DIVE COMPUTER PROFILE DATA AND RISK ESTIMATORS

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ABSTRACT

Dive computers and diveware are important underwater tools and staging devices across sport, technical, commercial, military, scientific, exploration and research diving sectors. They are supplanting traditional dive tables and their use is growing as decompression activities grow. While important computer parameters are displayed thoughout a dive, DCS risk associated with surfacing and arbitrary ascents to depths above the diver are not yet encoded into underwater devices and diveware and that is the focus here. Risk estimation is needed for diver safety and sensible dive planning. We discuss (two) basic biophysical models, oxygen toxicity and then methodology for risk estimators that can be employed in present generation dive computers and dive planning software for *end of dive* (EOD) and *on the fly* (OTF) risk at any point on a dive. Exponential risk functions are defined for dissolved gas and bubble models using profile data correlated with the LANL Data Bank, a collection of computer downloaded mixed gas decompression profile with DCS outcomes across OC and RB diving. Risk functions are based on profile supersaturations in excess over permissble supersaturations which are a standard metric. Comparative results and applications are given for both nonstop and deep decompression diving on OC and RB systems. Computer implementation is easily accomplished within existing dive computers and diveware platforms. Techniques are underscored and results are discussed. References detail background information and analyses and work extends earlier published analyses for EOD risk estimation. It is hoped that this methodology is useful, well defined and pertinent for the dive computer and dive software industry.

Keywords – dive computers, DCS risk, decompression models, profile data, data banks

Pages – 26, Tables – 12, Figures – 2, References – 22

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DEFINITIONS AND ACRONYMS

Standard (SI) and English units are employed. By convention, by usage or for ease, some nonstandard units are employed. Pressure and depth are both measured in feet of sea water (fsw) and meters of sea water (msw), with 1 atm = 33 fsw = 10 msw to good approximation. Acronyms are used herein. They are standard throughout the dive community with definitions:

ANDI: Association of Nitrox Diving Instructors.
BM: bubble phase model dividing the body into tissue compartments with hypothetical 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 called the phase volume.
BMI: body mass index, a fitness indicator defined as body weight divided by height squared with nominal values, 18.5 tp 25 kg/m^2, for healthy normal weight people.
CCR: closed circuit rebreather, a special RB system that allows the diver to fix the oxygen partial pressure in the breathing loop (set point).
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 storing downloaded computer profiles in 5-10 sec time-depth intervals.
DCS: 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.
diluent: any mixed gas combination that is used with pure oxygen in the breathing loop of RB devices.
diving algorithm: combination of a gas transport and/or bubble model with coupled diver ascent strategy.
DOD: Department ofDefense.
DOE: Department of Energy.
Doppler: a device for counting bubbles in flowing blood that bounces acoustical signals off bubbles and measures change in frequency.
DRA: Decompression Risk Analyzer, an online DSL software package to estimate EOD risk by communicating over mobile phones.
DSAT: Diving Science and Technology, a research arm of PADI.
DSG: Diver Safety Guardian, an DSL software package to link divers to an online risk analyzer (DRA).
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.
GAP: Gas Absorption Program, a technical diveware package.
GF: gradient factor, a multiplier of M-value and Z-value critical gradients, G, less than 1 that gives deep stops.
GM: dissolved gas model dividing the body into tissue compartments with hypothetical half times for uptake and elimination of inert gases with tissue tensions constrained by limit points called M-values or critical tensions.
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.
M-values: a set of limiting tensions for dissolved gas buildup in each tissue compartment at depth.
mixed gases: any combination of oxygen, nitrogen and helium gas mixtures breathed underwater.
ML: maximum likelihood, a statistical technique used to correlate models with DCS profile outcomes.

NAUI: National Association of Underwater Instructors.
NDL: no decompression limit, maximum allowable time at given depth and breathing mixture before immediate ascent to the surface.
NEDU: Naval Experimental Diving Unit, the diver testing arm of the USN in Panama City.
nitrox: breathing gas mixture of nitrogen and oxygen used in recreational diving.
NLLS: non linear least squares, a mathematical technique of fitting models to data using the squares of differences between data points and model estimators.
OC: open circuit, underwater breathing system using mixed gases from a tank that are exhausted after exhalation.
OT: oxtox, pulmonary (full body) and/or central nervous system (CNS) oxygen toxicity resulting from over exposure to oxygen at depth or high pressure.
OTF: on the fly risk estimator computed at any point on the dive for ascending above the diver.
PADI: Professional Association of Diving Instructors.
PDE: Project Dive Exploration, a computer dive profile collection project at DAN.
phase volume: limit point for bubble growth under decompression.
RB: rebreather, underwater breathing system using mixed gases from a cannister that are recirculated after carbon dioxide is scrubbed from exhalant and 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 outcomes from computer downloaded profiles by Wienke.
risk estimator: mathematical expression for risk associated with ascents to the surface or arbitrary points above the diver that is correlated with DCS outcomes or Doppler scores.
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.
support team: a collection of surface and underwater divers providing life support and necessary equipment for deep and extended decompression diving.
TDI: Technical Diving International.
technical diving: mixed gas (nitrogen, helium, oxygen), OC and RB, deep and decompression diving.
TM algorithm: an Australian separated phase (pseudo-bubble) staging model correlated with the profiles of pearl divers in the Torres Straits by Hills that set the stage for a generation of bubble models to follow.
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.
UDI: underwater digital interface, an underwater dive computer with surface and diver communication capabilities.
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 computer system (UDI) using sonar, GPS and underwater communications with a range of about 2 *miles*.
VPM algorithm: an American bubble staging model based on gels by Yount.
WLM: Weibull-Levenberg-Marquardt algorithm, a statistical software package used to correlate low probabilty DCS events with risk functions of assumed forms, usually exponential.
Z-values: another set of 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

Dive computers and diveware are useful tools across recreational and technical diving *[1-6]*. They are supplanting traditional dive tables and their use is growing as diving activities grow *[7-13]*. Able to process depth-time readings in fractions of a second, modern dive computers routinely estimate and display hypothetical dissolved gas loadings, bubble buildup, ascent and descent rates, diver ceilings, time remaining, decompression staging, oxygen toxicity and many related variables. Estimates of these parameters made at any point on the dive are nested within two basic models *[4,6,8]*, namely, the classical dissolved gas model (GM) and the modern bubble phase model (BM). Both have seen meaningful correlations with real dive data over limited ranges but differ in staging regimens. Dissolved gas models (GM) focus on controlling and eliminating hypothetical dissolved gas by bringing the diver as close to the surface as possible. Bubble phase models (BM) focus on controlling hypothetical bubble growth and coupled dissolved gas by staging the diver deeper before surfacing. The former gives rise to *shallow* decompression stops while the latter requires *deep* decompression stops in the popular lingo these days. As models go, both are fairly primitive, only addressing the coarser dynamics of dissolved gas buildup and bubble growth in tissues and blood. Implementations of both are however extensive across the market of popular dive computers. Obviously, their use and implementation is limited,but purposeful when correlated with available data. To coin a phrase from a community at large, *all models are wrong but some are useful*. Useful ones are models correlated with diving data, that is, test, databank or long term safe operational protocols. Useful and popular models include the USN, ZHL, VPM and RGBM algorithms and they will be employed in comparative risk estimation to follow.

