RGBM ALGORITHM OVERVIEW: CONCEPTS, BASES, VALIDATION, TESTING AND REFERENCES

B.R. Wienke
Nuclear Weapons Technology/Simulation And Computing
Applied And Computational Physics Division
Counter Terror And Counter Measures Dive Team Leader
Los Alamos National Laboratory
Los Alamos, N.M. 87545

T.R. O'Leary
American Diving And Marine Salvage
Director NAUI Technical Diving
Admiral Texas Navy
South Padre Island, Texas 78597

INTRODUCTION

Gas exchange, bubble formation and elimination, and compression-decompression in blood and tissues are governed by many factors, such as diffusion, perfusion, phase separation and equilibration, nucleation and cavitation, local fluid shifts, and combinations thereof. Owing to the complexity of biological systems, multiplicity of tissues and media, diversity of interfaces and boundary conditions, and plethora of bubble impacting physical and chemical mechanisms, it is difficult to solve the decompression problem *in vivo*. Early decompression studies adopted the supersaturation viewpoint. Closer looks at the physics of phase separation and bubbles in the mid-1970s, and insights into gas transfer mechanisms, culminated in extended kinetics and dissolved-free phase theories. Integration of both approaches can proceed on the numerical side because calculational techniques can be made equivalent. Phase and bubble models are more general than supersaturation models, incorporating their predictive capabilities as subsets. Statistical models, developed mostly in the mid-1980s, are gray from mechanistic viewpoint, but offer the strongest correlations with actual experiments and exposures, possibly the best approach to table fabrication.

Computational models gain efficacy by their ability to track data, often independently of physical interpretation. In that sense, the bottom line for computational models is utility, operational reliability, and reproducibility. Correct models can achieve such ends, but almost any model with sufficient parameter latitude could achieve those same ends. It is fair to say that deterministic models admit varying degrees of computational license, that model parameters may not correlate as complete set with the real world, and that not all mechanisms are addressed optimally. That is, perhaps, one reason why we see representative diving sectors, such as sport, military, commercial, and research, employing different tables, meters, models, and algorithms Yet, given this situation, phase models attempting to treat both free and dissolved gas exchange, bubbles and gas nuclei, and free phase trigger points appear preferable to other flags. Phase models have the right physical signatures, and thus the potential to extrapolate reasonably when confronting new applications and data. Expect to see their further refinement and development in the future.

We now turn to a modern phase model, the Reduced Gradient Bubble Model (RGBM), and detail models underpinnings, physical bases, testing and validation, and a extensice list of references bearing on discussion herein.

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.

NITTY GRITTY ISSUES

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 also grew from the needs of the recreational community for a consistent models to address reverse profiles (RPs), short surface intervals (SIs), multiday diving, and altitude excursions. These concerns traditionally fall outside of dissolved gas (only) models, ala Haldane, and require consideration of bubble dynamics.

The RGBM has gained tremendous popularity in the recreational and technical diving worlds in just the past 5 - 7 years, due to meter implementations, Internet software packages, specialized Table releases, technical word of mouth, NAUI training testing and adoption, Internet traffic, chamber tests, and, most of all, actual technical and recreational RGBM diving and validation. And the reasons are fairly clear.

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 stategies;
- 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 detailed earlier, and have the right signatures for diving applications across the full spectrum of actvities. 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, Mares, Dacor, Zeagle, Hydrospace, Plexus, Steam Machines, Abysmal Diving (ABYSS), Gas Absorption Program (GAP), and others unnamed herein, developed and released (are releasing) products incorporating the validated and tested RGBM phase algorithm. With an iterative approach to 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 released an exhaustive set of RGBM tables for those mixes (some 500 pages of Tables). Included are constant ppO2 Tables for rebreathers. ANDI uses GAP RGBM as their official training algorithm. NAUI also released sets of RGBM no-group, no-calc, no-fuss recreational Tables for air and nitrox, sea level to 10,000 feet elevation (9 plastic Tables).

The site RGBMdiving.com hosts information on all apsects of RGBM. plus offers premixed and custom tables for technical and recreational diving.

