Full Paper/Talk

Deep Stops and Shallow Stops – Fact and Fancy

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Abstract

The question of deep stops and shallow stops is interesting and fraught with controversy in diving circles and operations, training, exploration and scientific endeavors. Plus frought with some misunderstanding which is understandable as the issues are complex. We therefore attempt a short history of deep and shallow stops, physical aspects, staging differences, diving tests, models with data correlations and data banks with user statistics and DCS outcomes as diver amplification. Pros and cons of both deep stop and shallow stop staging are presented. Misfacts are righted when appropriate. Chamber, wet and Doppler tests are contrasted. A compendium of Training Agency Standards regarding deep and shallow stops is included. Dive software is also detailed. Some commercial diving operations are discussed. A short tabulation of dive computer and software algorithms is given. From diving data, tests, DCS outcomes and field usage, we conclude that both deep stops and shallow stops are safely employed in recreational and technical diving. That is a good thing but choose your deco wisely and know why.

Keywords: computational models, decompression staging, profile data, risk, statistical correlations, tests

Acronyms and Nomenclature

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 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.
diluent: any mixed gas combination used with pure oxygen in the breathing loop of RBs.
diving algorithm: combination of a gas transport and/or bubble model with coupled diver ascent strategy.
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 of USN and ZHL critical gradients, G and H, that try to 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.
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 oxy gen fraction in the same amount thereby keeping nitrogen constant.
mixed gases: combination of oxygen, nitrogen and helium gas mixtures 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 from a tank 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, a simple modification of M-value (dissolved gas) staging using M-values divided by absolute pressure, R=M/P.

Pyle stops: special decompression stops made on ascent in 1/2 present depth multiples.
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.
RGBM algorithm: an American bubble staging model correlated with DCS computer outcomes by Wienke.
RN: Royal Navy.
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 tensions extended to altitude and similar to M-values.
ZHL algorithm: a Swiss dissolved gas staging model developed and tested at altitude by Buhlmann.

Introduction

Real diving and decompression 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. 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 reduced 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 *(Workman, 1965).* 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 the diving trials and DCS outcomes (*Boycott, 1908; Behnke, 1945; Golding, 1960; Hennessy and Hemplmen, 1977; Keller and Buhlmann, 1965; Walder, 1968; Workman, 1965; Yarborough, 1937).* Extension to helium mixtures followed in lockstep *(Duffner et al, 1959)*

Shallow stops thus relate directly to Haldane and dissolved gas models (GM) used for staging over a span of a century or so *(Boycott, 1908; Yarborough, 1937; Hempleman, 1952; Workman, 1965: Behnke, 1945).* Shallow stops have been extensively tested and validated since 1908 and formed 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 *hr* range. To address this problem, the USN (*Workman, 1965*) introduced an 8 compartment Haldanean (GM) model with halftimes ranging 5-240 *min* and no repetitive diving allowed. This 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 *(Spencer, 1976)* were published and implemented in tables of the time. Interestingly, Doppler also suggested that deep stops reduced bubble counts dramatically *(Neumann et al, 1976; Pilmanis, 1976)* also portending the upcoming deep stop evolution and bubble model growth and meter implementation.

VVAL18 Compilation: The recent VVAL18 compilation *(Thalmann et al, 1997)* 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 *(Thalmann, 1997)* 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 today, the same effect of slowing outgassing can be accomplished by increasing tissue halftimes whenever the instantaneous total gas tensionis greater than ambient pressure in what is called the asymmetric tissue model (ATM) *(Wienke, 2016, 2008).* Greater 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 one of the most important undertaking is 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, 1960)*. It was real diving that initially tweaked interest in deep stops which was something of heresy in the pre-1960s.

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 *(LeMessurier and Hills, 1965)*. 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 (*Yount and Strauss, 1976)* which is quite extraordinary.

Hawaiian Diving Fishermen: Similar schedules and procedures have evolved in Hawaii among diving fishermen according to Farm and Hayashi *(Farm et al, 1986)*. 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 *(Kunkle and Beckman, 1983; Strauss, 1974)*. 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 the these dives as published and analyzed in excellent sources *(Hills, 1978, 1977; Hennessy and Hempleman, 1977)* Profile and model comparisons can be seen therein. As you might expect this caused quite a stir then with opposition almost religious in some quarters. That is maybe strange when you look at the collective practices of pearl and fishing deep divers. What works, works as Bill Hamilton would say.

