Physiol. Res. 45: 467–470, 1996

Importance of Surface Tension in Therapeutic Compression in Decompression Sickness

E. HRNČÍŘ

Clinic of Occupational Diseases, Third Faculty of Medicine, Charles University, Prague, Czech Republic

Received January 26, 1996
Accepted May 13, 1996

Summary

The aim of this investigation was to study the effect of environmental pressure and surface tension on the size of gas bubbles in tissues and on their inner pressure. Due to the action of surface tension, the pressure inside the bubbles is always greater than the surrounding pressure. This phenomenon is the more marked, the smaller are the bubbles. Therapeutic compression leads to diminution of the volume of gas bubbles and thus to a rise of that portion of their inner pressure which is due to surface tension. In small bubbles the surface tension may cause their dissolution and disappearance. It is therefore correct to implement therapeutic compression in decompression sickness as soon as possible before the fusion of a significant number of small bubbles into larger ones occurs.

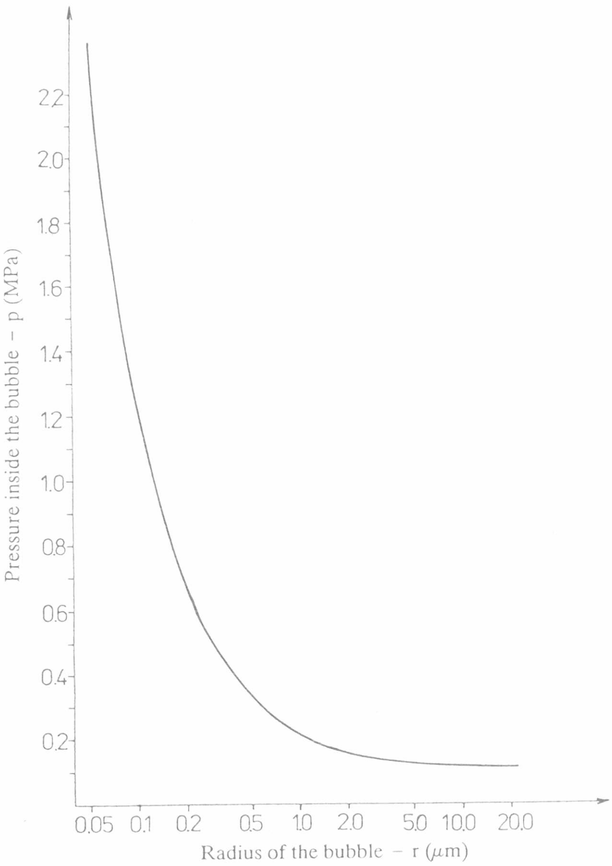
Key words

Therapeutic compression – Gas bubbles in tissues – Surface tension – Decompression sickness

Introduction

Gas bubbles in tissues may be the cause of serious damage of the organism. This happens, for instance, in decompression sickness of divers or caisson workers where gas accumulated in tissues under hyperbaric conditions is released in the form of bubbles after too rapid decompression (McCallum 1983, Kindwall 1988, Hrnčíř 1993). Another example of this is air embolism in the circulation which develops during barotrauma of the lungs or iatrogenically (Kindwall 1988). In these instances the basic therapeutic method is to place the affected subject in an environment with an elevated environmental pressure. This therapeutic procedure is described as therapeutic compression (or recompression). Its favourable effect is usually explained by Boyle-Mariotte's law, i.e. by reduction of the volume of gas bubbles under hyperbaric conditions (Barcal *et al.* 1992). (The gas volume at a constant temperature is inversely proportional to its pressure.) Moreover, when the surrounding pressure is raised, the difference between the pressure inside the bubbles and the partial pressure of gas dissolved in the surrounding tissues increases and thus the gas absorption from the bubbles is accelerated. If the patient during therapeutic recompression breathes pure oxygen, or at least air enriched with oxygen, the partial pressure of the other gases (in particular nitrogen) in tissues declines and the gas absorption from bubbles is thus further facilitated (Barcal *et al.* 1992).