Suunto VYTEC/VYPER/COBRA/STINGER are RGBM meters for recreational diving (plus nitrox). Suunto extended their recreational RGBM algorithm for deep stops in their new D9 tec/rec computer. The HydroSpace EXPLORER is a mixed gas decompression meter for technical and recreational diving, as are the ABYSS and GAP software vehicles. The EXPLORER is the first ever full RGBM computer for all diving. Hydrospace also provides an RGBM Simulator as a software package with the EXPLORER. The Dacor DARWIN is an integrated RGBM air and nitrox console for diving, and uses the very same basic recreational RGBM algorithm as Mares. The Mares M1 and NEMO computers are recreational RGBM air and nitrox computers with deep stops for light and near deco diving. Zeagle will be introducing a full RGBM computer (like the EXPLORER) for mixed gas technical and recreational diving. Steam Machines is developing an integrated RGBM computer module for their PRISM family of closed circuit (CCR) rebreathers (RBs). ABYSS, GAP, and Hydrospace Simulator are full up RGBM software packages with application to all diving, air to mixed gases, sea level to altitude, decompression to nonstop, and single to repetitive.

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. Count on it.

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 other major RGBM implementation projects in the works for meters and software packages.

The USN is factoring information from RGBM into deep stop man trials at NEDU in Panama City, for air and/or nitrox exposures in the 150+ fsw range. Such testing is monumental for the USN to to say the least.

The RGBM extends earlier work of the Tiny Bubble Group at the University of Hawaii, updating missing physics and extending their early work to multidiving, 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. Differences focalize, in a word or two, on source generation mechanisms and persistence time scales for bubbles and seeds, bubble structural mechanics and materials, consistent treatment of all bubble expansion and contraction venues, and real world testing.

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).

The computational issues of bubble dynamics (formation, growth, and elimination) are mostly outside Haldane framework, but get folded into halftime specifications in a nontractable mode. The very 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, however, do not behave the same way under decompression. Care must be exercised in applying model equations to each component. In the 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 become necessary for optimality. Considerations of excitation and growth invariably require deeper staging procedures than supersaturation methods. Though not as dramatic, similar constraints remain operative in multiexposures, that is, multilevel, repetitive, and multiday diving.

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, Mares, Dacor, Hydrospace, Steam Machines, Zeagle, Plexus, GAP, and ABYSS implementations, and imbedded in released NAUI, ANDI, and RGBMdiving.com Tables:

1. 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 linearily with pressure for constant composition breathing mixture, and decreases linearily 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, Mares, Dacor, Hydrospace, Steam Machines, Zeagle, 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.

2. 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 extravasular 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 thin 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 of the surfactants coating the inside of the bubble. Material behavior can vary from thin elastic films to almost solid shell beebees,

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, impacting repetitive, reverse profile, multiday, altitude, and gas mixes on varying time scales. Colloidal particles are not the stabilizing material inside seeds and bubbles.

3. Temperature

   Bubbles are affected by temperature much like gases, but only coupled through skin EOS of the material surrounding the gases inside the bubbles. Broadly speaking, bubbles will expand with temperature increases, and contract with temperature decreases, all subject to skin behavior, and material properties of same.

   The effects of temperature over nominal water temperatures and diving activities are small, especially since body core temperatures and those of surrounding tissues and blood vary little under changes in outside temperature. Some data support higher DCS incidence rates for divers undergoing both warm-to-cold and cold-to-warm temperature switches following diving. But more reliable data support higher DCI incidence in warm environment versus colder ones. Naval Special Warfare suggests that underwater operations in temperature zones above 90 F^o pose higher risks to SEALs. Divers salvaging TWA 200 in hot suits exhibited a higher

proportion of DCS than those in wetsuits. Back in the early 50s, USN studies suggested that divers in colder waters (45 C^o) had lower DCS incidence rates than divers in warmer waters (73 C^o).

Still, cold divers are expected to eliminate inert gases slower than warm divers, and so risk of DCS might increase in divers who are cold following exposure. Doppler studies by Dunford and Hayward in the early 80s confirm the presence of more VGE in warm divers versus cold divers. Of course, if DCS correlates with Doppler score, these warm divers should be at higher risk. And they were not. Studies by NEDU in Panama City also suggest that cold water divers are at higher DCS risk than warm water divers for the same profiles. These studies are still underway.

