Review articles

Gas-content versus bubble decompression models

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Decompression models, diving theory, review article

Abstract

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Decompression models predict the probability of decompression sickness from the characteristics of a dive. The first step in this procedure is to calculate an index of decompression stress from the depth/time/breathing-gas history. Gas-content models and bubble models are two major classes of decompression models that differ in this method of calculating decompression stress. Calculation of decompression stress typically involves simulating the amount of gas (in units of pressure) that dissolves in theoretical 'tissue' compartments during a dive. For gas-content models, the decompression stress is simply any positive value of supersaturation (tissue gas pressure – ambient pressure). For bubble models, the decompression stress is the simulated number or volume of bubbles formed as the result of any supersaturation. These two model classes result in a different shape of decompression, with bubble models typically beginning decompression stops deeper. There is as yet no scientific evidence supporting one format of decompression over the other. Gas-content models are the most widely used method of decompression calculation although bubble models have gained recent popularity with technical divers.

Introduction

Decompression sickness (DCS) is a disease caused by bubble formation in body tissues from excess dissolved gas upon reduction in ambient pressure (decompression). Bert (1878) first made the association between nitrogen in compressed-air breathing, bubbles, and DCS.[1] Haldane and colleagues (1908) developed the first practical decompression model and produced the first decompression schedules. These minimised the risk of DCS by controlling the depth and duration of compression and the decompression rate.[2]

Decompression models link the probability of decompression sickness (pDCS) to an index of decompression stress calculated from the depth/time/breathing-gas history of a dive. Decompression models developed and tested through experimental dives can then be used to predict the outcome of future, similar dives and therefore be used to produce decompression schedules. A previous paper provided an overview of decompression model structure, examined the probabilistic and deterministic functions used to link decompression stress to outcome, and compared the development and testing of probabilistic and deterministic decompression models.[3]

This paper provides a brief overview of the biophysical component of decompression models, which is the method of calculating decompression stress from the depth/time/breathing-gas history of a dive. In particular this paper will compare gas-content models and bubble models – two major classes of decompression models that differ in this biophysical component.

Decompression stress

DCS probably results from bubbles formed in body tissues, so a natural choice for measuring decompression stress would be estimation of the number and size of those bubbles. The actual bubbles that cause DCS have not been measured, not least because their size, number, and location have not been identified. Some intravascular bubbles can be detected by ultrasonic methods leading to a useful but indirect measure of decompression stress.[4] Therefore, in decompression models, decompression stress is not a measured quantity, but rather a theoretical index calculated from the characteristics of the dive thought to influence pDCS, typically the depth/time/breathing-gas history. Decompression stress is typically a calculated index of bubble number or volume (bubble models), or of the excess inert gas that drives bubble growth (content models).

Uptake and washout of inert gas

Calculation of the uptake and washout of inert gas based on depth/time/breathing-gas history is common to both model classes. Breathing gas must be delivered at ambient pressure. With the increase in ambient pressure encountered in underwater diving, the inert gas component of the breathing mixture is absorbed into tissues during a dive, approaching equilibrium with the partial pressure of the inspired gas. Excess inert gas is eliminated from tissues both during and after ascent. The dominant route of inert gas into and out of the blood is via the lungs. Alveolar partial pressure and arterial tension (concentration/solubility, units of pressure) of the inert gases commonly used as breathing gas diluents (nitrogen and helium) equilibrate rapidly. Therefore, over a time course relevant to DCS, the inert gas kinetics can be reduced to a model of exchange between the blood and the tissues. The main factor that determines tissue uptake and washout of gas is the rate at which gas is carried in the blood perfusing the tissue, although these kinetics are modified by diffusion processes.[5]

Nevertheless, the most common structural model of gas uptake and washout is the single exponential tissue compartment where the rate-limiting process is usually considered blood perfusion. In this context a compartment is represented by a single, time-varying concentration. Underlying this notion is the assumption that, owing to rapid diffusion, equilibration of inert-gas concentration gradients across the tissue region represented by the compartment is much faster than transport in and out of the compartment. In this model, the arterial to tissue inert-gas-tension difference declines mono-exponentially according to a half-time notionally determined by tissue:blood perfusion ($ml.100ml^{-1}.min^{-1}$) and the blood:tissue partition coefficient of the gas. Figure 1 shows mono-exponential uptake and washout of an inert gas from one such compartment. Several (typically five to sixteen) parallel perfusion-limited compartments with different half-times are used to accommodate different rates of gas uptake and washout across the relevant body tissues.

