Reduced Gradient Bubble Model
A Modern Decompression Algorithm

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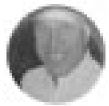
Dissolved Gas Modeling

The French physiologist, Paul Bert, first clinically described "bubble trouble" or caissons' disease in 1878. He determined that breathing air under pressure forced the nitrogen into solution in the tissues and blood of the body; and that as long as the pressure was constant, the nitrogen remained in solution. But when the pressure was rapidly released, the nitrogen would return to a gaseous state (free phase) much too rapidly to pass out of the body in a natural manner. This led Bert to the conclusion that divers and caisson workers needed to return to the surface slowly.

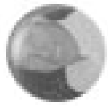
Although slower ascents certainly improved decompression for divers and caisson workers alike, some divers continued to suffer from "bubble trouble" (decompression sickness). At this time, there was a general feeling that the limit of diving was around 120 feet of sea water (36 msw).

In 1908, while working with the Royal Navy, the English physiologist John Scott Haldane composed a set of tables and schedules for diving at sea level. He observed that goats, when brought to the surface after being saturated to 165 feet of sea water (46 msw), did not develop decompression sickness (DCS) if subsequent decompression ceilings were limited to half the prior ambient pressure. Extrapolating these observations to humans, researchers reckoned that tissues tolerate elevated dissolved gas pressures (tensions), greater than ambient by a factor of two, before the onset of symptoms. Haldane then constructed schedules, which limited the critical supersaturation to two in hypothetical tissue compartments

A "compartment" is merely a mathematical model and does not directly correspond to any specific tissue in our bodies. The compartments were characterized by their half time (half life). That is, in this model, absorption or elimination of gas in tissues is at an exponential rate; in a given half time a compartment will gain (or lose) one-half of the total amount of inert gas that it could gain (or lose) at the present pressure of the gas. Within this model fast compartments control deep, short dives while slower compartments control shallower longer exposures. If pressure is increased, a "five minute" tissue compartment will be 50 percent saturated in five minutes, 75 percent saturated in 10 minutes, 87.5 percent saturated in 15 minutes, and essentially saturated in 30 minutes (six half times). Haldane used five compartments (five, 10, 20, 40, 75 minute half times), which were employed in decompression calculations for the next 50 years. An immediate result of Haldane's studies was an extension of the practical operating depth for air divers to around 200 feet.



At the same time Haldane was working on his dissolved gas model, Sir Leonard Hill was developing a model that advocated a slow uniform reduction in pressure to accommodate the slowest saturating tissue. Hill proposed that to prevent bubble growth, decompression depended on a maximum state gradient between tissue and environment (ambient) pressure. This was a pressure differential (delta P) model and not the ratio as Haldane proposed. Sir Leonard Hill's work is called the "Critical Pressure Hypothesis". Sir Leonard Hill first questioned the wisdom of staged decompression vs. continuous uniform decompression since body tissues are more likely to act in an "analog" than a "digital" manner. This would appear very similar to the saturation tables that were developed by Lambertsen and others that are still in use today. In the past, the difference in applicability between Haldane and Hill was whether or not exposures were short or long, relatively shallow or deep. Neither model would work for all applications, however, had Hill's work been more universally accepted, deeper stops and slower ascents might have been commonplace decades before now.




In 1937, the U.S. Navy then developed its own set of tables. The major difference of the USN tables was the assignment of separate limiting tensions (maximum or "M" values) to each individual compartment. Simply put, the M-value is the maximum allowable nitrogen pressure in a specific theoretical tissue within the decompression model. Later, in the 1950s and early 1960s, other U.S. Navy investigators, in addressing

repetitive dive exposures, advocated the use of six half-time compartments (five, 10, 20, 40, 80, 120 minutes) in constructing decompression schedules, with each tissue compartment again possessing its own limiting tension (M-value). The tables are still in use by the U.S. Navy and many certification agencies today.

The modern Royal Navy Tables are also descendants of Haldane's early work. However, they provide more conservative limiting tensions (M-values) than the United States Navy and they provide more conservative repetitive dive procedures.

Professor A. A. Buhlmann also utilized Haldane's theory with 16 half time compartments ranging from 2.65 to 635 minutes. Many of the dive computers designed over the last six years are utilizing compartments with half times up to 720 minutes. This proliferation of compartments is a clue that we have not fully understood what is going on. Originally, Buhlmann employed an E-E algorithm (exponential ongassing and exponential offgassing) but later models employed E-L algorithms (exponential in-linear out) that stipulate that inert gas elimination is slower than uptake.

All biophysical models of inert gas transport and bubble formation try to prevent "bubble trouble". However, they differ on a number of basic issues that are still mostly unresolved today:

1. The rate limiting process for inert gas exchange, blood flow rate, or gas transfer across tissues,
2. The composition and location of critical tissues (or bends sites),
3. The formation and growth of bubbles,
4. The critical trigger point best delimiting the onset of symptoms such as the amount of dissolved gas in the tissues, volume of the bubbles, the number of bubbles within the unit tissue volume,
5. The very nature of the critical insult that causes the bends.

While these issues confront every modeler and table designer, they remain ambiguous and perplexing in application. These concerns translate into dilemmas for the decompression modelers and have limited or qualified their best efforts to describe decompression phenomena.

Dissolved gas models limit degrees of tissue saturation, assuming that gas exchange is controlled by circulatory rate of delivery (perfusion) or gaseous diffusion between blood and tissue. The exchange of inert gas in the Haldane model is driven by the local gradient, which is the pressure differential between dissolved gas in the arterial blood and the local tissue tension (dissolved gas pressure within the tissue).

Haldanean models will seek to maximize the rate of gas uptake or elimination by maximizing this gradient. Upon ascent, this model takes the diver from depth to as close to the surface as possible within M-value constraints. Any bubbles are now at their largest permissible cumulative volume and bubble (free phase) size for that depth or M-value. When compared to modern decompression models, some have observed that the Haldanean model appears to work more like a treatment table than a decompression table. This is because it treats larger cumulative volumes and bubble size with pressure in the shallow zone in lieu of increasing free phase (bubble) elimination at depth. Oher Haldanean critics note that contrary to a dissolved gas model, bubbles appear before the supersaturation ratio is met.

A New Look at Decompression Tables

Today, several groups of scientists have been saying that Haldane did not present all the answers. Their studies on the origin and growth of bubbles have formed the basis for new set of decompression algorithms and diving tables named the Reduced Gradient Bubble Model by Dr. Bruce Wienke. The problems that these scientists addressed were the gaps in our tables that have been left unexplained by Haldanean theory. Saturation diving at one extreme and bounce diving at the other fit neatly (but not simultaneously) into Haldane's theory. But over the years of use, gaps have appeared in the tables that remained unexplained by dissolved gas theory. On some exposures, Haldanean tables presented a higher incidence of bends. Table modelers to cover those circumstances, even when the revisions did not agree with Haldane's original calculations, would then revise the tables.

In recent years many changes and modifications have evolved in our use of diving tables such as shorter no-stop times, slower ascent rates and recommended safety stops. These modifications were developed through Doppler technology that detects a symptomatic bubble in the body, dive computer development, statistics, and a more conservative diving consensus among the community. All of these changes are supported on operational, theoretical and experimental grounds by phase modeling.

A New Era: Phase Modeling

Pearling fleets that operated in deep water off northern Australia employed Okinawa divers who

dived to depths of 300 fsw for as long as one hour, two times a day, six days a week, and 10 months out of the year. For their own economic concerns, they used diving schedules that were developed by trial and error and not by science. As reported by Brian Hills and Le Messurier in 1965, these divers began their staged decompression stops much deeper but with less overall decompression times than would have been required by Haldanean theory. The tables were developed empirically, but they worked.

Similar schedules and procedures also evolved in Hawaii, among diving fishermen according to Farm and Hayashi. Harvesting the oceans for food and profit, Hawaiian divers would make between eight and 12 dives a day to depths beyond 350 fsw. A typical dive series might start with a dive to 220 fsw, followed by two dives to 120 fsw and end with three or four more dives to less than 60 fsw with little or no surface intervals between dives. These dive profiles literally clobber conventional tables, but when analyzed using bubble and phase mechanics, these extreme profiles gain credibility.

In the mid 1980's, decompression bubble models began to gain some acceptance within the diving community from the work done by David Yount (Varying Permeabilty Model) Tom Kunkle (Surfactant Stabilized Model). While David Yount's work did begin to simplify the detailed physics of the gas nuclei, it did not quantify the formation and stabilization mechanisms for bubble seeds.

Phase mechanics as it pertains to diving begins with the concept that our body's tissues store persistent gas micronuclei over a time scale of minutes and hours. Micronuclei can be thought of as "bubble seeds." They have been demonstrated experimentally in agar, salmon and shrimp. These "bubble seeds" are about one micron in size and for comparison red blood cells measure three microns in size. While the origin of these "bubble seeds" is not fully understood they are thought to be caused from blood and tissue rubbing together (friction), gas in out intestines, exercise, mechanics of blood coursing through our circulatory system and even cosmic radiation and charged particles.

Micronuclei are stable when held at a fixed pressure but can become unstable when exposed to changes in pressure. These micronuclei are classified into families according to size and the characteristics of their surfactants. The surfactant is a bubble film surface of activated molecules that coats the bubble and are both lipid and aqueous. The composition of the surfactant affects the rate at which gas diffuses in and out of the bubble. The larger the micronuclei the more readily they will develop and grow into bubbles.

The establishment and growth of bubbles and possible bubble trouble involve a number of distinct yet overlapping steps:

1. The birth of the bubble,
2. The dissolved gas builds up within the body,
3. The excitation of the micronuclei and growth of the bubble from free phase (bubble) and dissolved phase interaction,
4. The aggregation of the bubbles,
5. The tissue damage and ischemia caused from both the aggregation and growth of the bubbles.

As pressure decreases on ascent, the dissolved gas, which is now at a higher pressure than the pressure within the bubble seed, begins to diffuse from tissues across the bubble boundary and into the seed interior. This increases the internal bubble pressure and causes the bubble to grow. RGBM then stages the diver at a permissible super saturation that has been fitted to laboratory observations, diver data, and maximum likelihood to risk. The permissible super saturation within RGBM continually changes with the equations of state for time, temperature and pressure.

The very tenet of Dr. Wienke's Reduced Gradient Bubble Model (RGBM) is to maintain the diver at depth to both crush bubbles and squeeze out the gas via diffusion across the surfactant. Since both the dissolved gas and the free phase (bubble) gas must be eliminated it becomes a playoff in staging the diver. RGBM determines a decompression rate that limits and tracks both the size as well as the cumulative volume of the bubbles during the ascent phase of the dive. This is done while using real equations of state to determine rate of diffusion through the bubble film surface and small-scale changes in the radius of the gas nuclei during compression-decompression This is a major breakthrough for decompression modeling.

Wienke's RGBM model is a dual phase approach to decompressing divers under wide array of conditions including multi-day, multi-level, repetitive, non-stop, altitude, decompression, mixed gas and saturation diving. RGBM assumes that during the compression phase of the dive, the "bubble seeds" are crushed to smaller sizes and apparently stabilize at their new reduced size. During the decompression phase of the dive, it is also assumed a certain critical radius will separate those bubbles that will grow from those bubbles that will contract. It is during this stage of the dive that RGBM defines the fundamental difference between free phase (bubble) modeling and dissolved gas modeling. RGBM gradients for the elimination of bubbles increase with depth. That is directly opposite to the dissolved-phase gradient that decreases with depth. RGBM minimizes bubble growth and cumulative volume (phase volume) during decompression while reducing physiological insult and overall decompression time.

Wienke has extended the Reduced Gradient Bubble Model over other bubble models to repetitive/multiday diving with three gradient reduction factors that are applied to both the size of the bubble and the cumulative volume of the bubbles. The first factor reduces the allowable gradient by accounting for new bubble seeds generated over a time scale of days. The second factor reduces the allowable gradient by allowing for the birth of additional bubble seeds generated on reverse diving profiles. The third factor reduces the allowable gradient by accounting for bubble growth during repetitive exposures on a time scale of hours, and this gradient was reduced with observable diffusion into bubbles during the first two hours of fast tissue compartments.

While RGBM is certainly changing the face of advanced diving protocols, at the recreational, non-stop level few changes will be evident to the untrained eye. But it is the correct physics of the RGBM that will reduce the effective risk of all levels of diving. In the recreational diving arena, RGBM will require mandatory safety stops, restrict deep dives with short surface intervals, and penalize no-stop limits on reverse dive profiles.

RGBM Validation, Testing, and Implementation:

The following are some important facts about RGBM validation and testing:

1. Los Alamos National Laboratory has used the RGBM (full up iterative deep stop version) for number of years, logging some 389 dives on mixed gas (trimix, heliox, nitrox) without incidence of DCI. Thirty five percent of these dives were decompression dives and 25 percent were repetitive dives without decompression with at least two hours surface intervals.

2. NAUI Technical Diving Operations has been diving the full up deep stop version for the past four years, with some 700 dives logged worldwide with a wide array of mixed gases from nitrox through trimix. Diving depths have ranged from 60 fsw to over 500 fsw without incidence. These dives have ranged from warm tropical Caribbean waters to the cold waters of northern Europe.

3. Modified RGBM recreational algorithms (Haldane imbedded with bubble reduction factors limiting reverse dive profiles, repetitive, and multiday diving), as coded into SUUNTO, ABYSS, HYDROSPACE ENGINEERING, ATOMIC AQUATICS, and PLEXUS dive computers lower and already low incidence rate of approximately 1/10,000 or less.

4. A cadre of divers and instructors in the mountainous New Mexico, Utah, and Colorado have been diving the modified (Haldane imbedded) RGBM altitude tables with an estimated 400 dives, without incidence. Again, this is not surprising since the altitude RGBM is slightly more conservative than the usual Cross correction used routinely to about 8,000 feet.

5. Within the dive computer implementations of the RGBM, not a single hit has been reported in the multi diving category. Up to now this encompasses several thousand dives.

6. Extreme chamber tests (300 fsw and beyond) for mixed gas RGBM are currently being run without incidence.

7. Recent experiments by Alf O. Brubakk of the University of Trondheim, Norway and Bruce Wienke of Los Alamos National Laboratory, New Mexico compared the effects of three different decompression schedules on pigs. They tested the standard Haldanean U.S. Navy model against two faster ascent rates congruent with the Reduced Gradient Bubble Model. The researchers tested whether or not the RGBM type profile would give effectively deeper decompression staging, with a resulting reduction in bubble expansion and growth of cumulative volume. The schedule that most closely resembled the RGBM model produced significantly fewer bubbles than any other profile tested. See: "The effect of in-water decompression profile on bubble formation after dives with surface decompression", Brubakk A.O., Wienke B.R. et al. (J. Appl. Physiol.).

An approach treating bubble nucleation, excitation, and growth in tissue and blood is termed bubble mechanical, because it focuses on bubble and their interactions with dissolved gas in tissue and blood. It is with this approach that NAUI Technical Operations will begin implementing the NAUI RGBM tables for recreational and technical diving alike.