Open Ocean Deep Stop Trials: Starck and Krasberg in open ocean conducted a series of important deep stop tests *(Krasberg, 1969)*. 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 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 *(Bennett and Marroni, 2007).* He 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 *(Marroni and Bennett, 2004).* 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. He has been conducting further tests along those lines. The Bennett and Marroni findings were formally incorporated into NAUI Recreational Air and Nitrox Tables *(O'Leary, 2011)* 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 *(Lang and Egstrom, 1990*) 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 found that longer and shallower decompression times are not always better when it comes to bubble formation in pigs *(Brubakk et al, 2003)*. 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. Correlations of models and test data are always sought in real life and diving is an important endeavor.

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 *(Bennett and Elliot, 1996).* 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 *(Balestra, 2010).* 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.

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 (*Wienke, 2015).*

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 *(Bowker and Lieberman, 1964)* 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 grows daily.

Methods

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 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 *(Leebart, 1991; Kahaner et al, 1989).*

Published results of deep stop Doppler scores vary all over the map and are not necessarily indicative of DCS stress *(Eckenhoff, 1985; Sawatzky, 1990)*. Same 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. Yeah for both. 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.

To say bubble models have not been tested and validated is nonsense and untrue. Differential chamber tests certainly are absent 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 (*Wienke and O'Leary, 2016, 2008; Wienke, 2016).* Tests support their viability as well as agency testing for training purposes *(O'Leary, 2011).* 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. Certainly deep stops and bubble models are under the microscope today and that is a good thing.

Some Recent Test Pros And Cons
Keeping in mind that single test profiles are differential across all diving that Doppler is not definitive and that arbitrary insertions of deep stops on shallow stop staging are 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 *(Ljubkovic, 2010)* 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 *(Spisni et al, 2017)* is another test of R-values in a shallow stop model with arbitrary deep stops imposed. From a bubble model perspective, there is nothing learned here 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 M-value deep stop profile against another M-value deep stop profile says little about deep stops in general especially when they are arbitrarily inserted. Comparing apples to apples is not the same as apples to oranges. Despite new name, ratio deco is nothing more than M-value deco in an equivalent representation, R, of 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 later and now again R. Ratio deco is still dissolved gas deco with arbitrary deep stops.

Gradient Factors: It is *cool* that GFs 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 Algorithms Comparisons: This study *(Fraedrich, 2018)* 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. Very nice 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 *(Doolette et al, 2011; Bennett et al, 2008)* 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. Yeah again.

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* with 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 meaningless 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 *(Yount and Hoffman, 1986; Wienke and O'Leary, 2016, 2008; Wienke, 2015*). And see comparisons of USN and ZHL anti-correlations just for completeness *(Wienke and O'Leary, 2018).*

Fast Compartments And Middle Compartments: It is untrue as claimed in some quarters that deep stops only control the fast compartments and that middle compartments are clobbered in gas content and 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 2 that the control structure of compartments for the NEDU 170/30 air dive are the same for ZHL and RGBM staging across overlapping (later) 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 clobbered 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.

Table 1. Controlling Tissues on 170/30 Air Dive

ZHL			RGBM		
depth (*fsw*)	wait (*min*)	controlling tissue (*min*)	depth (*fsw*)	wait (*min*)	controlling tissue (*min*)
170	30.0	12.5	170	30.0	12.5
			100	0.5	5.0
			90	1.5	8.0
			80	2.5	8.0
			70	2.5	12.5
			60	4.5	12.5
50	1.5	12.5	50	5.0	18.5
40	6.0	18.5	40	7.5	18.5
30	9.0	27.1	30	11.0	27.1
20	17.0	38.4	20	16.0	38.4
10	43.5	77.1	10	28.0	77.1
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	114.9			115.2	

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 *(Blatteau et al, 2008).* Deep stops were inserted into the MN90 shallow stop schedules at 90 *fsw*. Why not 150 *fsw*? And why should the impending shallow stop ascension schedule be even remotely consistent with the first deep stop?

NEDU Deep Stops Air Trials: The NEDU Deep Stop Air Trials at 170 *fsw* for 30 *min* were concluded after some 100+ trials with a 5.5% DCS hit rate using the USN BVM3 (pseudo bubble) model *(Bennett et al, 2009; Doolette et al, 2009)* 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 next page and discussion generated suggest that the NEDU test was removed from technical diving, deep or shallow stop. Hopefully USN divers benefitted in ways not clear at the time. Looking at the standard USN Tables for a 170/30 air dive the test was longer and outside the Table.