Bubble formation

If the sum of inert and metabolic-tissue gas tensions (P_{tis}) exceeds ambient pressure (P_{amb}) during or after decompression, gases can leave solution forming bubbles in tissues and blood. In Figure 1 the maximum supersaturation ($P_{ss} = P_{tis} – P_{amb}$) for this particular compartment is indicated.

The pressure inside a bubble (P_{bub}) is the sum of the external pressures applied to the bubble including ambient pressure, pressure due to surface tension, and any mechanical compression from the tissue. Ignoring the latter factor for simplicity:

$$P_{bub} = P_{amb} + 2st/R_{bub} \qquad \text{Equation 1}$$

where st is surface tension and R_{bub} is bubble radius. P_{bub} exceeds ambient pressure for small bubbles but approaches ambient pressure for mechanically stable, large (e.g., ultrasonically detectable) bubbles. Therefore, for a bubble to form:

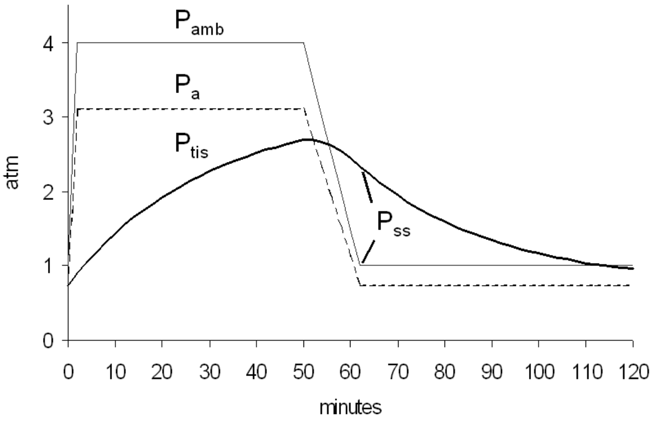
$$P_{tis} > P_{amb} + 2st/R_{bub} \qquad \text{Equation 2}$$

or equally:

$$P_{tis} – P_{amb} = P_{ss} > 2st/R_{bub} \qquad \text{Equation 3}$$

The extent of supersaturation determines the probability (or the rate) not only of bubble formation, but also bubble growth. If the partial pressure of gases inside a bubble exceeds the tissue gas tensions the bubble will shrink; conversely, bubbles of sufficient size can grow, acquiring gas by diffusion from adjacent, supersaturated tissue. The tissue metabolic gases' tensions and the bubble metabolic gases' partial pressures can be considered to be equal, so for a single inert gas, the conditions for bubble growth are also determined by Equation 3.

Figure 1
Exponential approach of tissue gas pressure (P_{tis}) to arterial gas pressure (P_a) with changing ambient pressure (P_{amb}) during a 30 metres' sea water dive. The maximum supersaturation (P_{ss}) is indicated.



Gas-content models

Since supersaturation determines the probability of bubble formation and represents the tissue gas content available for bubble growth it has been used as an index of decompression stress. Deterministic content models prescribe a schedule's ascent rate and decompression stops according to ascent rules that limit supersaturation without directly calculating any bubble index. A widely used format for ascent rules is:

$$P_{tis\_inert} < z \cdot P_{amb} + w \qquad \text{Equation 4}$$

where P_{tis_inert} is the tissue inert-gas tension and z and w are experimentally derived constants.[6] Equation 4 can be solved for supersaturation ($P_{ss} = P_{tis} – P_{amb}$) and Figure 2 illustrates how increasing supersaturation is allowed at greater depths. However, Equation 4 is more useful in the form:

$$P_{amb\_tol} = (P_{tis\_inert} – w)/z \qquad \text{Equation 5}$$

where P_{amb_tol} is the minimum tolerated ambient pressure. To calculate decompression according to a content model, P_{tis_inert} and P_{amb_tol} are calculated for each compartment according to the preceding depth/time/breathing-gas history. Decompression stops may be required so that the P_{amb} is never lower than the maximum value of P_{amb_tol}.