The relationship between the volume of gas bubbles and the environmental pressure is in fact more complicated than ensues from Boyle-Mariotte's law. The gas pressure inside the bubbles, and thus also their volume, are determined not only by the environmental pressure but also by the surface tension of the bubble. This fact can participate in a significant manner in the mechanism of action of therapeutic compression. Therefore, it is important to assess, from the physical aspect, the relationship between the volume of gas bubbles in tissues and the magnitude of the environmental pressure and surface tension and to reflect what role this can play in therapeutic compression.



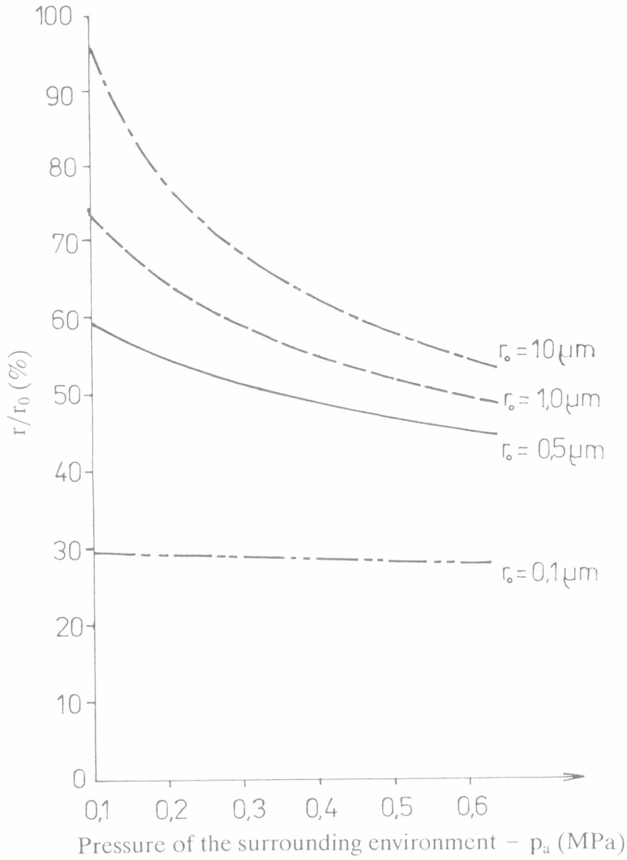


Fig. 1
Correlation between pressure inside gas bubbles in the blood stream at a pressure of 0.1 MPa and their radius.

Fig. 2
Correlation between radius of gas bubbles in the blood stream and pressure of the surrounding environment.

Methods

The basic principle is the simplified idea that bubbles are spherical in shape and that the gas pressure inside the bubble **p** follows the relationship

$$\mathbf{p} = \mathbf{p_a} + \mathbf{p_b} \qquad (1)$$

where $\mathbf{p_a}$ is the pressure outside the bubble (Pa), and $\mathbf{p_b}$ is the pressure caused inside the bubble by the surface tension (Pa)

Moreover the following relationships hold

$$\mathbf{p_b} = 2\sigma/\mathbf{r} \qquad (2)$$

where σ is the surface tension ($N.m^{-1}$), and **r** is the radius of the bubble (m)

$$\mathbf{p.V} = \mathbf{n.R.T} \quad \text{(equation of state)} \qquad (3)$$

where **V** is the volume of the gas bubble (m^3),
n is the amount of gas in the bubble (mol),
R is the universal gas constant (8.31441 $J.mol^{-1}.K^{-1}$), and
T is the absolute temperature (K)

$$\mathbf{V} = 4\pi.\mathbf{r}^3/3 \qquad (4)$$

where π is Ludolf's number.

Results

The pressure inside gas bubbles in the blood stream at normal atmospheric pressure (0.1 MPa) and the surface tension of the blood σ=0.0562 $N.m^{-1}$ (Barcal *et al.* 1992) is given in Figure 1. (derived from equations (1) and (2).) It is obvious that in bubbles the radius of which is smaller than 0.1 μm the pressure is more than double, as compared with the surrounding environment.

By substitution and mathematical modification of equations (1), (2), (3) and (4) the following equation is obtained

$$\mathbf{r}^3 + (2\sigma/\mathbf{p_a}).\mathbf{r}^2 - 3\mathbf{n}.\mathbf{R}.\mathbf{T}/4\pi.\mathbf{p_a} = 0 \qquad (5)$$

which is an equation of the type $x^3 + ax^2 - b = 0$, which is easily solved for real parameters a and b. From equation (5) it is possible to assess the radius of a spherical bubble containing a known amount of gas **n** in a medium with pressure $\mathbf{p_a}$ and surface tension σ at temperature **T**. From this the volume of the bubble can be calculated (equation (4)) and the gas pressure inside the bubble (equations (1) and (2)).

