OPTIMAL DECOMPRESSION FROM 90 MSW

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Introduction

> *" The key to making technical trimix diving practical was the ability to perform an efficient and reliable decompression from a dive with minimal narcosis and without posing a substantial risk of oxygen toxicity"*
> *Hamilton and Thalmann (2004).*

The aim of all decompression procedures is to reduce the risk of serious injury, in particular to the central nervous system, to an acceptable level. Furthermore, decompression time should be reduced as much as possible without increased risk. These requirements are generally accepted as being mutually exclusive. However, a recent paper from our group demonstrated experimentally that a significant reduction in decompression time can be achieved with a dramatic reduction in bubble formation (Brubakk, *et al.* 2003). These results indicate that it should be possible to develop an optimal decompression profile.

It is generally accepted that the risk of injury following decompression is related to the formation of gas bubbles as gas comes out of solution. A large number of different decompression models have been developed to describe the relationship between gas elimination and the formation of bubbles. There have been, however, few efforts to develop methods for optimizing the formulation of procedures from these models.

The currently implemented decompression models iteratively calculate the time to stay at each depth based on either supersaturation criteria or on bubble growth suppression criteria. Using this approach, there is no guarantee that the optimal profile is calculated. Both experimental evidence and bubble growth theory show that bubble growth is initiated at the start of decompression, but that critical separated gas volumes and clinical problems occur at the end of decompression or after the surface has been reached. With a chosen critical risk level for decompression sickness (DCS) based on evolved bubble spectra, the solution is not trivial due to higher order bubble dynamics. Dynamic optimization techniques can be used to optimize the decompression profile based on the model response over a prediction horizon. This method allows calculation of both the optimal stop times as well as the depth where these stops should be made.

The 90 MSW Scientific Dive

Long and deep bounce dives raise some very difficult questions. Using the method developed by Hennessy and Hempelman (1977), the risk for DCS can be calculated from the formula p√t, where p is pressure in bar and t is time in minutes. The study by Childs *et al* (1977) on commercial divers in the North Sea showed that the risk of DCS increased significantly above a p√t of 25. This increase was found irrespective of type of dive or decompression procedure used. A dive to 90 msw for 25 minutes has a p√t of 50. From this, one can assume that any dive in this range can be considered a high risk dive, as reducing the time at depth to 10 minutes still will give us a p√t of 31.

Another problem is the exceptionally long decompression time that is needed under the current procedures. Following the USN procedures, a dive to 90 msw for 25 minutes requires 163 minutes of decompression, while a similar dive using DCIEM tables requires 159 minutes. About 90 minutes of this time is spent breathing oxygen.

In a series of trimix dives to 80 msw for 30 minutes, decompression required 140 minutes, about half of that on oxygen (Shreiner and Kelley, 1970). Furthermore, scientific diving requires exceptional safety and efficiency. This is due to the fact that scientific divers probably have the lowest incidence of DCS of any diving group and that each dive trip is a unique opportunity where diving accidents will be very un-welcome. Data from a commercial diving company shows an incidence of DCS following mixed gas bounce dives between 0.05 and 1.8 % in the time period 1998-2004 (Joar Gangenes, pers. comm.) The so-called “technical divers” regularly perform this type of dive, however, they accept higher risks and long decompressions with long periods of oxygen breathing. Most of these divers do not use computers or accepted tables and most decompression procedures are estimated based on the divers’ personal experience (Unpubl. comm.).

For these dives, trimix (nitrogen-helium-oxygen) is the only viable option. To our knowledge, no good decompression models exist that take the properties of the three gases involved into account. Most commercial diving companies do not use mixed-gas bounce diving procedures for dives between 100 and 300 fsw due to the high risk of DCS (Hamilton and Thalmann, 2004). As the solubility and diffusivity of the two inert gases (nitrogen and helium) are quite different, there is a possible advantage of having continuous mixing during the dive. This is a technique that was used successfully by Bühlmann (1988) and also by a number of technical divers. Because of the risk of nitrogen narcosis, the maximum nitrogen tension of the breathing gas is given as 400 kPa and the maximum oxygen tension at 130 kPa to prevent oxygen toxicity. However, oxygen breathing is regularly used during decompression.