Today, some 15 -25 companies manufacture dive computers and associated dive planning software employing both the GM and BM algorithms in another 70 - 90 models by last count. Recreational dive computers mainly rely on the GM while technical dive computers use the BM. In the limit of nominal exposures and short time (nonstop diving), the GM and BM converge in diver staging. Dive planning and decompression software are also readily available from Vendors. But risk estimation for arbitrary ascents is not yet encoded into existing dive computers and diveware. It is sorely needed for diver safety and sensible dive planning. And this is our focus here with methods developing a simple correlated approach to estimating risk for any gas mixture, OC and RB system, deep or shallow dive, long and short bottom time, nonstop and decompression dive and staging algorithm presently embedded in any computer of the USN, ZHL, VPM or RGBM genre. We first discuss dive computers, computational models, statistical techniques, data and related protocols then followed by risk estimators and applications. Applications focus on both nonstop and decompression diving on mixed gas, OC and RB systems.

The state of present models follows. There are just two basic ones, dissolved gas (GM) and bubble (BM) models. It is easy to couple parameters basic to both models to risk estimation in real dive computers and dive planning software. They differ on staging regimens as seen in Figure 1 and both have a good record of safe and sane dive computer utilization. That is certainly good and some reasons why are suggested later. Both are thus readily amenable to the EOD and OTF risk estimation ansatz proposed with little additional algorithm encoding.

BASIC DIVE COMPUTER MODELS

Instantaneous estimates of parameters needed to stage divers by underwater computers rely an mathematical relationships coupled to pressure sensors and clocks in the unit. The two basic ones follow *[4,6,8]* as well as quantification of oxygen toxicity in diving *[2,3,6]*.

Dissolved Gas Model (GM)

Diver staging in the classical Haldane approach limits inert gas tissue tensions, p, across all tissue compartments, λ, with halftimes, τ, by a limit point, called the critical tension, M, according to,

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

with p_a ambient gas partial pressure, p_i initial partial tension, t exposure time at p_a and,

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

with corresponding critical gradient, G,

$$G = M - P$$

Halftimes range,

$$3 \le \tau \le 540\ min$$

in applications and critical tensions, M, are linear functions of depth, d, with roughly,

$$M = \tau^{-0.25}(153.3 + 4.11d)\ fsw$$

Deep Versus Shallow Staging-- Bubbles Or Dissolved Gas?

Dual Phase Dilemmas

If M is exceeded at any point on ascent, a decompression stop is required. Helium tissue halftimes are 1/3 nitrogen tissue halftimes. Algorithm is used in recreational and technical diving across OC and RB systems.

The GM algorithm typically brings diver into the shallow zone for decompression (shallow stops). Ascent rates are nominally a slow 30 fsw/min. Critical tensions, M, have little to nothing to do with actual bubble formation in the tissue and blood but are (statistical) medical limit points to observed nonstop diving outcomes using basically arbitrary tissue compartments, τ. The approach dates back to Haldane and the 1900s and has been used extensively since then with little change and some tweaking of values. Much testing by World Navies has ensued on the medical side. Notable are the USN *[14]* and ZHL*[15]* models and details follow:

1. **USN Model (Workman 1965)** In the Workman USN approach, the permissible gas tension, Π, (nitrogen plus helium) 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,

   $$d = P - P_0$$

   Table 1. Workman USN M-Values

τ_{N_2} (min)	nitrogen M_0 (fsw)	ΔM	τ_{He} (min)	helium M_0 (fsw)	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

   Corresponding permissible gradients, G, then satisfy,

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

   with P_0 ambient pressure at the surface as noted,

   $$P_0 = 33\ exp\ (-0.038h)$$

   for elevation, h, in multiples of 1000 ft.

2. **ZHL Model (Buhlmann 1990)** The Buhlmann ZHL approach was tested at low altitude and is similar to the Workman USN approach, that is, the permissible gas tension, Π (nitrogen plus helium again), is limited by fit parameters, a and b, lumped in Table 2,

   $$\Pi \leq Z$$

   with critical tensions, Z, given by,

   $$Z = a + \frac{P}{b} = a + \frac{P_0 + d}{b} = Z_0 + \Delta Z d$$

   with,

   $$Z_0 = a + \frac{P_0}{b}$$

$$\Delta Z = \frac{1}{b}$$

Accordingly, we have,

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

for constants, a and b, defining Z at sea level ($P_0 = 33\ fsw$) in Table 2. The expressions put the ZHL Z-value model in the same computational framework as the USN M-value model

Table 2. Buhlmann Swiss Z-Values

τ_{N_2} (min)	nitrogen $Z_0 = a + 33/b$ (fsw)	$\Delta Z = 1/b$	τ_{He} (min)	helium $Z_0 = a + 33/b$ (fsw)	$\Delta Z = 1/b$
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

Bubble Phase Model (BM)

Modern bubble phase models (BM) couple tissue tensions to bubbles directly by assuming an exponential distribution, n, of bubble seeds in radii, r, excited into growth by changing ambient, P and dissolved gas, p, total pressure,

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

for N and β constants obtained and/or fitted to laboratory or dive data. To date, distributions of bubble seeds have not been measured *in vivo*. Using the same set of tissue halftimes and inert gas tension equations above in the GM, diver staging in the BM requires the cumulative bubble volume excited into growth by compression-decompression, ϕ, to remain below a critical value, Φ, throughout all points of the dive and in all tissue compartments,

$$\int_t \frac{d\phi}{dt} dt = 4\pi DS \int_t \int_r nr^2 \left[p - P - \frac{2\gamma}{r}\right] drdt \le \Phi$$

with D tissue diffusivity, S tissue solubility and γ bubble surface tension. In applications, the critical phase volume, Φ, is taken near 600 $microns^3$ and surface tension, γ, is roughly 20 $dyne/cm$. Diffusivity times solubility, DS, is also fitted to diving data. If Φ is exceeded at any point on ascent, a decompression stop is necessary. The decompression schedule is computed from permissble tissue-bubble gradients and applied iteratively until the surfacing separated phase volume, ϕ, stays below the limit point, Φ. Convergence of the iterative process usually occurs within 2-3 passes.

The BM algorithms are used across recreational and technical diving on both OC and RB systems. Staging starts in the deep zone and continues into the shallow zone (deep stops). Ascent rates are also 30 fsw/min. Bubbles are assumed using realistic properties and exponential distributions in size but have never been really measured in humans. The phase volume limit point, Φ, is also deduced and fitted from diver exposure profiles using data from the LANL Data Bank within statistical correlations of bubble model and exposure data. Testing is nowhere near as extensive as dissolved gas approaches but is growing. The model relies on correlations with actual mixed gas diving across OC and RB, deep and decompression diving on arbitrary breathing mixtures. Application and use is growing, particularly in the technical diving sector, over the past 20-25 years with new computers implementing bubble models. In particular, the VPM *[16]* and RGBM *[17]* models are noteworthy and used extensively within recreational and technical diving sectors. They also follow:

1. **Varying Permeability Model (Yount 1986)** The tissue compartments in the Yount VPM for nitrogen consist of the set,

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

   with the helium compartments scaling,

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

   The VPM model 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 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 $1/\varepsilon\ \mu m^{-1}$ for diving applications. The staging protocol in the VPM limits the permissible supersaturation, G to prevent bubble growth on ascent,

   $$G = \Pi - P \leq \frac{\gamma}{\gamma_c}\left[\frac{2\gamma_c}{\varepsilon} - \frac{2\gamma}{\varepsilon_0}\right]$$

   with γ the usual bubble surface tension and γ_c the crushing bubble surface tension, roughly 20 $dyne/cm$ and 150 $dyne/cm$ respectively. 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.

2. **Reduced Gradient Bubble Model (Wienke 2008)** Nitrogen tissue compartments in the Wienke RGBM range,

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

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

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

   so that,

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

   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 ZHL 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 20 $dyne/cm$, and excitation radii are below 1 μm.