Figure 2 indicates the radius of bubbles of a known amount of gas in the blood stream (σ = 0.0562 $N.m^{-1}$) in a medium with a varying pressure $\mathbf{p_a}$ at a temperature of 37 °C (310.15 K). Figure 3 indicates the inner pressure **p** in these bubbles. Note that $\mathbf{r_o}$ is the radius of a globe of the same volume as taken up by the given amount of gas at pressure 0.1 MPa and temperature of 37 °C (310.15 K).

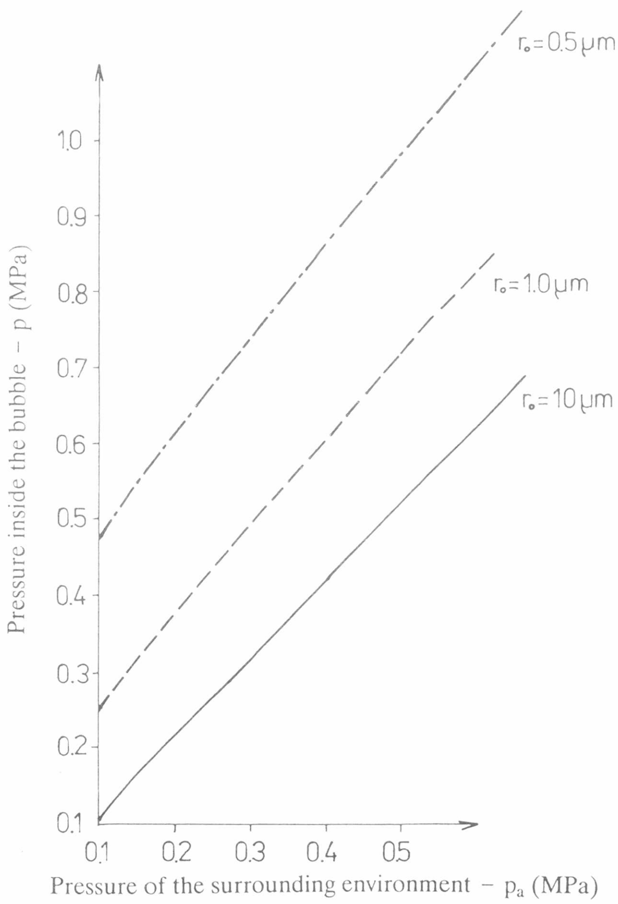


Fig. 3
Correlation between pressure inside gas bubbles in the blood stream and pressure of the surrounding environment.

Discussion

Figures 1, 2 and 3 express the values calculated for gas bubbles in blood with a known surface tension (0.0562 $N.m^{-1}$). The data of different authors regarding the magnitude of surface tension in the blood vary somewhat and this is obviously due to its different composition at a given moment and the administration of some drugs (Hjelde *et al.* 1994). We did not find data in the literature on the magnitude of surface tension of other body fluids and tissues (e.g. interstitial fluid, intracellular fluid, tissues of the central nervous system, nerve sheaths, etc.). Therefore, we did not prepare any figures characterizing gas bubbles at these sites. No doubt, these figures would be analogous with those submitted, as the principle of action of surface tension on the size and pressure of gas bubbles is identical in all instances.

We are aware of the fact that properties of gas bubbles in the blood are also influenced by other factors than those considered in our simplified model, e.g. by the blood flow, blood pressure, its pressure gradient and possibly by the presence of so-called condensation nuclei. These factors are, however, involved to a varying extent, depending on circumstances, and cannot be defined in a simple mathematical manner and, in a medium with a higher external pressure, they are not significant from the quantitative aspect. For the sake of simplification their action is considered negligible in the present report.

It is obvious that during therapeutic compression, the volume of gas bubbles in tissues will diminish more than would correspond to Boyle-Mariotte's law (see Fig. 2) and that the pressure inside the bubbles will be greater than the external pressure (Fig. 3). The smaller the bubbles, the greater their inner pressure caused by surface tension. In very small bubbles surface tension may even account for the decisive part of the pressure. Gas from small bubbles is absorbed more rapidly than from large ones as the pressure in relatively large gas bubbles is close to the surrounding one, while it is significantly greater in small bubbles (see Fig. 3).

