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ENGINEERING ANALYSIS OF DIVER DECOMPRESSION SICKNESS

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Chemical Eng. Communic
In press, 1984

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ABSTRACT

Decompression sickness in divers is thought to occur when excess inert gas in the body forms bubbles. Description of the kinetics of gas exchange can be modeled by a variety of convective and diffusive processes. Treatment of bubble formation and growth is also subject to application of equilibrium and transport theory. Practical prevention of the disease is sought by complex models of the physical processes that can be improved by application of engineering and statistical methods of analysis.

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I. INTRODUCTION

As many occupational diseases, decompression sickness is a product of engineering development, albeit an unplanned one. The collection of symptoms, now referred to as decompression sickness, arrived with the invention of large-volume air pumps that allowed men to be exposed to raised environmental pressures. Whether this raised pressure resulted from men positioned under a layer of water, or in a pressurized environment such as the caissons around footings for major civil engineering projects, the symptoms are similar.^{1,2} They range from annoying aches and pains (especially in the skeletal joints of shoulders, knees and elbows) to the more disconcerting signs of sensory or motor nerve loss, to serious cardiovascular and pulmonary collapse, and finally death. The symptoms often occur in combination and are not well related to any known biological processes.

After several decades of very creative speculation, thoughts on the origin of decompression sickness converged to a common verbal description:

Inert gas breathed under pressure enters the body and causes internal bubbles if the diver is returned to the surface (decompression) "too fast" when compared to the rate of gas elimination.

This general view, first espoused a century ago,³ still exists in present studies. Essentially, we have a biological disease process with widespread and varying symptoms that is related to essentially physiochemical processes. In adopting this view, the chemical engineer has a unique opportunity to help prevent or cure a human disease.

This engineering viewpoint becomes slightly more quantitative when presented as in Fig. 1. Pressure is plotted against time for both the external hydrostatic pressure sensed by the diver's body and the internal partial

pressure of the inert gas breathed by the diver. The external exposure is frequently approximated by a series of square waves with one or more steps in the reduction of pressure back to one atmosphere. The smaller amplitude steps at pressures near ambient pressure are the decompression stops (designed to avoid the "too fast" return) that are calculated by any of the decompression models. The internal pressure of the gas rises much more slowly, remains at a high level after the initial return to lower pressure and only returns gradually to its asymptotic value of equilibrium with a normal atmosphere. The shape of the curve of internal gas pressure, and the area between that curve and the external pressure, are both unknown and subject to engineering analysis. In the remainder of this paper I will discuss both of these aspects of decompression, but will not attempt a comprehensive review of the subject.

II. GAS EXCHANGE IN TISSUE

In order to define the history of internal gas pressure (Fig. 1), we must isolate the major transport mechanisms in the body. Gas normally enters the body through the lungs. The time constant of gas mixing in the lung is much less than 1 min. As a result, the transport lag due to gas inspiration and mixing in the lungs is normally neglected because the pressure exposure and decompression occur over many minutes or hours. Gas can also enter the body through the skin. Because this transport rate is examined in another paper in this journal,⁴ I will not examine it further. Note, however, that gas permeation of the skin, combined with a driving force of high ambient pressure, can actually deliver a fatal quantity of gas to experimental animals.⁵ Normally, after gas leaves the lungs it traverses the heart and several major arterial blood vessels before reaching the microcirculation. During the transit of arterial vessels, some dispersion of solutes occurs that blunts the arrival of square waves in the tissues.⁶ More importantly, residence times in

the smaller arterial vessels are long enough for gas molecules to escape into tissue. This effect is only now being recognized and will probably become a major research topic in the future.^{7,8}

Most gas-exchange theories have focused on the capillary level. Numerous studies of these theories have been summarized recently.^{9,10} The capillary, the smallest functional unit of blood circulation, is frequently modeled as a cylinder and named after the first person to use this geometrical shape, A. Krogh.¹¹ The Krogh cylinder is a single blood vessel surrounded by a lining of endothelial cells and a thick annulus of tissue that has no convective component (Fig. 2). Many exchange mechanisms are possible within this relatively simple geometry.

