

Deep Stop Model Correlations

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Abstract

Data correlations of computer, table, and software real world implementations of useful and popular diving models are warranted for surety, testing, reproducibility, and safety. Model correlations are of broad interest across the diving community and the focus of this communication. Permissible supersaturation is a fundamental model element for correlation and we analyze four popular ones, namely the USN, ZHL16, VPM, RGBM model permissible supersaturations within model dynamical constraints. Correlations are obtained in statistical likelihood analysis from computer profile records with DCS outcomes in the Los Alamos National Laboratory Data Bank (LANL DB). Permissible supersaturations, limited by model staging constraints varying across depths, times, and gas mixtures, are quantified for the four models. Parameters and risk functions useful to estimate profile risk are also obtained. To correlate and fit data, a modified Weibull-Levenberg-Marquardt routine is employed across 2994 computer downloaded (only) profile records with 23 cases of DCS in nitrox, trimix, and heliox deep and decompression diving. The routine is useful for low probability (*low-p*) data usually encountered in the diving accident arena. Model agreement with data is χ^2 significant as follows, using the logarithmic likelihood ratio of data set to fit set:

$$\text{USN}-(\chi^2=0.081)$$

$$\text{ZHL16}-(\chi^2=0.131)$$

$$\text{VPM}-(\chi^2=0.717)$$

$$\text{RGBM}-(\chi^2=0.861)$$

LANL DB computer profiles exhibit very low DCS prevalence and correlate well with the deep stop models, VPM and RGBM, and further manned testing is always welcome. This correlation suggests that dive computers, software and tables based on deep stop models like VPM and RGBM can safely be used by sport and technical divers. The shallow stop models, USN and ZHL, have, of course, been used safely in computers, tables, and software for decades while deep stop models are fairly new on the diving scene.

Keywords: Diving Models; Validation; Correlation; Deep Stop Data; Maximum Likelihood; Diving Safety

Introduction

A diving *protocol* is a combination of model, data and ascent staging procedure that can be safely used across commercial, sport, technical, research, and scientific underwater operations [1-13,14-21]. Accordingly, this work analyzes four popular models against actual diver deep stop profile data and DCS outcomes. Only computer downloaded profiles with DCS outcomes are considered in this analysis. The models are the USN [20], ZHL16 [3], VPM [21], and RGBM [19]. The USN and ZHL16 models are dissolved gas models [1] that ultimately require decompression stops in the shallow zone to eliminate dissolved nitrogen and helium. The VPM and RGBM are coupled bubble-dissolved gas models [9] that require deeper decompression stops to control bubble growth and dissolved gas elimination. The efficiency of shallow stops versus deep stops is one of current interest [11-13,17], and this study further suggests the utility of coupled deep stop model and data as a useful and safe diver staging tool. Many protocols are based on shallow stop data which focus on just dissolved gas buildup and elimination. Both are used today. The shallow stop models, USN and ZHL16, have been tested in man trials over the years, while the deep stop models, VPM and RGBM, have not yet.

Collecting real world diving data is a global alternative to differential wet and dry testing; a very precise but limited statistical procedure. The approach here [17,19] for technical, mixed gas, and deep decompression diving parallels the Project Dive Exploration (PDE) and Diving Safety Laboratory (DSL) efforts at DAN [15] for

recreational air and nitrox diving, but does not overlap significantly. As will be seen, the deep stop models (VPM, RGBM) correlate well with the LANL DB, while the shallow stop models (USN, ZHL16) do not. Turns out that both shallow and deep stops can be made at the same relative risk level, but deep stops usually admit shorter overall decompression times [5,12,13,19,21], an important aspect of operational diving when mission objectives are folded over diving requirements, especially diver safety.