The RGBM treats temperature explicitly in skin EOS and staging regimens. Warmer temperatures promote larger bubbles and bubble seeds. Colder temperatures, however, in warm-to-cold temperature switches also provide a fracture mechanism for skins through the EOS. The fracture mechanics suggest a means to bubble depletion in the model. Cold water also results in slower gas elimination in the RGBM.

4. 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. 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 anbient pressure. The size of seeds excited into growth is inversely proportional to the supersaturation gradient. RGBM excitation radii, r, start in the 0.01 μm 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). 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 interfriction, and persistence time scales range from minutes to tens of hours.

5. 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 multidiving 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 multidiving 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 slower compartments is a central focus in calculations over long time scales, and the same for fast tissue tissue compratments over short time scales, that is, scales over 2 or 3 times the compartment halftime.

6. 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 sugested by Spencer (and others), but within the phase volume constraint. The Mares, Dacor, and Suunto implementations penalize ascent violations by requiring additional safety stop time dictated by risk analysis of the violation. All RGBM implementations supply user knobs for aggressive to conservative diving modifications, thru EOS in the full versions and M-values in the Haldane folded algorithms. Doppler scores over surface intervals are employed to calibrate RGBM bubble factors, both short and long intervals.

7. Multidiving

   Concerns with multidiving 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 implement 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. Here 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 multidiving. In the RGBM, the phase volume depends on the number of seeds excited plus 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, multidiving 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 reduces the phase volume limit in multidiving 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.

8. 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 adapatation 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 adapatation 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 PROFILE DATA BANK

Divers using RGBM are reporting their profiles to a Data Bank, located at NAUI Technical Diving Operations (also LANL). The information requested is simple:

1. bottom mix, depth, and time (square wave equivalent);
2. ascent and descent rates;
3. stage and decompression mixes, depths, and times;
4. surface intervals;
5. time to fly;
6. diver age, weight, and sex;
7. outcome (health problems).

This information aids in further validation and extension of model application space. Approximately 2,300 profiles now reside in the RGBM Data Bank. These profiles come from the technical diving community mostly, essentially mixed gas, extended range, decompression, and extreme diving. Profiles from the recreational community are not included, unless they are involve extreme exposures on air or nitrox (many repetitve dives, deeper than 150 fsw, altitude exposures, etc). Approximately 20 DCS profiles reside in the RGBM Data Bank, mainly within repetitive deco diving on nitrox, and reverse profiles.

NAUI Tec Instructors are a special class of users/testers, and have been over the past 5 - 7 years or so. They are largely responsible for the success and release of NAUI RGBM Tables.

RGBM FIELD TESTING

Models need field 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, meters, and software. These profiles are recorded in the RGBM Data Bank, and represent a random sampling and dive count over the full base (*RGBMdiving.com*).

1. 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 repets (no deco) with at least 2 hr SIs, and in the forward direction (deepest dives first);

2. 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;

3. NAUI Worldwide released a set of no-group, no-calc, no-fuss RGBM Tables for air, EAN32, and EAN36 recreatational 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 Insructor Trainers, Instructors, and Divemasters over a 2 year period without mishap;

4. modified RGBM recreational algorithms (Haldane imbedded with bubble reduction factors limiting reverse profile, repetitive, and multiday diving), as coded into Suunto, Mares, Dacor, ABYSS, GAP, 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);

5. 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;

6. within decometer implementations of the RGBM, not a single DCS hit has been reported in nonstop and multidiving categories, beyond 300,000 dives or more, up to now;

7. extreme chamber tests for mixed gas RGBM are in the works, and less stressful exposures will be addressed shortly – extreme here means 300 fsw and beyond;

8. 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);

9. 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).