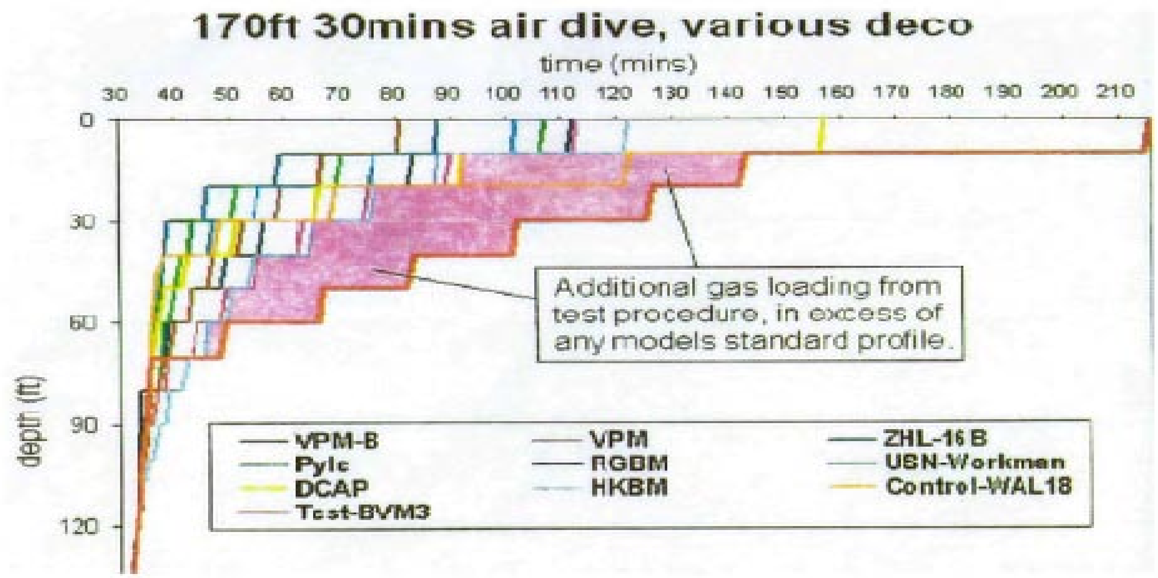
Results

Data banks and statistical analyses of profile DCS outcomes have been a major development in model correlations and validation for safe and sane diving using tables, meters and diveware.

Data Banks

Profile Data Banks are extended collections of dive profiles with conditions and outcomes (*Wienke, 2016, 1987; Vann et al, 1989).* 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.

One well known DB is the DAN Project Dive Exploration (PDE) collection *(Bennett and Elliot, 1996)*. The PDE collection focuses on recreational air and nitrox diving up to now, 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 under the guidance of 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 following 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 likely quadrupled 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. The 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 years or so. Tech diver computer downloads also reside in the DB. In LANL DB, the actual incidence rate is 0.0069, roughly 10 times greater than PDE and SDL. Such might be expected as LANL DB houses mixed gas, decompression profiles, a likely riskier diving activity with more unknowns.

For illustration an early 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 2 indicates an earlier breakdown.

Table 2. 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 trimx	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	0.0070
all	2879	20	0.0069

Maximum Likelihood And USN, ZHL, VPM, RGBM Data Fits

Maximum likelihood is a general statistical approach to fitting large scale data to models *(Parzen, 1990; Wienke, 2010; Kahaner et al, 1989; Johnson and Riess, 1962)* 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 *(Wienke, 2015).* Opposite cases 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 with the corresponding data sets underscoring safe and consistent diver utilization.

Computer Vendor And Training Agency Deep Stop DCS Poll

At the UHMS/NAVSEA Workshop *(Bennett et al, 2008)* 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 DCS incidence rate suggested 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 their estimates (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*:

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.

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 *(Bennett et al, 2008).* 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 atitude while applying their own testing and modified training regimens to BM algorithms, mostly VPM and RGBM. Without DCS and oxtox issues with deep stops, deep stop training standards were then 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 commercial 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 GFs to 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 employ RGBM tables, meters and software *(O'Leary and Wienke, 2012).* 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

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 *(Blogg et al, 2014; Vann et al, 1989; Sheffield, 1990))* 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 to be sure.

