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Diving Bubble Model Data Correlations

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Abstract

This short article deals with useful and modern bubble models used to stage divers to the surface and correlations, if and when they exist, with actual data, usually decompression sickness (DCS) outcomes across a limited spectrum of exposures. Many of the early (wet) tests were carried out by world Navies, later by hyperbaric chamber testing and today also by statistical inference from downloaded computer profiles. All have contributed to correlation of models and data but in varying degrees as the scope of mixed gas, open circuit (OC) and rebreather (RB), nonstop to saturation and sea level to altitude diving is immense. No amount of wet or chamber testing will ever cover the ground here, but there is considerable hope and potential for downloaded computer profile data coupled to DCS outcomes to provide necessary correlations across the varied activities of modern diving.

Keywords: Bubble; Decompression; Nucleation

Introduction

It is first worthwhile to take a look at the enormous complexity facing modelers and table designers. Models presently cannot cover all aspects of the bubble problem in divers; in fact, the whole process is stepwise and dynamically limited. Establishment and evolution of gas phases, with possible bubble trouble, involves a number of distinct, yet overlapping, steps:

- Nucleation and stabilization (free phase inception);
- Supersaturation (dissolved gas buildup);
- Excitation and growth (free-dissolved phase interaction);
- Coalescence (bubble aggregation);
- Deformation and occlusion (tissue damage and ischemia).

The computational issues of bubble dynamics (formation, growth and elimination) are mostly outside dis-solved gas frameworks, but get folded into halftime specifications in a non-tractable mode. The slow tissue compartments (halftimes large, or diffusivities small) might be tracking both free and dissolved gas exchange in poorly perfused regions. Free and dissolved phases do not behave the same way under decompression. Care needs be exercised in applying model equations to each component. In presence of increasing proportions of free phases, dissolved gas equations cannot track either species accurately. Computational algorithms tracking both dissolved and free phases offer broader perspectives and expeditious alternatives, but with some changes from classical schemes. Free and dissolved gas dynamics differ. The driving force (gradient) for free phase elimination increases with depth, directly opposite to the dissolved phase elimination gradient which decreases with depth. Then, changes in operational procedures are suggested for optimality. Considerations of bubble excitation and growth invariably suggest deeper staging procedures than super-saturation methods. The gradient for free phase elimination is the difference between dissolved gas partial pressure and ambient pressure, while the gradient for free phase elimination is the difference between bubble internal pressure and ambient pressure. In essence this separates bubble models from dissolved gas models.

Other issues concerning time sequencing of symptoms impact computational algorithms. That bubble formation is a predisposing condition for decompression sickness (DCS) is universally accepted. However, formation mechanisms and their ultimate physiological effect are two related, yet distinct, issues. On this point, most hypotheses make little distinction between bubble formation and the onset of bends symptoms. Yet we know that silent bubbles [1] have been detected in subjects not suffering from decompression sickness. So it would thus appear that bubble formation per se and bends symptoms do not map onto each other in a one-to-one manner. Other factors are operative, such as amount of gas dumped from solution, size of nucleation sites receiving the gas, permissible bubble growth rates, deformation of surrounding tissue medium and coalescence mechanisms for small bubbles into large aggregates, to name a few. These issues are the focus of bubble theories, but the complexity of mechanisms addressed does not lend itself easily to table, nor even meter, implementations. Difficulties accepted, model development and data correlation are ongoing efforts important in table fabrication, meter development and dive planning software. Bubble models provide a firm foundation for extension, data updating and broader range of application. Expect to see their continuing use and development, particularly dual phase models.

Diving computers are fairly recent developments on the diving scene, with seemingly no spikes in DCS incidence rates reported within categories of divers employing them. Yet certainly, few computer algorithms have been laboratory tested, particularly in the deep, decompression and mixed gas diving zones. And likely never will. But in time, many algorithms will be tested or analyzed with growing profile data, and protocols validated, modified, or discarded. Of course, wet and dry testing is expensive, limited in range and not always viable operationally. In that respect, profile Data Banks with diver outcomes are enormously important to cover a full spectrum of diving not amenable nor feasible for wet and dry testing. The profile

Data Banks at Divers Alert Network (DAN) [2] and Los Alamos National Laboratory (LANL) [3] are two modern ones, with DAN focused on recreational diving and LANL concerned with technical deep, mixed gas and decompression diving. To say these Data Banks help fill holes in the testing arena might be an understatement.

