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Diffusion and nucleation of gas in gel and some implications for the development of decompression procedures

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Le Messurier, D. H., T. N. Smith, and W. R. Wood. 1979. Diffusion and nucleation of gas in gel and some implications for the development of decompression procedures. Undersea Biomed. Res. 6(2): 175–188.—Attention is directed to certain incongruities among accepted diving procedures in order to emphasize the need for a more complete understanding of the interactions between the factors involved in diving and decompression and in the onset of decompression sickness. It is suggested that physiological responses derived from the effects of diffusion and nucleation of gas in tissue might be interpreted in terms of similar events in specimens of gelatin subjected to patterns of compression and decompression. A model for behavior of specimens in gel is developed and conformity with the results of a program of experimentation is demonstrated. With the insight provided by this model, a substantial analogy between important aspects of the behavior of gel and tissue is claimed and application of this model to the refinement and development of diving and decompression procedures is proposed.

decompression
decompression procedures
decompression sickness
diffusion
gas bubbles
gelatin
nucleation

In an earlier communication from this laboratory (Le Messurier and Hills 1965), attention was drawn to the existence of a diversity of accepted procedures for ascent after exposure to a given depth. Cited in particular was the difference between the practice developed by the pearl divers of the Torres Strait and that recommended in the U.S. Navy diving schedules (U.S. Navy 1970). After a dive for 50 min at 75 meters, for example, the Torres Strait divers stop first at a depth of about 40 m and subsequently at 30, 20, and 10 m, while the Navy procedure is to stop first at 21.5 m and subsequently at every 3 m on the way to the surface. The times of ascent are 156 min for the Torres Strait schedule and 217 min for the U.S. Navy schedule.

The pattern followed by the Torres Strait divers requires less time and, if it be equally safe, must be judged the more efficient. A favorable judgment in this comparison does not, however, give assurance that this particular procedure is the most efficient for decompression from the prescribed dive. The ideal ascent must be a continuous one in which the instantaneous rate of decompression is always adjusted to the limit beyond which symptoms of decompression sickness would be provoked. The practical ascent is discontinuous with fairly rapid movement between several intermediate stages at which there are prescribed waiting times. It is inevitably slower than the ideal.

The matter for concern here is not so much that discontinuous decompressions must always be longer than continuous ones but rather that the various procedures differ from the ideal in evidently distinct ways. Any marginally safe ascent must include some segment in which the rate of decompression is critical; indeed, it may contain a substantial transgression of the critical rate which is compensated subsequently by a period of very slow decompression. Where two procedures have developed to different forms it is reasonable to presume that the respective developments have been such as to approach or, perhaps, retreat from a limiting condition at different points on the ideal profile of ascent.

This is a consequence of the principal difficulty in the development of diving procedures, the identification of the crucial point in the decompression. Uncertainty in this respect arises because the manifestation of symptoms of decompression sickness may take some considerable time and would usually be subsequent to the whole ascent.

Given this uncertainty, the definition of an efficient procedure for decompression is a formidable task. Progress is necessarily slow because, with human subjects, it must be by refinement through accumulation of experience rather than by bold experimentation. Adding to the magnitude of the task is the infinite variability in possible exposures. For acceptable resolution in schedules, classification of depth, time, and gas composition into very many levels and combinations is necessary. A further complication is that the collection of reliable data from actual dives is not always a simple matter.

It is clear that much more rapid progress could be made in the development of diving practice if a satisfactory analogue of a diver were available. Existing procedures could be reviewed and irregular exposures could be scrutinized for significant interactions between variables. Programs of experimentation and computation could be formulated and executed with facility.

A DIVER ANALOGUE

Such a model may be constructed only upon a foundation of substantial understanding of the effects of compression and decompression on the human body. Though much remains to be learned, some essentials of the process have long been recognized. Particular attention has been directed to the mechanisms by which gas is absorbed by and eliminated from tissue. Hills (1977) discusses in some detail the roles of perfusion and diffusion and reaches the conclusion that both mechanisms are important. It is evident also that the times taken for transfer to and from various organs range from a few seconds to several hours. Tissues with long periods of exchange would be expected to present the ultimate limitation to rate of decompression. Such tissue must be poorly perfused, so that diffusion may well be the more significant factor under conditions of rapid change.

This is the assumption in the work that follows. The analysis and conclusions are, then, restricted in validity to those cases for which limitation of gas-exchange by diffusion is an adequate representation. Concerning the origin of the symptoms of decompression sickness, there is less difficulty. There is general agreement that the symptoms of decompression sickness are associated with the separation of gas from solution at particular sites in tissue or in circulating blood.

Diffusion is easily simulated either physically or mathematically but definition of the conditions for the growth of bubbles of gas in tissue presents some difficulties. Various proposals are reviewed by Le Messurier and Hills (1965), Hills (1966), and Vann and Clark (1975). Identification of the sites where bubbles may form and details of the associated histology remain in question, so that it is not possible, at this time, to prescribe a comprehensive model for the response of tissue. Investigations must proceed at a level of some simplification.

Le Messurier (1972), Strauss (1974), and Yount and Strauss (1976) describe experiments on the compression and decompression of specimens of gelatin. To the extent that gas diffuses to and from the specimen and that bubbles may be observed to form and to grow in its mass under sufficiently great decompression, a piece of gelatin might be regarded as a crude model of a piece of human tissue. Analysis of its response might then produce results that could serve as an outline for important aspects of the behavior of tissue.