A treatment of gas flow is necessary because the convective entry and exit of gas molecules in the capillary itself is usually considered to be the only way molecules cross the system boundaries. Blood flow is complicated on the capillary level because of the non-newtonian nature of blood plasma¹² and because of the presence of semisolid blood cells whose dimensions are very close to that of the capillary cylinder itself.¹³ For mass-transfer calculations, blood flow is either treated as leading to complete mixing or as plug flow with no axial diffusion. Under some conditions, axial diffusion of oxygen may become important.¹⁴

Within the tissue cylinder are three diffusive mechanisms: radial diffusion of molecules from the vessel to the radial boundaries of the cylinder; axial diffusion of molecules in a direction parallel to the capillary; and a barrier diffusion at the boundary between the capillary and the tissue region itself. Several combinations of these mechanisms have been applied in models. The partial differential equations describing the transport are awkward, but allow solutions in some cases.^{10,15,16,17} The normal no-flux

boundary conditions consistent with the physical boundaries of normal engineering equipment are not readily identifiable in the body, so the choice of suitable boundary conditions for a capillary cylinder continues to be a problem. Models with no-flux conditions on both the axial and radial boundaries lead to solutions with concentration profiles that fall between plug flow and continuous, stirred tank models. Allowing some transport across axial boundaries to account for multiple capillary arrangements recognizes some of the possible anatomic arrangements of neighboring capillaries. Treatments of both staggered¹⁶ and countercurrent¹⁹ geometries have been presented. Models allowing for diffusive transport across capillary entrance and exit planes have not received much attention, despite their appeal in terms of realistic physiology and their provision of large variances in transit times.¹⁷

Many of the Krogh geometry solutions can be successfully fit to data of experimental gas exchange.²⁰ Of course, this agreement between data and theory cannot be considered as "proof" of any model. One model that fails consistently to fit exchange data is the single exponential (well-mixed compartment) model, which has a long tradition of application to decompression theories. Models that fit better and include convective and diffusive parameters do best with characteristic diffusion distances of order 1 cm. Capillaries that are identifiable anatomically have dimensions about two orders of magnitude smaller. At this time, it appears impossible to choose a model that both fits experimental data well and agrees with plausible physiological information. In fact, experiments to differentiate among candidate theories are difficult to design.

To assist in comparing gas-exchange models and to summarize rather noisy experimental data, we apply the concept of "moments" to gas exchange. The

first and second moments of the time distribution of gas residence, or the mean and the variance of the distribution, are obtained from both models and data.²¹ Most continuous-exchange models lead to the same parametric expression for the mean residence time, specifically the ratio of the tissue volume (of distribution) to the volumetric flow rate of the capillary. The model expressions of the variance contain the diffusion coefficient, D , as well as the diffusion distances.¹⁷ It should be noted that variance due to axial diffusion increases with D , while significant radial diffusion reduces the variance with larger D . This implies that even when lacking precise data on capillary dimensions and flow, an informative experiment regarding diffusion is possible: simultaneous use of two tracers with differing D in the same capillary bed.

In an experimental setting, moments, as integral measures of data, are comparatively free from experimental noise, unlike raw data. Most experiments have sufficient information for relatively independent estimates of the first two moments of the distribution of residence times.²² The experimental moments can be paired with the moments generated from models of capillary gas exchange in order to obtain estimates of model parameters. Such a comparison frequently shows that although several models can fit data adequately, the estimated parameters are quite unrealistic for physiological systems.²⁰ The moments as summaries can also be used profitably for describing and evaluating the very large data sets that result from some gas-exchange experiments.²³ In examining the distribution of mean residence times of radioxenon in thousands of sites in dogs, we have been able to identify regions of particularly slow exchange. These regions correspond to skeletal joints (specifically the shoulder and elbow in dogs) that tend to be associated with predominant sites of

decompression pains. Currently, we are examining nitrogen exchange rates in man to obtain directly relevant data.

