

TECHNICAL RGBM

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BACKGROUND

Diving models address the coupled issues of gas uptake and elimination, bubbles, and pressure changes in different computational frameworks. Application of a computational model to staging divers is called a diving algorithm. The Reduced Gradient Bubble Model (RGBM) is a modern one, treating the many facets of gas dynamics in tissue and blood consistently. Though the systematics of gas exchange, nucleation, bubble growth or collapse, and decompression are so complicated that theories only reflect pieces of the decompression sickness (DCS) puzzle, the risk and DCS statistics of staging algorithms can be easily collected and analyzed. And the record of the RGBM, just over the past 5 years or so, has been spectacular, especially so far as safe staging coupled to deep stops with overall shorter decompression times. This is important. Models are one thing, even with all the correct biophysics, and actual diving and testing are something else.

The RGBM grew from needs of technical divers to more efficiently stage ascents consistent with coarse grain dissolved gas and bubble dynamics, and not just dissolved gas (Haldane) constraints. And the depth, diversity, mix variation, and self consistency of RGBM diving applicability has satisfied that need. And safely.

The RGBM has gained tremendous popularity in the recreational and technical diving worlds in just the past 2 - 3 years, due to meter implementations, Internet software packages, specialized Table releases, technical word of mouth, NAUI Training testing and adoption, Internet chat, WKPP extreme exposure correlations and calibrations, chamber tests, and, most of all, real technical and recreational RGBM diving and validation.

Here's why.

RGBM IMPLEMENTATIONS AND USE

Present notions of nucleations and bubbles suggest that decompression phase separation is random, yet highly probable, in body tissue. Once established, a gaseous phase will further grow by acquiring gas from adjacent saturated tissue, according to the strength of the free-dissolved gradient. Although exchange mechanisms are better understood, nucleation and stabilization mechanisms remain less so, and calculationally elusive. But even with a paucity of knowledge, many feel that existing practices and recent studies on bubbles and nuclei shed considerable light on growth and elimination processes, and time scales. Their consistency with underlying physical principles suggest directions for table and meter modeling, beyond parameter fitting and extrapolation techniques. Recovering dissolved gas algorithms for short exposure times, phase models link to bubble mechanics and critical volume trigger points. The RGBM incorporates all of the above in all implementations, and additionally supports the efficacy of recently suggested safe diving practices, by simple virtue of its dual phase mechanics:

- reduced nonstop time limits;
- safety stops (or shallow swimming ascents) in the 10-20 *fsw* zone;
- ascent rates not exceeding 30 *fsw/min*;
- restricted repetitive exposures, particularly beyond 100 *fsw*,
- restricted reverse profile and deep spike diving;
- restricted multiday activity;
- smooth coalescence of bounce and saturation limit points;
- consistent diving protocols for altitude;
- deep stops for decompression, extended range, and mixed gas diving with overall shorter decompression times, particularly for the shallow zone;

- use of helium rich mixtures for technical diving, with shallower isobaric switches to nitrox than suggested by Haldane strategies;
- use of pure oxygen in the shallow zone to eliminate both dissolved and bubble inert gases.

Bubble models tend to be consistent with the utilitarian measures listed above, and have the right signatures for diving applications across the full spectrum of activities. Or, said another way, bubble models are more powerful, more correct, and more inclusive. In terms of RGBM implementations, the mechanistics of dissolved gas buildup and elimination, inert gas diffusion across bubble interfaces, bubble excitation and elimination persistence time scales of minutes to hours from tissue friction, lipid and aqueous surfactant material properties, and Boyle expansion and contraction under ambient pressure change, are sufficient to address all of the above considerations.

So Suunto, HydroSpace, and Abysmal Diving developed and released products incorporating one such validated phase algorithm, the Reduced Gradient Bubble Model (RGBM), for diving. An iterative approach to staging diver ascents, the RGBM employs separated phase volumes as limit points, instead of the usual Haldane (maximum) critical tensions across tissue compartments. The model is tested and inclusive (altitude, repetitive, mixed gas, decompression, saturation, nonstop exposures), treating both dissolved and free gas phase buildup and elimination. NAUI Technical Diving employs the RGBM to schedule nonstop and decompression training protocols on trimix, helitrox, air, and nitrox, and will be releasing an exhaustive set of RGBM tables for those mixes shortly (some 500 pages of Tables). Included are constant ppO₂ Tables for rebreathers.

Suunto VYPER/COBRA/STINGER are RGBM meters for recreational diving (plus nitrox), while ABYSS/RGBM is a licensed Abysmal Diving software product. The HydroSpace EXPLORER is a mixed gas decompression meter for technical and recreational diving, as is the ABYSS/RGBM software vehicle. All are first-time-ever commercial products with realistic implementation of a diving phase algorithm across a wide spectrum of exposure extremes. And all accommodate user knobs for aggressive to conservative diving. Expect RGBM algorithms to surface in other meters and software packages on the Internet. NAUI Worldwide just released a set of RGBM no-group, no-calc, no-fuss recreational Tables for air and nitrox, sea level to 10,000 feet elevation.