That is the subject of this paper. A model for a gel subjected to compression and decompression is proposed and is applied to the results of a program of experimentation in order to make interpretations of the effects of particular interactions of pressure and time.

MODEL OF GEL

The model described is the product of evolution through the experimental program to conform with observations rather than a prior concept. It is, however, uncomplicated. The essential elements are a matrix, through which gas may diffuse under the prevailing gradient of concentration, and distributed nuclei where gas bubbles may form and grow.

Diffusion may be described, for linear geometry, by the relationship

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} \tag{1}$$

in which c is the mass or molar density of gas in the gel, D is the diffusivity of the gas in the medium, and x and t are the distance and time dimensions. For application to the current work, this relationship is more conveniently expressed in terms of the gas pressure, P, representing equilibrium with the concentration c, so that

$$\frac{\partial P}{\partial t} = D\frac{\partial^2 P}{\partial x^2} \tag{2}$$

Given the dimensions of the piece of gel and a value for the diffusivity, the equilibrium gas pressure at any point in the gel may be computed by simple, numerical techniques for any initial condition and subsequent pattern of exposure of the face of the specimen to gas pressure.

The crucial feature of the model is the nucleus. It becomes evident in subsequent discussion of the experimental results that nuclei diminish in size under compression but persist as sites of reduced susceptibility to growth into bubbles.

A simple, free, spherical bubble of gas cannot function as a nucleus. In a gel without elastic properties on the microscopic scale, such a bubble would shrink under compression and accelerate to extinction under the increasing stress of its own interfacial tension. Assignment of elastic strength to the matter surrounding the spherical nucleus does not lead to a viable model, either, since a bubble in such a medium would shrink under compression but would revert to its full size upon decompression. It is necessary, then, that nuclei be at sites in the matrix of the gel which are hydrophobic to the extent that some support of the interface between gas in the nucleus and water in the surrounding gel is afforded.

These requirements seem to be met by a model in which pockets of gas remain occluded in wedge-shaped or conical cavities formed by intersections or near-intersections of fibrous elements of the matrix of the gel, as depicted in Fig. 1. The interface between the occluded gas and the surrounding liquid is deformable and, ultimately, movable under a sufficiently large difference between internal gas pressure and external liquid pressure. These nuclei are distributed homogeneously throughout the gel and, though not uniform in size, have the same local average of size and shape-related properties at all points in the gel. In particular, the size of a nucleus is small, certainly not larger than a few micrometers, so that the rate of equilibration between gas pressure within the nucleus and gas concentration in the surrounding matter is very rapid. In the time scales associated with simulation of diving practices, constant equilibrium between gas pressure and gas in solution may be assumed.

A nucleus should remain stable in size so long as a balance of stresses across the gas-liquid interface can be maintained. Suppose that a specimen of gel is exposed to a pressure, P_H, at its face. This pressure is transmitted through the body of the gel and is applied to the locality of the nucleus. If the gel contains gas dissolved to the extent of an equilibrium saturation pressure, P, the net compressive pressure on the nucleus is $P_H - P$. For stability of the gas-liquid interface, this pressure must be balanced by stresses derived from deformation of the interface and the surrounding material. Such stresses could arise from curvature of the interface and from elastic deformation of the structure of the gel in the vicinity. In Fig. 1, the interface has moved from its original position before the application of P_H to a new position in which

$$P_H - P = P_S + P_E \quad (3)$$

Both P_S, the interfacial stress, and P_E, the elastic stress, increase with approach of the interface towards the apex of the nucleus, since the radius of the interface is decreasing and the deformation from its original posture is increasing. It is clear that, with this configuration, the interface could assume a stable position and shape in response to any value of the applied pressure difference $(P_H - P)$.

When the surface of a specimen of gel initially at atmospheric pressure is exposed to gas at a greater pressure, P_H, and this pressure is maintained on the specimen, the local concentration of gas in the material surrounding a nucleus must increase gradually as diffusion proceeds. This causes the compressive pressure on the nucleus, $(P_H - P)$, to decrease. To maintain pressure

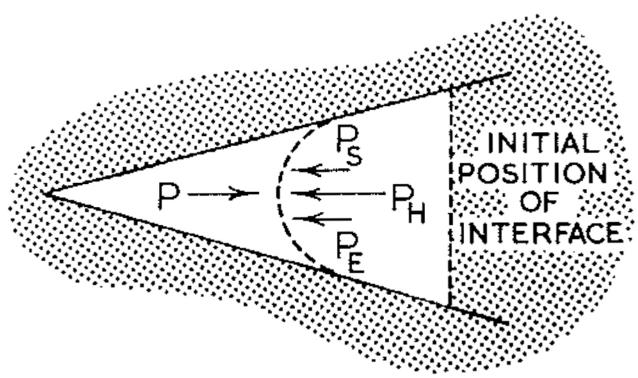

Fig. 1. A nucleation site. Inward displacement of gas-liquid interface to balance compressive stress, $(P_H - P)$, by interfacial and elastic stresses, P_S and P_E, is illustrated.

balance over the interface, the sum of the stresses P_S and P_E must also decrease. The simplest way in which this can happen is for the curvature of the interface to change. In Fig. 2, the positions 1, 2, and 3 of the interface represent responses to the changes in the unsaturation, $(P_H - P)$, from its initial large value through some intermediate level to its final zero value when the gel is saturated with gas. In the final position, the stress balance shows that

$$P_H - P = P_S + P_E = 0 \tag{4}$$

This means that, if there is a stress P_E resulting from elastic deformation, P_S must assume a negative value. The interface must then become convex in curvature but its position and perimeter need not change so long as P_S can reach a value large enough to balance P_E.

