Review article

Development and testing of deterministic and probabilistic decompression models

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Decompression, models, diving theory, review article

Abstract

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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 on the basis of experimental dives can then be used to predict the outcome of future, similar dives and, therefore, be used to produce decompression schedules. Deterministic decompression models categorise decompression schedules as either having a low pDCS ('safe') or not ('unsafe'). Probabilistic models define a unique pDCS for any dive. The methods for calculating decompression stress can be similar in the two types of models. These two model types are the result of different development and testing philosophies.

Introduction

Decompression sickness (DCS) is a disease caused by bubble formation from excess dissolved gas upon reduction in ambient pressure (decompression). Most readers will be familiar with the well-known beer-bottle analogy of DCS. The pressure inside an unopened bottle of beer is higher than the normal ambient pressure outside, and the beer (body tissues) contains a high concentration of dissolved carbon dioxide in equilibrium with a high partial pressure of carbon dioxide (nitrogen or other inert gas) in the gas space (lungs). The pressure inside the bottle is released by removing the cap (decompression) and the beer becomes supersaturated – the condition where the dissolved gas pressure (concentration/solubility) exceeds ambient pressure. Gas is released from the beer as bubbles. This beer-bottle analogy of DCS is a model; a simplified description of a complex system that helps conceptualisation.

The purpose of this paper is to define decompression models, to explain some terminology found in the scientific literature relating to decompression models, and to examine these in the broader context of models in general. Subsequently, this paper will examine how decompression models are developed and tested.

What is a model?

A model is a description of observed behaviour, simplified by ignoring certain details. Models allow complex systems to be understood and their behaviour predicted within the scope of the model but may give incorrect descriptions and predictions for situations outside the realm of their intended use.[1] The beer-bottle analogy is an analogue model whereby a complex system is modelled using a simple physical system. Models are commonly mathematical where the complex system is modelled using a set of equations. Often these models can be visualised as curves or surfaces that relate, for instance, independent variables (input) to dependent variables (output).

What is a decompression model?

An example of this is a simple decompression model, which links the probability of DCS (pDCS) to an index of decompression stress (Figure 1). Goats were compressed on air to different ambient pressures (x-axis), held for usually four hours, then decompressed more or less directly to one atmosphere absolute.[2] The pDCS, estimated from the relative frequency of signs of DCS, in groups of goats exposed to each pressure is plotted as circles. These data can be well described by a sigmoid curve (model) shown in Figure 1 produced by the risk function:

$$pDCS = 1\text{-}\exp(-0.00034atm\text{^}5.65)$$

This component of a decompression model is empirical, the linking function (curve) is chosen by inspection and expectation of the shape of the data. The shape of curve represents some unknown and unmeasured underlying physiological processes. Whereas this risk function is appropriate for decompression data, other types of data have different shapes. Readers might be more familiar with straight-line relationships or the slightly different-shaped sigmoid curve characteristic of dose-response relationships in pharmacology.

Figure 1
The probability of decompression sickness, pDCS (filled circles, estimated from the relative frequency of DCS), in goats for near-saturation dives followed by rapid decompression. 'Probabilistic' model with risk function fit to the data

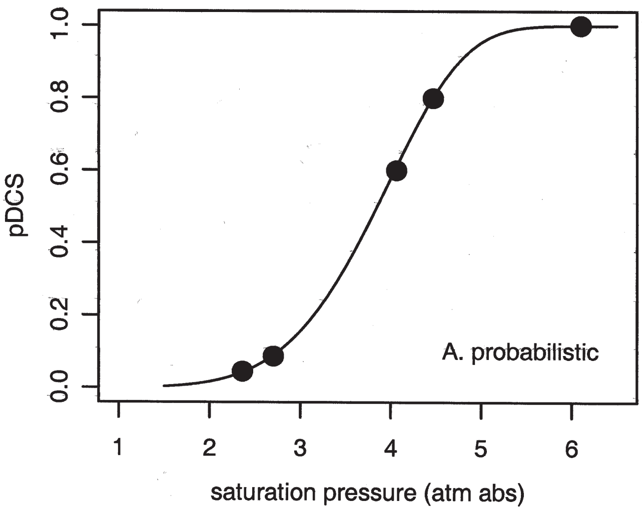
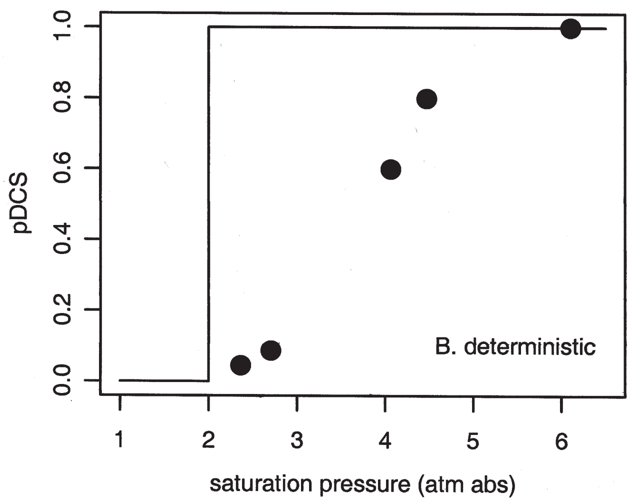


