Adherence to the diving tables was very poor and as there is a risk of decompression sickness even whilst staying within the tables (12 per cent of those this series said that they had dived within the tables), the risks of going outside the tables are obvious. Repetitive diving only helps to exacerbate these risks.

CAGE was treated generally within six hours. The one exception to that was initially treated in a chamber in the Maldives twenty-four hours after the onset of symptoms. DCS, however, presented usually at 2 to 3 days with substantial numbers up to 4 weeks and one at 2 months.

The majority of the cases treated were musculo-skeletal decompression sickness (57 per cent), though it is noted that three cases of CAGE (10 per cent) occurred during this period.

Treatment was usually with a RN Table 62 or an extended RN Table 62. Although initial improvement was usually good, 63 per cent relapsed. This was probably due to the delay in commencement of treatment. Of these relapses, 67 per cent resolved completely with further treatments.

This review illustrates the cross-section of cases that could be expected to present at a treatment facility. The question of delay before the patient presents is an important one, regardless of whether it is due to travelling delays or patient reticence at presenting. As it directly affects the chance of relapse and eventual recovery, efforts should be made to educate divers to keep treatment delays to a minimum.

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BEER, BUBBLES AND THE BENDS

THE BIOPHYSICS OF BUBBLE FORMATION IN DECOMPRESSION SICKNESS

HP De Decker

NOTES

It would be useful if the reader could pour himself (herself) a tall glass of slightly chilled beer (for illustrative purposes!).

All pressures are given as atmospheres absolute (ATA). Although not strictly SI, this unit has been used, following its popularity in diving literature, because of the ease of conversion from depth to ATA. Each 10m increment in depth equals an increase in pressure of 1 ATA. For the purists 1 ATA = 1 $kg.cm^2$.

I am indebted to Paul Hanekom of the Research Diving Unit, Department of Oceanography, University of Capt Town for the use of his library and for stimulating my interest in diving physiology.

I am fascinated by beer, and not only because of its inebriating effect. To me it illustrates some of the most fundamental aspects of that most dreaded of divers' diseases, the bends. Decompression sickness (DCS) or the bends, is an illness that follows a decrease in environmental pressure which is sufficient to cause the formation of bubbles from inert gases dissolved in the body tissues. It occurs in pilots and tunnel workers suddenly exposed to a large decrease in pressure. It is mainly seen, however, in divers who return from depths where the increased hydrostatic pressures cause high partial pressures of nitrogen in their tissues. This extra nitrogen is then released as bubbles if the ascent is too rapid. A beer, of course, is far from being a complete model of this complex syndrome with its cascading haematological effects, but it serves a useful purpose in illustrating the most fundamental aspect of DCS, bubble formation. And that is what we will explore. Stare into the depth of your beer to where the bubbles appear as if by magic from a single spot in an unending rising string of pearls. How do they form? What hidden forces shape their burst into existence? How does this relate to the bends?

DECOMPRESSION SICKNESS

It has been known since the middle of the last century that DCS is an illness related to bubbles in the blood and tissues.[1] Before 1968, however, literature on bubble formation was virtually non-existent, mainly due to the difficulty of actually observing bubbles in vivo, and to the use of subjective endpoints such as pain, paralysis and other clinical manifestations.[2] Until quite recently, no direct observations of bubble formation had been made in vivo and the link between the bends and bubbles could only be inferred from post mortem investigations. This meagre evidence, however, was used to construct decompression tables by which divers currently calculate a safe ascent rate from any depth. Although the tables are usually effective for the prevention of DCS, this is obviously an unsatisfactory basis for its treatment. Effective treatment of the disease necessarily requires detailed knowledge of bubble formation as this is its initiating event. But before explaining how the bubbles form, we need to know what they are. For answers, we look at the bubbles in your beer, and then see if we can apply our knowledge to living tissues.