10. ABYSS is a NET sotware package that offers the modified RGBM (folded over the Buhlmann ZHL) and, especially, 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;

11. 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;

12. extreme WKPP profiles in the 300 fsw 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;

13. Ellyat, a TDI Instructor, dived the Baden in the North Sea to 520 fsw on RGBM Tables on two different occasions, and is planning a 620 fsw 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;

14. NAUI Worldwide released sets of deep stop RGBM nitrox, heliox, 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,

15. Doppler and imaging tests in the laboratory, and analyses by Bennett, Marroni, Brubakk and Wienke, and Neuman all suggest reduction in free phase counts with RGBM staging;

16. Gozum, a DAN diving doctor, performed 37 repetitive air dives over 7 days, out to the NDLs, using the Suunto/VYTEC RGBM computer, and reported feeling better than on pure Haldane schedules;

17. Freauf, a Navy SEAL in Hawaii, logged 20 trimix decompression dives beyond 250 fsw on consecutive days using RGBM Tables (pure oxygen switch at 20 fsw);

18. Scorese, a NAUI Instructor, and his students made 34 dives on the Andrea Doria with rebreathers and RGBM (constant $ppO2$) Tables on nitrogen and trimix diluents. Aborted dives employed RGBM (open circuit) Tables as bailouts, and witnessed no mishaps;

19. Gerth, a USN researcher at NEDU, found that deep stops are necessary and cost effective for air and nitrox Navy divers, that is, risk versus decompression time;

20. more will be added when I get time here – including your input requested over NAUI Tec Yahoo.

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.

SUMMARY

The RGBM departs from other models in a number of ways, abandoning laboratory media parameterizations. Colloidal suspensions, such as gel, are far different than aqueous and lipid materials coating bubbles and seeds in the body. Additionally, typical gel-type micronuclei, with persistence time scales of tens of hours to days, have never been found in the body in any circumstance. Present wisdom suggests that seeds are produced by tribonucleation (tissue friction). 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 by diffusion. Depending on time scales and rate coefficients, one or another (or both) processes dominate the exchange. However, for most

meter 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 model includes this debt in calculations.

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.

The RGBM postulates bubble seeds with lipid or aqueous skin structure. Bubble skins are assumed permeable under all crushing pressure. The size of seeds excited into growth is inversely proportional to the supersaturation gradient. At increasing pressure, bubble seeds permit gas diffusion at a slower rate. The model 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 model assumes the size distribution is exponentially decreasing in size, that is, more smaller seeds than larger seeds in exponential proportions. The RGBM also employs an equation-of-state for the skin surfactants, linked to lipid and aqueous biophysical structures. Gas diffusion across the bubble film interface, and Boyle expansion and contraction under ambient pressure change are also tracked in the RGBM.

In tracking seed excitation and number, gas transport into and out of bubbles, and Boyle-like expansion and contraction under pressure changes, the RGBM incorporates a spectrum of tissue compartments, ranging from 1 min to 480 min, depending on gas mixture (helium, nitrogen, oxygen). Phase separation and bubble growth in all compartments is a central focus in calculations, over appropriate time scales, and the model uses nonstop time limits tuned to recent Doppler measurements, conservatively reducing them along the lines originally sugested by Spencer (and others), but within the phase volume constraint.

The Haldane folded RGBM reduces the phase volume limit in multidiving 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. The model generates bubble seed distributions on time scales of minutes to hours, adding new bubbles to existing bubbles in calculations. Phase volume limit points are also reduced by the added effects of new bubbles. In the Haldane folded algorithm, deep stops can be injected into staging procedures with a simple time-depth scaling law correlated with calculations from the full iterative RGBM model.

The modified (folded) RGBM extends the classical Haldane model to repetitive diving, by conservatively reducing the gradients, G. A conservative set of bounce gradients, G, can always be used for multiday and repetitive diving, provided they are multiplicatively reduced by a set of bubble factors, all less than one. Three bubble factors reduce the driving gradients to maintain the phases volume constraint. The first bubble factor reduces G to account for creation of new stabilized micronuclei over time scales of days. The second factor accounts for additional micronuclei excitation on reverse profile dives. The third bubble factor accounts for bubble growth over repetitive exposures on time scales of hours.

The RGBM (both versions) is a diveware implementation, accessible on the Internet at various sites. Additionally, the RGBM has been encoded into a number of commercial decompression meter products. Specific comparisons between RGBM and Haldane predictions for staging are summarized, with resultants generic for phase versus dissolved gas models. NAUI uses RGBM Tables for trimix, helitrox, nitrox, and altitude dive training.

