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BAROPHYSIOLOGY AND BIOPHYSICS

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INTRODUCTION

Decompression is an important aspect of extravehicular activity (EVA). Errors can result in decompression sickness (DCS) if the protective measures are too liberal, while valuable on-orbit time is dissipated in prophylactic methodologies that are excessively conservative. Nucleation is an important consideration in many natural events, and its *control* is very important in many industrial procedures. The amount of Extravehicular Activity (EVA) that will be required during the construction of the International Space Station exceeds all of the other activity combined. The requirements in astronaut time and consumables (breathing oxygen and air) will be considerable. In an attempt to mitigate these requirements, *Project ARGO* was instigated in 1990 to investigate the effects of gravitational forces on the musculoskeletal system. This work has led to the present plans for the reduction of prebreathe duration. Over the past decade, research has been directed towards an understanding of the biophysical basis of the formation and growth of the decompression gas phase with the goal of improving the efficiency of the EVA process. In the past, we have direct work towards a more complete understanding of gas bubble formation and growth and exercise-enhanced washout during oxygen prebreathe.

Theories of decompression have been based primarily on the concept originated by J. S. Haldane at the turn of the century, i.e., limited, stable supersaturation. NASA/JSC models have developed along the lines of the "Tissue Bubble Dynamics Model" devised originally by Dr. Michael Gernhardt. The original model has be revised and certain new parameters have been, or will be, inserted to allow for the changes in micronuclei prior to depress. Some primary concepts are [1.] There is not a mixture of aqueous and lipid tissues. 2. Supersaturation occurs in the tissue responsible for decompression sickness but is not the sole determinant of DCI. and 3. Several factors influence bubble growth. "Microbubble intermediates" (MBI) are preformed by a mechanism involving musculoskeletal activity. The MBI appear in a size distribution described by a power law function $n = no\ K\ r^{-D.}$

Critical Radii In decompression work, the failure of decompression tables has been dealt with almost solely by supersaturation control, accomplished by the tracking and control of inert gas uptake and elimination in body "compartments". As a general topic, however, nucleation and gas micronuclei has been discussed by virtually everybody in the field of hyper- and hypobaric decompression over the past several decades, but actual control of this parameter has not been thought possible. Efforts at JSC have been directed towards utilizing the concept of the critical radius R_c. The equation for the critical radius of a bubble with surface tension σ at the time of decompression for a pressure change ΔP is given by $R_c = 2\sigma / \Delta P$. The control of growth is dependent upon σ which is controlled by the biochemical composition of the cellular milieu, the temporal change of interfacial surfactants (the *Vroman effect* which is depended upon relative rates of bulk diffusion, adsorption and desorption, and convection). Many aspects of this can be studied with the oscillating bubble surfactometer.

Nucleation Of Bubbles There may exist small volumes of a gas phase ("micronuclei"), or "seed" micronuclei, in hydrophobic crevices exposed to the aqueous environment. It is commonly

Reduction of DCS Incidence Joint-pain decompression sickness ("the bends") occurs from the formation of a gas phase in connective tissue of joints. Astronauts appear to have a reduced risk of DCS following exposure to 0-g compared to other experimental subjects who have ambulated at 1-g before decompression. Continuing trends in the reported outcomes of decompression during EVA indicate that the incidence is still zero.

Astronauts have performed more than 100 manned-excursions for extravehicular activity that required significant decompression immediately preceding the activity, and not even mild DCS has apparently occurred Possibilities for this reduction are: 1. unnoted joint pain or soreness; 2. cluster phenomenon; 3. improved gas exchange at the lungs; 4. tissue perfusion increases; 5. use of analgesics; 6. extensions to the oxygen prebreathe protocols; and 7. reduction of stress-assisted nucleation

It is known that the supersaturation limits for the production of a decompression gas phase in vitro in quiescent fluids exceeds by several orders of magnitude that for in vivo systems. Altitude decompression sickness overwhelmingly involves the lower extremities because these are the most stress by gravitation. Straining has long been known to foster certain sites for DCS formation while the absence of kinetic activity has resulted in few bubbles being produced by decompression. The reduction in the effects of stress-assisted nucleation and/or the number of tissue gas micronuclei may explain the reduction of DCS during EVA. Such reduction could result a decrease in activity (hypokinesia) in space of the lower limbs and the lack of weight-bearing loads (adynamia) on the legs.

For the past several years, evidence has been accumulating from several laboratories around the world that adynamia can substantially aid in the reduction of the duration of oxygen prebreathe prior to EVA. It has not been clear, however, how to quantify the effects.