The popular USN, ZHL, VPM and RGBM algorithms implemented across the majority of marketed and tested dive computers have seen widespread and safe usage over many years with GM computers around since the 1970s and BM computers more recent and gaining in popularity since the 1990s especially in the technical diving community. Correlations and tests for USN and ZHL staging are referenced *[7,14,15]* and discussed elsewhere while correlations and tests for VPM and RGBM staging are similarly referenced *[4,18,20]* and discussed in the same frameworks. With extensive computer implementation and safe utilization without noted DCS nor oxtox spikes and staging issues, they all can be considered validated across nominal recreational and technical diving. It is also reasonable to assume they can and will be safely modified to accommodate diving *beyond the envelope* in the future.

Of course there are many models that fall into the GM and BM categories and some are depicted in Figure 2 which contrasts model staging predictions for the USN deep stop air tests at 170 fsw for 30 min. Roughly one might say that the models with long time tails in the shallow zone are GMs while those with more rapid ascent and shorter time tails in the shallow zone are BMs. Depending on user settings, dive computers and diveware can mimic all sets of staging options easily. Questions of right or wrong then relate to model correlations with diving data and that is where correlated and tested USN, ZHL, VPM and RGBM algorithms weigh more heavily.

Oxygen Toxicity (OT)

Both pulmonary and CNS toxicity are tracked by both GM and BM dive computers in a relatively simple way *[4,6]*. Pulmonary toxicity is tracked with a dose-time estimator, Γ, written,

$$\Gamma = \sum_n \left[\frac{pp_{O_2} - 0.5}{0.5} \right]_n^{0.83} t_n \leq 750 \, min$$

with, pp_{O_2}, oxygen tension (atm) and, t, exposure time (min). Dive segments, n, are tallied every 5-10 sec and Γ updated. Central nervous system toxicity is similarly tallied over dive segments, n, by a CNS clock, Ω, using the oxygen limit points, t_{O_2}, for exposure to oxygen partial pressure, pp_{O_2} (atm), for time, t (min),

$$\Omega = \sum_n \left[\frac{t}{t_{O_2}} \right]_n \leq 1$$

with approximate CNS oxygen time limits (min),

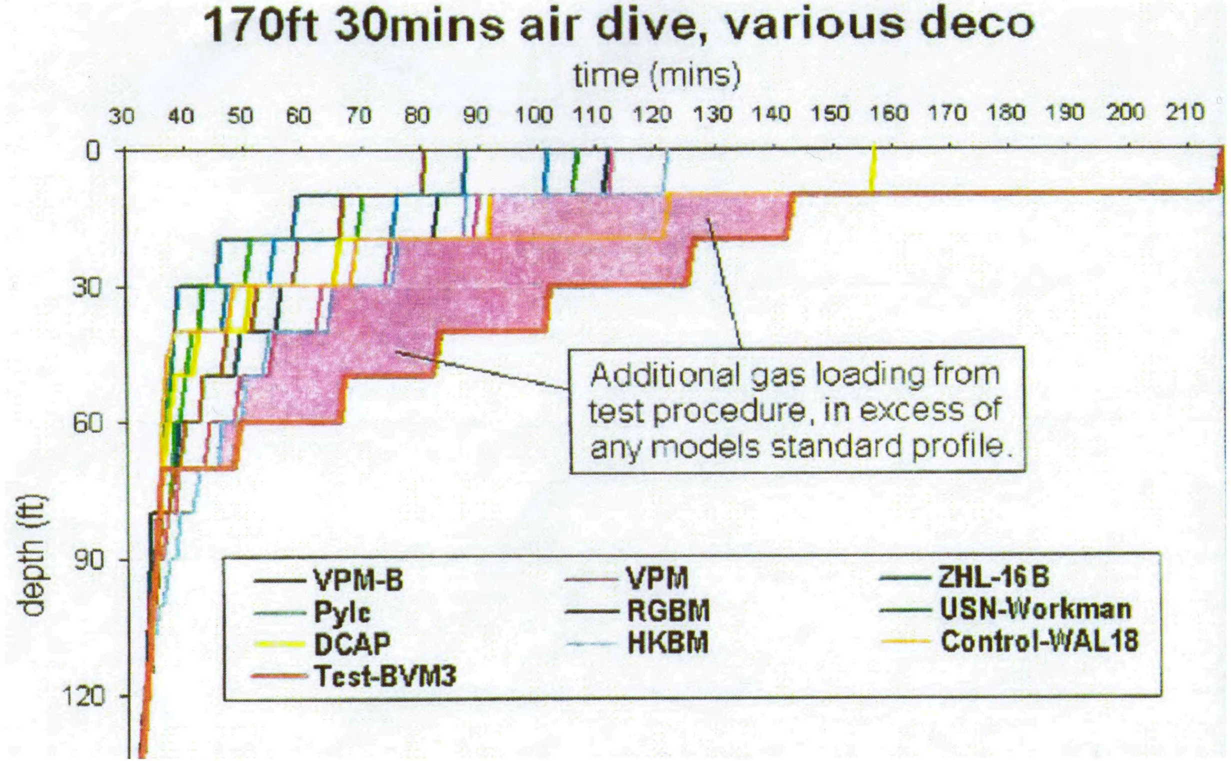
$$t_{O_2} = 4140 \, exp \, (-2.7 pp_{O_2}) \, min$$

In both cases, violations of OT limit points result in dive computer warnings. Variations in tested oxygen limit points are greater than variations in tested nonstop limits in air and nitrox exposures. This is probably a reason why technical divers often exceed CNS oxtox clock limits by large amounts – in the 2-3 range from some reports. With further testing in the future, one might reasonably expect some tuning of the oxtox dose-time relationships. Without noted oxygen toxicity problems in computer users of the above oxygen dose-time relationships, the present oxtox model seems safe and user validated across popular GM and BM computers on the whole. Reports of oxygen toxicity in divers are fewer and far more between than DCS reports *[3,11]*.

DIVE COMPUTER PROFILE DATA

To validate computer models *[6,7,18]*, real diving data is necessary. In the past, data consisted mostly of scattered open ocean and dry chamber tests of specific dive schedules. In such instances, the business of correlating model and diving data was only scratched. Today, profile collection across diving sectors is proceeding more rapidly. Notable are the efforts *[1,4]* of Divers Alert Network (DAN) and Los Alamos National Laboratory (LANL). DAN USA is collecting profiles in an effort called Project Dive Exploration (PDE) here and DAN Europe has a parallel effort called Diving Safety Laboratory (DSL). The DAN focus has been recreational dive profiles for air and nitrox. The LANL Data Bank collects profiles from technical dive operations on mixed gases for deep and decompression diving on OC and RB systems. Some interesting features of the data have emerged so far from these collections *[11-13]*:

- profile collection of diver outcomes is an ongoing effort at DAN USA, DAN Europe and LANL and has aided in model tuning using rigorous statistical techniques
- there are no reported spikes in DCS/OT rates for recreational and technical divers using dive computers



Additional gas loading from test procedure, in excess of any models standard profile.