THE BUBBLES

Physics

Let us first determine the forces which act on a bubble in a liquid or in tissues. For a bubble to exist, the total gaseous pressure inside the bubble must be equal or greater than the crushing pressures exerted on it.[3] The crushing pressures are:

1. the ambient pressure (Pamb), which by Dalton's Law equals the sum of the constituent gas pressures, ie.
   $$Pamb = P_{N_2} + P_{O_2} + P_{CO_2} + P_{H_2O} \text{ etc} \quad (1)$$
2. the tissue pressure (Ptissue), or the pressure the tissue exerts in resistance to deformation, and
3. the pressure due to surface tension (Py) of the bubble surface. This is given by Laplace's law as the relation between surface tension (y) and the radius of the bubble (r):
   $$P = 2y/r \quad (2)$$

It is obvious from this relationship that Py is negligible in large bubbles, but that very small bubbles are

subjected to extremely high crushing pressures. For a bubble to exist, therefore, the gaseous pressure inside the bubble (Pbubble) must be equal to or greater than the crushing pressures, ie.

$$Pbubble \geq Pamb + Ptissue + Py \qquad (3)$$

The bubbles in your beer consist of $C0_2$ gas. While the beer was under pressure, the $C0_2$ was in supersaturation, but bubbles could not form since Pamb was very high. As you opened the beer, Pamb was reduced and the $C0_2$ could come out of solution and form bubbles. Similarly, a diver is subjected to high Pamb at depth, but when he (rapidly) ascends, Pamb is reduced and the supersaturated gas (N_2 in this case) can come out of solution and form bubbles. This, however, still does not explain their formation.

If you peer closely into your beer, you will notice that the bubbles only arise from the walls or bottom of the glass. Submerge a solid object into the beer, and bubbles will form on its surface as well. This illustrates an important principle:

1. bubbles only arise from solid surfaces, or conversely,

2. bubbles do not arise de novo from the liquid.[4]

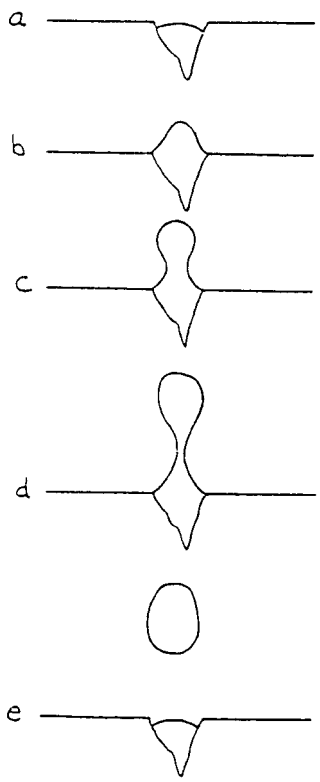
Does this mean that bubbles never arise de novo? If you shake your beer it will be obvious that they can, indeed, arise de novo. The turbulence in the beer causes sufficient reduction of local ambient pressures (Pamb) to allow the formation of additional gas bubbles.[4] However, in the still glass of beer, the bubbles only form at tiny cracks of imperfections in the glass. Since the walls of the crack are solid, Ptissue will have no effect, and, as the gas/liquid interface is flat (Figure 1a), surface tension (PY) will be negligible. At gaseous equilibrium, the pressure inside this "nucleus" equals the dissolved gas pressure in the liquid. When any gas inside the liquid is in supersaturation however, like the $C0_2$ in your beer, it will diffuse into the nucleus and expand its volume. The surface of the nucleus will bulge out into the liquid and, of course, its growth will be resisted by the surface tension of the curved surface. If the critical radius (eqn. 2) is exceeded, a bubble will form, break away and float to the surface (Figure 1). This then leaves the nucleus free to generate the next bubble.[2,3] The process will continue for as long as the gas is in supersaturation and if you stare at your beer for too long, all the super-saturated $C0_2$ will come out of solution, and your beer will be flat.

Now all this may sound like sophisticated bar talk, but how much of it is relevant to the study of the bends?