The RGBM has witnessed testing and validation across technical and recreational diving sectors the past 5 yrs or so, and its record is exemplarary. Deep stops with shorter overall decompression

times, and the use of helium for extended exposures are revolutions of sorts in the technical diving community. And the RGBM promotes both naturally and on first principles, because of coupled free and dissolved gas phase treatments.

An RGBM Data Bank has been established for mixed gas and decompression diving, plus extreme recreational air and nitrox, plus altitude exposures. Profiles stored in the Bank are used to extend the RGBM validation envelope, certify risk analysis, and offer technical divers information on actual exposure profiles.

REFERENCES

1. *Adamson A.W., 1976, The Physical Chemistry Of Surfaces, New York: John Wiley And Sons.*
2. *Batchelor G.K., 1953, Theory Of Homogeneous Turbulence, New York: Cambridge University Press.*
3. *Bateman J.B. and Lang J., 1945, Formation And Growth Of Bubbles In Aqueous Solutions, Canad. J. Res. E23, 22-31.*
4. *Behnke A.R., 1967, The Isobaric (Oxygen Window) Principle Of Decompression, Trans. Third Annual Conf. Marine Tech, Soc. 1, 213-228.*
5. *Behnke A.R., 1945, Decompression Sickness Incident To Deep Sea Diving And High Altitude, Medicine 24, 381-402.*
6. *Bennett P.B. and Elliot D.H., 1996, The Physiology And Medicine Of Diving And Compressed Air Work, London: Bailiere Tindall and Cassell.*
7. *Berghage T.E. and Durman D., 1980, US Navy Air Recompression Schedule Risk Analysis, Nav. Med. Res. Bull. 1, 1-22.*
8. *Boycott A.E., Damant G.C.C., and Haldane J.S., 1908, The Prevention Of Compressed Air Illness, J. Hyg. 8, 342-443.*
9. *Buckles R.G., 1968, The Physics Of Bubble Formation And Growth, Aerospace Med. 39, 1062-1069.*
10. *Buhlmann A.A., 1984, Decompression/Decompression Sickness, Berlin: Springer Verlag.*
11. *Conkin J. and Van Liew H.D., 1991, Failure Of The Straight Line Boundary Between Safe And Unsafe Decompressions When Extraoplated To The Hypobaric Regime, Undersea Biomed. Res. 18, 16.*
12. *Des Granges M., 1957, Repetitive Diving Decompression Tables, USN Experimental Diving Unit Report, NEDU 6-57, Washington DC.*
13. *Duffner G.J., Synder J.F., and Smith L.L., 1959, Adaptation Of Helium-Oxygen To Mixed Gas Scuba, USN Experimental Diving Unit Report, NEDU 3-59, Washington, DC*
14. *Dwyer J.V., 1956, Calculation Of Repetitive Diving Decompression Tables, USN Experimental Diving Unit Report, NEDU 1-57, Washington DC.*
15. *Eckenhoff R.G., Olstad C.E., Parker S.F. and Bondi K.R., 1986, Direct Ascent From Shallow Air Saturation Exposures, Undersea Biomed. Res. 13, 305-316.*

16. *Epstein P.S. and Plesset M.S., 1950, On The Stability Of Gas Bubbles In Liquid-Gas Solutions, J. Chm. Phys. 18, 1505-1509.*

17. *Evans A. and Walder D.N., 1969, Significance Of Gas Macronuclei In The Aetiology Of Decompression Sickness, Nature London 222, 251-252.*

18. *Fisher J.C., 1948, The Fracture Of Liquids, J. Appl. Phys. 19, 1062-1067.*

19. *Frenkel J., 1946, Kinetic Theory Of Liquids, New York: Oxford University Press.*

20. *Gernhardt M.L., Lambertsen C.J., Miller R.G., and Hopkins E., 1990, Evaluation Of A Theoretical Model Of Tissue Gas Phase Growth And Resolution During Decompression From Air Diving, Undersea Biomed. Res. 17, 95.*