Blood Flow Changes with Exercise Examination of decompression data by Loftin and Conkin implicates changes in blood flow as they affect decompression outcome, and the effects are profound. While it has been known for decades that blood flow is modified by exercise, in barophysiology this effect has generally *not* been ascribed to modifying the compartment half times by more than $\pm$ 20%. These flow changes have never really been incorporated into decompression algorithms, because the conditions are so varied under which any decompression table would be employed. Such variability is not present in NASA EVA operations, however. Because the conditions in space can be quite controlled, at least at the present time, NASA decompression procedures can be more specific. The variety of situations in space is currently very limited, the number of participants is limited and the depressurizations are of a very specialized type (as contrasted with tables for deep sea divers which must have a wide latitude).

It is know that a change in blood flow in muscle tissue with exercise is about ten-fold. Local blood flow and functional compartment half times can change approximately ten fold (0.04 to 0.4 l/kg-min.) while flow to bones and joints change little (0.03 to 0.06).

Blood Flow and Oxygen Consumption Oxygen consumption is a reflection of muscle activity and thus can be used to indicate the degree of local blood flow (which naturally carries oxygen to the tissues). Resting muscle has a very low blood perfusion rate, and this rises very rapidly with

but very modest amounts of physical activity ("functional hyperemia"). This rapid rise can be a very potent adjunct to the *in vivo* modification of inert gas partial pressures, especially during prebreathe when it is desired to eliminate as much dissolved inert gas as possible from tissues.

The salient point for inert gas washout with exercise in barophysiology is that the *fraction of blood flow* to muscle *increases considerably with the onset of even very little physical exercise.* The perfusion increases locally because a larger fraction of the cardiac output is shunted to muscle tissue (and supposedly tendon and ligament). Thus, it is not totally an effect of increased pumping action of the heart.

Half Times and Blood Flow It has been debated as to what is the actual meaning of the Haldanian halftimes. The original concept traced them to *actual, distinct tissue types* with rather narrow limits of perfusion. They could exceed their supersaturation limits and evolve gas bubbles which would be released into the blood stream. In the analytical system here, it appears that the tissue is one which has a highly variable blood flow that can vary within a factor of ten. This is similar to what has been proposed for muscle tissue. Wherever is the locus of gas bubble generation (and apparently also those tissue types related to DCI pain), it appears that a factor of ten is possible for blood flow.

It is possible to construct a relationship between the blood flow and the compartment half times through the standard Haldane perfusion equation. The blood flows, as measured in classical physiology, will produce half times that are too short in comparison to those derived from analysis of decompression data in barophysiology. (It is currently not known why this is the case.) To yield values of half times that are commensurate with experience, it is necessary to have a partition coefficient k equal to 1.96×10^3 (derived from resting blood flow = 360 minute half time). This is a very small value and does not appear to correspond to a true blood/tissue partition coefficient.

Effective Half Times Various altitude chamber tests have been performed over the past years where decompression illness rates have been modified by physical activity during oxygen prebreathe. From an analysis of the data concerning decompression illness, it is possible to determine how the body responded to the depressurization conditions. That is, the system behaves effectively as if the TR is lower. One can calculate what half time was required to reduce the inert gas loads from the initial to final state. This is designated as the "effective" half time.

Exercise and Decompression Illness Work by Henry, where weights were lifted by the arms, indicates that decompression illness in the upper limbs is proportional to the exercise level. The results were reported for different experiments in which the weights were lifted slowly, rapidly, in a jerking fashion, and simply hold a weight out in front of the subject. The incidence of DCI was related to the work load and not so much to the type of activity, at least within the confines of the experimental conditions. This needs further clarification. Similar results were found by Ferris and Engel where stair stepping exercise was used. It appears that the energy expenditure rather than the type of exercise, within limits, governs the incidence of joint pain decompression illness. The physical activity levels encountered during prebreathe are typically quite low as is seen in the figure.

Exercise, Effective Half Time and Adynamia It is possible to measure the oxygen consumption of a group of individuals and relate to the effective half-time according to the following equation $t_{1/2} = 1{,}741\ ([O_{2Consump.}] - 427.7)^{-0.5133}$. It has been shown that adynamia during the prebreathe period as well as during exposure to altitude, reduces the risk of bubble formation and DCS. An empirical relationship between TR_{ady} and TR is: $TR_{ady} = 0.7171\ [TR]^{1.19}$

Future Methods of Improvement The other effects which could be employed to reduce the Tissue Ratio (increase prebreathe efficiency) could include:

1. carbon dioxide in prebreathe mixture,
2. increased exercise in final phase,
3. "scaling" of EVA participants (or creation of individual prebreathe prescriptions).

They will require considerable development before they can be placed into operational use.