Figure 2
'Deterministic' model with threshold set arbitrarily at a low decompression stress



The parameters that provide the linking function of best fit in Figure 1 (0.0034 and 5.65) were found by a mathematical procedure, called 'least-squares' regression, which minimises the sum of the squared distances between each data point and the curve (unexplained random variation). This procedure is simple but has strict requirements of the data. A more general procedure is to maximise the product of the likelihood of each data point being the resulting distance from the model ('maximum likelihood' regression). For the frequency data in Figure 1 the result would be the same; however, the maximum likelihood method, but not least squares, is appropriate for modelling data with a binary outcome such as DCS or no DCS.

The value of a model is that it can be used to make educated guesses about similar systems. The model in Figure 1 is a statistical model because the probability of an event, in this case DCS for other similar dives, is inferred by taking a limited number of samples. Useful decompression models also have a mechanistic (not statistical) component, which is the method of calculating decompression stress. Decompression stress is typically some notional value of tissue supersaturation or bubble volume calculated from the depth/time/breathing-gas history of the dive using a model of known or assumed behaviour of gas in tissues.

This mechanistic component can take many forms and will not be dealt with in detail in this paper. In Figure 1, depth of the exposure is an approximate index of decompression stress (x-axis). The mechanistic model underlying this is that all tissue dissolved-gas pressures would have reached near equilibrium with inspired air during the long exposure and changed very little during the rapid decompression to one atmosphere absolute, so that the resulting tissue supersaturation is therefore proportional to the exposure depth. More widely applicable decompression models have a mechanistic component that can calculate decompression stress from the depth/time/breathing-gas history for dives of any complexity.

Probabilistic and deterministic decompression models

In decompression modelling jargon, the model depicted in Figure 1 is a 'probabilistic' decompression model because it links decompression stress to pDCS via a smooth risk function. Figure 2 shows a 'deterministic' decompression model. In a deterministic model there is a threshold decompression stress that separates dives with and without DCS. Decompression modelling jargon aside, a statistical model of the form in Figure 2 could link decompression stress to DCS via a Heaviside step function (a discontinuous function that takes values of zero or one) that sets pDCS = 0 below and pDCS = 1 above a threshold decompression stress that could be found by best fit to the data (and would be further to the right in Figure 2). In practice, and in Figure 2, the threshold decompression stress for a deterministic model is placed arbitrarily at a value resulting in low pDCS. Decompression schedules can be produced directly from deterministic decompression models. A probabilistic model must be converted to a deterministic model by selection of an acceptable pDCS before it can be used to produce decompression schedules.

Although the preceding description highlights the similarity between probabilistic and deterministic decompression models, practical models often have subtle differences in the methods of calculating decompression stress. In both Figures 1 and 2, decompression stress was proportional to the maximum supersaturation and this, or, similarly, maximum bubble volume, is characteristic of deterministic models. In probabilistic models the decompression stress is often the integral of supersaturation or bubble volume over some defined interval of time from the beginning of decompression. For instance, a similar decompression stress could result from a brief period of high supersaturation (such as following a brief, deep dive) or a sustained period of low supersaturation (such as following a long, shallow dive). Another difference between probabilistic and deterministic decompression models is that they usually result from different development and testing philosophies.

Model development and testing

Deterministic decompression models are primarily a means of producing decompression schedules and organising experience with decompression schedule outcomes. Deterministic decompression models have generally been developed *a priori* based on knowledge and assumptions, and then selected decompression schedules produced by the model are tested. If the results of schedule testing are not acceptable the model is modified and new schedules produced and tested. For instance, the model on which the 1957 US Navy standard air tables were produced is based on the original 1908 model of Haldane and colleagues but with incremental modifications made during approximately 2,000 test dives. The 1957 tables were promulgated after a series of 600 test dives where selected schedules were accepted if they had no DCS in four test dives.[3,4] In this sort of model development, the modifications to the mechanistic component of the model are made informally, based on the developers' instincts and knowledge of schedule-testing outcomes.

The ultimate utility of probabilistic models is to produce decompression schedules, but development focuses on the model rather than the schedules. Model development is mathematically formalised for probabilistic models. The structure of the mechanistic component is developed *a priori*, but the parameters of this part of the model are determined *a posteriori* by best fit of the decompression model to already available decompression data. In some cases, rather than testing schedules generated by the model of best fit, the model itself is validated via successful prediction of the outcomes of another set of decompression data.