Detection of bubbles

A major breakthrough in the study of the bends was achieved when methods were developed for the non-invasion detection of bubbles.[5] The existence of bubbles during DCS were now confirmed and experiments on animals and humans could be performed to determine their sites of origin, intravascular course and fate. Bubbles were first detected by using radiographs, electrical conductance and ultrasound.[6] The Doppler ultrasound method proved the most successful, but is limited to moving bubbles only. Subsequent methods, using pulse-echo ultrasonics,[5] or the velocity of ultrasound through tissue[6] have enabled the detection of static bubbles as well. By

FIGURE 1



The formation of a bubble at a crevice in a solid. Adapted from Reference 4.

using these techniques, it was possible to demonstrate that the minimum stable bubble size in tissues or blood is 10-20μm.[5] A more surprising result was the detection of bubbles in divers who remained well within decompression limits and who showed no symptoms of DCS. These were termed "silent bubbles"[7] and were shown to lead to significant haematological effects.[8] These effects, however, will not be discussed here.

Site of origin and intravascular course

Surgical procedures have recently also been used to determine the origin of bubbles and their course in the blood. By examining the microvasculature of the hamster cheek pouch, as well as its femoral artery and vein during decompression, Lynch et al[9] have managed to show that bubbles probably first arise in the venous vessels, and only under certain conditions enter the arterial system. Only during "explosive ascents", when decompression from 7 ATA to 1 ATA occurred rapidly, were bubbles observed in the arterial system.

By using a Doppler probe, Butler and Hills[7] have shown that the lungs act as excellent filters for microbubbles in the venous system. By placing the probe over the venous drainage of the lungs (precordial position) and infusing bubbles of varying size intravenously, they were able to demonstrate that almost all bubbles

larger than 22 μm were filtered from the blood by the lungs. Hills and Butler[10] repeated the experiment using a Coulter counter to determine the bubble size in blood drawn from the venous sinus of dogs. They could then show that bubbles would pass through the lungs if (1) too many bubbles were produced in the veins (2) vaso-dilation occurred in the lungs, or (3) the lungs were damaged in some way, for example by excessive oxygen exposure. Ohkuda et al[11] confirmed this result by showing that no air entered the arterial circulation under normal physiological conditions after intravenous infusion of 2 ml of air per minute into sheep for 3 hours.

Hemmingsen and Hemmingsen[12] had previously shown that bubbles seldom formed intracellularly, even at very high supersaturation levels of nitrogen. Even if bubbles did eventually form, their effect was overshadowed by that of the bubbles in the extracellular fluid. The picture now seems a bit clearer. The site of origin of the bubbles is probably extracellular and usually in the vein or extracellular fluid. Now that we know a little more about them, we can continue to investigate the mechanism of bubble formation.

Bubble formation

The formation of bubbles in decompressed animals and humans is described by two opposing theories.[13]

1. the mechanical stress theory,[2] generally known as "de novo nucleation".

2. the micronuclei theory.

Both can occur in your beer under different conditions, but which is more correct in its description of bubble formation in DCS? Let us investigate each of these, and some their variants.

The de novo nucleation theory

This theory predicts that bubbles will form de novo, ie. where none existed before, within the blood or extracellular fluid due to highly localised negative pressures induced by some kind of mechanical stress. The theory is neatly summarised in the equation which describes the conditions for nucleation:[2]

$$\Delta F = 4\pi r\{ y - rPbln(Pt/Pb)]/3 \qquad (4)$$

where F is the free energy of nucleation required to create a bubble of radius r,
y is the surface tension of the bubble,
Pt is the tissue pressure,
and Pb is the bubble pressure.

In a nutshell, the theory holds that during the random thermal motion in all liquids, submicroscopic cavities are formed, which collapse immediately under normal physiological conditions due to attractive intermolecular forces. If these cavities are placed under a negative pressure (mechanical supersaturation) of 100-1000 ATA, however, the intermolecular forces will be counteracted and the cavities will expand to reach stability.[14] Bubble formation can also occur de novo if the liquid is heated, or gas-supersaturated to approximately 150 ATA.[15] Since this pressure is equal to a depth in seawater of 1490m, while the bends can occur from any depth deeper than 10 m,[3] this theory seems to be inadequate.