Now if the external pressure on the gel is relieved, the gel is supersaturated with respect to the new ambient pressure. The position of the gas-liquid interface can remain stable only if the net internal pressure can be contained, that is, if

$$P - P_H \leq P_{SM} - P_E \tag{5}$$

where P_{SM} is the maximum value that the interfacial stress can assume at this position of the interface. This will be the value associated with cylindrical or spherical curvature, depending on geometry of the nucleus, and the corresponding value of $(P_{SM} - P_E)$ may be regarded as the strength of the nucleus with respect to supersaturation of gel. Any value of $(P - P_H)$ which exceeds this strength will move the interface. As soon as this happens, the perimeter of the interface is increased and the maximum available value of the interfacial stress, P_{SM}, must fall. The interface is now driven further against a falling resistance and rapid growth of the nucleus into a bubble ensues.

The size to which a nucleus shrinks during compression is defined by the stress equilibrium of Eq. 3, but the point in time at which this is reached is determined by kinetic factors. These are the rate at which the surrounding material can deform to allow the nucleus to shrink and the rate at which gas penetrates from the face of the body of gel to the site of the nucleus.

Deformation of the material near the gas-liquid interface of the nucleus depends upon its consistency. In a gel structure in which liquid is occluded in a fibrous mesh, deformation on the small scale of the nuclei would occur by viscous flow of the liquid. No elastic properties of consequence would be involved because no distortion of the fibrous structure is required. With removal of elastic stress from consideration, the resultant stress to push the gas-liquid interface towards the apex of the nucleus is $(P_H - P) - P_S$.

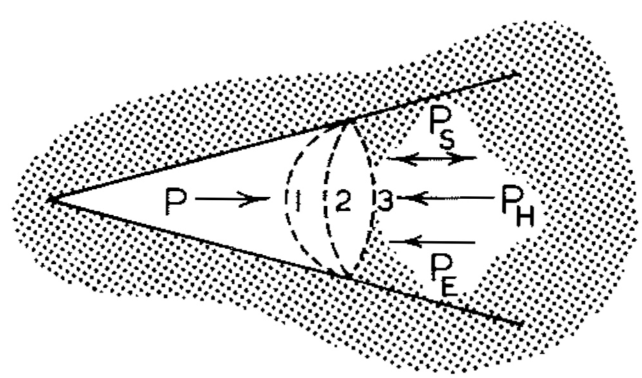

Fig. 2. Relaxation and reversal of interfacial curvature as gas pressure in nucleus approaches equilibrium with external pressure. Maximum attainable value of interfacial stress at any location corresponds to cylindrical or spherical curvature.

For deformation by simple, viscous flow into the apex of the nucleus under this stress, a general equation of the form

$$-\frac{1}{r}\frac{dr}{dt} = \frac{1}{\eta}\left[(P_H - P) - P_S\right] \qquad (6)$$

may be presumed. Here, r is the radius or length of the gas-liquid interface and η is a viscosity coefficient for the liquid phase in the gel. It may be further supposed that, during motion, the curvature of the interface is cylindrical or spherical so that P_S is related to r by $P_S = A/r$. Now

$$-\frac{1}{r}\frac{dr}{dt} = \frac{1}{\eta}\left[(P_H - P) - \frac{A}{r}\right] \qquad (7)$$

defines the rate of shrinkage of the radius of the nucleus in terms of the variables P_H, P, and r. Geometric factors associated with the detail of the shape of the nucleus are accounted for in the effective values of the viscosity, η, and of the interfacial tension, A.

Were the unsaturation, $(P_H - P)$, in Eq. 7 to remain steady, the nucleus size would diminish to approach its equilibrium with $\frac{A}{r} = (P_H - P)$ asymptotically. This does not happen when the sample of gel is pressurized with gas, however. Diffusion of gas to the locality of the nucleus causes $(P_H - P)$ to diminish while $\frac{A}{r}$ is increasing so that shrinkage of the nucleus is arrested when these values intersect. This event occurs at a definite point in time. Figure 3 shows this effect. Once arrested, the size of the nucleus cannot change again since $(P_H - P)$ is now less than $\frac{A}{r}$. Its strength toward subsequent decompression is established at the value $\left(\frac{A}{r}\right)_M$, which is the maximum containing stress available when the gas-liquid interface reverses curvature to become convex.

It is important to remark that without some mechanism such as viscous flow to prevent full, immediate compression of nuclei, the gel would be very much less liable to form bubbles on decompression. This is because supersaturations on decompression cannot be greater than unsaturations on compression unless the rate of ascent is faster than the rate of descent. If the strengths of nuclei were determined by the maximum unsaturations during descent, the internal pressure required to expand the nuclei into bubbles on ascent would not normally be reached.