- statistics gathered at DAN and LANL suggest that DCS/OT rates are low across recreational and technical diving, but that technical diving is some 10-20 times riskier than recreational diving
- data from Meter Manufacturers and Training Agencies, reported as anecdotal at recent Workshops, suggests the DCS/OT incidence rate is on the order of 143/6,000,000 dives (underlying incidence) for computer users
- the underlying incidences in the DAN and LANL profile data are small, on the order of 80/187451 and 28/3459 respectively
- Training Agencies, such as PADI, NAUI, IANTD, TDI, ANDI, SSI and GUE, have standardized and incorporated both GM and BM algorithms into their training regimens safely for spans of many years without DCS nor oxtox spikes and issues using tables, dive computers and diveware across recreational and technical diving

Profile collection efforts such as these can enormously benefit divers and diving science. Without downloadable profile data from dive computers, meaningful algorithm and protocol analysis is very difficult. Profile data banks are important resources for all kinds of diving.

In all cases, data collection is an ongoing effort and profile information can be narrowed down to its simplest form, most of it coming from dive computer downloads tagging information across variable time intervals (5 - 10 *sec*) which is then processed into a more manageable format for statistical analysis:

- bottom mix/pp_{O_2}, depth and time
- ascent and descent rates
- stage and decompression mix/pp_{O_2}, depths and times
- surface intervals
- time to fly
- diver age, weight, sex and health complications
- outcome rated 1 - 5 in order of bad to good
- environmental factors (temperature, current, visibility, equipment)

Different DBs will use variations on reported data but the above covers most of the bases. Consider the LANL DB in more detail. Risk estimates to follow are based on downloaded profiles and data in the LANL DB.

LANL DB

Some 3569 profiles now reside in the LANL DB. There are 28 cases of DCS in the data file. The underlying DCS incidence rate is, $p = 28/3569 = 0.0078$, below but near 1%. Stored profiles range from 150 fsw down to 840 fsw, with a major portion above 350 fsw. All data enters through the Authors, that is, divers, profiles and outcomes are filtered. The following summary breakdown of DCS hits (bends) updates our earlier reporting and data consists of the data:

- OC deep nitrox reverse profiles – 5 hits (3 DCS I, 2 DCS II)
- OC deep nitrox – 3 hits (2 DCS I, 1 DCS II)
- OC deep trimix reverse profiles – 2 hits (1 DCS II, 1 DCS III)
- OC deep trimix – 4 hits (3 DCS I, 1 DCS III)
- OC deep heliox – 2 hits (2 DCS II)
- RB deep nitrox – 4 hits (2 DCS I, 2 DCS II)
- RB deep trimix – 4 hits (3 DCS I, 1 DCS III)
- RB deep heliox – 4 hits (3 DCS I, 1 DCS II)

Open circuit is denoted OC and rebreathers are denoted RB. DCS I means limb bends, DCS II implies central nervous system (CNS) bends, and DCS III denotes inner ear bends (occurring more often on helium mixtures). Both DCS II and DCS III are fairly serious afflictions while DCS I is less traumatic. Deep nitrox means a range beyond 150 fsw, deep trimix means a range beyond 200 fsw and deep heliox means a range beyond 250 fsw as a rough categorization. Reverse profiles are any sequence of dives in which the present dive is deeper than the previous dive. Nitrox means an oxygen enriched nitrogen mixture (including air), trimix denotes a breathing mixture of nitrogen, helium, oxygen and heliox is a breathing mixture of helium and oxygen. None of the trimix nor heliox cases involved oxygen enriched mixtures on OC and RB hits did not involve elevated oxygen partial pressures above 1.4 *atm*. Nitrogen-to-helium (*heavy-to-light*) gas switches occurred in 4 cases, violating contemporary ICD (isobaric counterdiffusion) protocols. Isobaric counterdiffusion refers to two inert gases (usually nitrogen and helium) moving in opposite directions in tissues and blood. When summed total gas tensions (partial pressures) can lead to increased supersaturation and bubble formation probability.

None of the set exhibited pulmonary (full body) nor CNS (central nervous system) oxygen toxicity. The 28 cases come after the fact, that is, diver distress with hyperbaric chamber treatment following distress. Profiles originate with seasoned divers as well as from broader field testing reported to us from divers using wrist slate decompression tables with computer backups. Profiles reach us directly as computer downloads which we translate to a requisite format for further code processing. Approximately 88% of all LANL DB entries emanate from computer downloads (3569 profiles) and the rest are controlled C&C Team staging tests performed in the 1980s (491 test profiles). The latter are not used in this analysis.

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 useful in the following but first breakout of data into gas categories (nitrox, heliox, trimix) needs updating in earlier reporting *[6]*. Table 3 indicates the updated breakdown.

Table 3. Profile Gas-DCS Summary

mix	total profiles	DCS hits	incidence
OC nitrox	459	8	0.0174
RB nitrox	665	4	0.0060
all nitrox	1124	12	0.0107
OC trimix	771	6	0.0078
RB trimix	869	4	0.0046
all trimix	1640	10	0.0061
OC heliox	166	2	0.0120
RB heliox	639	4	0.0063
all heliox	805	6	0.0075
total	3569	28	0.0078

The DCS hit rate with nitrox is higher but not statistically meaningful across this sparse set. The last entry is all mixes as noted previously. In the above set, there are 49 *marginals*, that is, DCS was not diagnosed but the diver surfaced feeling badly. In such cases, one might statistically weight the dive 1/2.

It is also interesting to break mixed gas profiles into 50 fsw depth increments and is is obvious that 500 fsw or so is the limit statistically to the data set. It is for that reason that we limit applications of the LANL algorithm to 540 fsw in dive computers and planning software.

Table 4. Profile Gas-Depth Summary

	100 to 200 fsw	200 to 250 fsw	250 to 300 fsw	300 to 350 fsw	350 to 400 fsw	400+ fsw	total
OC nitrox	358	101					459
RB nitrox	223	311	131				665
OC trimix	30	443	266	26	4	2	771
RB trimix	32	393	321	113	10		869
OC heliox		62	69	30	5		166
RB heliox	52	230	188	142	17	10	639
total	695	1540	975	311	36	12	3569

The corresponding DCS hit summary for Table 4 is given in Table 5.

Table 5. Profile Gas-Depth DCS Summary

	100 to 200 fsw	200 to 250 fsw	250 to 300 fsw	300 to 350 fsw	350 to 400 fsw	400+ fsw	total
OC nitrox	5	3					8
RB nitrox		2	2				4
OC trimix		2	2	1		1	6
RB trimix		2	1	1			4
OC heliox			2				2
RB heliox		1	2	1			4
total	5	10	9	3		1	28

Commercial Units

The number of dive computers marketed has grown significantly in the past 20 years or so. A representative cross section of commercial units presently marketed is listed. 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 under many environmental conditions. All are amenable to implementation of the risk estimators to follow and include:

1. **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. The Zoop and Cobra are recreational computers for gauge, air and nitrox use.
2. **Mares** All Mares computers use the RGBM. Recreational models include the ICON HD, Matrix, Smart and Puck Pro for OC in gauge, air and nitrox modes.
3. **Uwatec** Uwatec computers are marketed by Scuba Pro 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.
4. **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.
5. **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.
6. **Cressisub** All 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.
7. **Sherwood** Sherwood computers all use the ZHL. Recreational models for air and nitrox include the Amphos and Wisdom computers.
8. **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.
9. **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.
10. **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.

11. **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.
12. **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.

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.

RISK ESTIMATORS

Risk estimation, on the fly (OTF) or end of dive (EOD), is not yet implemented in dive computers nor planning software. The following suggests appropriate methodology for implementation of both. As dive computers working in the recreational (air and nitrox) depth regime, $d < 130\ fsw$ roughly, use GM models for speed and simplcity and dive computers working in the technical (mixed gases and decompression) depth regime, $d > 130\ fsw$, employ BM models, we will use use GM risk functions in comparative applications for shallow recreational diving, $d < 130\ fsw$, and BM risk functions in comparative applications for deep and decompression technical diving, $d > 130\ fsw$.