Evaluation of Decompression Procedures

If new procedures are to be introduced, the method for their evaluation is of critical importance. This is particularly important if the aim is to reduce the risk for serious DCS, as deliberately provoking neurological symptoms may be ethically unacceptable, even if immediate treatment is available. Serious (neurological) DCS will not be acceptable, but musculoskeletal DCS can be tolerated.

Until now, no procedures have been developed that can distinguish between the risk of serious and non-serious (musculoskeletal) DCS (Tikuisis and Gerth, 2003). This is in spite of the fact that the pathophysiology of these conditions probably is quite different. Musculoskeletal DCS is most likely a localized phenomenon, caused by bubble formation in joints and muscles, probably on tendons, joint capsules and fascia (Harvey *et al,* 1944). It is our hypothesis that the main cause of serious neurological injury related to diving is caused by vascular bubbles. A number of studies have shown that there is strong correlation between vascular bubbles observed in the right ventricle and the pulmonary artery, an open foramen ovale (PFO) and neurological CNS symptoms (Moon *et al,* 1989; Wilmshurst and Bryson, 2000). Furthermore, studies have shown that AV channels open in the lung following even light exercise, allowing small bubbles to pass through (Eldridge *et al,* 2004). Even if bubbles observable by ultrasound were not seen after an air dive (Dujic *et al,* 2005), reduction in arterial endothelial function does not seem to require observable arterial bubbles (Brubakk *et al*, 2005). Thus, an initial test of any new decompression procedures would be its ability to reduce pulmonary artery bubbles.

Optimization of Decompression

Optimization has until now been defined rather loosely, but once agreement on the risk is defined, mathematical methods can be used to precisely define the procedure that will keep the risk below a certain level.

Bubble theory predicts that deeper stops than those suggested by the supersaturation models will reduce bubble formation on surfacing. Experimental evidence also suggests that the shape of the decompression profile significantly will reduce bubble formation in spite of a significant reduction of the time used for decompression (Brubakk *et al,* 2003).

The Copernicus Model

Most decompression models have been evaluated using clinical symptoms of DCS as an endpoint. Due to the low incidence of DCS, this approach requires an extensive amount of empirical data to achieve statistical significance for accepted risk. The actual gas dynamics and mechanisms behind DCS are never validated. For this reason, these models give unsatisfactory results when their operating domain is extrapolated to more extreme exposures. The principle behind Copernicus is to incorporate additional measurements to support the validation of the model. As mentioned earlier, our hypothesis is that the evolution of vascular bubbles is strongly linked to the risk of serious DCS. To achieve a good prediction of DCS it is necessary to have a model that adequately describes the dissolved gas tensions, the distribution and growth of gas bubbles in the human body, and the mechanism for injury by the bubbles. The Copernicus model is developed to predict these vascular bubbles as accurately as possible, still having the necessary simplicity to allow efficient computational implementation. Using bubble formation instead of clinical symptoms as a measurable end-point allows us to implement a more reliable validation with less empirical data. With a reliable criterion for DCS based on this bubble formation it is possible to calculate safer and/or faster decompression profiles. It is an important comprehension to distinguish between extension of deco time (conservatism) and increased safety. Dynamic two-phase models show the significance of the shape of the deco profile in addition to the time spent on the ascent. Both experimental results, theoretical knowledge and experience from currently used bubble models indicate that the way of calculating decompression procedures should be completely rethought compared to the traditional Haldanean principle.

Optimization Strategy

We may think of the diver as a system (black box) with a set of inputs and outputs (Fig. 1). The inputs *u*, are the time-varying parameters that influence the dynamic process. The Copernicus model uses three input parameters: ambient pressure, breathing gas composition, and blood perfusion. During decompression we can manipulate the ambient pressure (depth) and the gas composition to achieve the wanted outcome. Blood perfusion is estimated through measurements and is not an input we want to control. The output of the model x describes the evolved bubble spectra in the body. The optimization problem is formulated to get the diver as fast as possible to the surface without letting the stress y, exceed an accepted threshold.