III. GAS BUBBLE MECHANICS

According to our accepted verbal description of the mechanism of decompression sickness, gas bubbles form and grow in the body. Ample experimental observation of large bubbles in animal tissues and blood vessels after severe decompression supports this idea.²⁴ The quantitative description of the mechanisms of forming and growing bubbles, however, is another transport question that is suitable for engineering analysis. First, one has to account for the original source of bubbles. A variety of homogeneous (in a single fluid)²⁵ and heterogeneous (at the interface of multiple phases)²⁶ nucleation theories have been presented. These approaches combine thermodynamic arguments for phase stability and kinetic arguments for initial formation of a bubble from dissolved gases only. Another view is that bubbles are always present and are stabilized by a film of special surface-active material.²⁷

According to both the nucleation and stabilization views, the original gas nuclei are small and may not cause biological damage. The growth of these bubbles into larger phases somehow eventually leads to the symptoms of decompression sickness. Growth and decay of a spherical gaseous bubble in a fluid medium is a common geometry for transport analyses. Once again, the boundary conditions necessary to solve the appropriate differential equations causes problems.^{28,29} Body tissues are not stirred tanks, but rather a collection of convective and diffusive regions distributed nonrandomly in space. The available solutions for bubble growth assume a thin resistive shell, a very large homogeneous fluid or a uniformly distributed linear sink. The models predict growth rates differing by up to one order of magnitude.

Furthermore, local bubbles can both augment and decrease local convective transport.³⁰

Limited knowledge of specific biological parameters (capillary density, gas solubility, surface tension, etc.) prevents any of the models from providing much useful insight for practical application. The final choice of the biologically appropriate solution to the bubble-growth equations depends on the development of better systems to detect both bubble sizes and number densities of bubbles. Several systems have been proposed and are currently being developed.^{31,32,33,34} These include transmission, reflection and harmonic ultrasonic devices. An ultimately useful device will need excellent spatial resolution in an acoustically "noisy" environment: a living body. Its development is a challenging engineering task.

IV. COMPLETE MODELS

In lieu of quantitative experimental answers that are fully satisfactory, many competing theories of the importance of bubbles are being used. These competing theories view important bubble events alternately as: bubble nucleation;²⁵ bubble volume;³⁵ number of bubbles;³⁶ or the pressure generated within a bubble.¹ These various models of bubble mechanics have been combined with alternate models of gas exchange, leading to a variety of quantitative decompression theories. A small set of the large number of published theories is summarized in Table 1. Some are based on calculated gas behavior for a single set of gas-exchange parameters; others include parallel calculations for several "compartments." The equations used for gas-uptake rate and for bubble-growth rate vary among many possibilities. The final column in Table 1 refers to allowance of a failure of symmetry, or linearity, in the gas-exchange function after presumed bubble formation during the initial decompression. As a final note, only the first three entries of Table 1 are theories that have

been used in direct human testing. The other two and many more unlisted theories are speculative. The theories are similar in that they predict that slower decompression is safer, but they all lack sufficient evidence from useful experiments to separate the theoretical predictions. The amount of testing required would be enormous, with both financial and ethical implications.

To make optimum use of limited experimental observations, modern engineering and statistical techniques must be used. These include sequential analysis of ongoing human trials to minimize subject exposures. In the past when a set of trials (a large collection of binary outcome data) has been compared to a theory, common practice has avoided statistical principles and adjusted parameters by ad hoc methods to achieve a reasonable degree of safety. The first three entries of Table 1 have undergone that type of testing and parameter adjustment. All models have also presumed an infinitely sharp demarcation between safe and unsafe conditions. Since decompression sickness is notoriously subject to variability, a dose-response view that expects a finite but controlled incidence seems preferable. That approach leads to model adjustment using the statistical principle of Maximum Likelihood.²⁵ Eventually, other tools of modern engineering failure analysis will be helpful in solving the problem.

Decompression sickness in humans is a rare disease because its source is ascribed to principles that are almost entirely physical. Applying general principles to complicated conditions that involve data of uncertain reliability is a common engineering problem. Resolving the problem by identifying component questions that have definable answers, and then aggregating the answers into a statistically meaningful theory is a characteristic engineering

process. Today there is ample room for optimism that substantial increases in human safety in diving will be obtained.