As the basis for our calculation, we used the simplified assumption that the gas inside the bubbles has the properties of a so-called ideal gas and that the so-called equation of state (3) applies to it. Actually, van der Waals equation applies to real gas:

$$(\mathbf{p} + \mathbf{A}/\mathbf{V}^2).(\mathbf{V} - \mathbf{B}) = \mathbf{n}.\mathbf{R}.\mathbf{T} \qquad (6)$$

where A and B are constants depending on the type of gas

It can, however, be demonstrated that for pressures and gases considered in the present report the magnitude of constants A and B is very small in relation to the value of **V** (i.e. the gas inside the bubbles has properties close to those of the ideal gas), therefore, instead of van der Waals equation (6) the equation of state (3) may be used.

If a certain amount of gas is absorbed from a bubble, the bubble diminishes somewhat in size but the pressure inside the bubble does not decline. On the contrary, the pressure inside the bubble rises due to the action of surface tension. Hence, the difference between the gas pressure inside the bubble and the partial pressure of gas in its surrounding increases and the absorption of gas from the bubble is more rapid. Surface tension thus has the effect that the more the bubble diminishes in size, the more rapidly the gas from the bubble is absorbed. The increased rate of gas absorption persists until the bubble disappears due to complete dissolution.

In decompression sickness, the objective of therapeutic compression is to eliminate or at least to reduce bubbles which were formed in tissues and thus to eliminate their adverse mechanical action and development of subsequent pathological processes, in particular blood coagulation (Hrnčíř 1993). Compression leads to a diminution of bubbles and thus a part of their inner pressure caused by surface tension rises. This may be very important in particular in small bubbles. In untreated decompression sickness the gas bubbles in tissues are at first small and subsequently increase in size also due to fusion. From this ensues the demand to implement therapeutic compression as soon as possible after the development of decompression sickness, i.e. at a time before significant fusion of small bubbles in tissues occurs to form larger bubbles. This is consistent with clinical experience that in cases where it is possible to implement therapeutic compression shortly after the development of decompression sickness, this frequently leads to immediate and complete recovery of the patient and symptoms do not tend to relapse. In small bubbles, the gas pressure is significantly higher than the surrounding pressure due to compression and this leads to their rapid diminution and disappearance. Conversely, when therapeutic compression was implemented a long time after the development of decompression sickness, the effect is not great and there is a marked tendency of relapsing complaints after completed compression (Kindwall 1988). The pressure in large bubbles is only slightly higher than the surrounding pressure caused by compression and therefore the gas from these bubbles is absorbed relatively slowly. In this phenomenon, the surface of large bubbles may also participate because the area where diffusion of the gas takes place is, due to their volume, smaller than the surface of small bubbles from which they were formed by fusion. Bubbles which did not disappear completely during therapeutic compression may then cause a relapse of symptoms of decompression sickness after completed compression.

References

BARCAL R., EMMEROVÁ M., HADRAVSKÝ M.: *Basis of Hyperbaric Medicine* (in Czech). Karolinum, Prague, 1992, 126 pp.

HJELDE A., BRUBAKK A.O., EVJEN S., POPPE A.: Changes in surface tension and its possible relation to vascular bubbles. In: *Proceedings of XXth Annual Meeting of EUBS,* Istanbul, 1994, p. 125.

HRNČÍŘ E.: Decompression sickness (in Czech). *Pracov. Lék.* **45**: 213–216, 1993.

KINDWALL E.P.: Medical aspects of commercial diving and compressed-air work. In: *Occupational Medicine.* C. ZENZ (ed), Year Book Med. Publ., Chicago, 1988, pp. 383–425.

McCALLUM R.I.: Decompression sickness. In: *Encyclopedia of Occupational Health and Safety,* L. PARMEGGIANI (ed), International Labour Office, Geneva, 1983, pp. 596–598.

Reprint Requests

MUDr. E. Hrnčíř, CSc., Clinic of Occupational Diseases, Third Faculty of Medicine, Šrobárova 50, 100 34 Prague 10, Czech Republic.