The Countermeasures Dive Team at LANL employs the RGBM (last 8 years). Military, commercial, and scientific sectors are using and further testing the RGBM. And scores of technical divers are reporting their RGBM profiles over the Internet and in technical diving publications. There are presently four other major RGBM implementation projects in the works for meters and software packages.

RGBM UNDERPINNINGS

The RGBM extends earlier work of the Tiny Bubble Group at the University of Hawaii, updating missing physics and extending their Varying Permeability Model (VPM) to multiding, altitude, and mixed gas applications. While certainly fundamental, the RGBM is also different and new on the diving scene. And not unexpectedly, the RGBM recovers the Haldane approach to decompression modeling in the limit of relatively safe (tolerably little) separated phase, with tolerably little a qualitative statement here. There is quite a bit more and different about the RGBM than other and related phase models.

So let's take a closer look at the RGBM and its operational bases.

Here, our intent is to (just) look at the underpinnings of table, meter, and diveware implementations of the RGBM algorithm, one with extended range of applicability based on simple dual phase principles. Haldane approaches have dominated decompression algorithms for a very long time, and the RGBM has been long in coming on the commercial scene. With technical diving interest in deep stop modeling, helium, and concerns with repetitive diving in the recreational and technical community, phase modeling is timely and pertinent.

The establishment and evolution of gas phases, and 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).

Other issues concerning time sequencing of symptoms impact computational algorithms. That bubble formation is a predisposing condition for decompression sickness is universally accepted. However, formation mechanisms and their ultimate physiological effect are two related, yet distinct, issues. On this point, most hypotheses makes little distinction between bubble formation and the onset of bends symptoms. Yet we know that silent bubbles 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 truly operative, such as the amount of gas dumped from solution, the 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 pervue of bubble theories, but the complexity of mechanisms addressed does not lend itself easily to table, nor even meter, implementation. But implement and improve we must, so consider the RGBM issues and tacks taken in the Suunto, HydroSpace, and ABYSS implementations, and all ongoing and future implementations:

- Perfusion And Diffusion

Perfusion and diffusion are two mechanisms by which inert and metabolic gases exchange between tissue and blood. Perfusion denotes the blood flow rate in simplest terms, while diffusion refers to the gas penetration rate in tissue, or across tissue-blood boundaries. Each mechanism has a characteristic rate constant for the process. The smallest rate constant limits the gas exchange process. When diffusion rate constants are smaller than perfusion rate constants, diffusion dominates the tissue-blood gas exchange process, and vice-versa. In the body, both processes play a role in real exchange process, especially considering the diversity of tissues and their geometries. The usual Haldane tissue halftimes are the inverses of perfusion rates, while the diffusivity of water, thought to make up the bulk of tissue, is a measure of the diffusion rate.

Clearly in the past, model distinctions were made on the basis of perfusion or diffusion limited gas exchange. The distinction is somewhat artificial, especially in light of recent analyses of coupled perfusion-diffusion gas transport, recovering limiting features of the exchange process in appropriate limits. The distinction is still of interest today, however, since perfusion and diffusion limited algorithms are used in mutually exclusive fashion in diving. The obvious mathematical rigors of a full blown perfusion-diffusion treatment of gas exchange mitigate against table and meter implementation, where model simplicity is a necessity. So one or another limiting models is adopted, with inertia and track record sustaining use. Certainly Haldane models fall into that categorization.

Inert gas transfer and coupled bubble growth are subtly influenced by metabolic oxygen consumption. Consumption of oxygen and production of carbon dioxide drops the tissue oxygen tension below its level in the lungs (alveoli), while carbon dioxide tension rises only slightly because carbon dioxide is 25 times more soluble than oxygen.

Arterial and venous blood, and tissue, are clearly unsaturated with respect to dry air at 1 atm. Water vapor content is constant, and carbon dioxide variations are slight, though sufficient to establish an outgradient between tissue and blood. Oxygen tensions in tissue and blood are considerably below lung oxygen partial pressure, establishing the necessary ingradient for oxygenation and metabolism. Experiments also suggest that the degree of unsaturation increases linearly with pressure for constant composition breathing mixture, and decreases linearly with mole fraction of inert gas in the inspired mix.

Since the tissues are unsaturated with respect to ambient pressure at equilibrium, one might exploit this window in bringing divers to the surface. By scheduling the ascent strategically, so that nitrogen (or any other inert breathing gas) supersaturation just takes up this unsaturation, the total tissue tension can be kept equal to ambient pressure. This approach to staging is called the zero supersaturation ascent.

The full blown RGBM treats coupled perfusion-diffusion transport as a two step flow process, with blood flow (perfusion) serving as a boundary condition for tissue gas penetration (diffusion). Depending on time scales and rate coefficients, one or another (or both) processes dominate the exchange. However, for the Suunto, HydroSpace, Plexus, and ABYSS implementations, perfusion is assumed to dominate, simplifying matters and permitting online calculations. Additionally, tissues and blood are naturally undersaturated with respect to ambient pressure at equilibration through the mechanism of biological inherent unsaturation (oxygen window), and the RGBM includes this debt in calculations. Independent of perfusion or diffusion dominated gas transport,

the RGBM tracks bubble excitation and number, inert gas transfer across the surfactant skin, and Boyle-like expansion and contraction of bubbles with ambient pressure changes.