End Of Dive Risk Estimator (EOD)

In performing risk analysis with the LANL DB, the tissue gradient is useful. As detailed *[4,6,8]*, the gradient was 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 pressure in time, t, respectively. Risk is quantified by the difference between total tissue tension and ambient pressure divided by ambient pressure summed over time. Risk increases with increasing tissue tension and decreasing ambient pressure and increasing time. The approach was used before for overall dive risk estimation *[1,6,7]*. An asymptotic exposure limit is used in the risk integrals, that is, $t_{mx} = 48\ hrs$ after surfacing across all compartments, τ, in time, t,

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

with $r(\kappa,\omega)$ the usual cumulative risk after time, t. The first term in the risk function, ρ, links to dynamical supersaturation in the models while the second term is a smoothing function over dive time.

To estimate κ and ω within maximum likelihood (ML), a Weibull-Levenberg-Marquardt (WLM) *[4]* package was employed (*SNLSE*, Common Los Alamos Mathematical And Statistical Library *[21]*), a non linear least squares data fit (NLLS) to an arbitrary exponential function with minimization of variance over 3569 data points and $L2$ error norm. The computational program is straightforward but massive. Across all tissue compartments, τ, the maxiumum value of the gradient is cumulated in the risk integral every 5-10 *sec* until surfacing and across all profiles. A resulting 3659 x 3659 matrix is stored for further manipulation, inversion and minimization. Across GM and BM algorithms (USN, ZHL, VPM, RGBM) and using Table 5, there then obtains a range for the fit, parameters [19],

$$\kappa = 0.698 \pm 0.283\, min^{-1}$$

$$\omega = 0.810 \pm 0.240\, min^{-1}$$

Mathematical and computing details are given elsewhere for EOD risk estimation *[6,22]* and not repeated. To estimate κ and ω within maximum likelihood (ML), a Weibull-Levenberg-Marquardt (WLM) *[4] low p* package was employed (*SNLSE*, Common Los Alamos Mathematical And Statistical Library) *[21]*, a non linear least squares data fit (NLLS) to an arbitrary exponential function (minimization of variance over 3569 data points with $L2$ error norm) Note EOD risk estimates extend out to 2 *hrs* (t_{mx}) after the dive. Some of those EOD risk estimates follow *[20]* for select profiles and staging for completeness. Risk estimators are denoted, r_{GM} and r_{BM} to distinguish algorithms. For numerics the USN, ZHL, VPM and RGBM models were used in the following but the results are trendwise generic for GM and BM classes of algorithms. In the following depth, $d = 130$ fsw, separates GM and BM applications. Some 3659 EOD risk estimators generated from the LANL DB serve as surfacing bootstraps for OTF risk estimators in the next section. There the 3659 EOD risks are equated to surfacing 3659 OTF risk estimators using standard NLLS techniques to scale the OTF estimators.

Test Profiles and EOD Risk

Following examples are taken from the LANL DB and have been discussed and published earlier *[4,22]* with regards to models, staging comparisons, deep and shallow stops, tests and data.

1. **Deep OC Trimix Dive** Consider a deep trimix dive with multiple gas switches on the way up. This is a risky technical dive performed by seasoned professionals. Table 6 contrasts stop times for two gas choices at the 100 fsw switch. The dive is a short 10 *min* at 400 fsw on TMX 10/65 with switches at 235 fsw, 100 fsw and 30 fsw. Descent and ascent rates are 75 fsw/min and 25 fsw/min. Obviously, there are many other choices for switch depths, mixtures and strategies. In this comparison, oxygen fractions were constant in all mixes at all switches. Differences between a nitrogen or a helium based decompression strategy, even for this short exposure, are nominal. Such usually is the case when oxygen fraction is held constant in helium or nitrogen mixes at the switch.

Table 6. Comparative Helium and Nitrogen Gas Switches and Risk

depth (fsw)	time (min)	time (min)
	TMX 10/65	TMX 10/65
400	10.0	10.0
260	1.5	1.5
250	1.0	1.0
240	1.0	1.0
	TMX 18/50	TMX 18/50
230	0.5	0.5
220	0.5	0.5
210	0.5	0.5
200	0.5	0.5
190	1.0	1.0
180	1.5	1.5
170	1.5	1.0
160	1.5	1.5
150	1.5	2.0
140	2.0	1.5
130	2.0	2.5
120	4.0	4.0
110	4.5	4.0
	TMX 40/20	EAN40
100	2.5	2.0
90	2.5	2.0
80	2.5	2.0
70	5.0	4.0
60	6.5	5.5
50	8.0	6.5
40	9.5	7.5
	EAN80	EAN80
30	10.5	10.5
20	14.0	14.0
10	21.0	20.5
run time	123.0	116.0
	$r_{RGBM} = 6.42\%$	$r_{RGBM} = 6.97\%$

Comparative and anecdotal diver reports suggest that riding helium to the 70 fsw level with a switch to EAN50 is a good strategy, one that couples the benefits of well being on helium with minimal decompression time and stress following isobaric switches to nitrogen. Shallower switches to enriched air also work with only a nominal increase in overall decompression time, but with deeper switches off helium to nitrox a source of isobaric counterdiffusion (ICD) issues that might best be avoided. Note the risk, r_{RGBM}, for the helium strategy, TMX 40/20 at 100 fsw, is slightly safer than the nitrogen strategy, EAN40 at 100 fsw, but in either case the risk is high The logistics of such deep dives on OC are formidable for both diver and support crew if any. The number of stage bottles (decompression tanks) is forbidding for a single diver, of course, but surface support teams, themselves at high risk for placing bottles on a line at depth, can effect such a dive. These support teams are vested with immense responsibility for diver safety.

2. **Hydrospace EXPLORER Extreme RB Profile** Table 7 is a deep RB dive downloaded off the Hydrospace EXPLORER computer. From a number of corners reports of 400 fsw dives on rebreather systems are becoming commonplace. Consider this one to 444 fsw for 15 min. Diluent is TMX 10/85 and pp_{O_2} setpoint is 1.1 atm. From a decompression standpoint, rebreather systems are the quickest and most efficient systems for underwater activities. The higher the pp_{O_2}, the shorter the overall decompression time. That advantage, however, needs to

be played off against increasing risks of oxygen toxicity as oxygen partial pressures increase, especially above 1.4 *atm*. The higher percentage of oxygen and lower percentage of inert gases in higher pp_{O_2} setpoints of closed circuit rebreathers (CCRs) results in reduced risks simply because gas loadings and bubble couplings are less in magnitude and importance. This shows up in any set of RB comparative pp_{O_2} calculations as well as in OC versus RB risk estimates. Risk associated with this 444 *fsw* dive is less than a similar dive on trimix to roughly same depth for shorter time, that is, looking at Table 7. Certainly, this reduction relates to the higher oxygen fraction in RB systems.

Table 7. Extreme RB Dive and Risk

depth (fsw)	time (min)	depth (fsw)	time (min)
444	15.	150	2.0
290	0.5	140	2.0
280	0.5	130	2.0
270	0.5	120	2.5
260	0.5	110	3.0
250	0.5	100	3.5
240	0.5	90	4.0
230	1.0	80	4.5
220	1.0	70	5.0
210	1.0	60	7.0
200	1.0	50	7.5
190	1.5	40	8.0
180	1.5	30	12.5
170	1.5	20	14.0
160	1.5	10	15.5
			$r_{VPM} = 6.79\%$

The VPM encoded in CCPlanner was used here.