To correlate hundreds of *gbytes* of downloaded dive computer data (commercial and specialized meters) supercomputing power here at LANL is advantageous in performing maximum likelihood analyses of data and model. Using powerful software, the transitions from microprocessors to parallel processors are seamless. The software package, *CLAMSL* (Common Los Alamos Mathematical Statistical Library [22]), distributed across all processors both parses the data and

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performs calculations using the most appropriate statistical methods. Little user intervention is requisite and data problems are tagged as user flags if any occur. Run times for the full up analysis (data loading, correlation, risk function fitting) on the Blue Mountain Massively Parallel Processor (MPP) are of order 40 sec. Peak processing speeds of 3.1 tflops suggest (minimally) some 12.4 pflop over the full analysis. World fastest PCs operate at 374 gflops and, if able to even compile massive mathematical libraries and related software, would exhibit corresponding run times of 5+ hrs. Nominally, a 2.5 ghertz chip turns 10 gflops.

Staging Models

All models use the perfusion equations for dissolved gas buildup and elimination. Denoting instantaneous tension, p , for initial tissue tension, p_i , at ambient pressure, p_a , with tissue half-time,

τ , we have,

$$p - p_a = (p_i - p_a) \exp(-\lambda t)$$

at exposure time, t , and,

$$\lambda = \frac{0.693}{\tau}$$

Sets of tissue halftimes, τ , vary across models but differences are not important for this analysis, with an approximate range,

$$1 \leq \tau \leq 720 \text{ min}$$

Tissues with small τ are termed fast, while tissues with large τ are termed slow. Helium compartments are roughly 3 times faster than nitrogen compartments. In mixtures of inert gases (nitrogen and helium usually), the total tissue tension, Π , is the sum over mixture components,

$$\Pi = \sum_{j=1}^N p_j$$

with p_j the tension of the j^{th} gas component and N the number of gas components in the mixture, usually just nitrogen and helium. After this, models diverge in their diver staging regimens, with dissolved gas models (USN and ZHL16) limiting dissolved gas buildup, Π , and bubble models (VPM and RGBM) coupling dissolved gas buildup to bubble growth and limiting bubble volumes, Φ . In all models, a permissible supersaturation, G , can be defined at each point of the dive, and is the parameter that will be correlated with data and discussed next for each of the four models.

USN Model [20]

In the Workman USN approach, the permissible gas tension, Π , is limited by,

$$\Pi \leq M$$

with M critical tensions listed in Table 1 for depth, d ,

$$M = M_0 + \Delta M d$$

where depth, d , is the difference between total ambient pressure, p , and surface pressure, P_0 ,

$$d = P - P_0$$

Corresponding permissible gradients, G , then satisfy,

$$G = \Pi - P \leq M - P = (M_0 - \Delta M P_0) + (\Delta M - 1)P$$

nitrogen			helium		
τ_{N_2} (min)	M_0 (f sw)	ΔM	τ_{He} (min)	M_0 (f sw)	ΔM
5	104	1.8	5	86	1.5
10	88	1.6	10	74	1.4
20	72	1.5	20	66	1.3
40	56	1.4	40	60	1.2
80	54	1.3	80	56	1.2
120	52	1.2	120	54	1.2
160	51	1.1	160	54	1.1
200	51	1.1	200	53	1.0
240	50	1.1	240	53	1.0

Table 1: USN M-Values.

nitrogen			helium		
τ_{N_2} (min)	$a + 33/b$ (f sw)	$1/b$	τ_{He} (min)	$a + 33/b$ (f sw)	$1/b$
4.0	106.2	1.91	1.5	134.5	2.36
8.0	83.2	1.54	3.0	102.4	1.74
12.5	73.8	1.39	4.7	89.4	1.53
18.5	66.8	1.28	7.0	79.8	1.38
27.0	62.3	1.23	10.2	73.6	1.32
38.3	58.4	1.19	14.5	68.2	1.25
54.3	55.2	1.15	20.6	63.7	1.21
77.1	52.3	1.12	29.0	59.7	1.17
109.2	49.8	1.09	41.1	57.1	1.14
146.0	48.2	1.08	55.2	55.1	1.12
187.0	46.8	1.07	70.7	54.0	1.11
239.0	45.6	1.06	90.3	53.3	1.10
305.0	44.5	1.05	115.3	53.1	1.09
390.0	43.5	1.04	147.4	52.8	1.09
498.0	42.6	1.04	188.2	52.6	1.08
635.0	41.8	1.03	240.0	52.3	1.07