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ACKNOWLEDGEMENTS

We dedicate this study to Professor E.W. Merrill at the Alpha Chi Sigma Award Symposium, 75th AIChE Meeting, Washington, DC, 1983.

This study was supported by the Naval Medical Research and Development Command, Research Task No. M0099PN.01A.0001 and M0099PN.01A.0005. The opinions and assertions contained herein are the private ones of the author and are not to be construed as official or reflecting views of the Navy Department or the Naval Service at large.

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TABLE 1

Selected available decompression models

<u>Source</u>	<u>No. of Compartments</u>	<u>Gas-Exchange Mechanism</u>	<u>Bubble-Harm Criterion</u>	<u>Symmetry</u>
Workman (38)	6-9	Flow Only	Formation	Yes
Hempleman (39)	1	Slab Diffusion	Formation	Yes
Thalman (40)	5	Flow Only	Volume	No
Hills (1)	1	Flow and Radial Diffusion	Pressure	Partial
Yount (41)	5?	Flow Only	Number	No

FIGURE LEGENDS

Figure 1. Schematic pressure history of a dive and subsequent decompression.

Figure 2. Geometry used for classical (Krogh) models of the microcirculation. Convection (blood flow) occurs only in the central region of the cylinder; diffusion occurs in all regions subject to particular model assumptions.