EXPERIMENTS WITH GEL

Some effort was made to find a formulation of gelatin specimens that would have a response to exposure to gas pressure on the same general level as that of a human diver. The coincidence desired was the appearance of gas bubbles in the gel under one set of conditions which was known to cause symptoms of decompression sickness in a diver. Divers exposed to depths of 9 m for long periods experience difficulties upon rapid return to the surface (Spencer and Johanson 1974). Allowing for the inherent unsaturation of tissue owing to hemoglobin-oxygen equilibrium (Hills 1966; Hills and Le Messurier 1969; Bunker 1971), the pressure of dissolved gas at this depth is 170 kPa. The simplest way to test the sensitivity of a gel was to expose it to gas at this pressure, then to decompress rapidly and to examine the specimen for gas bubbles. Eventually, a gel containing 12 g of gelatin in 75 ml of water and 25 ml of Universal Indicator (BDH, Australia) was found to be suitable because 50% of the specimens showed bubbles on decompressions after exposure to air at 170 kPa for 15 min.

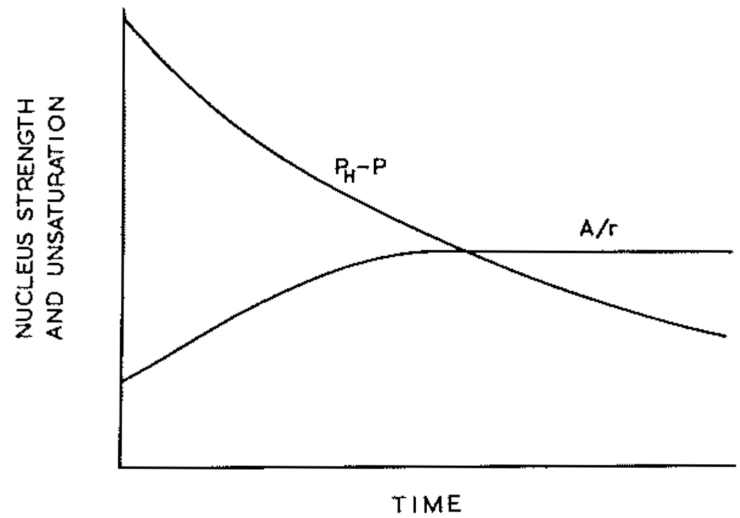

Fig. 3. Arrest of shrinkage of nucleus as unsaturation, $(P_H - P)$, falls below interfacial stress, A/r.

Specimens were prepared by running the gelatin solution into test cells that were recesses, 6 mm in diameter and of various depths, in acrylic plates. Tests were conducted in a pressure chamber to which air pressure was applied through regulators in order to give the desired profile of exposure for rate of compression, duration of pressure, and rate of decompression. The outcome of a trial was assessed by counting the number of gas bubbles which appeared in the specimen after final decompression or at some other time of interest. The numbers reported here are, in fact, averages over several test cells subjected simultaneously to the treatment.

Very many trials were made with both simple and complex patterns of exposure. The few results discussed here are typical of the behavior throughout the program of tests and have been chosen to delineate the effects of what are seen as the major variables of interest. Appreciation of these effects is facilitated by the presentation of corresponding computations using the model of the gel defined in the preceding section. Using Eq. 2 for the diffusion process and Eq. 7 for the determination of the size of a nucleus, the response of a sample of gel to any sequence of compressions and decompressions may be simulated.

To carry out the computations, values for some constants must be invoked. For the diffusivity of air in gel, the value of 1.6 10^{-9} m^2/s, close to that of air in liquid water, is taken. An effective value of the surface tension can be derived from tests of the strength of nuclei prepared at atmospheric pressure. When such a gel is decompressed, bubbles appear when the pressure has fallen by 40 kPa. If the condition for the formation of bubbles is that the supersaturation, $(P - P_H)$, should exceed the interfacial tension stress, $\frac{A}{r_0}$, then $\frac{A}{r_0} = 40$ kPa. The radius r_0 is that of a nucleus in the original, atmospheric gel and is, of course, the initial radius for computations of the shrinkage of nuclei. In Eq. 7, the radius of a nucleus at any time may evidently be expressed as $\frac{r}{r_0}$ and its strength as $\frac{A}{r_0} / (\frac{r}{r_0})$. Evaluation of the effective liquid viscosity, η, is less direct and relies on trials of the model with various values in order to find that which gives the best correspondence between the outcomes of the computations and the experiments. The result is that η should have a value of 40 10^6 Pa s. So great a value reflects the poor mobility of water through the structure of fine fibers in the gel.

The following description of the response of the gel to major variables is also a test of the model. The effects of the several variables are not, of course, independent but interact according to their involvements in Eqs. 2 and 7 so that the satisfactory performance observed over the wide range of trials is a strong validation of this model.

Thickness of specimen

In Fig. 4 are shown the experimental exposure, the computed profiles of strength of nucleus and of supersaturation and the experimental bubble counts for identical treatment of specimens of thicknesses 0.6 mm and 2.4 mm. There is a very noticeable difference between the strengths of nuclei for the two cases. This arises from the more rapid filling of the thinner specimen by diffusion of gas from its exposed face so that the gas concentration rises more quickly and the shrinkage of the nuclei is arrested sooner than in the deeper gel. On decompression, the supersaturation profile is well above the critical level for nucleation and many bubbles appear.