- Bubbles

We do not really know where bubbles form nor lodge, their migration patterns, their birth and dissolution mechanisms, nor the exact chain of physico-chemical insults resulting in decompression sickness. Many possibilities exist, differing in the nature of the insult, the location, and the manifestation of symptoms. Bubbles might form directly (de novo) in supersaturated sites upon decompression, or possibly grow from preformed, existing seed nuclei excited by compression-decompression. Leaving their birth sites, bubbles may move to critical sites elsewhere. Or stuck at their birth sites, bubbles may grow locally to pain-provoking size. They might dissolve locally by gaseous diffusion to surrounding tissue or blood, or passing through screening filters, such as the lung complex, they might be broken down into smaller aggregates, or eliminated completely. Whatever the bubble history, it presently escapes complete elucidation. But whatever the process, the end result is very simple, both separated and dissolved gas must be treated in the transfer process.

Bubbles may hypothetically form in the blood (intravascular) or outside the blood (extravascular). Once formed, intravascularly or extravascularly, a number of critical insults are possible. Intravascular bubbles may stop in closed circulatory vessels and induce ischemia, blood sludging, chemistry degradations, or mechanical nerve deformation. Circulating gas emboli may occlude the arterial flow, clog the pulmonary filters, or leave the circulation to lodge in tissue sites as extravascular bubbles. Extravascular bubbles may remain locally in tissue sites, assimilating gas by diffusion from adjacent supersaturated tissue and growing until a nerve ending is deformed beyond its pain threshold. Or, extravascular bubbles might enter the arterial or venous flows, at which point they become intravascular bubbles.

Spontaneous bubble formation in fluids usually requires large decompressions, like hundreds of atmospheres, somewhere near fluid tensile limits. Many feel that such circumstance precludes direct bubble formation in blood following decompression. Explosive, or very rapid decompression, of course is a different case. But, while many doubt that bubbles form in the blood directly, intravascular bubbles have been seen in both the arterial and venous circulation, with vastly greater numbers detected in venous flows (venous gas emboli). Ischemia resulting from bubbles caught in the arterial network has long been implied as a cause of decompression sickness. Since the lungs are effective filters of venous bubbles, arterial bubbles would then most likely originate in the arteries or adjacent tissue beds. The more numerous venous bubbles, however, are suspected to first form in lipid tissues draining the veins. Lipid tissue sites also possess very few nerve endings, possibly masking critical insults. Veins, thinner than arteries, appear more susceptible to extravascular gas penetration.

Extravascular bubbles may form in aqueous (watery) or lipid (fatty) tissues in principle. For all but extreme or explosive decompression, bubbles are seldom observed in heart, liver, and skeletal muscle. Most gas is seen in fatty tissue, not unusual considering the five-fold higher solubility of nitrogen in lipid tissue versus aqueous tissue. Since fatty tissue has few nerve endings, tissue deformation by bubbles is unlikely to cause pain locally. On the other hand, formations or large volumes of extravascular gas could induce vascular hemorrhage, depositing both fat and bubbles into the circulation as noted in animal experiments. If mechanical pressure on nerves is a prime candidate for critical insult, then tissues with high concentrations of nerve endings are candidate structures, whether tendon or spinal cord. While such tissues are usually aqueous, they are invested with lipid cells whose propensity reflects total body fat. High nerve density and some lipid content supporting bubble formation and growth would appear a conducive environment for a mechanical insult.

To satisfy thermodynamic laws, bubbles assume spherical shapes in the absence of external or mechanical (distortion) pressures. Bubbles entrain free gases because of a thin film, exerting surface tension pressure on the gas. Hydrostatic pressure balance requires that the pressure inside the bubble exceed ambient pressure by the amount of surface tension, γ . At small radii, surface tension pressure is greatest, and at large radii, surface tension pressure is least.

Gases will also diffuse into or out of a bubble according to differences in gas partial pressures inside and outside the bubble, whether in free or dissolved phases outside the bubble. In the former case, the gradient is termed free-free, while in the latter case, the gradient is termed free-dissolved. Unless the surface tension is identically zero, there is always a gradient tending to force gas out of the bubble, thus making the bubble collapse on itself because

of surface tension pressure. If surrounding external pressures on bubbles change in time, however, bubbles may grow or contract.

Bubbles grow or contract according to the strength of the free-free or free-dissolved gradient, and it is the latter case which concerns divers under decompression. The radial rate at which bubbles grow or contract depends directly on the diffusivity and solubility, and inversely on the bubble radius. A critical radius, r_c , separates growing from contracting bubbles. Bubbles with radius $r > r_c$ will grow, while bubbles with radius $r < r_c$ will contract. Limiting bubble growth and adverse impact upon nerves and circulation are issues when decompressing divers and aviators.