21. *Hamilton R.W., 1975, Development Of Decompression Procedures For Depths In Excess Of 400 Feet, Undersea And Hyperbaric Medical Society Report, WS: 2-28-76, Bethesda.*

22. *Harvey E.N., Barnes D.K., McElroy W.D., Whiteley A.H., Pease D.C., and Cooper K.W., 1944, Bubble Formation In Animals. I. Physical Factors, J. Cell. Comp. Physiol. 24, 1-22.*

23. *Harvey E.N., Whiteley A.H., McElroy W.D., Pease D.C., and Barnes D.K., 1944, Bubble Formation In Animals. II. Gas Nuclei And Their Distribution In Blood And Tissues, J. Cell Comp. Physiol. 24, 23-24.*

24. *Harvey E.N., McElroy W.D., Whiteley A.H., Warren G.H., and Pease D.C., 1944, Bubble Formation In Animals. III. An Analysis Of Gas Tension And Hydrostatic Pressure In Cats, J. Cell. Comp. Physiol. 24, 117-132.*

25. *Hempleman H.V., 1957, Further Basic Facts On Decompression Sickness, Investigation Into The Decompression Tables, Medical Research Council Report, UPS 168, London.*

26. *Hempleman H.V., 1952, A New Theoretical Basis For The Calculation Of Decompression Tables, Medical research Council Report, UPS 131, London.*

27. *Hennessy T.R. and Hempleman H.V., 1977, An Examination Of The Critical Released Gas Concept In Decompression Sickness, Proc. Royal Soc. London B197, 299-313.*

28. *Hennessy T.R., 1974, The Interaction Of Diffusion And Perfusion In Homogeneous Tissue, Bull. Math. Biol. 36, 505-527.*

29. *Hills B.A., 1977, Decompression Sickness, New York: John Wiley And Sons.*

30. *Hills B.A., 1968, Variation In Susceptibility To Decompression Sickness, Int. J. Biometeor. 12, 343-349.*

31. *Hills B.A., 1968, Relevant Phase Conditions For Predicting The Occurrence Of Decompression Sickness, J. Appl. Physiol. 25, 310-315.*

32. *Hirschfelder J.O., Curtiss C.F., and Bird R.B., 1964, Molecular Theory Of Gases And Liquids, New York: John Wiley And Sons.*

33. *Keller H. and Buhlmann A.A., 1965, Deep Diving And Short Decompression By Breathing Mixed Gases, J. Appl. Physiol. 20, 1267.*

34. *Kunkle T.D. and Beckman E.L., 1983, Bubble Dissolution Physics And The Treatment Of Decompression Sickness, Med. Phys. 10, 184-190.*

35. *Lambertsen J.L. and Bornmann R.C., 1979, Isobaric Inert Gas Counterdiffusion, Undersea And Hyperbaric Medical Society Publication 54WS(IC)1-11-82, Bethesda.*

36. *Lang M.A. and Vann R.D., 1992, Proceedings Of The American Academy Of Underwater Sciences Repetitive Diving Workshop, AAUS Safety Publication AAUSDSP-RDW-02-92, Costa Mesa.*

37. *Lang M.A. and Egstrom G.H., 1990, Proceedings Of The American Academy Of Underwater Sciences Biomechanics Of Safe Ascents Workshop, American Academy Of Underwater Sciences Diving Safety Publication, AAUSDSP-BSA-01-90, Costa Mesa.*

38. *Lang M.A. and Hamilton R.W., 1989, Proceedings Of The American Academy Of Underwater Sciences Dive Computer Workshop, University Of Southern California Sea Grant Publication, USCSG-TR-01-89, Los Angeles.*

39. *Lehner C.E., Hei D.J., Palta M., Lightfoot E.N., and Lanphier E.H., 1988, Accelerated Onset Of Decompression Sickness In Sheep After Short Deep Dives, University Of Wisconsin Sea Grant College Program Report, WIS-SG-88-843, Madison.*

40. *Leitch D.R. and Barnard E.E.P., 1982, Observations On No Stop And Repetitive Air And Oxynitrogen Diving, Undersea Biomed. Res. 9, 113-129.*