Pressure

The effect of the pressure of exposure is shown in Fig. 5. Most obvious is the graduation in nuclei strengths from the exposed face, where the strength is 40 kPa, that of fully sized nuclei, to deep in the specimen, where the strength approaches the actual pressure change in compression. Upon decompression, a section of the specimen just behind the face becomes susceptible to nucleation. Exposure at higher pressures increases both the depth of the sensitive section and the margin of supersaturation over nucleus strength.

Rate of compression

Only under extreme conditions is rate of compression a major variable with respect to strength of nuclei. Variation of rate of compression over the range 30 to 300 kPa/min, into which most practical diving would fall, shows little effect on the strength of nuclei in the sensitive zone near the face of the specimen. So long as pressure increases with time, a nucleus must continue to shrink and the unsaturation of the gel with dissolved gas to increase.

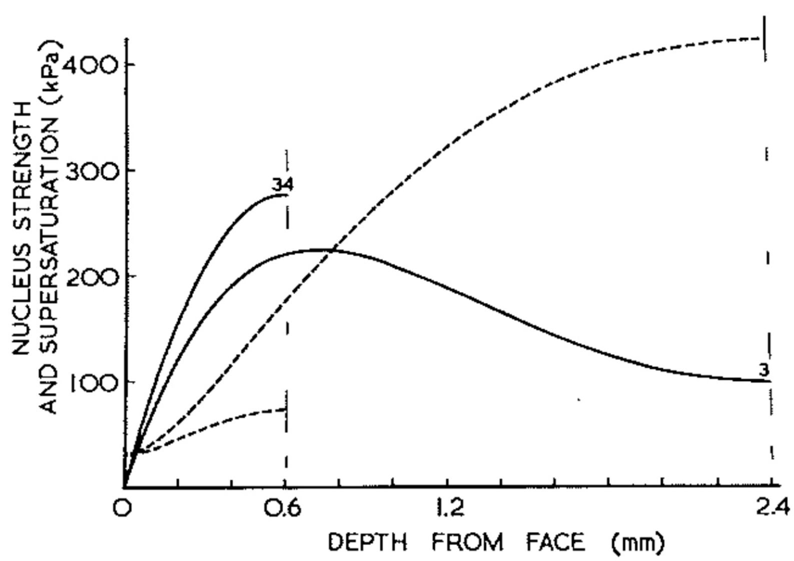

Fig. 4. Effect of thickness of specimen on nucleus strength (broken line) and on supersaturation (solid line). Specimens of gel 0.6 and 2.4 mm thick were compressed at 180 kPa/min to 570 kPa and held for 7 min before decompression to 101 kPa. Respective bubble counts are shown.

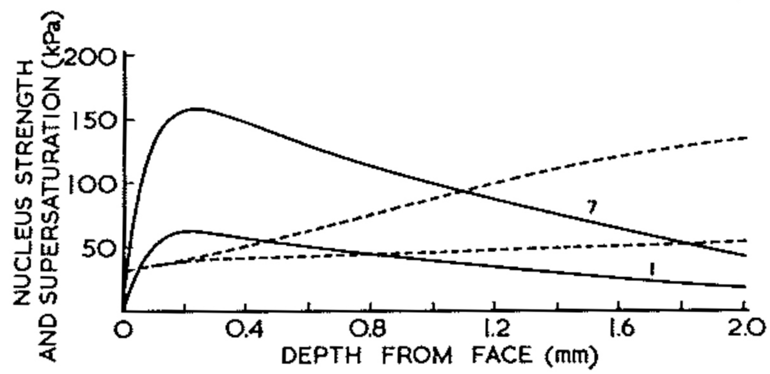

Fig. 5. Effect of pressure on nucleus strength (broken line) and on supersaturation. Two specimens of gel 10.0 mm thick were exposed to air at 275 kPa and 170 kPa, respectively, for 15 min before decompression to 101 kPa. Bubble counts are shown.

It is not until compression stops and the unsaturation begins to decrease that an intersection such as that shown in Fig. 3 becomes possible.

If the gel is compressed hydraulically and not by gas pressure, no intersection takes place and the nuclei shrink to such a size that eruption of bubbles during subsequent treatment with gas is possible only when supersaturation equals or exceeds the original hydraulic pressure. Table 1 shows the results of some tests of this kind. The numbers of bubbles observed in specimens subjected to the stated hydraulic pressure for 60 min and then to the various gas pressures for 15 min before decompression to atmospheric pressure are given. These results provide a clear demonstration of the existence of nuclei with the properties described in the model.

Duration of pressure

Duration of pressure increases the degree of saturation of the specimen and, upon decompression, its supersaturation. In Fig. 6, exposures of 2.4 mm gel to a pressure of 570 kPa for 7 min and 30 min are shown. The longer time produces excessive supersaturation and bubbles.