Table 2: Buhlmann Z-Values.

with P_0 ambient pressure at the surface as noted,

$$P_0 = 33 \exp(-0.0381h)$$

for elevation, h , in multiples of 1000 f t. The correlation parameter, χ , is,

$$\chi = G - (M - P)$$

with surfacing hit criteria,

$$\Pi > M_0$$

ZHL16 Model [3]

The Buhlmann ZHL16 approach is similar to the Workman USN approach, that is, the permissible gas tension, Π , is limited by,

$$\Pi \leq Z$$

with critical tensions, Z , given by,

$$Z = a + \frac{P}{b} = a + \frac{P_0 + d}{b}$$

so that,

$$G = \Pi - P \leq a + \left[\frac{1}{b} - 1 \right] (P_0 + d)$$

for constants, a and b, defining Z at sea level, in (Table 2).

The correlation parameter, χ , is,

$$\chi = G - (Z - P)$$

with hit criteria at the surface,

$$\Pi > a + \frac{P_0}{b}$$

Varying Permeability Model [21]

The tissue compartments in the Yount VPM for nitrogen consist of the set,

$$\tau_{N_2} = (1, 2, 5, 10, 20, 40, 80, 120, 160, 240, 320, 400, 480, 560, 720) \text{ min}$$

with the helium compartments scaling,

$$\tau_{He} = \frac{\tau_{N_2}}{3}$$

The VPM model [21,23] links to bubble experiments in gels and related strata. In gel experiments, Yount divided gas diffusion across bubble interfaces into permeable and impermeable regions. For dive model applications, the regions separate around 165 fsw. Bubbles of nitrogen and helium are excited into growth by pressure changes during the dive from some minimum excitation radius, ϵ , in the 0.5 μm range, with nitrogen bubbles slightly larger than helium bubbles and the excitation radius decreasing with increasing absolute pressure, P. The excitation radius separates growing from shrinking bubbles. The radial bubble distribution, n, in the VPM is given by,

$$n = n_0 \exp(-\beta r)$$

with n_0 an experimental normalization factor for gel sample size, and β on the order of $1/\epsilon \mu\text{m}^{-1}$ for diving applications. The staging protocol in the VPM limits the permissible super-saturation, G to prevent bubble growth on ascent,

$$G = \Pi - P \leq \frac{\gamma}{\gamma_c} \left[\frac{2\gamma_c}{\epsilon} - \frac{2\gamma}{\epsilon_0} \right]$$

with γ the usual bubble surface tension, and γ_c the crushing bubble effective surface tension, roughly 20 dyne/cm and 150 dyne/cm respectively [23]. The radius, ϵ_0 , is an experimental metric, somewhere near 0.7 μm . For diving, VPM ascents are limited by G at each stage in the decompression and staging profiles are iterated to convergence across all stops. The correlation parameter, χ , in the VPM is,

$$\chi = G - \frac{\gamma}{\gamma_c} \left[\frac{2\gamma_c}{\epsilon} - \frac{2\gamma}{\epsilon_0} \right]$$

and surfacing hit condition,

$$\Pi > P_0 + \frac{\gamma}{\gamma_c} \left[\frac{2\gamma_c}{\epsilon} - \frac{2\gamma}{\epsilon_0} \right]$$

Reduced Gradient Bubble Model [19]