An example bubble model

There are two general classes of bubble decompression models. Although there are overlapping aspects, one class focuses on the dynamics of gas transfer between bubbles and the surrounding tissue and is typified by the bubble volume model, which is central to current US Navy

Figure 2
Ascent rules expressed as allowed supersaturation in atmospheres absolute at different depths during decompression expressed in atmospheres gauge. In content models, different half-time compartments typically have a different rule (e.g., HT=5, HT=20). In bubble models allowed supersaturation is independent of depth (bubble).

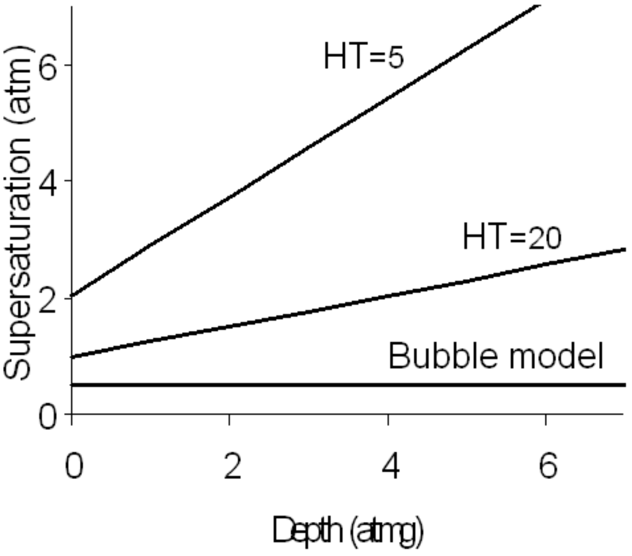
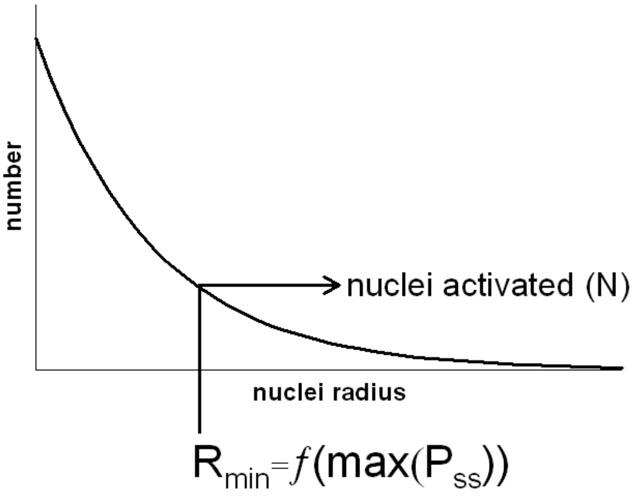


Figure 3
Exponential distribution of gas nuclei radii. The number of gas nuclei activated into growth as bubbles (N) is all nuclei of R_{min} and larger. R_{min} is a function of the maximum supersaturation (P_{ss}).



decompression research.[7] The second class, to be outlined here, focuses on the number of bubbles that form during decompression and is typified by the variable permeability model derived from observations of bubble formation in gelatine, derivatives of which are seeing increasing use amongst technical divers.[8]

Equation 3 describes the inverse relationship between bubble size and the supersaturation required to form that bubble. Bubbles can form *de novo* from chance clusters of dissolved gas in physical systems supersaturated at more than 10.1 Mpa (100 bar). The extent of supersaturation required for bubble formation is not well defined *in vivo*, but bubbles form after relatively trivial decompression; for instance, in humans, bubbles are detected in the venous blood by ultrasonic Doppler shift after decompression from prolonged air breathing at 3.6 metres' sea water (137 kPa) to the surface (101 kPa).[9] It seems more likely, therefore, that *in vivo* bubbles result from accumulation of gas into or around pre-existing gas nuclei (theoretical 'proto-bubbles'). One possible form of gas nucleus is a small bubble coated with surface-active agents that counteract surface tension, rendering the bubble relatively stable.