Iso Risk Deep Stop And Shallow Stop Profiles

To say that 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 *(Berghage and Durman, 1980; Wienke, Johnson and Riess, 1962; Thalmann 1984; Duffner et al, 1959).* Such risk functions are then useful for dive planning. A comparative example is seen in Figure 2 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 iso risk 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.

Discussion

The issues of deep stops versus shallow stops are really not big issues today for those involved in operational diving across many venues. Both stop schemes work and have been shown to be safe and useful. Technical diving camps tend to espouse one or the other for a variety of reasons. We hope the material presented herein is useful in making diving decisions about deep and shallow stops with tables, meters and software.

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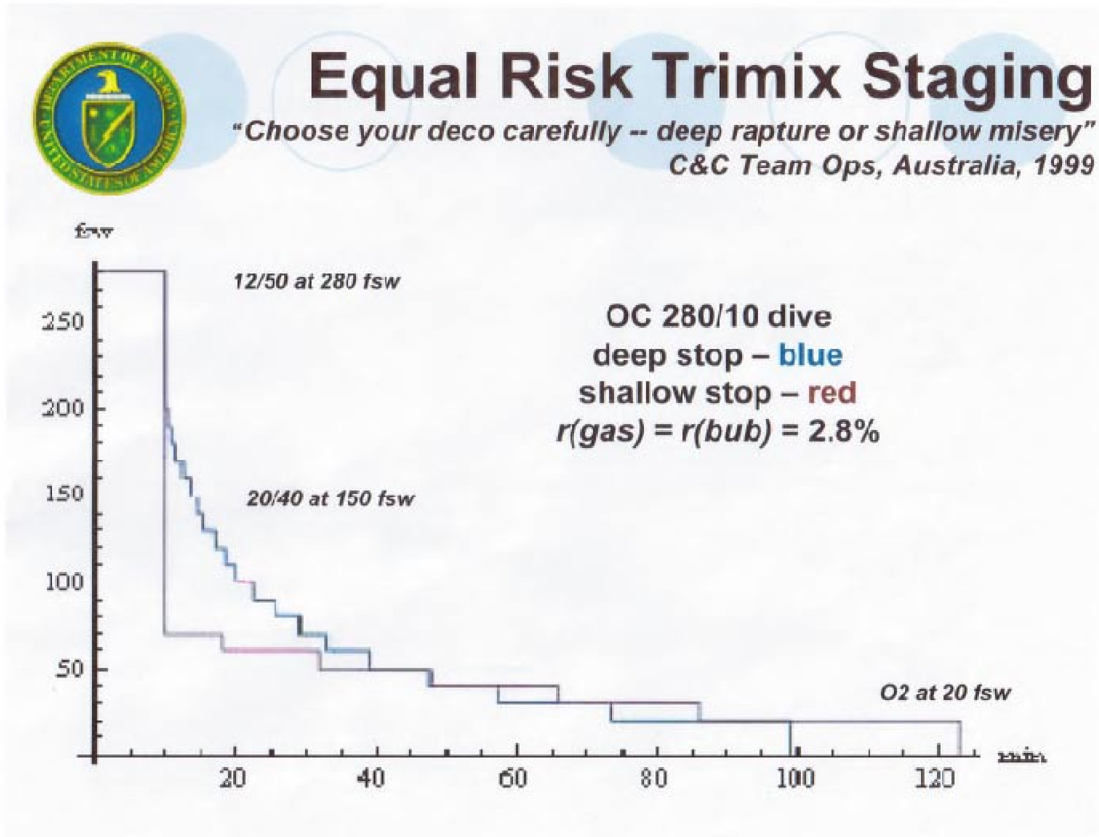

Literature Cited

Balestra C., Validation of Dive Computers Workshop, 2010, DAN-DSL Proceedings, Gdansk.

Behnke A.R., 1945, Decompression Sickness Incident to Deep Sea Diving and High Altitude, Medicine 24, 381-402.

Bennett P.B., Wienke B.R. and Mitchell S., Decompression and the Deep Stop Workshop, 2008; UHMS/NAVSEA Proceedings, Salt Lake City.

Bennett P.B. and Marroni A., Effect of Varying Deep Stop Times and Shallow Stop Times on Precordial Bubble Scores After Dives to 35 msw, Undersea Hyper. Med. 2007; 31, 399-406.