Bubbles grow or contract by gaseous diffusion across the film interface, due to dissolved gas gradients. Bubbles also expand or contract upon pressure changes according to Boyle-like equations of state (EOS), with the expansion or contraction rate a function of the material composition of the surfactants coating the inside of the bubble. Material behavior can vary from thin elastic films to almost solid shell bubbles, depending on the coefficients and pressure regimes of the EOS.

The RGBM assumes that a size distribution of seeds (potential bubbles) is always present, and that a certain number is excited into growth by compression-decompression. An iterative process for ascent staging is employed to control the inflation rate of these growing bubbles so that their collective volume never exceeds a phase volume limit point. Gas mixtures of helium, nitrogen, and oxygen contain bubble distributions of different sizes, but possess the same phase volume limit point. Distributions have lifetimes of minutes to many hours,

- Bubble Seeds

Bubbles, which are unstable, are thought to grow from micron size, gas nuclei which resist collapse due to elastic skins of surface activated molecules (surfactants), or possibly reduction in surface tension at tissue interfaces or crevices. If families of these micronuclei persist, they vary in size and surfactant content. Large pressures (not really known) are necessary to crush them. spanning repetitive and multiday activities. Micronuclei are small enough to pass through the pulmonary filters, yet dense enough not to float to the surfaces of their environments, with which they are in both hydrostatic (pressure) and diffusion (gas flow) equilibrium. When nuclei are stabilized, and not activated to growth or contraction by external pressure changes, the skin (surfactant) tension offsets both the Laplacian (film) tension and any mechanical help from surrounding tissue. Then all pressures and gas tensions are equal. However, on decompression, the seed pockets are surrounded by dissolved gases at high tension and can subsequently grow (bubbles) as surrounding gas diffuses into them. The rate at which bubbles grow, or contract, depends directly on the difference between tissue tension and local ambient pressure, effectively the bubble pressure gradient. At some point in time, a critical volume of bubbles, or separated gas, is established and bends symptoms become statistically more probable. On compression, the micronuclei are crunched down to smaller sizes across families, apparently stabilizing at new reduced size. Bubbles are also crunched by increasing pressure because of Boyle's law, and then additionally shrink if gas diffuses out of them. As bubbles get smaller and smaller, they probably restabilize as micronuclei.

The RGBM postulates bubble seeds with lipid or aqueous surfactants. Bubble skins are assumed permeable under all ambient pressure, unlike the VPM. The size of seeds excited into growth is inversely proportional to the supersaturation gradient. RGBM excitation radii, r , start in the 0.01 microns range, far smaller than other dual phase models, because the RGBM tracks Boyle expansion and bubble gas diffusion across the tissue seed interface (across the surfactant). At increasing pressure, bubble seeds permit gas diffusion at a slower rate. The RGBM assumes bubble skins are stabilized by surfactants over calculable time scales, producing seeds that are variably persistent in the body. Bubble skins are probably molecularly activated, complex, biosubstances found throughout the body. Whatever the formation process, the RGBM assumes the size distribution is exponentially decreasing in size, that is, more smaller seeds than larger seeds in exponential proportions. Skin response of the bubbles to pressure change is dictated by a material equation-of-state (EOS), again unlike the VPM. As stated, the RGBM diffuses gas from tissues to bubbles (and vice-versa) using a transfer equations across the film interface. This requires a mass transfer coefficient dependent on the gas solubility and diffusivity. The source of bubbles and seeds is probably tribonucleation due to muscle and tissue interfraction, and persistence time scales range from minutes to tens of hours.

- Slow Tissue Compartments

Based on concerns in multiday and heavy repetitive diving, with the hope of controlling staircasing gas buildup in exposures through critical tensions, slow tissue compartments (halftimes greater than 80 minutes) have been incorporated into some algorithms. Calculations, however, show that virtually impossible exposures are required of the diver before critical tensions are even approached, literally tens of hours of near continuous activity. As noted in many calculations, slow compartment cannot really control multiday diving through critical tensions, unless critical tensions are reduced to absurd levels, inconsistent with nonstop time limits for shallow exposures. That is a model limitation, not necessarily a physical reality. The physical reality is that bubbles in slow tissues are eliminated over time scales of days, and the model limitation is that the arbitrary parameter space does not accommodate such phenomena.

And that is no surprise either, when one considers that dissolved gas models are not suppose to track bubbles and free phases. Repetitive exposures do provide fresh dissolved gas for excited nuclei and growing free phases, but it is not the dissolved gas which is the problem just by itself. When bubble growth is considered, the slow compartments appear very important, because, therein, growing free phases are mostly left undisturbed insofar as surrounding tissue tensions are concerned. Bubbles grow more gradually in slow compartments because the gradient there is typically small, yet grow over longer time scales. When coupled to free phase dynamics, slow compartments are necessary in multiday diving calculations.