In the varying permeability model this surface-active coating makes available a population of stable gas nuclei some of which are sufficiently large that they can be activated into growing bubbles by supersaturation of the extent encountered in normal diving. In this model, the surface-active coating has the additional property of maintaining the pressure inside the gas nuclei equal to P_{tis}. For any particular sized gas nucleus from the population before a dive, the supersaturation subsequently required for growth is described by an equation similar to Equation 3, except that the right-hand side has additional terms that account for the difference in opposing forces of surface tension and the surface active agents, and for compression of the gas nucleus during descent. Ignoring these additional terms for simplicity, Equation 3 can be rearranged to give:

$R_{min} = 2st/P_{ss}$ Equation 6

where R_{min} is the radius of smallest gas nucleus that will be activated by any particular level of supersaturation.

By assuming a negative exponential distribution of radii for the population of gas nuclei, and substituting Equation 6 into that exponential equation, the number of gas nuclei activated into growing bubbles can be calculated for a maximum supersaturation encountered during decompression (Figure 3). For completeness, but with no further explanation, the model name refers to the assumption that the surface-active coating becomes impermeable to gas diffusion, and therefore the behaviour of the gas nuclei changes with compression beyond approximately 912 kPa.

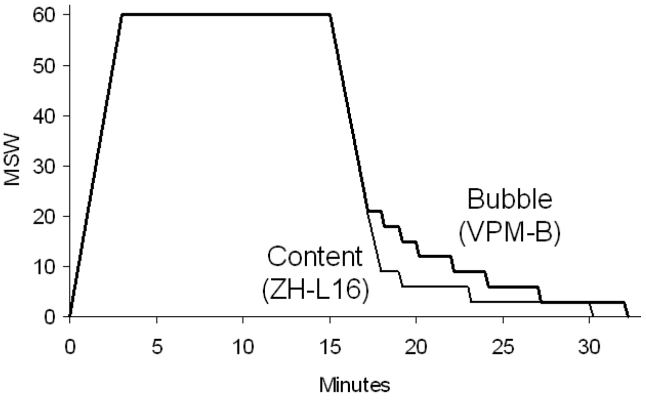
In the simplest form of the deterministic varying-permeability model, decompression can be controlled by a maximum-allowed number of bubbles and therefore a maximum-allowed supersaturation. Unlike in content models, this maximum-allowed supersaturation is constant throughout the decompression, as illustrated in Figure 2. Alternatively, decompression is controlled by a maximum-allowed index of bubble gas volume calculated by multiplying the excess number of bubbles (total number minus an always-safe number) by the integral of supersaturation and time, out to some long cut-off time after decompression. Additionally, this gas volume index can be subject to expansion according to Boyle's law with decompression.

Decompression models in recreational diving

Most recreational diving is conducted according to the prescription of gas-content decompression models. The differences among various content models are the number (typically five to sixteen) of parallel compartments used, the range of half-times covered (1 to 1000 minutes), and the experimental data (if any) used to derive the ascent rules. Well-known decompression tables based on content models are the DSAT recreational dive planner, the US Navy 1957 standard air tables, and the DCIEM standard air tables.[10–12] The latter two differ in some specifics from the above description.

To the best of this author's knowledge, at the time of writing, all diver-carried electronic decompression computers (dive computers) use a real-time gas-content model. Many of these dive computer models are based on the ZH-L16 gas-content model, as is much of the user-controllable decompression software used by technical divers.[13] Some newer dive computers have branding that implies a bubble decompression model. The models are proprietary information but, in fact, appear to be content models with user-controlled or dynamic modification of half-times, z or w parameters to result in longer decompression if the preceding dive history is notionally compatible with bubble formation (e.g., rapid ascent, repetitive diving). Some computers also prescribe, *ad hoc*, short decompression stops deeper than specified by the model. New computer models capable of real-time bubble-model calculations are likely to appear as processing power increases.