41. *Le Messurier D.H. and Hills B.A., 1965, Decompression Sickness: A Study Of Diving Techniques In The Torres Strait, Hvaldradets Skrifter 48, 54-84.*

42. *Neuman T.S., Hall D.A. and Linaweaver P.G., 1976, Gas Phase Separation During Decompression In Man, Undersea Biomed. Res. 7, 107-112.*

43. *Nishi R.Y., Eatock B.C., Buckingham I.P. and Ridgewell B.A., 1982, Assessment Of Decompression Profiles By Ultrasonic Monitoring: No Decompression Dives, Defense And Civil Institute Of Environmental Medicine Report, D.C.IEM 82-R-38, Toronto.*

44. *Pease D.C. and Blinks L.R., 1947, Cavitation From Solid Surfaces In The Absence Of Gas Nuclei, J. Phys. Coll. Chem. 51, 556-567.*

45. *Pilmanis A.A., 1976, Intravenous Gas Emboli In Man After Compressed Air Ocean Diving, Office Of Naval Research Contract Report, N00014-67-A-0269-0026, Washington, DC*

46. *Powell M.R., Waligora J.M., Kumar K.V., Robinson R., and Butler B., 1995, Modifications Of Physiological Processes Concerning Extravehicular Activity In Microgravity, Engineering Society For Advanced Mobility Land Sea And Space International Technical Series Report 951590, Warrendale.*

47. *Powell M.R., Waligora J.M., Norfleet W.T., and Kumar K.V., 1993, Project ARGO – Gas Phase Formation In Simulated Microgravity, NASA Technical Memo 104762, Houston.*

48. *Powell M.R., 1991, Doppler Indices Of Gas Phase Formation In Hypobaric Environments: Time Intensity Analysis, NASA Technical Memo 102176, Houston.*

49. *Sawatzky K.D. and Nishi R.Y., 1990, Intravascular Doppler Detected Bubbles And Decompression Sickness, Undersea Biomed. Res. 17, 34-39.*

50. *Schreiner H.R. and Hamilton R.W., 1987, Validation Of Decompression Tables, Undersea And Hyperbaric Medical Society Publication 74 (VAL), Bethesda.*

51. *Sears, F.W., 1969, Thermodynamics, Reading: Addison Wesley.*

52. *Sheffield P.J., 1990, Flying After Diving, Undersea And Hyperbaric Medical Society Publication 77 (FLYDIV), Bethesda.*

53. *Smith K.H. and Stayton L., 1978, Hyperbaric Decompression By Means Of Bubble Detection, Office Of Naval Research Report, N0001-469-C-0402, Washington DC*

54. *Spencer M.P., 1976, Decompression Limits For Compressed Air Determined By Ultrasonically Detected Blood Bubbles, J. Appl. Physiol. 40, 229-235*

55. *Spencer M.P. and Campbell S.D., 1968, The Development Of Bubbles In The Venous And Arterial Blood During Hyperbaric Decompression, Bull. Mason Cli. 22, 26-32.*

56. *Strauss R.H. and Kunkle T.D., 1974, Isobaric Bubble Growth: Consequence Of Altering Atmospheric Gas, Science 186, 443-444.*

57. *Tikuisis P., 1986, Modeling The Observations Of In Vivo Bubble Formation With Hydrophobic Crevices, Undersea Biomed. Res 13, 165-180.*

58. *Tikuisis P., Ward C.A. and Venter R.D., 1983, Bubble Evolution In A Stirred Volume Of Liquid Closed To Mass Transport, J. Appl. Phys. 54, 1-9.*

59. *Van Liew H.D. and Hlastala M.P., 1969, Influence Of Bubble Size And Blood Perfusion On Absorption Of Gas Bubbles In Tissues, Resp. Physiol. 24, 111-121.*

60. *Van Liew H.D., Bishop B, Walder P.D., and Rahn H., 1975, Bubble Growth And Mechanical Properties Of Tissue In Decompression, Undersea Biomed. Res. 2, 185-194.*

61. *Vann R.D., Grimstad J., and Nielsen C.H., 1980, Evidence For Gas Nuclei In Decompressed Rats, Undersea Biomed. Res. 7, 107-112.*