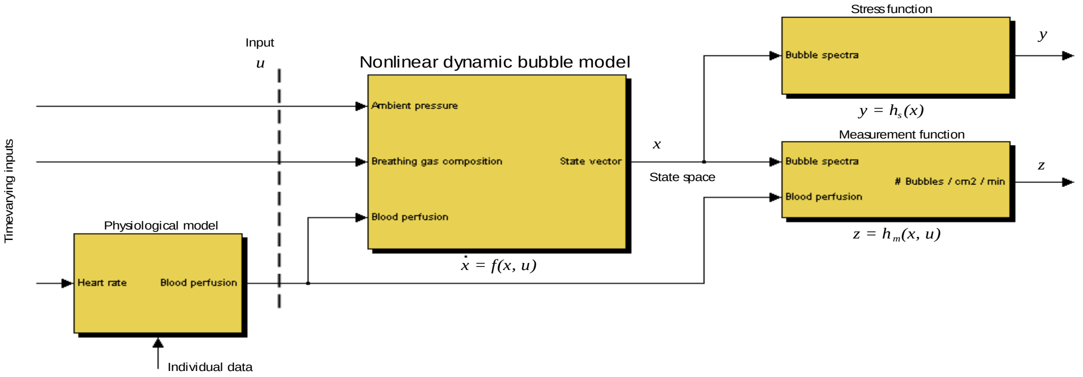

Figure 1. Schematic overview of the Copernicus model.

Optimizing Ascent Profile

Intuitively, the theoretical optimal solution would be a continuous depth profile or trajectory. However, such a solution is inconvenient for a diver to act in accordance with so a stepwise trajectory is preferable. We formulate the problem with a fixed number of stop-depths so the solution directly gives an optimal stepwise profile. Let us consider an assumed optimal decompression profile parameterization as shown in Figure 2

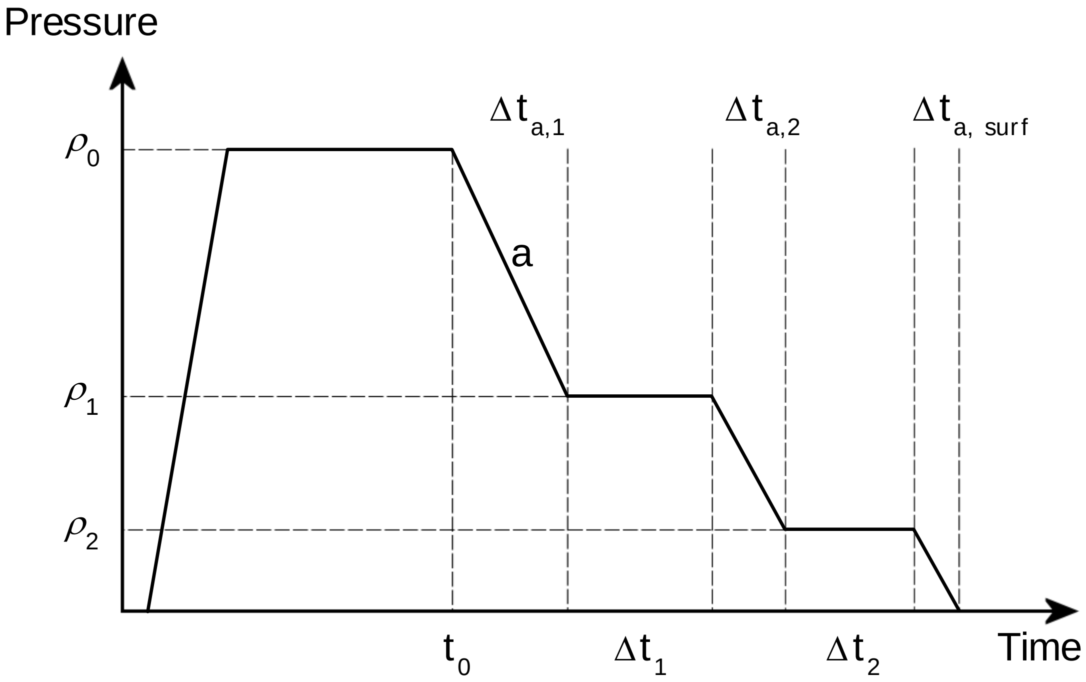

Figure 2. Parameterized decompression schedule.