Let's take a look at bubble models of interest and importance next. There are only 2-3 that really enjoy widespread utilization and acceptance, having withstood some of the ravages of time. The complex dynamics of bubble models are discussed elsewhere [4,5] not here. Testing and data correlations are our simpler focus.

Thermodynamic Model

The thermodynamic model (TM) of Hills [6], developed in the 60s, represents a giant leap. Not a true bubble model, but focusing on separated phase (bubble aggregate) in a dual dissolved and free gas approach, the TM related no-DCS-vs-DCS incidences via a single curve connecting maximum gas supersaturation, M, to ambient pressure, P. At increasing pressure, P, maximum permissible supersaturation, M, decreased according to the TM, resulting in deep stops. The curve represented a limit point of sorts for dive planning and table construction. Met with caution at the time, a number of tests and correlations followed. The Royal Navy [7] introduced the concept of deeper stops very cautiously by adding the 10 fsw stop time to their 20 fsw stop time with direct surfacing from that depth to complete decompression. Bennett and Vann [8] used a linear diffusion TM model to improve later stops for a dive to 500 fsw for 30 min which proved bends-free in chamber tests at Duke. Extensive ocean tests by Krasberg [9] in over 800 dives for up to an hour down to 600 f sw recorded only 4 bends cases. Extensions to 800 fsw followed. But by far, the most extensive correlations of the TM with actual diving is seen in the collective experiences of Australian pearl divers operating in the Torres Strait between Australia and New Guinea. Driven solely by profit and need and lacking formal diver education, Australian pearl divers (Okinawans more correctly) dived to 300 fsw on air for as long as an hour, making 2 such dives a day 6 days a week. With relatively high DCS incidence rates (maybe 2000 lives), schedules evolved which were correlated with the TM [10] in coarse granularity. Along with deep stops, drop out at 25-30 fsw was characteristic of profiles. The TM advocated drop out in the 30 fsw zone but later modifications added a Haldane tail above 30 f sw. Extremely complicated and predating dive computers (and later bubble model implementations), the TM remains an interesting icon spawning later developments. Hills has been called the Father of Deep Stops and rightly so.

Varying Permeability Model

The varying permeability model (VPM) of Yount [11] followed the TM in the late 60s and early 70s. Based on excitation and growth of a (exponential) distribution of bubble nuclei, increasing in number with decreasing radius, the VPM was the first real bubble model to enter the diving scene. Correlated with decompressed gel experiments in the laboratory, the VPM restricted permissible supersaturation at depth to control bubble growth and coupled that restriction to a surfacing phase limit point (total excited bubble phase volume). Bubble permeability to gas diffusion across tissue-bubble interfaces divided into 2 regions at roughly 165 fsw, that is, permeable above and impermeable below 165 fsw to gas (N_2, He, O_2) diffusion. Restricted supersaturation gradients with depth yield deeper decompression stops as with the TM and RGBM to follow. Apart from gel tests, the VPM has not reported formal man or animal testing to date. The VPM however is available in dive planning software and some 2-3 decompression meters and, from anecdotal reports from the technical diving community, is used widely and safely in that community. One impressive feat using the VPM according to reports [5] centers on cave diving by the Wakulla Karst Plains Project (WKPP) Dive Team undertaking extreme dives for an hour or more to 300 fsw with some 8 hrs of decompression obligation. In contrasting model correlations with deep stop computer downloads in the LANL Data Bank, the VPM correlated moderately well with profile data [12].