While the EOD approach is amenable to implementation in dive planning software with suitable computer processor speeds and storage resources (PCs Workstations, Mainframes, etc.), it is not always optimal in present generation underwater dive computers. They are more limited in computing speed and storage capabilities. Divers also want to know risks during a dive not just at the end. So a modified approach using the data in Tables 3-5 is suggested using *permissble* supersaturation during the dive. Consider the following model risk estimators easily generated on the fly by present dive computers. Unlike the previous cumulative estimators these can be viewed underwater as the dive progresses.

On The Fly Risk Estimator (OTF)

As DCS outcomes for excursions from any point on a dive to the surface or elsewhere above the diver are unknown the approach used for EOD risk is not portable directly to OTF risks. The foregoing does suggest another computational approach at any depth in terms of model limit points above the diver, specifically, critical gradients, G and H, for GM and BM models respectively. For closure, the approach link the EOD risk to the surfacing OTF risk across all profiles in the LANL DB using standard NLLS methods. And it goes like this.

For GM risk, we take,

$$r(\alpha,\beta,\varepsilon,t) = \alpha\, exp\left[-\left(\frac{\Pi(t) - P(t) - G(t)}{P(t)}\right)\right] + \beta[1 - exp\ (-\varepsilon t)]$$

with published permissible gradient, G, in the M-value picture (USN),

$$G = M - P$$

and similarly published gradient, G, in the Z-value picture (ZHL),

$$G = Z - P$$

Accordingly, for BM algorithms, we take

$$r(\alpha,\beta,\varepsilon,t) = \alpha\ exp\ \left[-\left(\frac{\Pi(t) - P(t) - H(t)}{P(t)} \right) \right] + \beta[1 - exp\ (-\varepsilon t)]$$

with one published permissible BM bubble-tissue gradient, H, averaged over the bubble seed distribution (RGBM),

$$H = 2\gamma\zeta \int_{r_c}^{\infty} \frac{exp\ [-\zeta(r - r_c)]}{r} dr$$

with surface tension, γ, given by,

$$2\gamma = 44.7 \left[\frac{P}{T} \right]^{1/4} + 24.3 \left[\frac{P}{T} \right]^{1/2}\ dyne/cm$$

for T temperature (^oK), P ambient pressure (fsw) and r_c critical radius (μm) for ζ a fitted constant (order 0.7 μm^{-1}) for the bubble distribution with nitrogen,

$$r_c = 0.007655 + 0.001654 \left[\frac{T}{P} \right]^{1/3} + 0.041602 \left[\frac{T}{P} \right]^{2/3}$$

and for helium,

$$r_c = 0.003114 + 0.015731 \left[\frac{T}{P} \right]^{1/3} + 0.025893 \left[\frac{T}{P} \right]^{2/3}$$

and another published BM permissible bubble-tissue gradient, H, of the gel form (VPM),

$$H = \frac{2\gamma\ (\gamma_c - \gamma)}{\gamma_c r_c} = \frac{11.01}{r_c}\ (fsw)$$

for γ and γ_c film and surfactant surface tensions, that is, $\gamma = 17.9\ dyne/cm$ and $\gamma_c = 257\ dyne/cm$ with critical bubble radius r_c in μm given by,

$$\frac{1}{r_c} - \frac{1}{r_i} = \frac{P - P_i}{2\gamma}$$

with $r_i = 0.6\ \mu m$ at sea level, that is, $P_i = 33\ fsw$. These BM permissible gradients range at 10-40 fsw roughly.

These OTF functions are quantified by the difference between existing and permissible supersaturation divided by ambient pressure. Risk increases with increasing difference between existing and permissible supersaturation and decreasing anbient pressure. First terms are measures of permissble supersaturation differences and second terms are overall smoothing functions that increase wih dive time, t. Similarly, but not integrated over run time, we define the instantaneous risk function, r, for ascents above the diver to arbitrary depths with critical parameters, G and H, and its complement, ρ,

$$\rho(\alpha,\beta,\varepsilon,t) = 1 - r(\alpha,\beta,\varepsilon,t)]$$

as OTF risk estimators depending on instantaneous depth, d, final ascent level, d_0, bottom time, t_b, and dive run time, t. In analogy with the EOD compilation, the maximum value of the risk function across all tissue compartments, τ, is tallied and used. This occurs with the (ascent) controlling tissue compartment at the end of nonstop bottom time or level decompression stop time with corresponding tissue tension, Π.

With data for OTF risk estimation nonexistent, we suggest an extrapolation scheme that fits the OTF risk estimator close to the surface to the EOD risk estimator after surfacing for all the profiles in the LANL DB using standard NLLS software. This is a task requiring LANL supercomputers with teraflop speeds (10^{12} floating point operations per second) and fast access mass storage accomodating a 3569 x 3569 matrix for NLLS inversion. What this amounts to is fitting the OTF risk function at the end of the last decompression stop or NDL for nonstop diving to the EOD risk estimator after surfacing at time, t_{mx}, across all 3569 profiles, that is,

$$r(\alpha,\beta,\varepsilon,t_{mx}) = r(\kappa,\omega,t_{mx})$$

with EOD risk estimation computed for each profile using,

$$\kappa = 0.698$$

$$\omega = 0.810$$

and α, β and ϵ then extracted in the NLLS fit to $r(\kappa, \omega, t_{mx})$. The resulting OTF risk functions are then used to estimate OTF risks at any point, d_0, above the diver with the surfacing case, $d_0 = 0$, the focus here. Obviously, for points above the diver but below the surface, risk decreases compared to surfacing risk.

For GM algorithms, we obtain using the ZHL critical gradient, G,

$$\alpha = 0.350 + 0.00125\,(d - d_0) \pm 0.081$$

$$\beta = 0.025 \pm 0.004$$

$$\epsilon = 1/t_b \pm 0.106\,min^{-1}$$

For BM algorithms we find employing the RGBM seed averaged permissble supersaturation, H,

$$\alpha = 0.550 + 0.00118\,(d - d_0) \pm 0.053$$

$$\beta = 0.022 \pm 0.005$$

$$\epsilon = 1/t_b \pm 0.079\,min^{-1}$$

The critical parameters, G and H (permissible tissue and bubble supersaturation gradients) are evaluated at the ascent point (d_0). Possible tissue outgassing and bubble growth during the ascent are included in the analyses assuming an ascent rate of 30 fsw/min. In GM staging, tissues likely outgas during ascent, reducing tissue tensions and risk. In BM staging, bubbles grow on ascent when not controlled by stops and risk increases. For surfacing ascents from any point on the dive, $d_0 = 0$. The risk for GM algorithms increases as the difference between actual tissue tension and critical tension at any point on the dive increases. For BM algorithms, risk increases as the difference between actual supersaturation and permissble bubble supersaturation increases.

Ingassing and outgassing during ascents and descents are incorporated directly into the tissue equations by assuming ambient pressure, p_a, is changing in time. For assumed linear ascent rate, v, we have,

$$p_a = p_0 - vt$$

with speed, v, positive for descents and negative for ascents (convention). The corresponding tissue equation becomes,

$$\frac{\partial p}{\partial t} = -\lambda(p - p_0 + vt)$$

with straightforward solution , $p = p_i$, at, $t = 0$,

$$p = p_0 + (p_i - p_0 + v/\lambda)\;exp\;(-\lambda t) - vt - v/\lambda$$

At initial time, $t = 0$, or stationary diver, $v = 0$, the equation reduces to the usual form. For long ascents or descents, tissue loadings become important and changes in gas tensions, p, need be included in calculations of risk. If omitted on descent tissue tensions are smaller and if omitted on ascent tissue tensions are larger than estimated with the static equation. Effects are seen in both GM and BM algorithms. For GM algorithms changes in gas loadings with ascent are fairly simple as seen above. For BM algorithms the situation is more complex in that changes in gas loadings on ascent affect gas diffusion across bubble interfaces with bubble behavior additionally becoming a matter of surface tension and bubble size. In the following, gas loadings and bubble changes are tracked during ascents and descents.