Bennett P.B. and Elliot D.H., 1996, The Physiology and Medicine of Diving and Compressed Air Work, London: Bailliere Tindall and Cassell.

Berghage T.E. and Durman D., 1980, US Navy Air Recompression Schedule Risk Analysis, Nav. Med. Res. Bull. 1, 1-22.

Blatteau J.E, Hugon M, and Gardette B, 2008, Deep Stops During Decompression From 50 to 100 *msw* Didn't Reduce Bubble Formation in Man, Decompression and Deep Stop Workshop, Salt Lake City.

Blogg S.L., Lang M.A. and Mollerlokken A., Validation of Dive Computers Workshop, 2011, EUBS/NTNU Proceedings, Gdansk.

Bowker A.H. and Lieberman G.J., 1964, Engineering Statistics, Engelwood Cliffs: Prentice-Hall.

Boycott A.E., Damant G.C.C. and Haldane J.S., 1908, The Prevention of Compressed Air Illness, J. Hyg. 8, 342-443. TR, NAUI Technical Diving Manual, 2011, NAUI Worldwide Publication, Tampa.

Brubakk A.O., Amtzen A.J., Wienke B.R. and Koteng S., Decompression Profile and Bubble Formation After Dives with Surface Decompression: Experimental Support for a Dual Phase Model of Decompression, Undersea Hyper. Med. 2003; 30, 181-193.

Buhlmann A.A., 1984, Decompression/Decompression Sickness, Berlin: Springer Verlag.

Doolette D.J., Gerth W.A. and Gault K.A., Redistribution of Decompression Stop Time From Shallow to Deep Stops Increases Incidence of Decompression Sickness in Air Decompression Dives, 2011, NEDU Report 2011-06, Panama City.

Duffner G.J., Synder J.F. and Smith L.L., Adaptation of Helium-Oxygen To Mixed Gas Scuba, USN Navy Experimental Diving Unit Report, 1959, NEDU 3-59, Washington, DC

Eckenhoff R.G., 1985, Doppler Bubble Detection, Undersea Biomed. Res. 12, 485-489.

Farm F.P., Hayashi E.M. and Beckman E.L., 1986, Diving and Decompression Sickness Treatment Practices Among Hawaii’s Diving Fisherman, University of Hawaii Sea Grant Report, UNIHI-SEAGRANT-TP-86-01, Honolulu.

Fraedrich D., 2017, Validation of Algorithms Used in Commercial Off-The-Shelf Dive Computers, Div. Hyp. Med. 24, 252-258.

Gerth W.A. and Vann R.D., 1997, Probabilistic Gas and Bubble Dynamics Models of Decompression Sickness Occurrence in Air and Nitrogen-Oxygen Diving, Undersea Hyp. Med. 24, 275-292.

Gerth W.D. and Vann R.D., 1996, Development of Iso-DCS Risk Air and Nitrox Decompression Tables Using Statistical Bubble Dynamics Models, National Oceanographic and Atmospheric Administration Report, NOAA-46RU0505, Washington DC.

Golding F.C., Griffiths P.D., Paton W.D.M., Walder D.N. and Hempleman H.V., 1960, Decompression Sickness During Construction of the Dartford Tunnel, Brit. J. Ind. Med. 17, 167-180.

Hempleman H.V., 1952, A New Theoretical Basis for the Calculation of Decompression Tables, Medical Research Council Report, UPS 131, London.

Hills B.A., 1977, Decompression Sickness, New York: John Wiley and Sons.

Hills B.A., 1968, Relevant Phase Conditions for Predicting the Occurrence of Decompression Sickness, J. Appl. Physiol. 25, 310-315.

Johnson L.W. and Riess R.D., 1962, Numerical Analysis, Reading: Addison Wesley.

Kahaner D., Moler C. and Nash S., 1989, Numerical Methods and Software, Englewood Cliffs: Prentice Hall.

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

Krasberg A., Saturation Diving Techniques, Proceedings Fourth International Congress.

Kunkle T.D. and Beckman E.L., 1983, Bubble Dissolution Physics and the Treatment of Decompression Sickness, Med. Phys. 10, 184-190.

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

Leebaert D., 1991, Technology 2001: The Future of Computing and Communications, Cambridge: Massachusetts Institute of Technology Press.