The RGBM incorporates a spectrum of tissue compartments, ranging from 1 min to 720 min, depending on gas mixture (helium, nitrogen, oxygen). Phase separation and bubble growth in slow compartments is a central focus in calculations over long time scales, and the same for fast tissue compartments over short time scales, that is to say, scales of 2 - 3 times the compartment half-time.

- Venous Gas Emboli

While the numbers of venous gas emboli detected with ultrasound Doppler techniques can be correlated with nonstop limits, and the limits then used to fine tune the critical tension matrix for select exposure ranges, fundamental issues are not necessarily resolved by venous gas emboli measurements. First of all, venous gas emboli are probably not the direct cause of bends per se, unless they block the pulmonary circulation, or pass through the pulmonary traps and enter the arterial system to lodge in critical sites. Intravascular bubbles might first form at extravascular sites. According to studies, electron micrographs have highlighted bubbles breaking into capillary walls from adjacent lipid tissue beds in mice. Fatty tissue, draining the veins and possessing few nerve endings, is thought to be an extravascular site of venous gas emboli. Similarly, since blood constitutes no more than 8% of the total body capacity for dissolved gas, the bulk of circulating blood does not account for the amount of gas detected as venous gas emboli. Secondly, what has not been established is the link between venous gas emboli, possible micronuclei, and bubbles in critical tissues. Any such correlations of venous gas emboli with tissue micronuclei would unquestionably require considerable first-hand knowledge of nuclei size distributions, sites, and tissue thermodynamic properties. While some believe that venous gas emboli correlate with bubbles in extravascular sites, such as tendons and ligaments, and that venous gas emboli measurements can be reliably applied to bounce diving, the correlations with repetitive and saturation diving have not been made to work, nor important correlations with more severe forms of decompression sickness, such as chokes and central nervous system (CNS) hits.

Still, whatever the origin of venous gas emboli, procedures and protocols which reduce gas phases in the venous circulation deserve attention, for that matter, anywhere else in the body. The moving Doppler bubble may not be the bends bubble, but perhaps the difference may only be the present site. The propensity of venous gas emboli may reflect the state of critical tissues where decompression sickness does occur. Studies and tests based on Doppler detection of venous gas emboli are still the only viable means of monitoring free phases in the body.

The RGBM uses nonstop time limits tuned to recent Doppler measurements, conservatively reducing them along the lines originally suggested by Spencer (and others), but within the phase volume constraint. The Suunto implementation penalizes ascent violations by requiring additional safety stop time dictated by risk analysis of the violation.

- Multidiving

Concerns with multiday diving can be addressed through variable critical gradients, then tissue tensions in Haldane models. While variable gradients or tensions are difficult to codify in table frameworks, they are easy to imple-

ment in digital meters. Reductions in critical parameters also result from the phase volume constraint, a constraint employing the separated volume of gas in tissue as trigger point for the bends, not dissolved gas buildup alone in tissue compartments. In the VPM the phase volume is proportional to the product of the dissolved-free gas gradient times a bubble number representing the number of gas nuclei excited into growth by the compression-decompression, replacing just slow tissue compartments in controlling multiday diving. In the RGBM, the phase volume depends on the number of seeds excited and the Boyle and gas diffusion expansion-contraction of the seeds excited into growth.

In considering bubbles and free-dissolved gradients within critical phase hypotheses, repetitive criteria develop which require reductions in Haldane critical tensions or dissolved-free gas gradients. This reduction simply arises from lessened degree of bubble elimination over repetitive intervals, compared to long bounce intervals, and need to reduce bubble inflation rate through smaller driving gradients. Deep repetitive and spike exposures feel the greatest effects of gradient reduction, but shallower multiday activities are impacted. Bounce diving enjoys long surface intervals to eliminate bubbles while repetitive diving must contend with shorter intervals, and hypothetically reduced time for bubble elimination. Theoretically, a reduction in the bubble inflation driving term, namely, the tissue gradient or tension, holds the inflation rate down. Overall, concern is bubble excess driven by dissolved gas. And then both bubbles and dissolved gas are important. In such an approach, multiday exposures experience reduced permissible tensions through lessened free phase elimination over time spans of two days. Parameters are consistent with bubble experiments, and both slow and fast tissue compartments must be considered.

The RGBM addresses the phase volume limit in multiday diving by considering free phase elimination and buildup during surface intervals, depending on altitude, time, and depth of previous profiles, Repetitive, multiday, and reverse profile exposures are tracked and impacted by critical phase volume reductions over appropriate time scales.

- Adaptation

Divers and caisson workers have long contended that tolerance to decompression sickness increases with daily diving, and decreases after a few weeks layoff, that in large groups of compressed air workers, new workers were at higher risk than those who were exposed to high pressure regularly. This acclimatization might result from either increased body tolerance to bubbles (physiological adaptation), or decreased number and volume of bubbles (physical adaptation). Test results are totally consistent with physical adaptation.