Figure 4
Comparison of decompression schedules following a 60 metres sea water dive prescribed by the ZH-L16 content model and by a variable permeability model derivative (VPM-B) with parameters set to provide an approximately equal duration of decompression. Note there appears to be no specific testing of the VPM-B model.



The use of bubble models by the recreational diving community to date is limited to the user-controlled decompression-planning software used primarily by technical divers. This software is based on the varying permeability model or a derivative called the reduced gradient bubble model.[8,14]

Bubble models typically prescribe deeper decompression stops than content models. Figure 4 illustrates the decompression schedule prescribed by the ZH-L16 content model and then how approximately the same amount of decompression time for the same dive is redistributed amongst a greater number of stops using a version of the varying permeability model (VPM-B). Theoretical analysis using a probabilistic bubble model suggests that such redistribution of decompression time to deeper stops can result in a lower risk of DCS (Gerth WA, personal communication, 2004) but this has yet to be objectively tested.

Conclusions

The previous paper in this series examined the functions that link calculated decompression stress to an observed outcome, either pDCS (probabilistic models) or usually adequate versus potentially inadequate decompression (deterministic models). The present paper provides an overview of how the measured depth/time/breathing-gas history of a dive is used to calculate decompression stress based on gas uptake and washout and bubble formation. This model component is the 'black box' between the measured dive history and outcome; none of gas uptake and washout, bubble formation and growth, or decompression stress is a measured value. These models are therefore useful only in so far as they can describe experimental decompression data and make predictions for dives similar to these experimental dives.

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International Marine Contractors Association publishes 2003 safety statistics

The latest safety statistics published by the International Marine Contractors Association (IMCA) are based on figures supplied by 311 IMCA contractor members covering approximately 200 million hours worked overall around the world during 2003 (an increase of some 2% over the previous year). "*Although only a lagging indicator of health, safety and environmental performance, safety statistics are nevertheless seen as providing a useful insight into the performance of a company in this area*," explains IMCA's Chief Executive, Hugh Williams. "*The purpose of the statistics is to record the safety performance of IMCA contractor members each year and to enable members to benchmark their performance. We also compare them with the figures published by organisations such as IADC (International Association of Drilling Contractors), OGP (International Association of Oil & Gas Producers) and IAGC (International Association of Geophysical Contractors).*"

"*We have seen an interesting development since the IMCA Safety, Environment & Legislation (SEL) Core Committee developed leading indicators (of health, safety and environmental performance), which can be promoted to clients and adopted by members, in order to get away from the high reliance on lagging indicators, for example lost-time injuries, as the arbiter of safety. Interestingly, the pleasing number of companies that supplied leading indicators for our 2003 survey would seem to have reaped the benefit of this commitment to safety, as their performance is generally better than the average.*"

Further information on leading performance indicators is available...in information note IMCA SEL 05/03. The 2003 statistics show that fatalities increased, with five reported in 2003 (one offshore), as opposed to three in 2002. Despite the various initiatives to improve safety, the offshore fatal accident rate (FAR) increased from 4.83 fatalities to 5.96 per 100,000,000 offshore working hours. There were 372 lost-time injuries reported (184 offshore) that resulted in at least one day off work.

"*All participating members providing figures to the exercise reported their offshore data, where over 67 million hours were worked, compared with about 62 million hours in 2002,*" explains Hugh Williams. "*The offshore lost-time injury frequency rate (LTIFR - Offshore LTIFR is calculated by multiplying the lost-time injuries offshore by a million and dividing by the number of offshore hours worked based on a 12-hour day) has continued to show an improvement over the last four years, from 4.25 in 2000 to 2.96 in 2002 and to 2.74 [in 2003]. This demonstrates that very definite benefits are being derived from safety initiatives.*"

"*If we are to eliminate injuries, damage or near miss incidents, it is imperative that we focus on at-risk acts and unsafe conditions, which have not yet caused loss or harm but have the potential to,*" says Hugh Williams. "*This is why safety guidance lies at the core of IMCA's work, and why we have published over 170 safety-related guidance notes.*"