The micronuclei theory

The first experimental evidence for this theory proposed by Harvey et al,[16] was provided by Evans and Walder.[17] Harvey et al[16] had managed to reduce the number of bubbles formed in water on decompression by applying hydrostatic pressure to the water before decompression. Pre-pressurising forced the gas in the micronuclei into solution, thereby reducing the number of nuclei available for bubble formation. The experiments of Evans and Walder[17] used this observation and are so elegant that I will give a brief resume here.

The brilliance of the investigators is shown by their choice of experimental animal: the common shrimp, Cragnon cragnon. There are two obvious advantages in that choice. Firstly, the shrimp is transparent, so that any macroscopic bubbles formed can readily be seen. Secondly, the shrimp is found at all depths in the sea and is consequently not affected by large changes in hydrostatic pressure. If the shrimp contained micronuclei, and their number could be reduced by pre-pressurisation, a degree of protection from bubble formation should be attained. Evans and Walder[17] decompressed 100 shrimps, of which 50 had been pre-treated by pressurisation to 400 ATA for 2 minutes. The results of their experiment are shown in Table 1.

TABLE 1

	NO. WITH BUBBLES	NO. WITHOUT BUBBLES
Untreated	48	2
Pressure Treated	4	46

The incidence of bubbles in pressure treated and untreated shrimp, Cragnon cragnon, after decompression (From Reference 17)

It is obvious from these results that the destruction of micronuclei leads to a drastic reduction of bubble formation.

Further evidence for the micronuclei theory came from Vann et al[13] who pressure treated Wistar rats before subjecting them to decompression. The reasoning was that if bubble formation occurred de novo, the pressure treatment would enhance the bends due to the higher supersaturation level in the rats' tissues. If gas bubbles formed from micronuclei, however, the pressure treatment would decrease the incidence of DCS due to the destruction of micronuclei. Their results showed a decrease of almost 20 per cent in the incidence of DCS after pressurisation and decompression. The second hypothesis was therefore accepted: bubbles form from micronuclei which could be reduced by pre-pressurisation. Now, of course, our next question follows logically: how do the micronuclei form?

The origin of micronuclei

In an extension of their micronuclei experiment Evans and Walder[17] gave a clue to the origin of micronuclei per se (not the bubbles). They repeated their previous experiment with 100 pre-pressurised shrimps, of which 50 were stimulated to perform vigorous flexural contractions and rapid leg movements. The results of this experiment are given in Table 2.

TABLE 2

	NO. WITH BUBBLES	NO. WITHOUT BUBBLES
Pressure treated only	4	46
Pressure and stimulation	16	34

The effect of stimulation on bubble formation in pre-pressurised shrimp, Cragnon cragnon, after decompression (From Reference 17)

Bubble formation was obviously increased in the stimulated shrimps, possibly due to the increase of micronuclei in their tissues caused by movement. Evans and Walder[17] attributed the increase in micronuclei to "high impulsive stresses" set up during movements in the tissues of the shrimps. It is certainly a well known fact that vigorous physical activity during ascent from a dive increases the probability of the bends in humans.

Tribonucleation is a theory originally proposed by Hayward[18] and later invoked by Vann and Clark[14] to attempt an explanation of the origin of micronuclei. The theory proposes that large local mechanical supersaturation pressures are generated when two closely opposed surfaces are separated in a liquid. This movement will produce super-saturations directly proportional to the product of the liquid viscosity and the velocity of the separation of the surfaces. Tribonucleation has been used by Unsworth et al[19] to explain the "cracking" of joints as the formation and collapse of cavitation bubbles within the joint capsules. It seems to me, however, that this brings us back full circle to do novo nucleation. In fact, the theory has not been used subsequently to explain the origin of micronuclei, which is still poorly understood.