Yet, there is slight inconsistency here. Statistics point to slightly higher bends incidence in repetitive and multiday diving. Some hyperbaric specialists confirm the same, based on experience. The situation is not clear, but the resolution plausibly links to the kinds of first dives made and repetitive frequency in the sequence. If the first in a series of repetitive dives are kept short, deep, and conservative with respect to nonstop time limits, initial excitation and growth are minimized. Subsequent dives would witness minimal levels of initial phases. If surface intervals are also long enough to optimize both free and dissolved gas elimination, any nuclei excited into growth could be efficiently eliminated outside repetitive exposures, with adaptation occurring over day intervals as noted in experiments. But higher frequency, repetitive and multiday loading may not afford sufficient surface intervals to eliminate free phases excited by earlier exposures, with additional nuclei then possibly excited on top of existing phases. Physical adaptation seems less likely, and decompression sickness more likely, in the latter case. Daily regimens of a single bounce dive with slightly increasing exposure times are consistent with physical adaptation, and conservative practices. The regimens also require deepest dives first. In short, acclimatization is as much a question of eliminating any free phases formed as it is a question of crushing or reducing nuclei as potential bubbles in repetitive exposures. And then time scales on the order of a day might limit the adaptation process.

The RGBM generates bubble seed distributions on time scales of minutes for fast tissues and hours for slow tissues, adding new bubbles to existing bubbles in calculations. Phase volume limit points are also reduced by the added effects of new bubbles. Repetitive and reverse profile diving are impacted by bubble growth in the fast compartments, while flying after diving and multiday diving are affected by bubble growth in the slow compartments.

RGBM APPLICATIONS AND COMPARISONS

So, having waded through the foregoing, a next question is how does the RGBM compare with classical Haldane models as far as staging ascents, limiting multiexposures, and treating mixed gases? Generally, for short nonstop air diving, the RGBM reproduces the Spencer limits. For multiding in spans shorter than 1-3 *hrs*, the RGBM reduces nonstop limits by 10% to 20% depending on surface interval, depth, altitude, and duration of present and previous dive. Multiday diving is impacted to lesser degree. Some comparisons appear in Table 1 for 3 days of repetitive air diving (120 *fsw*/10 *min* twice a day with 45 *min* surface interval). Computer choices are illustrative, not inductive.

Table 1. Nonstop Limits For VYPER/RGBM And Haldane Air Multiding

Computer/Algorithm	Dive 1 (<i>min</i>)	Dive 2 (<i>min</i>)	Dive 3 (<i>min</i>)	Dive 4 (<i>min</i>)	Dive 5 (<i>min</i>)	Dive 6 (<i>min</i>)
VYPER, EXPLORER/RGBM	10	6	9	5	9	5
COBRA/Spencer	10	9	10	9	10	9
DATA PLUS/USN	12	6	12	6	12	6
DELPHI/USN	10	10	10	10	10	10
ABYSS/RGBM	10	7	9	6	8	6
DC12/ZHL	9	7	9	7	9	7
ALADIN/ZHL	8	8	8	8	8	8
ALADIN PRO/ZHL	10	7	10	7	10	7
SOURCE/USN	12	9	12	9	12	9

The VYPER/RGBM (first dive) nonstop limits (depth/time) are 150/6, 140/7, 130/9, 120/10, 110/13, 100/17, 90/22, 80/28, 70/36, 60/51, 50/69, and 40/120. And the ABYSS/RGBM implementation is nearly the same for first dive NDLS. In the mixed gas arena, Table 2 lists nonstop time limits for ranged trimix, that is, 13% to 17% helium, 61% to 53% nitrogen, and 26% to 30% oxygen, according to RGBM and RGBM/ZHL (Buhlmann).

Table 2. Trimix Nonstop Limits For RGBM And RGBM/ZHL (Haldane).

Depth (<i>fsw</i>)	RGBM (<i>min</i>)	RGBM/ZHL (<i>min</i>)
80	28	26
90	23	22
100	19	18
110	16	15
120	14	13
130	12	11
140	11	10
150	10	9

These limits are used by NAUI Technical Diving for training purposes. While both sets of nonstop time limits are different in Tables 1 and 2, the more dramatic effects of the RGBM show up for deep staging, as seen in Table 3. Comparative deep schedules for a trimix dive to 250 *fsw* for 30 *min* are contrasted, following a switch to air at 100 *fsw* and a switch to pure oxygen at 20 *fsw* on the way up. RGBM and RGBM/ZHL are again employed, but with and without conservative safety knobs. In the case of RGBM/ZHL, the outgassing tissue halftimes are increased by 1.5 in the conservative case, while for RGBM the bubble excitation radius is increased by 1.2 for comparison. Deeper stops are noticeably requisite in RGBM, but total decompression times are less than RGBM/ZHL. The trimix is 33% helium, 51% nitrogen, and 16% oxygen.

