RGBM OVERVIEW AND UPDATE

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RGBM NITTY GRITTY ISSUES

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.

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.

RGBM DIVING NEEDS

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 notion of nucleation 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 utilitarian measures developed ad hoc style, having useful signatures for diving applications across the full spectrum of actvities. Or, said another way, bubble models appear 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.

RGBM IMPLEMENTATIONS

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).

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 LANL C & C Team employs the RGBM (last 13 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 say the least.

The site RGBMdiving.com hosts information on all apsects of RGBM. plus offers premixed and custom tables for technical and recreational diving. Check it out. A number of monographs on the RGBM have been also released by Best Publishing Company for the more fastidious reader.

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. The Table below collates diving activities by NAUI Tec for respondents to an RGBM Survey. At press time, some 10 - 15 % of NAUI Tec provided statistics. More information is gathering, and will contribute to final detailed statistical and risk analysis. Expect a longer report with names of contributors in the not too distant future.

NAUI Technical Diving RGBM Depth-Usage Tally

Depth Range	Total Dives
0 -100 fsw	8,166
100 - 200 fsw	6,128
200 - 300 fsw	1,136
300 - 400 fsw	441
400 - 500 fsw	31
500+ fsw	3

Tallies above include OC and RB dives, for both instructors and students. Thanks, NAUI Tec, for your input.

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. Bunches of these profiles are recorded in the RGBM Data Bank, and represent a random sampling and dive count over the full base (*RGBMdiving.com*).

1. LANL exercises have used the RGBM (full up iterative deep stop version) for a number of years, logging some 2245 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 4 yrs, some estimated 32,000 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, 2000 thru 2004;

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 deep/shallow 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;

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 800 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 in professional journals and diving circles; 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), plus RGBM Data Bank;

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 received only 1-2 reports of DCS since 1998;

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. 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 6 years, with success and no reported cases of DCS, for open circuit regulators and rebreathers,

14. 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, as reported in journals, trade magazines, and workshops;

15. Gozum, a 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;

16. 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);

17. Scorese, a NAUI Instructor, and his students, made 74 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;

18. 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;

19. Raine, a wreck diver in California, reports 100s of RGBM dives in the 250 fsw range with low Doppler scores;

20. Melton, owner of HydroSpace Emgineering and developer of the RGBM EXPLORER dive computer, plus a BOD member of CDS, reports 10s of dives in the 400+ fsw range on the RGBM EXPLORER;

21. GAP, an RGBM software product out of the Netherlands, supports brisk and sustained use of RGBM within the diving community;

22. ANDI has adopted a custom version of GAP for diver training on mixed gases.

There is more, but hopefully the above list gives a good flavoring of RGBM usage and viability.

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. Because of this, data collection projects like DAN Project Dive Exploration (PDE) and the RGBM Data Bank have come online in the past 6 - 8 years, ostensibly extending and augmenting manned testing and wet trials. While anecdotal data likely pervades the tec community, entries in DAN PDE and RGBM Data Bank are substantiated.