Rate of decompression

A safe decompression, in respect of no formation of bubbles, is possible only when the supersaturation does not exceed the strength of the nuclei in the gel. A sufficiently slow,

TABLE 1
EFFECT OF HYDRAULIC COMPRESSION ON NUCLEUS SENSITIVITY: AVERAGE NUMBER OF BUBBLES IN 36 TRIALS

Hydraulic Pressure, kPa (gauge)	Gas Pressure, kPa (gauge)			
	150	300	450	600
0	2.2	11.5	81	92
150	0.2	10.2	37	78
300	0	1.2	6.5	31
450	0	0	0.1	1.1

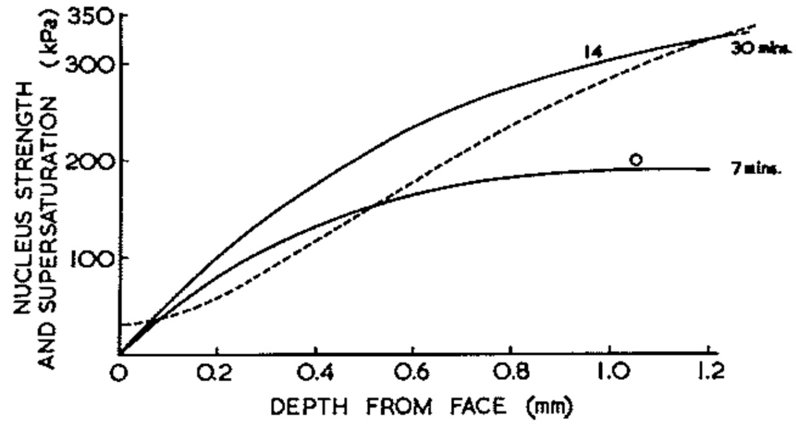

Fig. 6. Effect of duration of pressure on supersaturation. Two specimens of gel 2.4 mm thick were exposed to air at 570 kPa for 7 and 30 min, respectively, before decompression to 101 kPa. Bubble counts are shown.

perhaps stagewise, decompression is necessary. Figure 7 compares exposures in which different decompression rates are applied. At the slower rate, 80 kPa/min, gas diffuses from the gel during decompression to allow a "safe" return to atmospheric pressure, but at 360 kPa/min the decompression is too rapid and bubbles form.

In connection with this variable, rate of decompression, it should be remarked that an excessive supersaturation that exists for only a short time can be tolerated by the gel. Just as time is required for a nucleus to shrink under compression, so is time required for it to grow under supersaturation. It grows against a falling resistance as the effects of interfacial tension diminish with increasing size so that, with a maintained level of supersaturation, the rate of increase of size accelerates. If in the initial stages, however, the supersaturation falls more rapidly than the containing stress derived from interfacial tension, growth must be arrested. A short duration of hypercritical supersaturation does not then lead to emergence of visible bubbles. However, these larger nuclei are now more sensitive to supersaturations that might develop in subsequent stages of decompression.

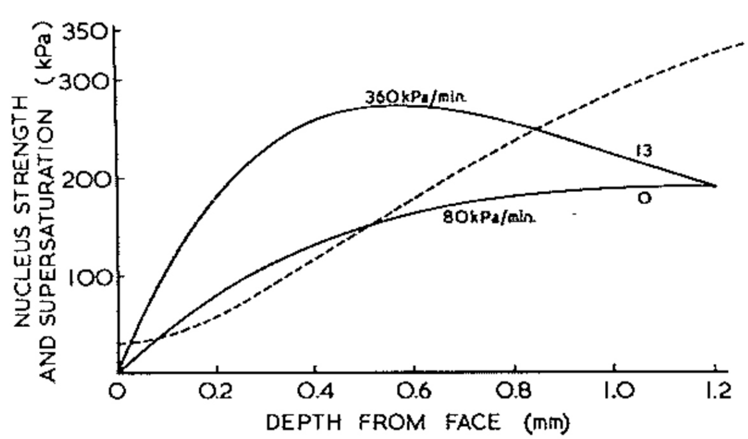

Fig. 7. Effect of rate of decompression on supersaturation. Exposure of two 2.4 mm specimens of gel at 570 kPa for 7 min was followed by decompression at 80 kPa/min and at 360 kPa/min, respectively. Bubble counts are shown.

REFLECTIONS ON DIVING PRACTICE

It can be accepted that, with the aid of the model, the behavior of a piece of gelatin subjected to compressions and decompressions has been fairly well understood and defined. Before an attempt can be made to draw inferences for diving practice, some further consideration must be given to the substance of the analogy between the processes in gel and in human tissue.

The essential processes in gel are diffusion and nucleation of gas and this much should be common with processes in tissue.

The geometry of the specimens of gel dictates a linear path for the diffusion of gas, but between capillaries and surrounding tissue, a radial path must be followed. Experiments with appropriate geometry could, of course, be done, but the results would differ in detail rather than in effect of the major variables. Where the sensitive region for nucleation of bubbles is close to the exposed face of the specimen, as illustrated by the discussion of Fig. 5, the differences would be minor.

Because of the hemoglobin-oxygen equilibrium in circulating blood, the pressure of dissolved gas is substantially that of the nitrogen and is always less than the ambient air pressure. The magnitude of this effect is known (Hills and Le Messurier 1969) and can be allowed for in any comparison between gas concentrations in gel and tissue.