Le Messurier D.H. and Hills B.A., 1965, Decompression Sickness: A Study of Diving Techniques in the Torres Strait, Hvaldradets Skrifter 48, 54-84.

Ljubkovic M., Marinovic J., Obad A.,Breskovic T., Gaustad S.E. and Dujic Z., 2010, High Incidence of Venous and Arterial Emboli at Rest After Trimix Diving Without Protocol Violations, J Appl. 109, 1670-1674.

Marroni A. and Bennett P.B., 2004, A Deep Stop During Decompression From 82 fsw Significantly Reduces Bubbles and Fast Tissue Tensions, Undersea Hyper. Med. 31, 233-243.

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

O’Leary T.R. and Wienke B.R., 2012, RGBM Manual, NAUI Worldwide Publication, Tampa.

O’Leary T.R., NAUI Technical Diving Manual, 2011, NAUI Worldwide Publication, Tampa.

Parzen E., 1970, Modern Probability Theory and Its Applications, New York: John Wiley and Sons.

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

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

Sheffield P.J., Flying After Diving, 1984, Undersea and Hyperbaric Medical Society Publication 77 (FLYDIV), Bethesda.

Spencer M.P., 1976, Decompression Limits for Compressed Air Determined by Ultrasonically Detected Blood Bubbles, J. Appl. Physiol. 40, 229-235

Spisni E., Marabotti C., DeFazio L., Chiara Valeril M., Cavazza E., Brambilla S., Hoxha K., L’Abbate A. and Longobardi P.A., 2017, Comparative Evaluation of Two Decompression Procedured for Technical Diving Using Inflammatory Responses: Compartmental Versus Ratio Deco, Diving Hyperb. Med. 47, 9-16.

Strauss R.H., 1974, Bubble Formation in Gelatin: Implications for Prevention of Decompression Sickness, Undersea Biomed. Res. 1, 169-174.

Thalman E.D., Parker E.C., Survanshi S.S. and Weathersby P.K., 1997, Improved Probabilistic Decompression Model Risk Predictions Using Linear-Exponential Kinetics, Undersea Hyp. Med. 24, 255-274.

Thalmann E.D., Phase II Testing of Decompression Algorithms for Use in the US Navy Underwater Decompression Meter, 1984, NEDU Report 1-84, Panama City.

Vann R.D., Dovenbarger J., Wachholz C. and Bennett P.B., 1989, Decompression Sickness in Dive Computer and Table Use, DAN Newsletter 3-6.

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

Wienke B.R., 2018, Dive Computer Profile Data and On the Fly and End of Dive Risk Estimators, J. Appl. Biotech. Bioeng. 5(2): 6-12.

Wienke B.R. and O'Leary T.R., 2016, Diving Bubble Model Data Correlations, J. Marine Sci. Res. Dev. 6(4): 7-10.

Wienke B.R., 2016, Biophysics and Diving Decompression Phenomenology, Bentham Science Publishers, Sharjah.

Wienke B.R., 2015, Deep Stop Model Correlations, J. Bioeng. Biomed. Sci. 5: 12-18.

Wienke B.R., 2010, Computer Validation and Statistical Correlations of a Modern Decompression Diving Algorithm, Comp. Biol. Med. 40, 252-260.

Wienke B.R., 2009, Diving Decompression Models and Bubble Metrics: Modern Computer Syntheses, Comp. Biol. Med. 39, 309-331.

Wienke B.R. and O'Leary T.R., 2008, Statistical Correlations and Risk Analysis Techniques for a Diving Dual Phase Bubble Model and Data Bank Using Massively Parallel Supercomputers, Comp. Biol. Med. 38, 583-600.

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

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

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

Workman R.D., Calculation of Decompression Schedules for Nitrogen-Oxygen and Helium- Oxygen Dives, USN Experimental Diving Unit Report, 1965, NEDU 6-65, Washington DC.

Yarborough O.D., 1937, Calculations of Decompression Tables, USN Experimental Diving Unit Report, EDU 12-37, Washington DC.

Yount D.E. and Hoffman DC, 1986, On the Use of a Bubble Formation Model To Calculate Diving Tables, Aviat. Space Environ. Med. 57, 149-156.

Yount D.E. and Strauss R.H., 1976, Bubble Formation in Gelatin: A Model for Decompression Sickness, J. Appl. Phys. 47, 5081-5089.

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