Decompression Theory Integration

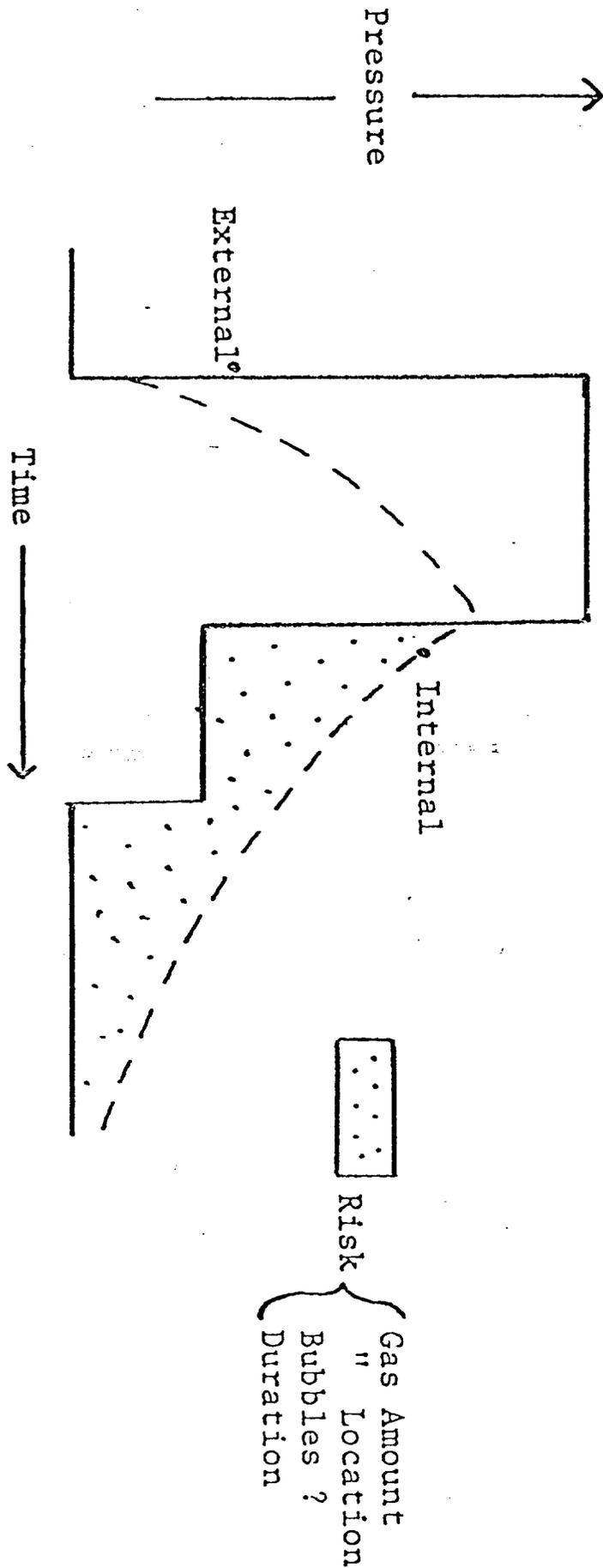
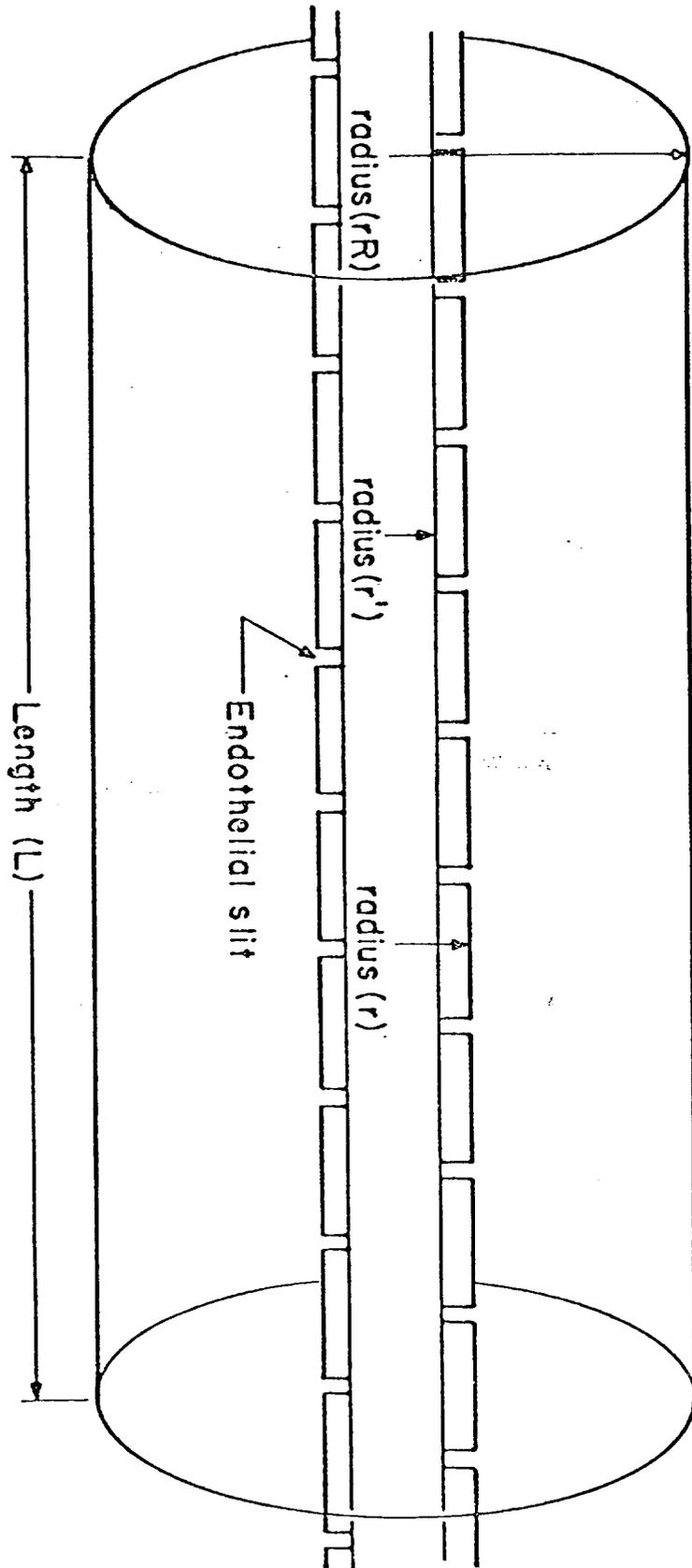


Fig. 1

CAPILLARY GEOMETRY



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Fig. 2