The sum of all stop times is $t_{tot}=\sum \Delta t_i$ The optimization problem is formulated to minimize t_{tot} subject to a set of constraints. The constraint yields for the output of the model shown in Figure 1 and the formulation define the fastest possible combination of stop times that keeps the stress, *y*, under a set level. To solve such problems, general purpose SQP algorithms (sequential quadratic programming) may be used.

Optimizing Gas Mixtures

Figure 2 shows the calculation of the stop times, but any controllable, time-varying input parameter may be included to the optimization problem. The composition of the gas mix can be constantly changed in order to achieve the fastest possible decompression time. Currently we have no implementation of the calculation of optimal gas composition but simulations on the model using different compositions of helium, nitrogen, and oxygen have been performed. Figure 3 clearly shows how the model responds to manipulation of the breathing gas during decompression.

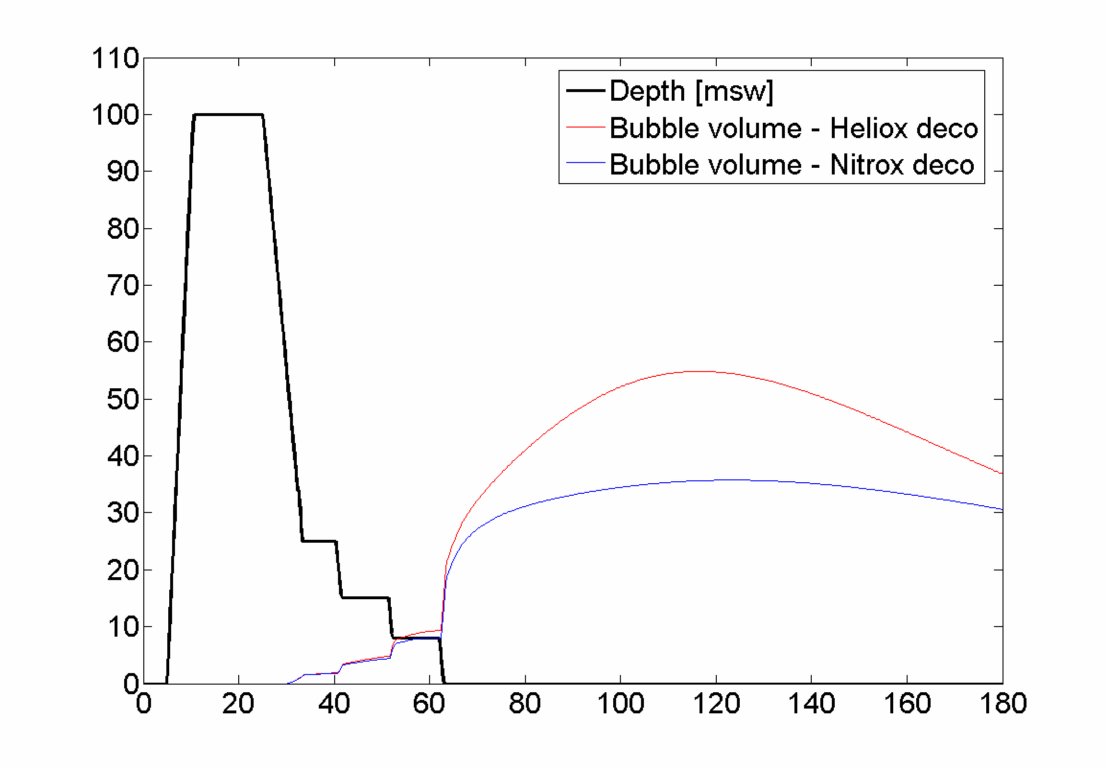

Figure 3. Simulation of bubble-volume in a 100 msw heliox dive following the same deco with different breathing gases. The upper blue line shows bubble-volume using 70% nitrox while the lower red line is using 70% heliox.