From arguments which follow, it is clear that definite sites for the nucleation of gas bubbles in tissue must exist. They have yet to be identified and no description of their morphology can be attempted. A critical value of supersaturation of gas which leads to the eruption of bubbles can, however, be defined for specified conditions. The experiments by Spencer and Johanson (1974) on direct returns from depth to the surface allow this to be done. From their respective analyses of data, Hills (1969) chose a critical value of 27 kPa and Rashbass (1954) a value of 93 kPa for the purpose of construction of decompression schedules. It can be surmised from all the available evidence that, as in the gel, a bubble in tissue erupts when the pressure of dissolved gas exceeds the ambient pressure by a margin equal to the strength of the nucleus. So long as the tissue remains supersaturated with gas, the bubble continues to grow and, when it becomes sufficiently large, symptoms of decompression sickness are manifested. With the subsidence of supersaturation, growth of the bubbles ceases. A large bubble formed in this way in gel would persist almost indefinitely since the internal pressure derived from surface curvature would impose a negligible potential for loss of the included air by diffusion. Such a bubble in tissue is, however, slowly absorbed. Because of the hemoglobin-oxygen equilibrium, the gas pressure in tissue eventually falls below the ambient pressure and the bubble begins to diminish in size under the action of this difference in pressure. Shrinkage must continue until the bubble is extinguished or the pressure difference is balanced by interfacial curvature, at which point the size is reduced to the range of the initial nucleus size. This process is the means by which decompression symptoms are relieved. It is also the means by which bubbles initiated in too rapid a decompression, which are potentially dangerous but are too small to provoke immediate symptoms, can be collapsed during a sufficiently long "stage" prior to further decompression.

There does, then, seem to be a substantial analogy between the fundamental processes which govern the appearance of bubbles in gel and the onset of symptoms of distress in a diver subjected to a pattern of compression and decompression.

Indeed, if the analogy is extended to a definition of response to major variables, useful explanations of effects observed in diving practice can be offered. The results of three particular analyses in terms of the model are presented below.

(1) Increasing exposure at constant pressure or increasing pressure for a constant time causes more ready nucleation of bubbles in the gel, just as it promotes the possibility of

decompression sickness in the diver. This effect is primarily the result of the increasing quantity of gas dissolved in the gel or tissue when diffusion is the governing mechanism.

(2) The critical decompression for gel depends not only upon the saturation pressure of the dissolved gas but also upon the pressure to which the gel has been exposed. This is the same effect observed by Van der Aue (1959) in divers. Albano (1962) reports a similar result. The experiments of Evans and Walder (1969) demonstrate, by actual formation of gas bubbles, this effect in shrimps subjected to various treatments before decompression. Figure 8 shows the distributions of gas concentration in the gel upon return to atmospheric pressure after compression equivalent to depths of 60 m, 29 m, and 14 m for the stated times. Each decompression produces bubbles and it is clear that a different value of supersaturation is critical for each case. This is a most significant aspect of response. It is to explain this effect that it becomes necessary to incorporate in the model of the gel the idea of a nucleus that can shrink under the influence of a pressure difference and so change its sensitivity to subsequent decompression.

(3) Specimens of gel exposed to pressure patterns based on dives and ascents according to the schedules used by the U.S. Navy and the Torres Strait pearl divers each show evidence of critical safety. A comparison of the profiles of ascent is given in Fig. 9. Also shown on the figure are values of supersaturation of gas computed from the model. The differences between the two patterns may be reconciled by consideration of these figures. Apparently the first stage of decompression according to the U.S. Navy schedules leads to an excessive supersaturation so that very low values must be maintained in subsequent stages to minimize the further growth of bubbles. The Torres Strait schedule, by comparison, maintains a modest supersaturation throughout.

These explanations in terms of events in gel and the mechanism of the model are so satisfactory that it may reasonably be asked if more complex processes are necessary to explain parallel events in tissue. It is certainly justifiable to invoke the model of the gel as at least a crude model of the processes in tissue. To do so, it is necessary to insert appropriate values of the variables in Eqs. 2 and 7 governing the diffusion of gas and the shrinkage of nuclei. These may be inferred from current knowledge except for the effective viscosity which must, as in

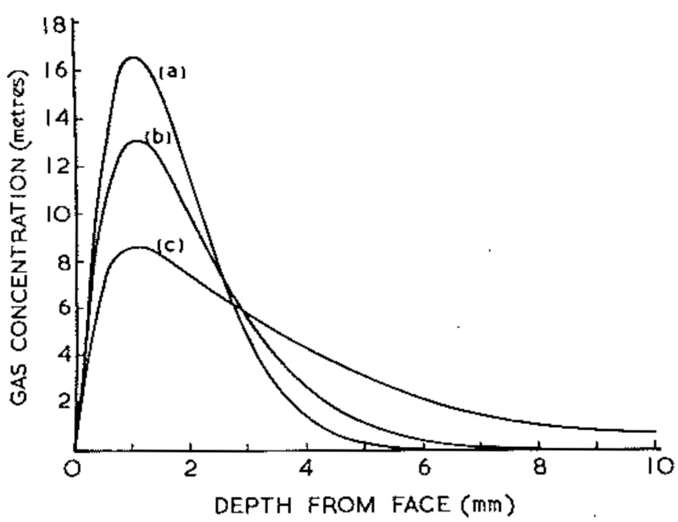

Fig. 8. Distribution of gas in 10 mm gel after exposure to air at (*a*), 48 m for 7 min; (*b*), 23 m for 27 min; (*c*), 11 m for 104 min. These pressures are equivalent, after allowance for unsaturation of tissue, to actual depths of 60 m, 29 m, and 14 m of dives reported by Van der Aue (1959).