Nitrogen tissue compartments in the Wienke RGBM range,

$$\tau_{N_2} = (2, 5, 10, 20, 40, 80, 120, 160, 200, 240, 300) \text{ min}$$

with helium compartments,

$$\tau_{He} = \frac{\tau_{N_2}}{2.65}$$

using the ratio of the square root of atomic weights as the scaling factor. The bubble dynamical protocol in the RGBM model [19] amounts to

staging on the seed number averaged, free-dissolved gradient across all tissue compartments, G, for P permissible ambient pressure, Π total inert gas tissue tension, n excited bubble distribution in radius (exponential), γ bubble surface tension, and r bubble radius,

$$G \int_{\epsilon}^{\infty} ndr = (\Pi - P) \int_{\epsilon}^{\infty} ndr \leq \int_{\epsilon}^{\infty} \left[\frac{2\gamma}{r} \right] ndr$$

so that,

$$G = (\Pi - P) \leq \beta \exp(\beta\epsilon) \int_{\epsilon}^{\infty} \exp(-\beta r) \left[\frac{2\gamma}{r} \right] dr$$

for ϵ the excitation radius at P. Time spent at each stop is iteratively calculated so that the total separated phase, Φ , is maintained at, or below, its limit point. This requires some computing power, but is attainable in diver wrist computers presently marketed, with the same said for the VPM. The USN and ZHL16 models are less complex for computer implementation. The limit point to phase separation, Φ , is near 600 μm^3 , and the distribution scaling length, β , is close to 0.60 μm^{-1} for both nitrogen and helium. Both excitation radii, ϵ , and surface tension, γ , are functions of ambient pressure and temperature, and not constant. The equation-of-state (EOS) assigned to the bubble surface renders the surface tension below lipid estimates, on the order of 15 dyne/cm, and excitation radii are below 1 μm [17]. Correlation parameter, χ , in the RGBM is given by,

$$\chi = G - \beta \exp(\beta\epsilon) \int_{\epsilon}^{\infty} \exp(-\beta r) \left[\frac{2\gamma}{r} \right] dr$$

and surfacing hit criteria has,

$$\Pi > P_0 + \beta \exp(\beta\epsilon) \int_{\epsilon}^{\infty} \exp(-\beta r) \left[\frac{2\gamma}{r} \right] dr$$

LANL Profile Data Bank

Divers are reporting their actual profiles to a DB, located at LANL. The profile information needed is simple and comes from dive computer downloads. Computer downloads are then processed for entry into the LANL DB. Powerful software translates dive computer (microcomputer) downloads into meaningful data for maximum likelihood analyses on the LANL Blue Mountain MPP. An earlier publication [18] describes profiles in the LANL DB, as well as broad field testing. Profiles come from seasoned divers and span the technical diving community at large, essentially mixed gas, extended range, decompression, and extreme diving. Computer profiles from the recreational community are not included, unless they involve extreme exposures on air or nitrox (many repetitive dives, deeper than 150 fsw, altitude exposures, etc) Another 500+ profiles reside in the DB but are not employed here as they are wet tests before the days of computers and bottom timers. The data sets for the USN and ZHL16 models were calibrated with male military divers mainly while the LANL DB spans male and female divers, some military but mostly civilian. Military divers are nominally in their 20s, while divers in the LANL DB range 20 - 60+ in age. 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. The tabulation follows in Table 3, with DCS hits, ι , and total of category dives, σ , denoted ι/σ in the Table (Table 3).

mix	0- 199 f sw	200- 299 f sw	300- 399 f sw	400- 499 f sw	500- 599 f sw	600+ f sw	total
OC nitrox	5/268	3/76					8/344
RB nitrox	0/213	1/246	1/91				2/550
OC trimix	0/10	2/388	0/226	1/26	0/4	1/2	4/656
RB trimix	0/22	0/393	1/291	2/118	1/5		4/819
OC heliox		0/42	2/49	0/25			2/116
RB heliox	0/12	0/215	1/163	1/117	1/2		3/509

Table 3: Profile Data.