NAUI Technical Diving Operations will release a set of ranged RGBM trimix, nitrox, and helitrox Tables. They can be obtained from NAUI Worldwide Headquarters (Tampa). The trimix Tables hold for 24% - 40% helium, 16% oxygen, with a switch to pure oxygen at 20 *fsw*. Similarly, the helitrox Tables range 13% - 17% helium, and 26% - 30% oxygen, with a switch to pure oxygen at 20 *fsw*, as with the trimix Tables. Maximum descent rate is 90 *fsw/min*,

and maximum ascent rate is 30 *fsw/min*. Minimum repetitive interval is 3 *hrs*, with a maximum of 2 dives. Flying time is 24 *hrs* for a single dive. At altitude, the standard (Wienke) equivalent sea level depth method for scaling depths at altitude to sea level for table entry can be used. Deeper stops and shorter deco times are standard features of diver staging in the full RGBM and released Tables.

Table 3. Deep Schedules According To RGBM And RGBM/ZHL (Haldane)

Stop	Depth (<i>fsw</i>)	RGBM/ZHL (<i>min</i>) (<i>standard</i>)	RGBM (<i>min</i>) (<i>standard</i>)	RGBM/ZHL (<i>min</i>) (<i>safer</i>)	RGBM (<i>min</i>) (<i>safer</i>)
1	180	0	0	0	1
2	170	0	1	0	1
3	160	0	1	0	1
4	150	0	1	0	1
5	140	0	1	0	2
6	130	0	2	0	2
7	120	0	2	0	2
8	110	0	2	1	2
9	100	0	2	2	2
10	90	2	2	3	3
11	80	2	2	4	3
12	70	2	3	5	4
13	60	5	5	8	6
14	50	7	6	12	7
15	40	12	9	18	19
16	30	18	12	28	13
17	20	16	10	28	11
18	10	28	16	48	18
		93	77	147	98

That in a nutshell is also a comparison of major differences between phase and dissolved gas models. The phase models recover dissolved gas models for short and nominal exposures, but require deeper stops and shorter decompression times for longer and exceptional exposures.

RGBM VALIDATION

Models need validation and testing. Often, strict chamber tests are not possible, economically nor otherwise, and models employ a number of benchmarks and regimens to underscore viability. The following are some supporting the RGBM phase model and (released) nitrox, heliox, and trimix diving tables and meters:

- counterterror and countermeasures (LANL) exercises have used the RGBM (full up iterative deep stop version) for a number of years, logging some 327 dives on mixed gases (trimix, heliox, nitrox) without incidence of DCS – 35% were deco dives, and 25% were repeats (no deco) with at least 2 hr SIs, and in the forward direction (deepest dives first);
- NAUI Technical Diving has been diving the deep stop version for the past 3 yrs, some estimated 600 dives, on mixed gases down to 250 *fsw*, without a single DCS hit. Some 15 divers, late 1999, in France used the RGBM to make 2 mixed gas dives a day, without mishap, in cold water and rough seas. Same thing in the warm waters of Roatan in 2000 and 2001;
- NAUI Worldwide released a set of no-group, no-calc, no-fuss RGBM Tables for air, EAN32, and EAN36 recreational diving, from sea level to 10,000 ft, a few years ago. Minimum SIs of 1 hour are supported for repetitive diving in all Tables, and safety stops for 3 minutes in the 15 *fsw* zone are required always. Tables were tested by NAUI Instructor Trainers, Instructors, and Divemasters over a 2 year period without mishap;

- modified RGBM recreational algorithms (Haldane imbedded with bubble reduction factors limiting reverse profile, repetitive, and multiday diving), as coded into Suunto, Mares, Dacor, ABYSS, HydroSpace, Plexus decometers, lower an already low DCS incidence rate of approximately 1/10,000 or less. More RGBM decompression meters, including mixed gases, are in the works (not named at this time);
- a cadre of divers and instructors in mountainous New Mexico, Utah, and Colorado have been diving the modified (Haldane imbedded again) RGBM at altitude, an estimated 350 dives, without peril. Again, not surprising since the altitude RGBM is slightly more conservative than the usual Cross correction used routinely up to about 8,000 ft elevation, and with estimated DCS incidence less than 1/10,000;
- within decometer implementations of the RGBM, not a single DCS hit has been reported in nonstop and multi-diving categories, beyond 200,000 dives or more, up to now;
- extreme chamber tests for mixed gas RGBM are in the works, and less stressful exposures will be addressed shortly – extreme here means 300 f_{sw} and beyond;
- probabilistic decompression analysis of some selected RGBM profiles, calibrated against similar calculations of the same profiles by Duke, help validate the RGBM on computational bases, suggesting the RGBM has no more theoretical risk than other bubble or dissolved gas models (Weathersby, Vann, Gerth methodology at USN and Duke);
- all divers and instructors using RGBM decometers, tables, or NET software have been advised to report individual profiles to DAN Project Dive Exploration (Vann, Gerth, Denoble and others at Duke).
- ABYSS is a NET software package that offers the modified RGBM (folded over the Buhlmann ZHL) and soon the full up, deep stop version for any gas mixture, has a fairly large contingent of tech divers already using the RGBM and has not received any reports of DCS;
- outside of proprietary (commercial) and RGBM Tables, mixed gas tables are a smorgasboard of no longer applicable Haldane dynamics and discretionary stop insertions, as witnessed by the collective comments of a very vocal and extremely competent, experienced technical diving community;
- extreme WKPP profiles in the 300 f_{sw} range on trimix were used to calibrate the full RGBM. WKPP profiles are the most impressive application of RGBM staging, with as much as 12 hours less decompression time for WKPP helium based diving on RGBM schedules versus Haldane schedules;
- a TDI instructor dived the Baden in the North Sea to 520 f_{sw} on RGBM tables on two different occasions, and is planning a 620 f_{sw} dive to an Andros Blue Hole with RGBM scheduling. In the North Sea dives, 3 hours were shaved off conventional hang time by RGBM application;
- NAUI Worldwide released sets of deep stop RGBM nitrox, helitrox, and trimix technical and recreational Tables that have been tested by NAUI Technical Diving Operations over the past 3 years, with success and no reported cases of DCS, for open circuit regulators and rebreathers.