Reduced Gradient Bubble Model

The reduced gradient bubble model of Wienke [13] was developed in the late 90s for recreational and technical diving. Using equations-of-state (EOS) from lipid and aqueous substrates to parameterize the structure of bubble skins, the RGBM uses an exponential number distribution (decreasing with bubble radius) for bubble nuclei excited into growth by compression-decompression. That number is summed over the exposure profile in 10 fsw increments and allowed to expand or contract under pressure and temperature changes to yield a surfacing estimate of excited bubble volume. A limit point to surfacing bubble volume, with permissible supersaturation and gas diffusion across bubble interfaces also limited on the way up, constrains the dive schedule. Deep stops and shallow stops are admitted within the general model, depending on the size and properties of the bubbles initially. The RGBM is implemented in some 10-12 dive computers for recreational and technical diving and has witnessed extensive safe utilization across both with no DCS spiking nor tendencies noted [14]. It is also marketed and employed in many diveware packages with positive reports [15]. Earlier during testing phases, the RGBM was correlated by Brubakk et al. [16] with Doppler scores and medical images of decompressed pigs in the Trondheim laboratory. The RGBM was also correlated with Bennett and Maronni [17] Doppler score reductions with 1/2 deep stops in recreational air diving. A very interesting study by Balestra [18-20] of DAN-DSL Europe centers on DCS incidences using dissolved gas (shallow stop ZHL16) computers versus bubble model (deep stop RGBM) computers. In 11,738 recreational dives, a total of 181 DCS cases were recorded and were almost equally divided between the ZHL16 and RGBM computers, that is, the ZHL16 incidence rate was 0.0135 and the RGBM incidence rate was 0.0175. But by far, we believe, the most important correlation of the RGBM is seen in profile correlations of global deep stop data [12] across mixed gas, OC, and RB diving in decompression arenas. Model and data agreement were significant at (chi squared) 90% levels. The RGBM is the basis of the National Association of Underwater Instructors (NAUI) Technical Nitrox, Helitrox and Trimix Decompression Tables, released and used since the latter 90s safely for training purposes and diveware comparisons. The Association of Nitrox Diving Instructors (ANDI), Irish Diving Federation (IDF) and Finnish Diving Federation (FDF) use RGBM tables for technical and recreational diving.

Deep Stop Ad Hoc Protocols

Much like functional hook or crook approaches of Australian pearl divers, deep stop protocols on top of existing shallow stop procedures surfaced in the last 20 years or so. To date, most have not been tested nor correlated with actual data. Anecdotally, these procedures seem to work though, at least reports contraindicating their usage are not generally recorded. Just briefly, 2 are mentioned.

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Pyle 1/2 Stops - Pyle is a diving specimen fisherman out of the Bishop Laboratories at the University of Hawaii. Pyle pioneered the technique of making 1/2 stops for minutes on top of decompression requirements within Haldane dissolved gas tables. Stop times vary from a few minutes at the deepest stop to minutes on the way up the 1/2 stop ladder to the surface. Some of the profiles with 1/2 stops mimic the VPM and RGBM in broadest features [12]. The Bennett and Maronni 1/2 stop Doppler scores were also correlated within the RGBM as mentioned above. They are also protocols embedded within the NAUI Recreational Air and Nitrox Tables formulated in the late 90s.

Gradient Factors – Gradient factors (GFs) are a spinoff of published RGBM reduction factors (RFs) for recreational diving [13]. They merely reduce dissolved gas limiters (M-Values) at depth thus producing deep stops on top of dissolved gas staging. They are usually employed by technical divers for deep and decompression diving. They can be constructed in principle to mimic both the VPM and RGBM, an academic exercise that we might pursue as a safety exercise. GFs are obviously less than 1 to produce deep stops. RFs are always less than 1 to restrict reverse profiles, surface intervals less than 60 min, ascents faster than 30 fsw/min and heavy differing-depth multiday diving.

Lore

Some common perceptions in diving quarters are briefly discussed. Explanations tie to the foregoing discussions. Hopefully, they are helpful.

Bubble model staging usually leads to deeper stops and shorter overall decompression run times than classical M-value models? Yes, in the broad sense but only categorically true when equal risk profiles are compared. That requires both deep and shallow stop data and analysis [4,5] for instance.

The TM was sometimes problematic with drop out at 35 fsw? Yes, problems occurred in some hyper-baric chamber tests.

The 1/2 deep stop for recreational diving is just precautionary? No, not quite. The Bennett and Marroni testing showed that Doppler scores were systematically lowered with 1/2 deep stops in the 2 minute range. This is incorporated into the NAUI Tables [15,17].

Recreational shallow safety stops are also precautionary? Maybe, but hard to tell as statistics on recreational diving to the NDLs suggest the DCS incidence rate is in the noise level. Others point out that shallow safety stops force diver buoyancy control as beneficial spinoff [15].

Bubble models are riskier than dissolved gas models or vice versa? Nada. Seems both are being dived safely with decompression meters, tables and dive planning software. If there were DCS spikes in either usage, we would hear about it rapidly from all quarters, particularly the meter folks. Reasons for this are topics for another article [5].

Gel bubbles and body bubbles are the same? Nope, body bubbles are perfused and metabolic. Big differences are seen in structures of gel and body bubble skins. Gel bubbles are used by the VPM while lipid and aqueous bubbles are the RGBM bubbles using EOS data from substrates.

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