Estimator	LL	parameters	LLR	α
6 step set	$\Psi_6 = -124.86$	$p = 0.0095, 0.0044, 0.0061, 0.0140, 0.1818, 0.5000$	$\Gamma_6 = 0$	1.000
3 step set	$\Psi_3 = -133.71$	$p = 0.0112, 0.0054, 0.0080$	$\Gamma_3 = 16.7$	0.031
1 step set	$\Psi_1 = -134.86$	$p = 0.0077$	$\Gamma_1 = 20.0$	0.027
USN	$\Psi_{USN} = -133.0$	$\kappa = 0.45 \pm 0.16 \text{ min}^{-1}$ $\omega = 0.82 \pm 0.09 \text{ min}^{-1}$	$\Gamma_{USN} = 8.3$	0.081
ZHL16	$\Psi_{ZHL16} = -128.3$	$\kappa = 0.56 \pm 0.23 \text{ min}^{-1}$ $\omega = 0.89 \pm 0.16 \text{ min}^{-1}$	$\Gamma_{ZHL16} = 7.1$	0.132
VPM	$\Psi_{VPM} = -126.9$	$\kappa = 0.83 \pm 0.17 \text{ min}^{-1}$ $\omega = 1.02 \pm 0.29 \text{ min}^{-1}$	$\Gamma_{VPM} = 2.1$	0.717
RGBM	$\Psi_{RGBM} = -126.1$	$\kappa = 0.96 \pm 0.13 \text{ min}^{-1}$ $\omega = 0.91 \pm 0.18 \text{ min}^{-1}$	$\Gamma_{RGBM} = 1.3$	0.861

Table 4: Logarithmic Likelihood and Logarithmic Likelihood Ratio.

In the above set, there are 35 marginals. Marginals can be entered with statistical weight of 0.5 in likelihood analysis, but we do not include them [24]. The profiles in the 500+ f sw category are record attempts on OC and RB systems and are not part of operational diving in the broad sense. The maximum likelihood fits link directly to the binomial probability structure of DCS incidence [22,16] in divers and aviators. Consider it briefly, and the likelihood maximization technique.

Probabilistics and Data Correlation

Decompression sickness is a hit, or no hit, situation. Statistics are binary, as in coin tossing. Prob-abilities of occurrence are determined from the binomial distribution, which measures the numbers of possibilities of occurrence and non-occurrence in any number of events, given the incidence rate. Specifically, the probability, P, in a random sample of size, N, for n occurrences of decompression sickness and m non-occurrences, takes the form,

$$P(n) = \frac{N!}{n!m!} p^n q^m$$

with,

$$n + m = N$$

p the underlying incidence rate (average number of cases of decompression sickness), and q,

$$q = 1 - p$$

the underlying nonincidence. For large sample sizes, $N = n + m$,

$$\ln P(n) \approx N \ln N - n \ln n - m \ln m + n \ln p + m \ln q$$

The likelihood of binomial outcome, Φ, of N trials is the product of individual measures of the form,

$$\Phi(n) = p^n q^m = p^n (1 - p)^m$$

given n cases of decompression sickness and m cases without decompression sickness, and,

$$n + m = N$$

The natural logarithm of the likelihood (LL), Ψ, is easier to use in applications, and takes the form,

$$\Psi = \ln \Phi = n \ln p + m \ln (1 - p)$$

and is maximized when,

$$\frac{\partial \Psi}{\partial p} = 0$$

The multivalued probability functions, p(x), generalize in the maximization process according to,

$$\frac{\partial \Psi}{\partial p} = \sum_{k=1}^k \frac{\partial \Psi}{\partial x_k} \frac{\partial x_k}{\partial p} = 0$$

satisfied when,

$$\frac{\partial \Psi}{\partial x_k} = 0 \quad \text{for } k=1, K$$

In application, such constraints are solved on computers numerically. The likelihood, Ψ, is typically a function of arbitrary parameters over the whole set of profiles, requiring computing power coupled to sophisticated numerical techniques and software.