The role of surfactants

A further development of the micronuclei theory is that nuclei without solid bases (eg. in blood) are surrounded and stabilised by "skins" of surface-active compounds.[20] This followed from the reasoning that if these micronuclei were larger than 1 μm, they should rise to the surface of the liquid, while if they were smaller than 1 μm, they should dissolve due to the intense pressure generated by the surface tension of the gas/liquid interface. Since neither event occurred, the existence of a stabilisation membrane of surfactants of varying permeability was postulated. At gaseous equilibrium, the membranes are permeable, but they become effectively impermeable if the hydrostatic pressure is increased rapidly to sufficiently high levels.[20] Very little is known of the surfactants, except that they are composed of non ionic hydrocarbon moieties[21] and that the desorption of the surfactants from the gas/ liquid interface would presumably lead to the dissolution of the micronuclei.

The Varying-Permeability Model

Recently, Yount and Strauss[22] and Yount et al[23] have developed a model from the micronuclei theory to describe a wide range of cavitation phenomena related to decompression. The model, called the varying-permeability model, has since been used successfully to describe decompression limits (limits to which decompression can be taken before bubbles start to form) in rats and humans[24] as well as fingerling salmon.[25]

The model is a mathematical description of the formation of bubbles of a minimum radius at different supersaturation levels, crushing pressures crumbling compressions (the mechanical strength of the surface membrane) and surface tensions. Ultimately, the model relates the ambient pressure to micronuclear radii, and therefore, by Laplace's Law (eqn. 2), to the number of bubbles that are able to exist at that pressure. Above a certain minimum radius, nuclei originally present will grow to form macroscopic bubbles, while those below the minimum radius will either dissolve or remain as micronuclei.[25]

CONCLUSION

The varying-permeability model is not a model of the bends, but only of the initiating step in this complex disease. It has already been of practical benefit, however, in the prevention and treatment of DCS. This is an excellent example of how basic research into fundamental principles can lead to advances in practical knowledge.

By now your beer will be flat. I hope, however, that it will not have been wasted, but has served a useful purpose, I am sure that when next you enjoy an ice cold lager, like me, you will not see it as just another glass of bubbly liquid, but will spare a moment to reflect on the bends in your beer. Prost!

SUMMARY

Decompression sickness (DCS) is an illness which follows a decrease in environmental pressures which is sufficient to cause the formation of bubbles from inert gas dissolved in the body tissues.

Bubble formation, therefore, is the initiating event in the pathogenesis of this syndrome with its cascading haematological sequelae.

Effective prevention and treatment of DCS can be derived from a better understanding of bubble formation.

Bubbles exist when the gaseous pressure inside the bubble is equal or greater than the crushing pressures (ambient pressure, tissue pressure and the pressure of surface tension).

Two theories describe bubble formation: the mechanical stress theory (de novo nucleation), and the micronuclei theory. The latter is currently favoured.

The micronuclei theory holds that bubbles form from microscopic gaseous nuclei, either lodged in a crevice, or stabilised by surfactant "skins" of varying permeability. When any gas in the surrounding liquid is in supersaturation, it will diffuse into the nuclei, expanding its volume until a bubble forms.

The varying-permeability model was developed from the micronuclei theory to quantitatively describe cavitation phenomena. It has been successful in predicting decompression limits for various animals and man, illustrating the usefulness of theoretical models to practical medicine.

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A NEW SYSTEM OF GIVING OXYGEN TO DIVERS IN AN EMERGENCY

Ken Wishaw

I would like to describe a simple alternative method of delivering high concentration oxygen to awake patients with decompression sickness. I believe it is an improvement on systems at present in use, and does not appear to have been described before.

With the increasing emphasis on the value of normobaric oxygen therapy as soon as possible after the onset of decompression sickness, this method should be of interest to members of SPUMS and to divers generally.

The following are the desirable features of such a system: