Modern Approaches in Oceanography
and Petrochemical Sciences

DOI: 10.32474/MAOPS.2019.03.000154

ISSN: 2637-6652

Review Article

Downs and Ups of Decompression Diving: a Review

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Received: November 13, 2019 **Published:** December 02, 2019

Abstract

The question of deep and shallow decompression stops is interesting and fraught with controversy in diving circles and operations, training, exploration and scientific endeavors. Plus, fraught with some misunderstanding which is understandable as the issues are complex. We accordingly detail a short history of deep and shallow stops, physical aspects, staging differences, diving tests, models, data correlations, data banks, diver statistics and DCS outcomes for diving amplification. Pros and cons of deep stop and shallow stop staging are presented. Misinformation is corrected. Training Agency Standards regarding deep and shallow stops are included. A tabulation of well-known and popular dive computers and software algorithms is given. From diving data, tests, DCS outcomes, data banks and field usage, we conclude that both deep stops and shallow stops are safely employed in recreational and technical diving today. For diver safety this is important.

Keywords: Data banks; models; risk; correlations; tests; validation; profile downloads; statistics

Introduction

Real diving and decompression protocols presently accommodate both shallow and deep stop staging safely judging from recent experiment, data and collective diver outcomes. The record of tables, meters and diveware is a safe and sane one in both instances. One approach (shallow stops) treats the bubble and the other (deep stops) controls the bubble. Staging is thus a mini-max problem of doing both (eliminating dissolved gas and controlling bubble growth) optimally. Analyses are evolving and bubble models (BM) seem the best hope to accommodate both safely and sanely. Dissolved gas models (GM) are 100 yrs old and dynamically incomplete though devotees today apply patches such as GFs, Pyle stops, variable M-values or R-values and variants to deco schedules to mimic bubble behavior. Bubble models reduce to dissolved gas models in the limit of little phase separation (NDL diving). Let's take a closer look at both deep stops and shallow stops, models, history, data and scattered tests.

Shallow Stops

Haldane was commissioned in 1908 by the Royal Navy to investigate the problem of human air decompression by subjecting goats to high pressure and devising safe ascent protocols. Using tissue compartments in the halftime range 5-40 min and exponential tissue equations for dissolved gas buildup he suggested that safe decompressions from any depth need only restrict gas buildup across all compartments to twice the ambient pressure to allow safe ascent. This was called the 2 to 1 law. Later it was determined that the ratio need be increased and that each tissue compartment had its own ratio. Switching from ratios to permissible gas loadings in each compartment called M-values the staging algorithm evolved and changed in time mostly drive by Navies [1]. Limiting dissolved gas buildup by M-values using exponential tissue functions resulted in a staging strategy that always tried to bring the diver as close to the surface as possible (GM). The stop structure is consequently shallow across all tissue compartments which across the years has had an extended halftime range 5-240 min. Analyses and diving wet tests resulted in new DBs with requisite M-value modifications to accommodate diving trials and DCS outcomes [2-4]; Hennessy and Hemplmen [5] Walder [1,6]. Extension to helium mixtures followed in lockstep [7]. Shallow stops thus relate directly to Haldane and dissolved gas models (GM) used for staging over a span of a century or so [2,8,1,3]. Shallow stops have been extensively tested and validated since 1908 forming the nexus of diver staging until roughly the 1960s when open water and laboratory tests strongly suggested alternative staging and diving protocols. The history of testing and GM algorithm modifications is extensive since the time of Haldane and interesting in wet testing scope.

Submarine Escape Trials: In 1930, USN submarine personnel suggested that Haldane's 2 to 1 law was too conservative. Some 2143 dives were performed over 3 years and revaluation of the data resulted in higher decompression ratios for the fast compartments while the slower compartments stayed close to the Haldane limit.

USN Exceptional Exposure Tables: The standard USN Tables in 1956 were found to be problematic for deep dives to 300 fsw for long bottom times in the 2-4-hour range. To address this problem, the USN [1] introduced an 8 compartment Haldanian (GM) model with halftimes ranging 5-240 min and no repetitive diving allowed. The compilation addressed many of the shortcomings of earlier dissolved gas models and DB fits for deep and long decompression diving on air and helium. This work is monumental in diving importance.

Early Doppler: Ultrasound studies in 1970s portended the era of Doppler measurements to follow. Reductions in air NDLs [9] were published and implemented in tables of the time. Interestingly, Doppler also suggested that deep stops reduced bubble counts dramatically [10,11] also portending the upcoming deep stop evolution and bubble model growth and meter implementation.

VVAL18 Compilation: The recent VVAL18 synthesis [12] by USN investigators is both a massive undertaking and update to USN diving data and operational protocols. With a data base of many 1000s of dives, Thalmann correlated a linear-exponential model (LEM) to data [12] and all present USN Tables and protocols are based on it. Some impetus for this undertaking was a need for safe constant ppO2 staging regimens after traditional GM approaches proved unsafe. The USN LEM is an exponential gas uptake and linear gas elimination GM model whereas traditional GM algorithms are exponential in both gas uptake and elimination. Linear gas elimination is slower than exponential gas elimination. In marketed dive computers, the same effect of slowing outgassing can be accomplished by increasing tissue halftimes whenever instantaneous total gas tension is greater than ambient pressure in what is called the asymmetric tissue model (ATM) [13,14]. Longer tissue halftimes slow outgassing resulting in increased dissolved gas loadings and subsequent decompression debt. Asymmetric gas uptake and elimination can be applied to any GM or BM protocol with the same result. In the case of BM algorithms, slower outgassing contributes to bubble growth with increasing decompression requirements. A later impetus was the need for a USN dive computer for SEAL Team operations and recorded higher incidence of DCS in very warm waters. This compilation of shallow stop data is a very important undertaking in recent diving history.

Deep Stops

Deep stops track more recently to Hills and phase models (BM). Haldane as mentioned above also found that deep stops where necessary in his early tunnel work Golding. It was real diving that initially tweaked interest in deep stops which was something of heresy before the1960s.

Australian Pearl Divers: Pearling fleets operating in the deep tidal waters off Northern Australia employed Okinawan divers who regularly journeyed to depths of 300 fsw for as long as one hour, two times a day, six days per week and ten months out of the year. Driven by economics and not science these divers developed optimized decompression schedules empirically even with the sad loss of 1000s of lives. What a wet test. As reported and analyzed by LeMessurier and Hills, deeper decompression stops but shorter decompression times than required by Haldane theory were characteristics of their profiles [15]. Recorders placed on these divers attest to the fact. Such protocols are consistent with minimizing bubble growth and the excitation of nuclei through the application of increased pressure. Even with a high incidence of surfacing decompression sickness following diving, the Australians devised a simple but very effective in-water recompression procedure. The stricken diver is taken back down to 30 fsw on oxygen for roughly 30 min in mild cases, or 60 min in severe cases. Increased pressures help to constrict bubbles while breathing pure oxygen maximizes inert gas washout (elimination). Recompression times scale as bubble dissolution experiments in the lab [16] which is extraordinary.

Hawaiian Diving Fishermen: Similar schedules and procedures evolved in Hawaii among diving fishermen according to Farm and Hayashi [17]. Harvesting the oceans for food and profit, Hawaiian divers make between eight and twelve dives a day to depths beyond 350 f sw. Profit incentives induce divers to take risks relative to bottom time in conventional tables. Repetitive dives are usually necessary to net a school of fish. Deep stops and shorter decompression times are characteristics of their profiles. In step with bubble and nucleation theory, these divers make their deep dive first, followed by shallower excursions. A typical series might start with a dive to 220 fsw followed by two dives to 120 fsw and culminate in three or four more excursions to less than 60 fsw. Often little or no surface intervals are clocked between dives. Such types of profiles literally clobber conventional GM tables but with proper reckoning of bubble and phase mechanics acquire some credibility. With ascending profiles and suitable application of pressure, gas seed excitation and bubble growth are likely constrained within body capacity to eliminate free and dissolved gas phases. In a broad sense, the final shallow dives have been tagged as prolonged safety stops and the effectiveness of these procedures has been substantiated in vivo (dogs) by Kunkle and Beckman [18,19]. In-water recompression procedures similar to the Australian regimens complement Hawaiian diving practices for all the same reasons. Australian and Hawaiian diving practices ushered in a new era of diving practices especially deep stops and related protocols. And this diving was real world and certainly not academic in scheduling. The early thermodynamic model (TM) of Hills played heavily in analyses of these dives as published and analyzed in excellent sources [20] Hennessy and Hempleman. Profile and model comparisons can be seen therein. As might be expected this caused quite a stir then with opposition almost religious in some quarters. That is certainly strange when you look at the collective practices of pearl and fishing deep divers applying the diving idiom "what works, works" [3,21].

Open Ocean Deep Stop Trials: Starck and Krasberg in open ocean conducted a series of important deep stop tests [22]. In deep waters in over 800 dives for up to an hour and down to 600 fsw they recorded only 4 DCS cases. Extensions to 800 fsw followed. This effort was part of a massive program to test new RB designs. The impact at the time was notable and still is today across the full spectrum of diving.

Recreational 1/2 Deep Stops and Reduced Doppler Scores: Analysis of more than 16,000 actual dives by Divers Alert Network (DAN) prompted suggestions that decompression injuries are likely due to ascending too quickly [23]. Bennett found that the introduction of deep stops, without changing the ascent rate, reduced high bubble grades to near zero from 30.5% without deep stops. He concluded that a deep stop at half the dive depth should reduce the critical fast gas tensions and lower the DCS incidence rate. Earlier Marroni concluded studies with the DSL European sample with much the same thought [24]. Although he found that ascent speed itself did not reduce bubble formation, he suggested that a slowing down in the deeper phases of the dive (deep stops) should reduce bubble formation. Both have been conducting further tests along those lines. The Bennett and Marroni findings were formally incorporated into NAUI Recreational Air and Nitrox Tables [25] for both conventional USN and No Group RGBM Tables. The recreational regimen adopted for nonstop and light decompression diving in the NAUI Tables is straightforward and simple:

1) make a 1 min stop at 1/2 bottom depth;

2) make a 2 min stop at 1/4 bottom depth and if necessary and deeper than 160 fsw;

3) make a 3 min stop at 1/8 bottom depth and all 1/2 deep stops made within any requisite light decompression schedules Shallow safety stops [21] are also made inside the deep stop recreational regimes. Obviously shallow safety and 1/2 deep stops can overlap in the 20-30 fsw range.

Trondheim Pig Decompression Study: Brubakk and Wienke also found that longer and shallower decompression times are not always better when it comes to bubble formation in pigs [26]. They found more bubbling in chamber tests when pigs were exposed to longer but shallower decompression profiles, specifically staged shallow decompression stops produced more bubbles than slower (deep) linear ascents. RGBM model predictions of separated phase under both types of decompression staging correlated with medical imaging. Correlation of models and test data are always sought in real life and diving is an important case.

Duke Chamber Experiments: Bennett and Vann used a linear diffusion (TM variant) model to improve stops in a dive to 500 fsw for 30 min which proved DCS free in chamber tests at Duke [27]. The early TM of Hills however at the time suggested dropout in the shallow zone which was troublesome in tests and was later modified with additional shallow decompression time. BMs today while making necessary model deep stops also require time in the shallow zone (10-30 fsw). Unfortunately, premature dropout in the shallow zone may have discredited deep stop models especially the TM. That doesn't happen anymore in bubble models.

ZHL and RGBM DCS Computer Statistics: An interesting study by Balestra of DAN Europe (DSL) centered on DCS incidence rates in dissolved gas, shallow stop (ZHL) computers versus bubble model, deep stop (RGBM) computers [28]. In 11,738 recreational dives, a total of 181 DCS cases were recorded and were almost equally divided between the ZHL and RGBM computers, that is, the ZHL incidence rate was 0.0135 and the RGBM incidence rate was 0.0175. Clearly both RGBM and ZHL computers are nominally safe at roughly the 1% DCS level in this wet test. DCS rates for both computers, however, are higher than published DAN recreational rates nearer 0.1% or so.

Pyle Stops: Richard Pyle is a diving fish specimen collector out of the Bishop Laboratory at the University of Hawaii who pioneered the ad hoc practice of making deep stops at multiples of half the bottom depth for a few minutes or so. Stops were interposed on standard deco regimens like the USN, ZHL, VPM and RGBM for a minute or so at the first half stop and up to a few minutes at successively shallower later stops at 1/4, 1/8, etc multiples of the bottom depth. These stops were made on top of any requisite deco stops. Except for recreational diving, nothing has been tested or correlated for this half stop approach, but Pyle apparently uses the protocol safely in his fish collecting ventures. In the recreational arena, the Doppler tests of Bennett and Marroni described above certainly support the Pyle half stop approach. For this reason, technical divers quickly adopted and extended Pyle half stops across mixed gas, OC and RB deco diving. It remains one of the few apparently successful ad hoc deep stop procedures backed up with some Doppler measurements.

Computer downloads

Computer downloaded profiles serve as a global set of diving outcomes across all diving venues and provide statistical data that can never be reproduced in chambers, wet pods and open ocean testing because of cost and diversity. The low incidence rates in these collections suggest that divers on computers are not at high risk, DCS and oxtox spikes are nonexistent, models and algorithms are safe and divers are using them sensibly [29].

LANL DB: With a low prevalence of deep stop DCS hits in the LANL DB (28/3569), some regard the downloaded profiles as a wet test of real OC and RB diving. While low incidence rates are beneficial to divers, low incidence rates make statistical analysis more difficult. With the incidence rate so low in the LANL DB, the (low p) Weibull function [30] is a more economical descriptor of the bends distribution than the canonical binomial distribution. The DCS incidence rate in the LANL DB is 28/3569, less than 1%.

DAN DB: Like the LANL DB the massive DAN DB can also be regarded as an extended wet test for air and nitrox diving. Mixed gas and altitude profiles are also being included at last reading. With a low incidence rate (80/18745) the DAN DB underscores the relative safety of recreational air and nitrox diving. Both GM and BM profiles are stored. The collection obviously grows daily under ambitious collection of computer profile downloads with DCS outcomes by DAN and DSL.

Issues

Model correlations and validation

With paucity of DCS outcome data across the full spectrum of diving it is very difficult to validate decompression models. Unlike scientific experiments in a laboratory under controlled conditions diving varies across OC and RB systems, gas mixtures, altitude, physiological and environmental factors, depth and time and each has its own set of subtle impacts on the diver. There will never be enough time and money to characterize diving outcomes across the full spectrum of possibilities, but some testing and model correlations have been useful over limited ranges of diving as described in the foregoing. As seen the only correlated and validated models are USN, ZHL, VPM and RGBM.

Staging pros and cons

The full ascent schedule of any deco strategy is equally as important as the first stop and in fact must be consistently followed after the first stop using models or protocols tuned to global diving data and not just isolated and disjoint experiments or tests. This is the problem with tests that arbitrarily interpose a deep stop some point on a schedule, continue with the rest of the schedule (usually dissolved gas) and get widely varying Doppler counts and outcomes. It is simply a question of staging consistency and not disjoint experiments and ad hoc stop insertions. Of course, to have a consistent ascent strategy (first stop plus ascension levels) you need a correlated model. Not GFs or Pyle stops. Random deep stops inserted into shallow stop schedules are inconsistent and of little use for staging analysis except to say "don't do this" when something happens. Some of the early and later deep stop tests suffer in this respect (Pyle, French Navy, Spisni, Ljubkovic just for example). It is hit or miss as far as gas transport is concerned and not always consistent further up the ascent schedule. One chamber or wet pod test of a profile is not necessarily definitive against the full spectrum and set of actual mixed gas, OC and RB, altitude and sea level, deco and nonstop diving outcomes and it does not follow that all other diving is the same. One test is not the whole of diving and is thus differential not integral as needed in experimental science (French Navy, NEDU, Ljubkovic, Spisni again just for example). This is why DAN, DSL and LANL use the global approach (as many diving profiles and DCS or Doppler outcomes as possible across all diving) in constructing optimal ascent strategies (models, tables, software). Such requires high powered computers and sophisticated statistical software not always accessible [31,32].

Published results of deep stop Doppler scores vary all over the map and are not necessarily indicative of DCS stress [33,34]. Same of course said about shallow stops. Across all staging regimens, Doppler correlates weakly with DCS incidences excepting limb bends (maybe). Thus, DCS outcomes as a final metric appear superior to Doppler counts for developing ascent staging procedures and correlating models. Not that high Doppler scores are being dismissed here. Of course, DCS varies all over the body making things more complicated. But DCS outcomes are the bottom line on staging no matter what disjoint and scattered wet and dry tests claim about diving in general. Such is the approach taken in real operational diving quarters and used to fabricate diving regimens and tables from basic and complete staging models. Shallow stops are basically medical contraindications while deep stops come from laboratory studies and bubble model correlations fitted within medical inventions. Both certainly work safely as witnessed by the plethora of deep stop and shallow stop tables, meters, software and dive protocols utilized by divers at all levels over many years. Here (LANL) we have many thousands of deep stop and shallow stop computer downloaded profiles and DCS outcomes with the overall incidence rates of both below 1%. That is good for divers but not necessarily statistics. To cure some of the statistical limitations, packages that are built on low DCS incidences (low p) are used and helpful. Focus is operational diving and the need to get a job done safely and timely outside and independent of conflicting opinion, tests, Doppler, models and arbitrary rules. Again, such requires high powered computers and attendant statistical software.

To say bubble models have not been tested and validated is false. Differential chamber tests certainly are absent in number but deep stops and bubble models (VPM and RGBM) have been validated and correlated over the past 20 yrs using computer downloaded profiles from DBs and comparative results published [35, 13,14]. Tests support their viability as well as Agency testing for training purposes [25]. Deep stop tests and correlations are fewer in number than shallow stop tests but are growing. And the collective experiences of divers using deep stop tables, meters and software cannot be easily discounted today. Literally millions of deep stop dives across technical and recreational diving pay witness to their safety and utility. Certainly, deep stops and bubble models are under the microscope today and that is a good thing. One interesting issue for bubble models is the question of bubble regeneration and Ostwald bubble growth (broadening) [36-38] and impacts on decompression schedules. Initial estimates suggest that both increase decompression debt.

Some recent test pros and cons

Keeping in mind that single test profiles are differential across all diving that Doppler is not necessarily definitive and that arbitrary insertions of deep stops on shallow stop staging are ad hoc and can be inconsistent (and vice-versa) some further test specific comments are interesting we hope. The following pop up in various Training Agency publications, online blogs and technical diving forums.

Ljubkovic VPM Bubble Study: The Ljubkovic test [39] looked at the VPM to assess Doppler bubble formation and noted high bubble incidence using VPM the study returned null results for VPM because it was not comparative against a shallow stop model which may or may not show less bubbling.

Spisni ratio deco test

The Spisni study [40] is another test of R-values in a shallow stop model with arbitrary deep stops imposed. From a bubble model perspective, there is little learned in either case unless a bubble model profile is tested against the modified dissolved gas profile. The same comments hold for GF reductions of Buhlmann critical parameters and tests. Comparing one R-value deep stop profile against another R-value deep stop profile says nothing about deep stops in general especially when they are arbitrarily inserted. Comparing apples to apples is not the same as apples to oranges.

Ratio Deco: Despite new name, ratio deco is nothing more than M-value deco in an equivalent representation, R, namely M-value divided by absolute pressure P, that is R = M/P. This was the original Haldane model with R = M/P = 2 changed to variable M-values later and now back again. Ratio deco is still dissolved gas deco with arbitrary deep stops imparted in manner similar to GFs. Nothing is really new here, but R-values are popular with technical divers. Without too much extra work, ratio deco can be extended to the critical gradients or G-values, G=M-P, with R=G/P thereby connecting to gradients factors (GF).

Gradient factors

It is opportunistic that GFs (ξ) mimic bubble models to some extent but why use GFs that are not correlated with any data when correlated bubble models (VPM and RGBM) are available and consistent across the whole dive. Correlation of GFs with RGBM are underway at LANL as a service to the diving community not familiar or not using full up BMs.

Fraedrich Computer Algorithm Comparisons: This study [41] took a closer look at 4 computer algorithms, namely Suunto RGBM, VPM-B, EMC-20 and ZHL, focusing on first stops and total run time. It was important that the Fraedrich study looked at full up shallow and deep stop staging with dissolved gas and bubble model computers. However, using the results of the NEDU 2008 study [42,43] as a baseline is questionable and not well defined as the NEDU study is controversial. The comparisons have some validity and we are looking at the results across profile data in the LANL DB. Studies like this are headed in the right direction.

Equal risk staging

Deep stops are and remain the norm in technical diving because of a record of safe and sane usage in tables, meters and software and no DCS spiking. At the same risk level (computed from profile data and DCS outcomes) deep stops are always shorter in total decompression time than shallow stops. A comparative example is seen in the appended schematic as reported at the Deep Stops Workshop in Salt Lake City in 2008. Shown is a trimix 12/50 dive to 280 fsw for 10 min with gas switch to 20/40 trimix at 150 fsw and pure oxygen at 20 fsw for both shallow stop (ZHL) and deep stop (RGBM) staging and equal risk. Professional and savvy divers know this from experience and training.

Arbitrary deep stops

Deep stops are mostly arbitrary as seen outside correlated model staging requirements and the question of deep stop semantics is indeed confusing. Real bubble models (TM, TBDM, VPM, RGBM) will all have first stops deeper than traditional USN and ZHL models. With GFs you can get almost anything for stops and nothing about GFs has ever been correlated and validated in the same manner as VPM and RGBM have been correlated and published. See References for details of VPM and RGBM published model correlations and validation [44,35,14,45]. And see comparisons of USN and ZHL correlations just for completeness [37].

Fast Compartments and Middle Compartments: It is false as claimed in some quarters that deep stops only control the fast compartments and that middle compartments are supersaturated in gas content with bubble formation. Bubble models control gas buildup and bubble formation in lockstep across all compartments not just fast ones. Troublesome compartments violating both gas buildup and bubble volume limits are controlled at every point across the whole ascent profile and at the surface within bubble models. It turns out as seen in Table 1 that the control structure of compartments, τ, for the NEDU 170/30 air dive are the same for ZHL and RGBM staging across overlapping segments of the decompression schedules. Nothing much can be said of ZHL controlling tissues in the deep stop region of the RGBM. Calculations were performed with CCPlanner at nominal settings and can easily be checked with most GM and BM diveware packages. Run times are very close when allowing Boyle expansion for bubbles in the shallow zone. Thus, we suggest claims of oversaturated middle compartments in bubble model staging are suspect at best. (Table 1) is also interesting because it clearly shows the staging differences in GM (shallow stop) and BM (deep stop) algorithms. The computed surfacing risks [45] are seen to be larger in the deeper zones for the RGBM and shallower zones for the ZHL. RGBM is conservative in deep zones while ZHL is conservative in shallow zones. The surfacing risks are 0.029 and 0.021 on this profile. If deep stops and BMs are endangering middle compartments, then from Table 1 shallow stops and GMs are doing the same because of the equality of controlling compartments as seen in Table 1.

French navy deep stops tests

The French Navy Tests were air tests at 200 fsw and fall into the category of arbitrary deep stop insertions [46]. Deep stops were inserted into the MN90 shallow stop schedules at 90 fsw. Why not 150 fsw? And why might the impending shallow stop ascension schedule be remotely consistent with the first deep stop? This is a standard question that is raised in deep stop tests with arbitrary deep stop insertions.

Nedu deep stops air trials

The NEDU Deep Stop Air Trials at 170 fsw for 30 min were terminated after some 100+ trials with a 5.5% DCS hit rate using the USN BVM3 (pseudo bubble) model [42, 43]. The profile generated resembled nothing that tec divers seemingly employ and stirred considerable discussion and related counterpoint. Air diving at depths beyond 150 fsw is a seldom occurrence outside Navies and as COMEX data suggests air diving beyond 170 fsw incurs risk 5-7 times greater than at shallower depths. Using the LANL DB at the time a DCS hit rate of 11% was projected. The staging divergences shown following and discussion generated suggest the NEDU test was removed from technical diving, deep or shallow stop. Hopefully USN divers benefitted in ways not clear at the time. In Table 2, looking at the standard USN Extreme Exposure Tables for a 170/30 air dive the NEDU test was longer and outside the USN Table by at least 2. So why would anyone dive or opt for a longer NEDU test schedule over a Standard USN schedule unless risk is very low which it isn't according to the outcome of the trials. By way of aside, what is going on with the long Haldane test tail in the shallow zone versus the schedule in the USN Extreme Exposure Tables? Run times in the NEDU Test are doubled over run times in the USN Extreme Exposure Tables. The surfacing (EOD) risk is listed after the 10 fsw stop in both cases using the RGBM DB. For the USN Extreme Exposure Table the surfacing risk (EOD) is estimated to be 0.029 while the NEDU Test Schedule has an (updated) estimated surfacing risk of 0.097. Both can be compared to the actual DCS incidence rate in the 170/30 air test of 0.055 and the corresponding ZHL and RGBM schedules and risks are indicated in Table 1. There are some big differences between the test schedule and ZHL, RGBM and USN Extreme Exposure schedules as well as in estimated surfacing risk. Further model differences are seen in the graphic following the Summary. The LANL DB was used for risk estimates in Table 2 with deep stop data for the NEDU Test Schedule and shallow stop data for the USN Extreme Exposure Schedule.

Table 1: Controlling Tissues On 170/30 Air Dive.

ZHL			**RGBM**			
Depth (fsw)	**Wait (min)**	**τ (min)**	**Risk**	**Wait (min)**	**τ (min)**	**Risk**
170	30	12.5	0.257	30	12.5	0.388
100				0.5	5	0.311
90				1.5	8	0.296
80				2.5	8	0.278
70				2.5	12.5	0.26
60				4.5	12.5	0.238
50	1.5	12.5	0.156	5	18.5	0.214
40	6	18.5	0.136	7.5	18.5	0.174
30	9	27.1	0.121	11	27.1	0.12
20	17	38.4	0.096	16	38.4	0.076
10	43.5	77.1	0.029	28	77.1	0.021
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	114.9			115.2		

Table 2: USN Extreme Exposure Schedule and NEDU Test Schedule.

USN Table Schedule			**NEDU Test Schedule**	
Depth (fsw)	**Wait (min)**	**Risk**	**Wait (min)**	**Risk**
170	30.0	0.379	30.0	0.390
70			12.0	0.358
60			17.0	0.312
50			15.0	0.301
40	5.0	0.272	18.0	0.297
30	11.0	0.212	23.0	0.249
20	21.0	0.169	17.0	0.179
10	53.0	0.029	72.0	0.097
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	90.0		206.0	

Modern Developments and Tools

Data Banks and coupled statistical analyses of profile DCS outcomes are a major development in model correlations and validation for safe and sane diving using tables, meters and diveware. Expect their usefulness to grow. In some broad sense, DBs represent an ultimate set of wet tests across the full spectrum of diving in ways that single wet and chamber tests cannot duplicate especially for model correlations and validation. Costs and time are prohibitive for broad scale wet and dry testing. And here is where DBs are useful.

Data banks

Profile Data Banks are extended collections of dive profiles with conditions and outcomes [35,47]. To validate tables, meters, and software within any computational model, profiles and outcomes are necessarily matched to model parameters with statistical (fit) rigor. Profile-outcome information is termed a Data Bank (DB) these days and there are a couple of them worth discussing. Others will surely develop along similar lines. Their importance is growing rapidly in technical and recreational sectors not only for the information they house but also for application to diving risk analysis and model tuning. In a physical world of models DBs are the only way to really validate staging and ascent protocols. Disjoint and scattered tests by themselves fall short in scope of application and validation. The following represent data estimates in the 2010 time frames roughly.

One well known DB is the DAN Project Dive Exploration (PDE) collection [27]. The PDE collection focuses on recreational air and nitrox diving initially but is extending to technical, mixed gas and decompression diving. Approximately 87,000 profiles reside on PDE computers with some 97 cases of DCS across the air and nitrox recreational diving. PDE came online in the 1995 timeframe under the guidance of Peter Bennett, Dick Vann and Petar Denoble. DAN Europe under Alessandro Marroni joined forces with DAN USA in the 2000s extending PDE. Their effort in Europe is termed Dive Safe Lab (DSL). DSL has approximately 50,000 profiles with 18 cases of DCS. For simplicity we group PDE and DSL together as one DB as information is easily exchanged across their computers. In combo, PDE and DSL house some 137,000 profiles with 105 cases of DCS as of 2010 roughly. The incidence rate is 0.0008 or so. This is a massive and important collection. Today it has grown since the early 2000s.

Another more recent DB focused on technical, mixed gas and decompression diving is the Data Bank at Los Alamos National Laboratory (LANL DB). Therein some 3579 profiles with 28 cases of DCS across mixed gas, OC and RB diving reside now. Authors and C&C Dive Team are mainly responsible for bringing the LANL DB online in the early 2000s. Much of the LANL DB rests on data extracted from C&C Dive Team operations over the past 20 yrs or so. Tech diver computer downloads also reside in the DB. Therein the actual incidence rate is 0.0069, roughly 10 times greater than PDE and DSL. Such might be expected as LANL DB houses mixed gas, OC, RB and decompression profiles which are likely a riskier diving activity with more unknowns. For illustration an earlier sample breakdown of LANL DB profile data and outcomes follows. The data is relatively coarse grained making compact statistics difficult. The incidence rate across the whole set is small on the order of 1% and smaller. Fine graining into depths is not meaningful yet so we breakout data into OC and RB gas categories (nitrox, heliox, trimix). (Table 3) tabulates an earlier data compilation Wienke.

Table 3: Profile Data.

Mix	Profiles	DCS	Incidence
OC nitrox	344	8	0.0232
RB nitrox	550	2	0.0017
all nitrox	894	10	0.0112
OC trimix	656	4	0.0061
RB trimix	754	2	0.0027
all trimix	1410	6	0.0042
OC heliox	116	2	0.0172
RB heliox	459	2	0.0044
all heliox	575	4	0.007
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Maximum likelihood and USN, ZHL, VPM, RGBM data fits

Maximum likelihood is a general statistical approach to fitting large-scale data to models [32,48-50] and is a useful technique for fitting GMs and BMs to real diving data. The useful models, of course, are the USN and ZHL on the shallow stop side and the VPM and RGBM on the deep stop side. These 4 models have been correlated and safely dived for many years now, forming the bases for worldwide dive tables, meters and desktop software. Millions of dives have been logged using them. Recreational divers tend toward USN and ZHL while technical divers prefer VPM, RGBM and ZHL with GFs. Using deep stop and shallow stop profiles in the LANL DB, maximum likelihood analyses suggested that the USN and ZHL models correlate with shallow stop data very well and the VPM and RGBM models correlate very well with the deep stop data [29]. Opposite cases (GMs against deep stops and BMs against shallow stops) did not correlate in chi squared, Γ, goodness of fit. For the deep stop data,

$$\Gamma = 0.717 \text{ (VPM)}$$

$$\Gamma = 0.081 \text{ (RGBM)}$$

and for the shallow stop data,

$$\Gamma = 0.934 \text{ (USN)}$$

$$\Gamma = 0.869 \text{ (ZHL)}$$

Clearly both shallow stop and deep stop models correlate well within their corresponding data sets scoring safe and consistent diver utilization of both within model constraints. Chi squared fit, Γ, is a standard numerical test that quantifies how well models track experimental data and ranges,

$$0 \le \Gamma \le 1$$

in quantifying model correlations for Γ close to 1 or anti-correlations for Γ close to 0.

Computer vendor and training agency deep stop DCS poll

At the UHMS/NAVSEA Workshop [43] deep stop statistics from dive computer Vendors and Training Agencies were presented following polling. In the anecdotal category as far as pure science and medicine they are reproduced below. The reader can take them for whatever worth but the suggested DCS incidence rate is low. That is no surprise as DCS, and oxygen toxicity spikes would likely lead to recalls and replacement units. Training Agencies, decompression computer Manufacturers and dive Software Vendors were queried prior to the Workshop for estimated DCS incidence rates against total dives performed with deep stops. Both recreational and technical diving are lumped together in the estimates below (guesstimates). Keep in mind that polling does not involve controlled testing and only echoes what the Agencies, Manufactures and Vendors glean from their records and accident reports. Both GM and BM algorithms with deep stops were tallied. A rough compendium of the poll is tabulated below as DCS incidences/total dives in the list. Deep Stop Decompression Meters: Suunto, Mares, Dacor, Hydrospace, UTC, Atomic Aquatics, Cressisub report 47/4,000,000 with 950,000 meters marketed. Deep Stop Software Packages: Abyss, GAP, NAUI GAP, ANDI GAP, Free Phase RGBM Simulator, NAUI RGBM Dive Planner, RGBM Simulator and CCPlanner report 68/920,000 with 50,000 CDs marketed. Deep Stop Agency Training Dives: NAUI, ANDI, FDF, IDF report 38/1,020,000 in open water training activities. Commercial Operations: Exxon-Mobil, Chevron tally (trimix only) some 13/43,000 tethered dives.

So, broadly, the tally is 166/6,000,000, probably on the conservative side and slightly limited in participation. The incidence rate is small. Nothing scary is seen as DCS spikes or trends. This again is not science but if alarming DCS statistics were to surface the meter folks (Vendors) would respond very rapidly to the algorithm problem with recalls, new meters and fixes for any perceived liability and safety concerns.

Training agency testing and standards

Some Agencies have conducted wet tests and implemented deep stop protocols into training regimens formally or optionally (NAUI, PADI, GUE, TDI, ANDI, IANTD). This is described in the Deep Stop Workshop Proceedings in completeness and we only summarize a few other points in addition to the above poll [43]. Prior to the introduction of deep stops Training Agencies relied on GM approaches in training divers and instructors with successful and safe results. The ZHL and USN table and computer implementations were mainstays in their training. When deep stop protocols entered the training scene in the 1990s, some Agencies (rather quickly) adopted a look and see attitude while applying their own testing and modified training regimens to BM algorithms, mostly VPM and RGBM. Without DCS and OT issues, deep stop training standards were then strategically drafted and implemented. As far as training regimens go, the following summarizes training standards for some well know US Agencies:

NAUI: A recreational and technical Training Agency using RGBM tables, meters and linked software

PADI: A recreational and technical Training Agency using DSAT tables, meters and software with deep stop options

SSI: A recreational Training Agency using modified USN tables

ANDI: A technical Training Agency using RGBM table, meters and diveware

SDI/TDI/ERDI: A recreational and technical Training Agency using USN tables, computers and com- mercial diveware

IANTD: A recreational and technical Training Agency employing the ZHL and VPM tables, computers and software

GUE: A technical Training Agency that uses ZHL with GFs and VPM tables, computers and software

Training Agencies using USN and ZHL protocols for technical instructor often couple gradient factor (ξ) modifications into dive planning. Some using tables have modified times and repetitive groups to be more conservative. CMAS affiliated Training Agencies are free to choose their tables, meters and software for training. FDF and IDF use RGBM tables, meters and software [51]. An important thing here to mention is that across standards, tables, meters and software the training record of all Agencies collectively is safe and sane.

Dive computers and diveware

The number of dive computers marketed has grown significantly in the past 20 years or so. Units incorporate both GM and BM protocols. These units are modern and engineered for performance and safety. Most have PC connectivity and dive planning software along with interfaces to DAN and LANL DBs for profile downloading. The record of all is one of safe and extensive real-world diving [52,47,53] under many environmental conditions and altitude. Most dive computers are manufactured by one of 4 companies, namely Seiko, Timex, Citizen and Casio, certainly a storied and well-known group of fine instrument makers. The situation with dive planning software is less transparent and less quantitative for user statistics. It is almost impossible to track DCS statistics from divers using diveware and dive planning software. However, the record seems fairly safe and sane from reports and sales usage information. Diveware is used extensively in the technical sectors.

Isorisk deep stop and shallow stop profiles

To say deep stop schedules are shorter than shallow stop schedules needs a metric and qualification. This is only true at the same risk level. To assess risk DBs are necessary and a mathematical risk function needs be assigned to fit the data. In the case of diving, a supersaturation risk function is easily constructed for shallow stops and a bubble number risk function can similarly be devised for deep stops [54,55,57]. Such risk functions are then useful for dive planning. A comparative example is seen in the following graphic contrasting deep stop and shallow stop equal risk (2.8%) profiles for a trimix dive to 280 fsw for 10 min. The LANL DB of deep stop and shallow stop downloaded computer profiles is used. Clearly, the isorisk comparison in the following slide shows deep stop staging is shorter than shallow stop staging. ZHL was used for the shallow stop calculation and RGBM for the deep stop calculation. To round out discussion and provide a short reference list of popular deep stop and shallow stop dive computers and associated dive planning software the following lists complete our analysis in terms of actual diving and algorithm usage [56-59].

Commercial dive computers

Major dive computers incorporate both GM and BM algorithms with user knobs for conservative to aggressive staging, that is, from nonstop to decompression diving on OC and RB systems for nitrox, heliox and trimix. Well known and popular Vendors and models include:

Suunto: Suunto markets a variety of computers all using the RGBM. The EON Steel and DX can be used in gauge, air, nitrox, trimix, OC and CCR modes. The D6, D4 and Vyper are OC computers in gauge, air and nitrox modes. Zoop and Cobra are recreational computers for gauge, air and nitrox use [60].

Mares: Mares computers use the RGBM. Recreational models include the ICON HD, Matrix, Smart and Puck Pro for OC in gauge, air and nitrox modes

Uwatec: Uwatec computers are marketed by ScubaPro and all use the ZHL algorithm. The M2 and Pro Mantis are targeted for both recreational and technical diving with gauge, air, nitrox, trimix and CCR modes. The Pro Galileo Sol is a technical dive computer with gauge, air, nitrox and trimix capabilities.

UTC: UTC markets a message sending-receiving computer called the UDI for air and nitrox. All UDIs employ the RGBM. The message exchanging capabilities extend out to 2 miles using sonar, GPS and underwater communications systems. Models include the UDI 14 and UDI 28. Underwater special military units, search and recovery teams and exploration operations use the UDIs routinely today. UDIs also have high resolution compasses for extended navigation [61-63].

Huish/Atomic Aquatics/Liquivision: Huish Outdoors owns both Atomic Aquatics and Liquivision. Atomic Aquatics markets a recreational dive computer using the RGBM called the Cobalt for air and nitrox. Liquivision models include the Kaon, Lynx, X1 and Xeo. The Lynx and Kaon are technical and recreational computers for gauge, air and nitrox modes using the ZHL with GFs. The X1 and Xeo are full up technical dive computers for air, nitrox, trimix and CCR using offering both the ZHL with GFs and RGBM.

Cressisub: Cressisub computers use the RGBM in recreational gauge, air and nitrox modes. The Newton Titanium, Goa, Giotta and Leonardo are Cressisub models. Cressisub markets a complete line of diving gear in addition to dive computers.

Sherwood: Sherwood computers all use the ZHL. Recreational models for air and nitrox include the Amphos and Wisdom computers.

Oceanic: Oceanic computers use the DSAT and ZHL algorithms for recreational diving. Many models are marketed for gauge, air and nitrox diving and include the VTX, Datamax, Geo, Pro Plus. OCi, Atom, Veo and F10.

Shearwater: Shearwater computers are targeted for technical diving. All use the ZHL with GFs and VPM may be downloaded as an option, The Petrel, Perdex and Nerd2 models address air, nirox, trimix and CCR. Some RB Manufacturers are integrating Shearwater computers into their RB units.

Ratio: Ratio computers employ the ZHL and VPM algorithms for technical and recreational diving. Models include the iX3M Pro and IX3M GPS (Easy, Deep, Tech+, Reb versions) plus the iDive Sport and iDive Avantgarde (Easy, Deep, Tech+ versions) series with air, nitrox, helium and CCR capabilities and GPS and wireless connectivity. The model list is impressive and complete with a strong offering of technical and professional diving units [64,65].

Cochrane: Cochrane computers are marketed for recreational and technical diving using the USN LEM (VVAL18). The EMC16 a is recreational air and nitrox computer. The EMC20H is a technical air, nitrox and helium unit. Military units include the EODIII for USN EOD operations and the NSWIII for USN Special Warfare (SEAL) evolutions.

Aeris: Aeris computers are directed at recreational divers using (modified USN) DSAT algorithms for air and nitrox. Models include the A100, A300, A300AI, XR1, NXXR2, Elite T3, Epic and Manta.

Commercial dive planning software

Online and commercially available software packages span GM and BM algorithms along with OT estimation and include:

Free Phase RGBM Simulator: Free Phase RGBM Simulator is a software package offered by Free Phase Diving incorporating the ZHL and RGBM algorithms. Both the ZHL and RGBM algorithms are user validated and correlated with actual diving data and tests as mentioned. The Free Phase RGBM Simulator for nominal settings is one-to-one with the published and released NAUI Technical Diving Tables used to train mixed gas OC and RB divers. As such, it is a valuable training and diving tool for deep and decompression diving. No other diveware packages, excepting NAUI GAP and ANDI GAP, provide such correlation with published and user validated Dive Tables. It is also keyed to the Liquivision RGBM implementation plus others under construction in the Far East.

Abyss: Abyss in 90s first introduced the full RGBM into its diveware packages. The Buhlmann ZHL model was also included as the dissolved gas package. It has seen extensive use over the past 20 yrs or so in the technical diving area. A variety of user knobs on bubble parameters and M-values permit aggressive to conservative staging in both models. Both the ZHL and RGBM have been published and formally correlated with diving data. Later, the modified RGBM with M-value reduction factors, χ, was incorporated into Abyss. Modified RGBM with χ was published and correlated with data in the late 90s and also served as the basis for Suunto, Mares, Dacor, ConnXion, Cressisub, UTC, Mycenae, Aqwary, Hydrospace, ANO, Artisan and other RGBM computers. Full RGBM was first incorporated into Hydrospace computers and today in Suunto, Atomic Aquatics, Liquivision and ANO computers. ABYSS was a ground breaker.

VPlanner: VPlanner first introduced the VPM in the late 90s. Based on the original work of Yount and Hoffman, the software has seen extensive use by the technical diving community. Formal LANL DB correlations of the VPM and thus VPlanner have been published. User knobs allow adjustment of bubble parameters for aggressive to conservative staging. VPlanner is also used in Liquivision and Advanced Diving Corporation computers for technical diving.

ProPlanner: ProPlanner is a software package using modified Z-values for diver staging. Buhlmann Z-values with GFs are employed with user knobs for conservancy. The model is called the VGM (variable gradient model) ProPlanner. Some GFs claim to mimic the VPM. Correlations have not been published about VGM and ProPlanner.

GAP: GAP is a software package similar to Abyss offering the full RGBM, modified RGBM with χ and Buhlmann ZHL with GFs. Introduced in the mid-90s, it has seen extensive usage in recreational and technical sectors. Apart from user GFs, the models and parameters in GAP have been published and correlated with diving data and profiles tested over years. Adjustable conservancy settings for all models can be selected. GAP has been keyed to Atomic Aquatics and Liquivision dive computers. Training Agency spinoffs also include ANDI GAP and NAUI GAP.

DecoPlanner: DecoPlanner is a diveware package offered by GUE. Both VPM and Buhlmann ZHL with GFs are available in DecoPlanner. Evolving over the past 10 - 15 yrs, DecoPlanner also incorporates GUE ratio deco approaches which are just another modification of the original Haldane 2/1 law applied to M-value ratios, M/P. This is just another representation of M-values for diver staging. Nothing is published about ratio deco data correlations but both the ZHL and VPM have been correlated. It has seen extensive use in the technical diving community and GUE diver training.

Analyst: Analyst is a software package marketed by Cochrane Undersea Technology for PCs. It is keyed to Cochrane computers as a dive planner and profile downloader. The Cochrane family of computers use the USN LEM for recreational, technical and military applications. The LEM is a neo-Haldanian model with exponential uptake and linear elimination of inert gases and imbedded in the USN VVAL18 project.

DiveLogger: DiveLogger is linked to Ratio technical and recreational computers. Ratio computers provide GPS and wireless connectivity and offer the ZHL and VPM algorithms to divers. Dive planning and profile downloading capabilities are included in the diveware package. As mentioned, both VPM and ZHL have been correlated with data.

DiveSim: DiveSim is a UDI software package for dive planning and profile downloading. UDI computers and diveware employ the correlated RGBM for air and nitrox. The software packages also include diver to diver, diver to surface, GPS, compass and related communications capabilties. UDIs are highly technical and useful underwater tools used by military, search and rescue and exploration teams but are readily accessible to recreational divers needing underwater communications and boat connectivity.

Citation: Wienke BR, Leary TRO. Downs and Ups of Decompression Diving: a Review . Mod App Ocean & Pet Sci 3(1)-2019. MAOPS. MS.ID.000154. DOI: 10.32474/MAOPS.2019.03.000154.

DSG: A similar development from Dan Europe (DSL) is the Diver Safety Guardian (DSG) software package providing the diver with feedback from an online Deco Risk Analyzer (DRA). Based on permissible supersaturation it is under testing and development. As just an end of dive (EOD) risk estimator now plans are in the works to make it a wet (OTF) risk estimator.

CCPlanner: CCPlanner is a LANL software package offering full RGBM, modified RGBM, USN M-value and Buhlmann Z-value algorithms for dive planning. It is used by the C&C Team and is not distributed commercially but is obtainable under written contract. Also encoded is the Hills TM. It is also provided with licensed LANL RGBM codes. A risk analysis routine using the LANL DB is encoded in CCPlanner and imbedded in licensed RGBM OC and RB codes.

Output is typically extensive from modern diveware. Platforms range from PCs to Droid devices as well as Workstations to Mainframes. Languages employed in codes include VIZ, BASIC, FORTRAN, C, and derivatives. Meter Vendors (Suunto, Mares, Liquivision, UTC, Atomic Aquatics, Cressisub, Sherwood, Oceanic, Genesis, Shearwater, Uwatec, Cochrane, Ratio and Aeris to name a few) often supply proprietary software packages keyed to their meter algorithms for coupled dive planning. These are useful diving tools (Figure 1).

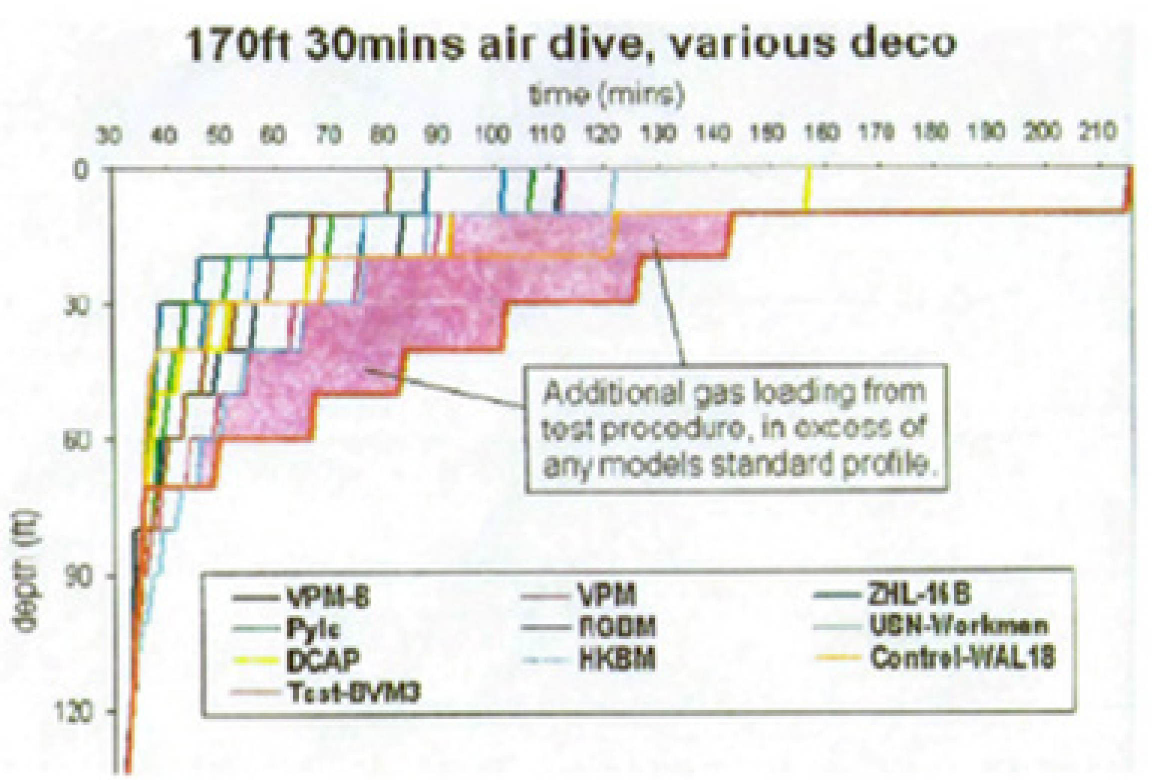


Figure 1:

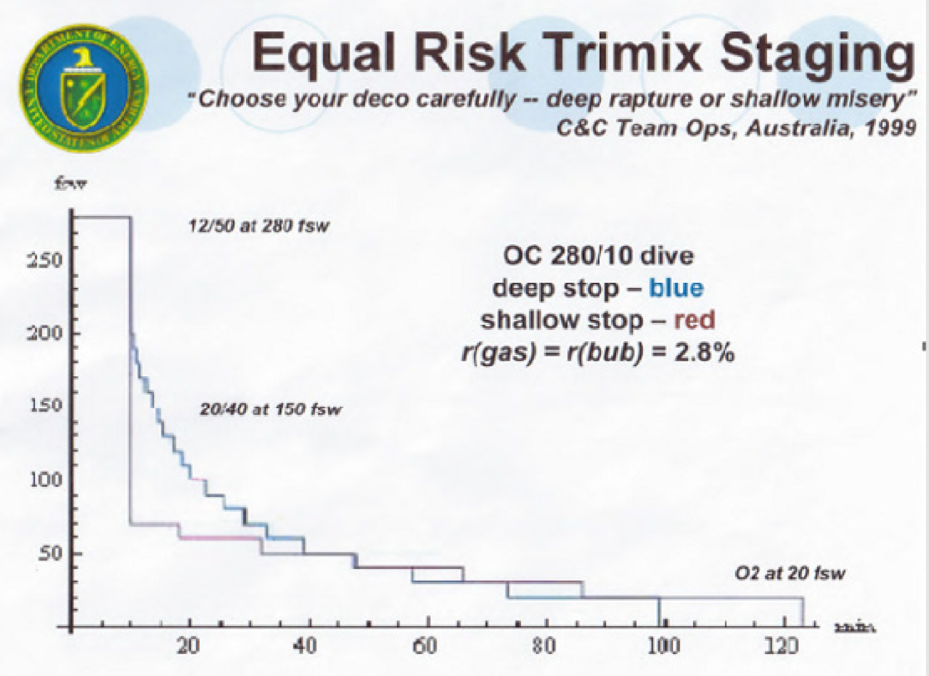
Summary

The issues of deep stops versus shallow stops are not real issues today for those of us involved in operational diving across diverse venues. Both stop schemes work and have been shown to be safe and useful. In common parlance, deep stops control the bubble while shallow stops treat the bubble. Shallow stops have seen more testing than deep stops but real world DCS incidence rates for both are small and DCS spikes are not seen in either case. Technical diving camps use both deep and shallow stops plus hybrids in between. Recreational camps tend toward shallow stops. Commercial diving is in a transitional mode between both. Basic and correlated models employed are the USN, ZHL, VPM and RGBM. These algorithms alone exhibit extensive and safe diving utilization. In closing, we hope the material presented is and will be useful in making safe and sane diving decisions about deep and shallow stops with tables, meters, software and ad hoc protocols. Happy diving.

Acknowledgements

Thanks to Professional Colleagues, Dive Testers, Trainers, Data Collectors, Table Fabricators, USN, USAF, USCG, Scientists, Laboratory Experimenters, Chamber Techs and Dive Physicians in the Living Laboratory of real diving including but not limited to LANL, C&C Dive Team, Exxon-Mobil, Chevron, Brazilian Mergubhador de Combate, Trondheim Laboratory, UW BIOTRON and Tiny Bubble Group Hawaii plus Meter Vendors Suunto, Mares, Atomic Aquatics, Aqwary, Cressisub, Free Phase, ConneXon, Artisan, Plexus and Hy-

drospace plus Software Purveyors Abysmal Diving, GAP, RGBM Simulator and CCPlanner plus Training Agencies NAUI, IANTD, ANDI, FDF, IDF and PADI to mention a few. Special thanks to Spouses, Luzanne Coburn and Diane O'Leary, for their support (Figure 2).



Equal Risk Trimix Staging

"Choose your deco carefully -- deep rapture or shallow misery"

C&C Team Ops, Australia, 1999

Figure 2:

Acronyms and Nomenclature: These are standard and extensively employed by the diving community at large. For brevity we also pen them in the following paper and analysis:

ANDI: Association of Nitrox Diving Instructors.

BM: Bubble phase model dividing the body into tissue compartments with halftimes that are coupled to inert gas diffusion across bubble film surfaces of exponential size distribution constrained in cumulative growth by a bubble volume limit point.

Bubble broadening: Noted laboratory effect that small bubbles increase, and large bubbles decrease in number in liquid and solid systems due to concentration gradients that drive material from smaller bubbles to larger bubbles over time spans of hours to days.

Bubble regeneration: Noted laboratory effect that pressurized distributions of bubbles in aqueous systems return to their original non pressurized distributions in time spans of hours to days.

CCR: Closed circuit rebreather, a special RB system that allows the diver to fix the oxygen partial pressure in the breathing loop (setpoint).

CMAS: Confederation Mondial des Activites Subaquatiques.

Critical radius: Temporary bubble radius at equilibrium, that is, pressure inside the bubble just equals the sum of external ambient pressure and film surface tension.

DB: Data bank, stores downloaded computer profiles in 5-10 sec time-depth intervals.

DCS: Decompression sickness, crippling malady resulting from bubble formation and tissue damage in divers breathing compressed gases at depth and ascending too rapidly.

Decompression stop: Necessary pause in a diver ascent strategy to eliminate dissolved gas and/or bubbles safely and is model based with stops usually made in 10 fsw increments.

Deep stop: Decompression stop made in the deep zone to control bubble growth.

DAN: Divers Alert Network.

Diveware: Diver staging software package usually based on USN, ZHL, VPM and RGBM algorithms.

Diving algorithm: Combination of gas transport and/or bubble model with coupled diver ascent strategy.

Diluent: Any mixed gas combination used with pure oxygen in the breathing loop of RBs.

DOD: Department of Defense.

DOE: Department of Energy.

Doppler: A device for counting bubbles in flowing blood that bounces acoustical signals off bubbles and measures change in frequency.

DSAT: Diving Science and Technology, a research arm of PADI.

DSL: Diving Safety Laboratory, the European arm of DAN.

EAHx: Enriched air helium breathing mixture with oxygen fraction, x, above 21% often called helitrox.

EANx: Enriched air nitrox breathing mixture with oxygen fraction, x, above 21%.

EOD: End of dive risk estimator computed after finishing dive and surfacing.

ERDI: Emergency Response Diving International.

FDF: Finnish Diving Federation.

GF: Gradient factor, multiplier, ξ, of USN and ZHL critical gradients, G and H, that can mimic BMs.

GM: Dissolved gas model dividing the body into tissue compartments with arbitrary half times for uptake and elimination of inert gases with tissue tensions constrained by limit points.

GUE: Global Underwater Explorers.

G-values: A set of critical gradients obtained by subtracting absolute pressure, P, from M-values.

Heliox: Breathing gas mixture of helium and oxygen used in deep and decompression diving.

IANTD: International Association of Nitrox and Technical Divers.

ICD: Isobaric counter diffusion, inert dissolved gases (helium, nitrogen) moving in opposite directions in tissue and blood.

IDF: Irish Diving Federation.

LEM: Linear exponential model, a dissolved gas model with exponential gas uptake and linear elimination by Thalmann

LSW theory: Lifschitz-Slyasov-Wagner Ostwald bubble ripening theory and model.

M-values: Set of limiting tensions for dissolved gas buildup in tissue compartments at depth.

Mirroring: The gas switching strategy on OC ascents of reducing the helium fraction and increasing the oxygen fraction in the same amount thereby keeping nitrogen constant.

Mixed Gases: Any combination of oxygen, nitrogen and helium gas breathed underwater.

NAUI: National Association of Underwater Instructors.

NDL: No decompression limit, maximum allowable time at given depth permitting direct ascent to the surface.

NEDU: Naval Experimental Diving Unit, diver testing arm of the USN in Panama City.

Nitrox: Breathing gas mixture of nitrogen and oxygen used in recreational diving.

OC: Open circuit, underwater breathing system using mixed gases exhausted upon exhalation.

Ostwald ripening: Large bubble growth at the expense of small bubbles in liquid and solid systems.

OT: Oxtox, pulmonary and/or central nervous system oxygen toxicity resulting from over exposure to oxygen at depth or high pressure.

PADI: Professional Association of Diving Instructors.

PDE: Project Dive Exploration, a computer dive profile collection project at DAN.

Phase Volume: Surfacing limit point for bubble growth under decompression.

Ratio Deco: R-value deco, a simple modification of M-value (dissolved gas) staging using M-values divided by absolute pressure, R=M/P.

Pyle Stop: Deep ad hoc decompression stops made on ascent in successive half, quarter, eight multiples of bottom depth.

RB: Rebreather, underwater breathing system using mixed gases from a cannister that are recirculated after carbon dioxide is scrubbed with oxygen from another cannister injected into the breathing loop. recreational diving: air and nitrox nonstop diving.

RF: Reduction factor, one of a set of published M-value multipliers, χ, that reduce diving risk.

RGBM Algorithm: An American bubble staging model correlated with DCS computer outcomes by Wienke.

RN: Royal Navy.

R-Values: A set of critical ratios obtained by dividing M-values or G-values by absolute pressure

SDI: Scuba Diving International.

Shallow Stop: Decompression stop made in the shallow zone to eliminate dissolved gas.

SI: Surface interval, time between dives.

SSI: Scuba Schools International.

TDI: Technical Diving International.

Technical Diving: mixed gas (nitrogen, helium, oxygen), OC and RB, deep and decompression diving.

TM: Thermodynamic model, a phase staging model introduced by Hills in 1965 that first consistently coupled dissolved gas and phase separation in divers.

TMX x/y: Trimix with oxygen fraction, x, helium fraction, y, and the rest nitrogen.

Trimix: Breathing gas mixture of helium, nitrogen and oxygen used in deep and decompression diving.

USAF: United States Air Force.

USCG: United States Coast Guard.

USN: United States Navy.

USN Algorithm: An American dissolved gas staging model developed by Workman of the US Navy.

UTC: United Technologies Center, an Israeli company marketing a message sending-receiving underwater system (UDI) using sonar, GPS and underwater communications with range 2 miles.

VPM Algorithm: An American bubble staging model based on gels by Yount.

Z-Values: another set of Swiss limiting tension extended to altitude and similar to M-values.

ZHL Algorithm: A Swiss dissolved gas staging model developed and tested at altitude by Buhlmann.

χ: Set of correlated and published M-value reduction factors (RF) for deeper than previous, short surface interval and multiday dives.

ξ: Set of unpublished and uncorrelated critical G-value multipliers (GF) that try to mimic BMs or extend stop time in the shallow zone.

τ: Controlling tissue halftime at a decompression stop on ascent restricted by dissolved gas buildup and/or separated bubble volume.

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DOI: 10.32474/MAOPS.2019.03.000154