Example

To illustrate the principle we have simulated a dive to 42 msw for 20 minutes and bring the diver to the surface using only one decompression stop. We let the stop time and the depth be parameters to our optimization problem. Figure 4 shows the simulated decompression stress for a wide range of both stop times and depths. We can see that the decompression stress is constant for stop time $\Delta t_1=0$. This is the generated stress if the diver ascends directly to the surface. If the diver chooses to have his stop very deep, it will generate more stress, which comes as a result of increased gas uptake. The shallower he takes the stop, the more beneficial it becomes, until a certain point where the stop depth becomes too shallow to be efficient. The optimal point is somewhere in the hollow depending on the acceptable threshold of generated stress.

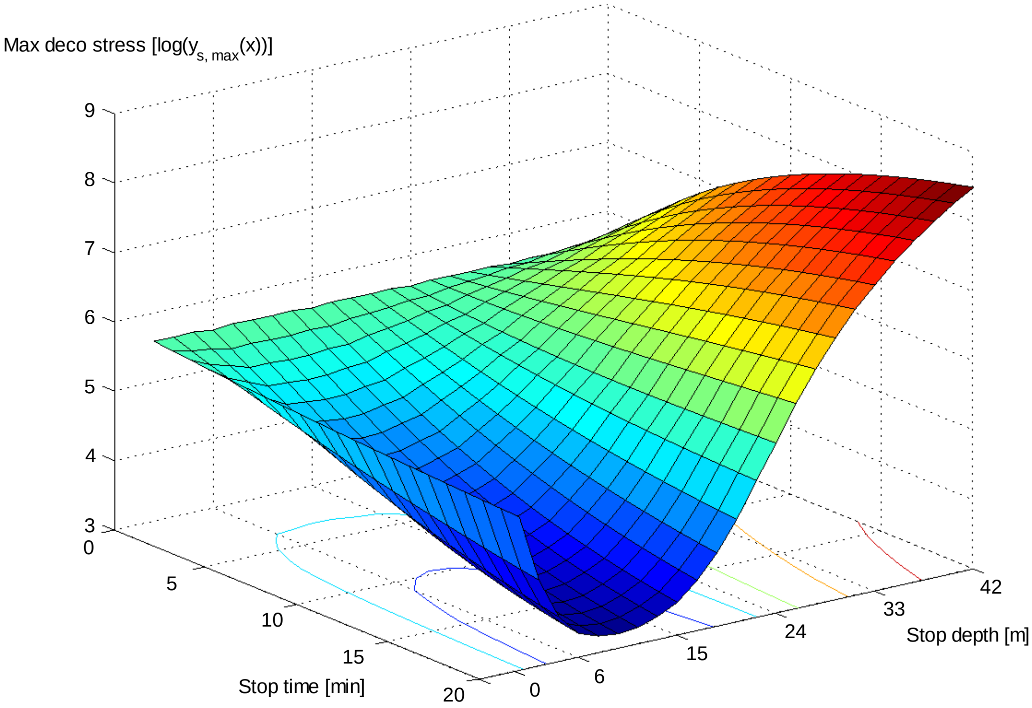

Figure 4. Simulated decompression stress for a range of stop times and depths for a single stop decompression case.

Future Work

The paper presented here shows how a four-phase model and optimization can be used for designing decompression profiles for deep mixed-gas diving. The optimization method is model independent, allowing easy comparison of how different models will influence actual dive procedures.

One significant advantage of the model is that it can incorporate new measurement modalities that can be used to modify diving behavior during the actual dives. From ultrasonic studies, it has been known for a long time that gas phase formation in the muscles is an early warning of DCS (Daniels, 1984). Recent new developments in ultrasound detection techniques can make on-line detection of tissue gas bubbles feasible.

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