On the fly risk estimates for various trimix, nitrox and heliox dives follow. In all cases, OTF surfacing risks at the end of the decompression stop time or NDL are tabulated using nominal values for α, β and ϵ listed.

Test Profiles and OTF Risk

As with EOD profiles, the following examples are also taken from the LANL DB having been discussed and published earlier *[4,18,32]* with regards to models, staging comparisons, deep and shallow stops, tests and data.

1. **Recreational Nonstop Air Diving** Many hundreds of air dives were analyzed by the USN permitting construction of decompression schedules with 95% and 99% confidence (5% and 1% bends probability). These tables were published by USN investigators *[1,7]* and Table 8 tabulates the corresponding nonstop time limits ($\sigma = 0.05, 0.01$) and also includes the old USN (Workman) limits for comparison in the fourth column. They date back to the 1950s. Later re-evaluations of the standard set of nonstop time limits estimate a probability rate of 1.25% for the limits. In actual usage, the incidence rates are below 0.01% because users do not dive to the limits generally. In the last columns are listed risk estimates, $r_{ZHL} and \mathrm{r}_{RGBM}$, for the 1% DCS probabilty USN limits, $\sigma = 0.01$, using on the fly estimators. Again, $d_0 = 0$ in the nonstop case for the conservative NDLs. The risk estimates in the last two column include outgassing during ascent (30 fsw/min) and ingassing during descent (60 fsw/min).

   Table 8. Nonstop Air Limits and Risk

depth d (fsw)	nonstop limit t_n (min) $\sigma = 0.05$	nonstop limit t_n (min) $\sigma = 0.01$	nonstop limit t_n (min) USN	risk r_{ZHL}	risk r_{RGBM}
30	240	170		0.0160	0.0160
40	170	100	200	0.0162	0.0161
50	120	70	100	0.0166	0.0163
60	80	40	60	0.0166	0.0165
70	80	25	50	0.0177	0.0169
80	60	15	40	0.0174	0.0173
90	50	10	30	0.0179	0.0178
100	50	8	25	0.0190	0.0184
110	40	6	20	0.0199	0.0192
120	40	5	15	0.0204	0.0196
130	30	4	10	0.0208	0.0200

   It is clear in Table 8 that the USN 1% and corresponding on the fly risks, r_{ZHL} and r_{RGBM}, are very close. Both ZHL and RGBM risks in Table 8 are, however, slightly larger and so more conservative in dive computer and diveware applications. As noted before, GM and BM algorithms overlap in the nonstop diving limit because phase separation is minimal in BM algorithms *[6,19]*. Over nonstop air diving to recreational limits, we have across the ZHL,

   $$1.60\% \leq r_{ZHL} \leq 2.08\%$$

   with for the RGBM,

   $$r_{RGBM \leq r_{ZHL}}$$

   for USN corresponding 1% risk. The decrease in nonstop time limits as risk drops into the 1% range is interesting compared to early USN compilations (Workman). This was run with GAP and CCPlanner.

2. **Deep Trimix OC Dive** The following is a deep TMX 16/46 dive with helium-oxygen mirroring and contant nitrogen gas fraction on all ascent switches, that is, $f_{N_2} = 0.38$ until a final switch to EAH80 at 20 fsw. The switches are TMX 18/44 at 220 fsw, TMX 20/42 at 140 fsw, TMX 22/40 at 80 fsw and EAH80 at 20 fsw. This is an optimal strategy on many counts. Table 9 lists pertinent dive variables and corresponding OTF risks for immediate (emergency) surfacing ascent after the stops. Variable *psat* is permissible supersaturation. Other entries are self explanatory.

Table 9. Deep Trimix OC Dive and Risk

depth (fsw)	wait (min)	tissue (min)	tension (fsw)	psat (fsw)	pp_{O_2} (atm)	risk r_{RGBM}
300	15.0	3.3	274.5	30.7	1.6	0.407
190	0.5	3.3	205.5	32.3	1.2	0.330
180	0.5	5.3	202.3	33.3	1.2	0.320
170	1.0	5.3	189.4	33.3	1.1	0.308
160	1.0	5.3	182.0	33.3	1.1	0.236
150	1.0	5.3	170.6	33.3	1.0	0.200
140	1.0	8.2	162.6	34.3	1.0	0.197
130	1.5	8.2	151.7	34.1	1.0	0.195
120	1.5	8.2	141.7	34.1	0.9	0.193
110	1.5	12.2	134.1	34.9	0.9	0.189
100	2.5	12.2	123.7	34.9	0.8	0.184
90	2.5	12.2	114.1	34.9	0.7	0.179
80	3.0	17.8	105.1	35.5	0.8	0.170
70	4.0	17.8	94.9	35.5	0.7	0.160
60	4.5	25.3	85.6	35.9	0.6	0.147
50	6.5	25.3	75.4	35.9	0.6	0.132
40	7.5	35.9	66.1	36.2	0.5	0.112
30	10.5	35.9	56.0	36.2	0.4	0.087
20	8.5	50.8	46.2	36.3	1.3	0.051
10	12.5	72.0	36.3	36.4	1.0	0.031
	101.5					

This and following examples were tabulated using CCPlanner with nominal parameter settings corresponding to settings in meters and software.

3. **Shallow Nitrox OC Dive** A decompression dive on EAN32 without any gas switches is analyzed in Table 10. The profile is EAN32 at 100 fsw for 65 min. Entries are the same as Table 9. The OTU and CNS entries are the full body and CNS cumulations at each level. Decompression profile and surfacing risks are listed.

Table 10. Shallow Nitrox OC Dive and Risk

depth (fsw)	wait (min)	tissue (min)	tension (fsw)	psat (fsw)	pp_{O_2} (atm)	OTU (min)	CNS	gas (ft^3)	risk r_{ZHL}
100	65.0	18.5	89.4	49.1	1.3	95.0	0.42	200	0.173
20	5.5	27.1	43.5	43.0	0.5	0.3	0.00	7	0.067
10	24.0	54.4	23.9	32.9	0.4	0.0	0.00	23	0.019
	99.5					95.3	0.42	230	

4. **Heliox RB Dive** The last OTF risk example is a pure heliox CCR dive to 344 fsw for 15 min with three setpoint changes on the way up. The diluent is heliox 21/79. Setpoints are 1.0 atm at the bottom, 1.1 atm at 200 fsw, 1.2 atm at 100 fsw and 1.3 atm at 30 fsw. Table 11 gives the decompression profile with risks for surfacing from stops.