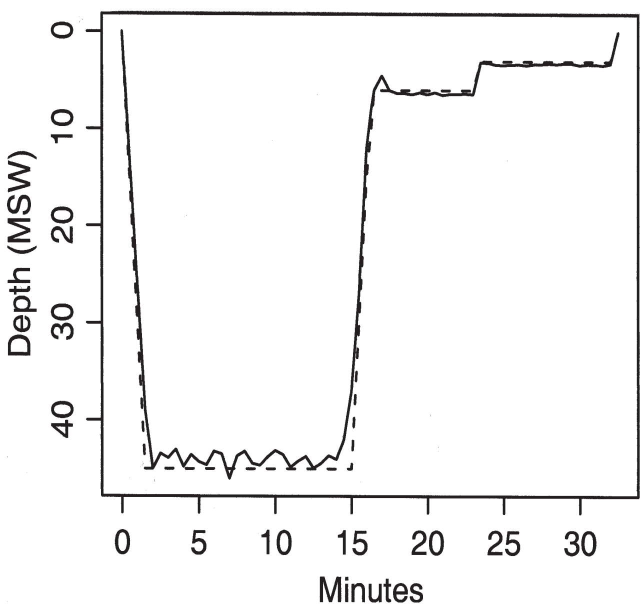
The requirements for decompression data for probabilistic modelling are a large number of dives with well-defined pressure/time/breathing-gas history and outcome such as DCS or no DCS. The dives in the database used to train the decompression model should be similar to the intended use of the calibrated model. For instance, a database comprising heliox and surface decompression dives would be unsuitable to calibrate a model for air diving with in-water decompression. If the new model is for a type of diving that is not well represented in the decompression database, traditional test trials of schedules are required. These dives can be added to the database for future use and recalibration of the model. One of the primary sources of data for air and nitrox diving is the US Navy database.[5] This database contains over 8,000 well-documented dives with an approximate 5% rate of DCS collected from previous decompression trials from several laboratories. Unlike traditional schedule testing, for probabilistic modelling there is no requirement for dives to follow a specified format or be repeated, so data can be collected from the field. Some recent well-documented US Navy operational dives will be added to the US Navy database (Gerth, personal communication, 2004). Divers Alert Network is collecting field data from recreational divers that are suitable for probabilistic modelling, and to date approximately 102,000 dives have been collected, although the incidence of DCS is low.[6]

The probabilistic-model approach to testing and validation has several advantages compared with the deterministic approach. First, as noted above, there is not always a need for a specific testing programme for probabilistic modelling, as existing or operational data can be used.

Second, in the deterministic approach, testing individual schedules results in broad binomial confidence intervals for pDCS. For instance, the 95% confidence interval for pDCS for any particular schedule from the USN 1957 standard air tables accepted following four DCS-free dives is 0–0.6. It is now more common to use a larger number of dives per schedule to narrow this confidence interval, for instance zero DCS in 20 dives has pDCS 95% confidence interval of 0–0.17. Considerable economy can be achieved by using well-designed sequential trials but large testing programmes are necessary.[7] In the probabilistic approach different schedules do not have to be analysed separately.

Third, the deterministic approach results in a more subtle loss of information compared with the probabilistic approach. Figure 3 shows a decompression schedule (dashed) and an

Figure 3. Dive profile (solid line) and decompression schedule (dashed line). See text for explanation



actual dive profile (solid). In the first instance assume, reasonably, that this dive did not result in DCS. In a probabilistic approach the very minor depth violations of the schedule during the bottom phase and at the first decompression stop would result in a small increase of the pDCS. In the deterministic approach, this dive would have to be considered 'unsafe' despite having a low pDCS and would, therefore, contaminate the data. Finally, in the probabilistic approach the time of symptom onset can be used as information to input to the model since the time course of decompression stress is followed. Consider the pDCS with symptom onset 10 minutes or alternatively 10 hours following the dive in Figure 3. To use time of symptom onset, the decompression stress and pDCS are calculated for successive intervals of time from the beginning of decompression. In the example dive, the decompression stress would be highest during and soon after decompression so pDCS would be higher for an interval including 10 minutes than for an interval including 10 hours following diving. This information is typically lost in the deterministic approach.

Summary

Decompression models can be broken down into a biophysical component that calculates decompression stress from the depth/time/breathing-gas history of a dive and a function that links decompression stress to an outcome such as DCS. Probabilistic and deterministic models can have similar biophysical components but differ in how they link decompression stress to outcome. Probabilistic models are powerful tools for model development and validation but must be converted into a deterministic format for production of decompression schedules.

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David Doolette, PhD, was a guest speaker at the SPUMS Annual Scientific Meeting in Noumea in 2004. This paper is based on presentations he gave at that meeting.

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