Because DCS is binomially distributed in incidence probability, many trials are often needed (or other close profiles) to fully validate any model at the 1% level. Additionally, full validation requires DCS incidences, the higher the number, the better, contrary to desired dive outcomes.

BIOSKETCHES

Bruce Wienke is a Program Manager in the Nuclear Weapons Technology/ Simulation And Computing Office at the Los Alamos National Laboratory (LANL), with interests in computational decompression and models, gas transport, and phase mechanics. He authored *Physics, Physiology And Decompression Theory For The Technical And Commercial Diver, High Altitude Diving, Basic Diving Physics And Applications, Diving Above Sea Level, Basic Decompression Theory And Application*, and some 200 technical journal articles. Diving environs include the Caribbean, South Pacific, Asia, inland and coastal United States, Hawaii, and polar Arctic and Antarctic in various technical, scientific, military, and recreational activities. He functions on the LANL Nuclear Emergency Strategy Team (NEST), in exercises often

involving Special Operations Units (SEAL, Delta), above and underwater. He heads Southwest Enterprises, a consulting company for computer research and applications in wide areas of applied science and simulation.

He is an Instructor Trainer with the National Association Of Underwater Instructors (NAUI), serves on the Board Of Directors (Vice Chairman for Technical Diving, Technical and Decompression Review Board Member), is a Master Instructor with the Professional Association Of Diving Instructors (PADI) in various capacities (Instructor Review Committee), is an Institute Director with the YMCA, and is an Instructor Trainer with Scuba Diving International/Technical Diving International (SDI/TDI).

Wienke, a former dive shop owner in Santa Fe, presently works with DAN on applications of high performance computing and communications to diving, and is a Regional Data Coordinator for Project Dive Safety. Mares, Dacor, Scubapro, Suunto, Abyssal Diving, HydroSpace Engineering, and Atomic Aquatics engage (or have) him as Consultant for meter algorithms. He is the developer of the Reduced Gradient Bubble Model (RGBM), a dual phase approach to staging diver ascents over an extended range of diving applications (altitude, nonstop, decompression, multiday, repetitive, multilevel, mixed gas, and saturation). Suunto, Plexus, and HydroSpace dive computers incorporate the RGBM into staging regimens for recreational and technical diving on air, nitrox, heliox, and trimix. NAUI will be releasing a set of full mixed gas tables based on the RGBM, and a short, no-group, no-calc set of air tables for the recreational air and nitrox diver, from sea level to 10,000 ft. ABYSS, a commercial software product, features some of the RGBM dynamical diving algorithms developed by him for Internet users and technical divers. He is also Associate Editor for the International Journal Of Aquatic Research And Education, and is a former Contributing Editor of *Sources*, the NAUI Training Publication.

Wienke received a BS in physics and mathematics from Northern Michigan University, an MS in nuclear physics from Marquette University, and a PhD in particle physics from Northwestern University. He is a member of the Undersea And Hyperbaric Medical Society (UHMS), American Physical Society (APS), Society Of Industrial And Applied Mathematics (SIAM), and the American Academy Of Underwater Sciences (AAUS).

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Tim O'Leary is Director of NAUI Worldwide Technical Training Operations, Course Director for NAUI Worldwide, Inspector Trainer for PSI, and President of American Diving And Marine Salvage. He has spoken at many underwater symposiums, as well as contributing to recreational and technical periodicals.

He has dived in Asia, South Pacific, North Sea, Mediteranian, Mexico, Central and South America, and the United States as both a mixed gas Commercial Diver and technical diving Instructor Trainer.

O'Leary received a BS in zoology from Texas AM University, a DMT and CHT from Jo Ellen Smith Medical Ceneter at the Baromedical Research Institute. He has worked as a Commercial Diving Instructor at the Ocean Corporation, a Saturation Diver, Gas Rack Operator, Saturation Supervisor, and Chamber Supervisor for many of the world's commercial diving companies. He currently serves as a Consultant for the offshore oil industry, and is a Level III NDT Technician.

O'Leary is a member of the Undersea And Hyperbaric Medical Society (UHMS), Society Of Naval Architects And Marine Engineers (SNAME), National Association Of Diver Medical Technicians (NADMT), and is an Admiral in the Texas Navy.

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