62. *Vann R.D. and Clark H.G., 1975, Bubble Growth And Mechanical Properties Of Tissue In Decompression, Undersea Biomed. Res. 2, 185-194.*

63. *Walder D.N., Evans A., and Hempleman H.V., 1968, Ultrasonic Monitoring Of Decompression, Lancet. 1, 897-898.*

64. *Walder D.N., 1968, Adaptation To Decompression Sickness In Caisson Work, Biometeor. 11, 350-359.*

65. *Weathersby P.K., Survanshi S. and Homer L.D., 1985, Statistically Based Decompression Tables: Analysis Of Standard Air Dives, 1950-1970, Naval Medical Research Institute report, NMRI 85-16, Bethesda.*

66. *Weathersby P.K., Homer L.D., and Flynn E.T., 1984, On The Likelihood Of Decompression Sickness, J. Appl. Physiol. 57, 815-825.*

67. *Wienke B.R., 2003, Reduced Gradient Bubble Model In Depth, Flagstaff: Best (in press).*

68. *Wienke B.R., 2001, Technical Diving In Depth, Flagstaff: Best.*

69. *Wienke B.R., 1992, Numerical Phase Algorithm For Decompression Computers And Application, Comp. Biol. Med. 22, 389-406.*

70. *Wienke B.R., 1991, Basic Decompression Theory And Application, Flagstaff: Best.*

71. *Wienke B.R., 1991, Bubble Number Saturation Curve And Asymptotics Of Hypobaric And Hyperbaric Exposures, Int. J. Biomed. Comp. 29, 215-225.*

72. *Wienke B.R., 1991, High Altitude Diving, National Association Of Underwater Instructors Technical Publication, Montclair.*

73. *Wienke B.R., 1990, Reduced Gradient Bubble Model, Int. J. Biomed. Comp. 26, 237-256.*

74. *Wienke B.R., 1990, Modeling Dissolved And Free Phase Gas Dynamics Under Decompression, Int. J. BioMed. Comp. 25, 193-205.*

75. *Wienke B.R., 1989, Equivalent Multitissue And Thermodynamic Decompression Algorithms, Int. J. BioMed. Comp. 24, 227-245.*

76. *Wienke B.R., 1989, Tissue Gas Exchange Models And Decompression Computations: A Review, Undersea Biomed. Res. 16, 53-89.*

77. *Wienke B.R., 1989, N_2 Transfer And Critical Pressures In Tissue Compartments, Math. Comp. Model. 12, 1-15.*

78. *Wienke B.R., 1987, Computational Decompression Models, Int. J. BioMed. Comp. 21, 205-221.*

79. *Wienke B.R., 1986, DECOMP: Computational Package For Nitrogen Transport Modeling In Tissues, Comp. Phys. Comm. 40, 327-336.*

80. *Wittenborn A.F., 1963, An Analytic Development Of A Decompression Computer, Proc. Second Symp. Underwater Physiol., Washington, DC: National Academy Of Science 1, 82-90.*

81. *Workman R.D., 1965, Calculation Of Decompression Schedules For Nitrogen-Oxygen And Helium-Oxygen Dives, USN Experimental Diving Unit Report, NEDU 6-65, Washington DC*

82. *Yang W.J., 1971, Dynamics Of Gas Bubbles In Whole Blood And Plasma, J. Biomech. 4, 119-125.*

83. *Yount D.E. and Hoffman DC, 1986, On The Use Of A Bubble Formation Model To Calculate Diving Tables, Aviat. Space Environ. Med. 57, 149-156.*

84. *Yount D.E., Gillary E.W., and Hoffman DC, 1984, A Microscopic Investigation Of Bubble Formation Nuclei, J. Acoust. Soc. Am. 76, 1511-1521.*

85. *Yount D.E., 1982, On The Evolution, Generation, And Regeneration Of Gas Cavitation Nuclei, J. Acoust. Soc. Am. 71, 1473-1481.*

86. *Yount D.E., 1979, Skins Of Varying Permeability: A Stabilization Mechanism For Gas Cavitation Nuclei, J. Acoust. Soc. Am. 65, 1431-1439.*