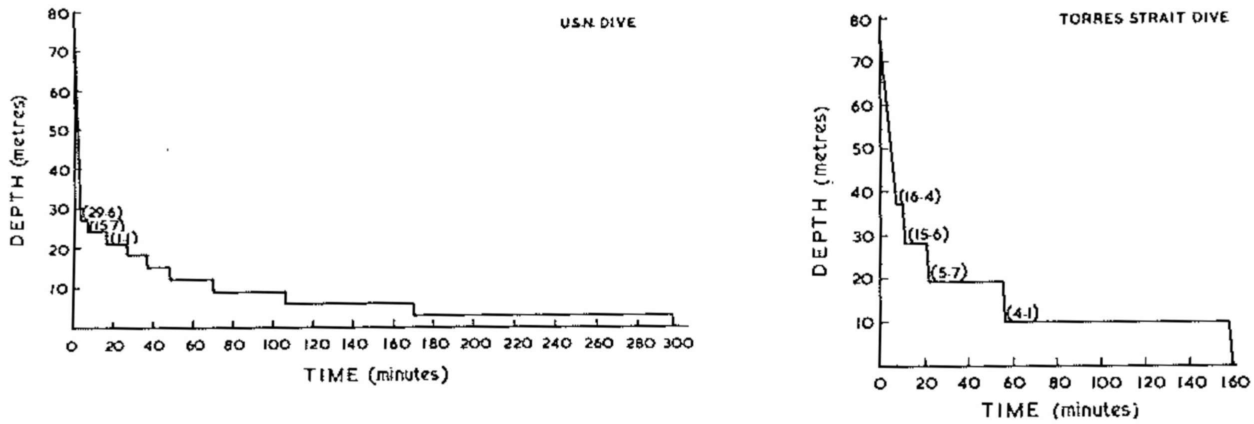

Fig. 9. Comparison of ascent profiles and computed supersaturations (shown in brackets) for 1.2 mm gel specimens exposed to an air pressure of 60 m (equivalent to a 73 m dive) for 60 min and then decompressed according to U.S. Navy schedule (for 73 m) (*left panel*) and to Torres Strait practice (for 73 m) (*right panel*).

the case of the gel, be determined by matching the results of computations on the model to actual events. The model is, of course, very much simplified and absolute conformity with the real process is not to be expected. A satisfactory correspondence should, however, be obtainable through fine adjustment of the variables. Were it ultimately found to be necessary, the model could be extended to include several classes of tissues with diverse sets of properties.

CONCLUSION

The processes of diffusion of gas and nucleation of bubbles in specimens of gelatin subjected to compression and decompression experiments are accounted for by a physical model. A particular feature of the model is the incorporation of gas nuclei that have a variable sensitivity to decompression. Any pattern of compression and decompression may be analyzed with the aid of the essential relationships between variables expressed by Eqs. 2 and 7.

The satisfactory performance of this model of the gel and a demonstrable analogy between the behaviors of gel and human tissue encourage the belief that the model has potential for application to the refinement and development of diving procedures. Optimization of the decompression procedure after a dive is an immediate application. The ultimately necessary experimentation could be directed much more closely with the aid of computations to identify and to modify most appropriately the critical features in currently used schedules. Procedures for new or exceptional dives could be planned with some assurance.

A "real-time" analogue for tissue could be constructed. Computations on the model could be carried out while the diver works and his condition at any time would be known. A diffusion analogue of this kind has, indeed, been used in this laboratory (Svilans 1974). The present state of miniaturization of computing equipment allows the possibility of a scuba diver carrying with him a device to indicate his current margin of safety. The value of real-time information in unusual exploits and emergencies is obvious.

Mixed-gas diving techniques could be subjected to critical analysis with the aid of a model. It is easy to extend the model to accommodate several gases with their respective diffusivities and, to the degrees to which they become important as reservoirs for the growth of bubbles, their solubilities. Recorded exposures could be examined for narcotic and toxic limits and procedures could be developed and refined accordingly.

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LeMessurier, G. H., T. N. Smith, and W. R. Wood. 1979. La diffusion et la nucleation d'un gaz dans une gelatine: implications pour la mise au point de schemas de decompression. Undersea Biomed. Res. 6(2): 175–188.—On mentionne certains procédés de plongée généralement acceptés et apparamment contradictoires pour souligner le besoin d'une comprehension plus étendue des rapports entre les facteurs de la plongée, de la décompression, et de la maladie de décompression. Les réponses physiologiques dues à la diffusion et a la nucléation de gaz dans les tissus peuvent être comparées aux phénomènes semblables ayant lieu dans des gélatines exposées à la compression et à la décompression. On décrit un modèle du comportement en gélatine, et démontre la conformité du modèle avec les résultats expérimentaux. L'analogie de la gélatine et du tissu sert de base pour l'application de ce modèle à la mise au point de tableaux de plongée et de décompression.

décompression
schémas de décompression
maladie de décompression
diffusion
bulles de gaz
gélatine
nucléation

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