Rigorous statistical techniques can be applied to binomial data for arbitrary values of the under-lying incidence, p. While large values of p might be desirable for laboratory (controlled) wet and dry testing, they are not desirable for real divers submitting profiles to DBs in general. The underlying incidence in the DAN and LANL DBs is less than 1%. The Weibull function is useful for fitting applications where $p \leq 0.01$ and used herein. Computer records from real divers are likely to stay below incidences rates of 1%.

To perform risk analysis with the LANL DB, an estimator need be selected. For both dissolved gas and phase models the permissible

supersaturation, G , is useful. As detailed earlier [17] and discussed elsewhere [16,18], the permissible supersaturation, G , is cast into normalized risk function, ρ , form,

$$\rho(\kappa, \omega, t) = \kappa \left[\frac{\Pi(t) - P(t)}{P(t)} \right] - \kappa \exp(-\omega t)$$

with $\Pi(t)$ and $P(t)$ total tissue tension and ambient pressures in time, t . the exponential term, $\exp(-\omega t)$, damps out early unimportant scatter in the profiles. The asymptotic exposure limit is used in the likelihood integrals for risk function, r , across all compartments, τ ,

$$1 - r(\kappa, \omega) = \exp \left[- \int_0^{\infty} \rho(\kappa, \omega, t) dt \right]$$

with $hit - \eta \rho$ hit , likelihood function, Ω , of form,

$$\Omega = \prod_{k=1} \Omega_k$$

$$\Omega_k = r_k^{\delta_k} (1 - r_k)^{1 - \delta_k}$$

and logarithmic reduction, Ψ ,

$$\psi = \ln \Omega$$

where, $\delta_k = 0$ if DCS does not occur in profile, k , or, $\delta_k = 1$ if DCS does occur in profile, k . To estimate κ and ω in maximum likelihood, a modified Weibull-Levenberg-Marquardt [22,19] model is employed (SN LSE, Common Los Alamos Mathematical Statistical Library) [19], a nonlinear least squares data fit (NLLS) to an arbitrary logarithmic function (minimization of variance over K data points with $L2$ error norm).

We assign numerical tasks to the 2000 processors on the LANL Blue Mountain MPP according to tissue compartments and the 6 (nitrox, trimix, heliox) data sets. Risk estimates emerge and risk parameters are finally averaged and variance computed. In diver staging, certain tissue compartments control the exposure, This is true within dissolved gas models, as well as bubble models. These compartments change on ascent from fast to slower compartments. In applications from nonstop to decompression diving in the LANL DB, controlling compartments, τ_c , range roughly,

$$2 \leq \tau_c \leq 300 \text{ min}$$

and long, prolonged, saturation diving is not a profile characteristic. It is these compartments at various points in the ascent that are correlated, as the others do not control the ascent at that point in space and time.

Finally, we fit across the 6-step nitrox, heliox, trimix data set:

$$\text{USN} - \kappa = 0.45 \pm 0.16 \text{ min}^{-1}, \omega = 0.82 \pm 0.09 \text{ min}^{-1}$$

$$\text{ZHL16} - \kappa = 0.56 \pm 0.23 \text{ min}^{-1}, \omega = 0.89 \pm 0.16 \text{ min}^{-1}$$

$$\text{VPM} - \kappa = 0.83 \pm 0.17 \text{ min}^{-1}, \omega = 1.02 \pm 0.29 \text{ min}^{-1}$$

$$\text{RGBM} - \kappa = 0.96 \pm 0.13 \text{ min}^{-1}, \omega = 0.91 \pm 0.18 \text{ min}^{-1}$$

The logarithmic likelihood (LL), Ψ , is a rough metric for fits to bubble and super saturation risk estimators. The canonical value, Ψ_6 , is the LL for the 6-step data set. No fit value, Ψ , will better the canonical value, Ψ_6 , that is,

$$\Psi_6 = -124.86$$

$$\Psi \leq \Psi_6$$

meaning all fits will be more negative (smaller LL). Results are tabulated as follow in Table 4. The 6-step set, nitrox OC and RB, heliox OC and RB, and trimix OC and RB profiles, is non-sparse and is the same set employed in previous analyses. The 3-step set is all nitrox, heliox, and trimix profiles across all depths and breathing systems. The 1-step set is just all profiles across depths, breathing mixtures, and breathing systems.

