ultrasound over the past two decades have shown that gas bubbles can be present in blood and tissue without producing overt signs and symptoms of DCS.

Based on the concept of critical released volume, the study of decompression sickness may be divided into three parts. The first part involves elucidating the mechanisms responsible for the initial formation of bubbles within the body; the second part concerns calculating the total volume of gas evolved into these bubbles; and the third part deals with estimating the probability and severity of decompression sickness associated with a given volume of evolved gas.

Concept: if no bubbles have formed, there is *ipso facto* no chance of decompression sickness.

The concept of critical released gas volume is synonymous with the assumption that the determining factor in the onset of decompression sickness is the number of bubbles formed per unit volume of tissue.

Decompression data for rats and humans show that decompression thresholds depend almost linearly on the exposure pressure, which indicates that bubble formation is a threshold phenomenon in the sense that critical supersaturation pressures are required to induce bubble formation.

Two important characteristics of gas nuclei have been demonstrated in experiments: that a critical decompression is necessary to induce the growth of bubbles and that for saturation exposures this limit increases with increasing pressures. This behavior is similar to that observed in gelatin, and suggests that the cavitation nuclei present in living animals are similar to those observed in water and gelatin, i.e., they are surfactant-stabilized gas nuclei. This supposition is not surprising since animals are, from a microscopic point of view, composed mainly of water and gelatin.

The upper limit to the size of gas nuclei may be controlled by one or more of the various filter systems in the human body. In particular, the spleen may be critical in determining the upper limit, since it is the smallest blood filter in the body. The spleen is a blood filter and reservoir placed in the pathway of a wide blood stream, the lienal or splenic artery. It removes dead and worn-out erythrocytes (red blood cells), bacteria, and other debris. Included among the debris filtered from the blood are, presumably, any nuclei larger than the effective filter size of the spleen. This filter diameter is not well known, but from measurements of photomicrographs it appears to be between 2 and 3 microns.

An independent estimate of pore diameter can be arrived at by considering that one of the prime functions of the spleen is to remove non-elastic erythrocytes from the body. A normal erythrocyte is an extremely elastic torus, 7.7 microns in diameter, which is capable of deforming to pass through apertures much smaller than its normal diameter; the splenic filter removes those cells unable to deform adequately. The minimum diameter which an erythrocyte can assume may occur when the normally flat torus is rolled into an incomplete cylinder. The diameter of the resulting cylinder is related to its initial size by the equation pi*d = 7.7 microns which indicates that the effective size of the splenic filter pores should be about 2.4 microns. This implies that the largest radius of gas nuclei normally present in the human body should be about 1.2 microns.

The effect of rapid compression on the equilibrium size of a surfactant-stabilized gas nucleus reduces the size of the nucleus by forcing surfactant molecules to desorb from the nuclear skin into the surrounding fluid (reservoir). Because the equilibrium radius of a nucleus is inversely proportional to the supersaturation pressure required to induce bubble growth, a rapid compression results in an increase in the pressure reduction necessary to form a fixed number of bubbles. The observed increase in pressure reduction limits in both rats and humans with increasing exposure pressure can be understood in terms of a similar reduction in nuclear sizes.

The rapid application of sufficiently large pressure will decrease the size of the gas nuclei and thus increase the pressure reduction limit (allowable supersaturation gradient). For example, a rapid compression from 1.0 bar to 9.3 bar absolute raises the decompression limit in humans from around 0.7 bar to 3.03 bar; the size of the largest nuclei prior to decompression is evidently reduced from say 1.2 microns to 0.25 microns. The increase in pressure reduction limits in humans with increasing pressure exposure is therefore quantitatively similar to that observed in gelatin, and this strongly suggests that cavitation nuclei occurring in humans are in fact surfactant-stabilized nuclei.

The equilibrium size of a surfactant-stabilized nucleus depends on the type and number of surface-active molecules composing the nuclear skin. Over long periods of time, the number of molecules will fluctuate slowly and randomly (VPM "statistical" regime). After a nucleus is compressed, it will not remain at the reduced radius indefinitely. It will begin accreting surfactant molecules. As the nucleus is restored, its decompression limit decreases. The process may end when the nucleus grows large enough to be trapped in the splenic filters and be destroyed. If a long enough period of time has elapsed, the radial distribution of nuclei should be restored to its "pristine" initial distribution and decompression limits should return their "pristine" values, regardless of saturation pressure.

Experience with long duration exposures has shown that the predicted nuclear restoration does indeed happen. Evidently, "short" saturation exposures must be handled differently than "long" saturation exposures.

The "crushing" (i.e. compression) and slow regrowth of gas nuclei provide an explanation of the common qualitative observation that greater pressure reductions can be tolerated on repetitive dives than on first dives. This behavior is quantitatively shown by the data of Watt and Lin (1979) where the no-bubble decompression limits are seen to be significantly larger for second exposures than for first exposures. Now consider a diver who works daily at a depth pressure of 8.3 bar. On his first dive the largest nuclei are reduced in size from say 1.2 microns to about 0.25 microns. The next day the nuclei have grown larger but have not yet been fully restored to their original size; the diver therefore begins the second day with nuclei of substantially reduced size, which are made even smaller by that day's dive. This process continues until an equilibrium condition is reached where during each day's diving the largest nuclei are crushed by an amount equal to that which they grew overnight [or in that day's decompression schedule!]. The decompression table is adjusted to reflect the corresponding increase in pressure reduction limits, and the work progresses. The diver then takes a week of vacation, during which time the largest nuclei are fully restored to their original 1.2 micron size, thereby decreasing the pressure reduction limit. The diver returns to work and dives using the same "safe" schedule used by his comrades, who have not been on vacation. The result may be a bent diver.