The logarithmic likelihood ratio (LLR), denoted Γ , tests two models, and is χ^2 distributed,

$$\Gamma = 2(\Psi_6 - \Psi)$$

for Ψ the bubble and supersaturation estimators in Table 4. The percentage point, α , is the area under the chi squared curve, from Γ to ∞ , measuring the goodness of fit, ranging 0 to 1, and denoted in customary fashion,

$$\int_{\Gamma}^{\infty} \chi^2(x, \nu) dx = \alpha$$

with,

$$\chi^2(x, \nu) = \frac{1}{2^{\nu/2} \Gamma(\nu/2)} x^{\nu/2-1} \exp(-x/2)$$

With, $\Gamma(\nu/2)$ the complete gamma function for ν the degrees of freedom (6 minus the number of USN, ZHL16, VPM, RGBM, 3, or 1-step degrees of freedom). Here, ν will vary between 5 and 3, that is, for the USN, ZH16, VPM, and RGBM correlations, $\nu = 4$, while for the 3-step correlation, $\nu = 3$, and for the 1-step correlation, $\nu = 5$. Standard software is available to estimate α for given Γ and ν and used here.

It is important to note that specific model parameters are fixed herein, and not fitted in likelihood analysis. Such would be a separate study, [25] which using the 6-step set, would allow up to 5 model values to be optimized. Nominal model parameters were briefly mentioned and annotated earlier in the discourse. Data correlations with nominal model parameter settings are of general interest across the diving community and our focus here (Table 4).

Conclusion

The USN, ZHL16, VPM, and RGBM models and protocols were statistically correlated with profiles in the LANL DB. The DB stores technical, decompression, mixed gas diving profiles with outcomes. Some 2900+ computer downloaded, deep stop, profiles reside within the DB, with 23 cases of DCS. Nominal model user parameters were employed in calculations and are representative of values used popularly in decompression meters, dive tables, and dive planning software. Correlation functions were the model constrained permissible supersaturations which vary widely across dissolved gas and bubble models. Dissolved gas models admit greater supersaturations than bubble models.

Statistically, the outcomes of hit or no-hit were used as endpoints for this analysis. Other end-points employed include Doppler bubble counts and various imaging metrics. All have their merits and the latter collect different information.

The USN and ZHL16 models correlate weakly:

$$\text{USN} - \chi^2 = 0.081$$

$$\text{ZHL16} - \chi^2 = 0.131$$

while the VPM and RGBM models correlate more strongly:

$$\text{VPM} - \chi^2 = 0.717$$

$$\text{RGBM} - \chi^2 = 0.861$$

Such might be expected in various quarters and this analysis thus both affirms and more importantly quantifies these speculations. While the correlation of VPM and RGBM with deep stop data is expected to be high, the correlation of USN and ZHL is surprisingly higher than expected from many researchers. Perhaps the optimal approach to safe diving is a model somewhere between the extremes of each.

Our focus is safe operational diving. The LANL DB suggests that the diving profiles collected are low risk across the spectrum of activities (underlying incidence less than 1%), and the correlations of deep stop models (VPM and RGBM) within this DB also suggest that deep stop models are safe, practical, realistic, and reproducible for sport and technical diving with deep stop computers, software, and tables. Modern dive computer offering with deep stop implementations are legion and increasing in number and we hope this analysis helps in their continued validation and safe diver usage.

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