Table 11. Heliox RB Dive and Risk

depth (fsw)	wait (min)	tissue (min)	tension (fsw)	psat (fsw)	pp_{O_2} (atm)	OTU (min)	CNS	risk r_{VPM}
344	15.0	1.9	344.1	43.6	1.0	15.0	0.04	0.206
240	0.5	3.0	269.8	43.9	1.1	0.6	0.00	0.183
230	0.5	4.7	260.5	43.4	1.1	0.6	0.00	0.184
220	0.5	4.7	252.4	43.4	1.1	0.6	0.00	0.182
210	1.0	4.7	239.2	43.4	1.1	1.2	0.00	0.178
200	1.0	4.7	230.8	43.4	1.2	1.3	0.01	0.176
190	1.0	7.0	222.8	43.1	1.2	1.3	0.01	0.177
180	1.5	7.0	210.1	43.1	1.2	2.0	0.01	0.172
170	1.5	7.0	201.0	43.1	1.2	2.0	0.01	0.170
160	1.5	7.0	191.8	43.1	1.2	2.0	0.01	0.167
150	1.5	10.2	182.6	42.8	1.2	2.0	0.01	0.165
140	2.0	10.2	171.6	42.8	1.2	2.6	0.01	0.160
130	2.0	10.2	160.7	42.6	1.2	2.6	0.01	0.156
120	1.5	10.2	152.1	42.6	1.2	2.0	0.01	0.152
110	2.5	14.5	141.3	42.4	1.2	3.3	0.01	0.147
100	2.5	14.5	131.6	42.4	1.3	3.7	0.02	0.141
90	2.5	14.5	121.9	42.4	1.3	3.7	0.02	0.134
80	3.0	20.5	111.9	42.2	1.3	4.4	0.02	0.127
70	4.0	20.5	101.6	42.2	1.3	5.9	0.03	0.116
60	4.0	20.5	91.2	42.1	1.3	5.9	0.03	0.103
50	5.0	29.1	81.4	42.0	1.3	7.4	0.03	0.090
40	5.5	29.1	71.6	41.9	1.3	8.1	0.04	0.074
30	6.5	41.2	61.6	41.7	1.3	9.6	0.04	0.053
20	8.5	41.2	51.2	41.6	1.3	12.6	0.06	0.041
10	10.0	55.2	41.3	41.4	1.3	14.8	0.07	0.033
	102.2					115.1	0.47	

Overall risks for the deep heliox CCR dive are smaller than corresponding risks for OC dives to the same depths. The higher oxygen and lower helium gas fractions in the breathing loop lower risk as requisite. Both tissue tensions and bubbles remain smaller. Said another way, RB diving is safer for given depth and time.

Equal Risk Deep And Shallow Stop Profiles

Computationally, equal risk shallow and deep stop profiles can be compared using the BM risk functions described versus a known shallow stop GM profile and its risk. The BM risk function is parametrized within the deep stop RGBM discussed while the shallow stop GM profile and risk are taken from actual tests *[22]*, that is, an air dive to 150 fsw for 30 min. The 150/30 profile had an incidence rate of 2.1% over 96 dives (2/96). Both deep stop RGBM and shallow stop USN profiles are given in Table 12 for equal surfacing risk estimators, $r_{USN} = r_{VPM} = 2.1\%$. CCPlanner with risk estimators detailed is used for analysis, encoded with both USN and RGBM staging algorithms.

Table 12. Equal Surfacing Risk Deep and Shallow Stop Air Dives

USN depth (fsw)	shallow stop time (min)	r_{USN}	RGBM depth (fsw)	deep stop time (min)	r_{RGBM}
150	30	0.224	150	30	0.298
80			80	1	0.210
70			70	1	0.201
60			60	2	0.180
50			50	3	0.152
40	3	0.129	40	4	0.125
30	7	0.101	30	5	0.093
20	12	0.069	20	7	0.050
10	31	0.024	10	10	0.023
0	83	0.021	0	63	0.021

Model differences in the OTF risk estimators on the way up are obvious as are the staging protocols. At the end of the dive, OTF and EOD estimators converge as expected from the surfacing fit described. In these calculations, outgassing on the way to the surface after the 10 fsw decompression stop is included for the controlling tissue compartment to give the most realistic estimates of surfacing risk. Outgassing during the ascent to the surface is what drops the risk to 2.1% at dive conclusion. As usual case with GM versus BM staging, run times are always shorter for BM versus GM staging at the same risk level, in this case, 63 *min* versus 83 *min*. But given the relative safety record of both GM and BM computers, both model approaches work suggesting there are two ways to dive safely, *control the bubble at depth or treat the bubble in the shallows* as a number of medical observers and seasoned divers suggest. To compare apples to apples, of course, it is necessary to first normalize the risk to the same level in both models as done here.

DIVEWARE

A number of popular dive planning software packages are amenable to direct implementation of EOD and OTF risk estimation methodology. Online and commercially available software packages span GM and BM algorithms along with oxtox estimation and include:

1. **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 *[29]* 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 a few others under construction in the Far East.
2. **Abyss** Abyss in the mid 90s first introduced the full RGBM into its diveware packages. The Buhlmann ZHL model was also included in 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 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 dive computers. Full RGBM was first incorporated into Hydrospace computers and today in Suunto, Atomic Aquatics, Liquivision and ANO computers.
3. **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 *[20]*. 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.

4. **ProPlanner** ProPlanner is a software package that uses modified Z-values for diver staging. Buhlmann Z-values with GFs are employed with user knobs for conservancy. The model is called the VGM ProPlanner by designers. Some GFs claim to mimic the VPM. Correlations have not been formally published about VGM and ProPlanner.
5. **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 the 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.
6. **DecoPlanner** DecoPlanner is a diveware package offered by the GUE Training Agency. Both the VPM and Buhlmann ZHL with GFs are available in DecoPlanner. Evolving over the past 10 - 15 yrs, DecoPlanner also incorporates GUE *ratio deco* ($\Pi/P \leq \xi$) approaches to modifying GFs. Nothing is published about ratio deco data correlations but both the ZHL and VPM have been correlated *[4,20]*. It has seen extensive use in the technical diving community and GUE diver training.
7. **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. It is part of the massive USN VVAL18 project.
8. **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.
9. **DiveSim** DiveSim is a UDI software packake for dive planning and profile downloading. UDI computers and diveware employ the correlated RGBM for air and nitrox. The software packages also includes diver to diver, diver to surface, GPS, compass and related communications capabilties. UDIs are obviously 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.
10. **DRA** 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 gradients, it is under testing and development. An EOD risk estimator now, plans are in the works to make it a wet (OTF) risk estimator
11. **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 iusing the LANL DB is encoded in CCPlanner and imbedded in licensed RGBM OC and RB codes.

RECAP

Methods were presented and quantified for estimating diver surfacing DCS risk from arbitrary points on a dive for both dissolved gas (GM) and bubble model (BM) computer and diveware implementations. Risk functions were defined and correlated with profiles in the LANL Data Bank. The EOD and OTF risk functions are exponential representations of differences between actual supersaturations and permissble supersaturations. Both nonstop and decompression examples were given and compared for OC and RB applications. In the ascent, outgassing and bubble impacts were included in model risk estimates. Methodology is easily encoded into modern GM and BM dive computers and dive planning software within existing coding. Major players in the dive computer business include Suunto, Mares, Cochrane, Atomic Aquatics, Sherwood, UTC, Ratio, Shearwater, Uwatec, Cressisub, Oceanic, Aeris and new ones coming online in Japan, South Korea and China. Diveware purveyors include Abyss, ProPlanner, VPlanner, GAP, DecoPlanner, RGBM Simulator, Analyst, Free Phase RGBM Simulator, DiveSim, DiveLogger and CCPlanner to name a few. Hope this paper helps in the implementation of both EOD and OTF risk estimation in modern dive computers and coupled diveware. Risk assessment for arbitrary underwater exposures in recreational and technical diving is needed for diver safety and sensible dive planning.

Happy and safe diving always.

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BIOSKETCHES

Bruce Wienke is a Program Manager in the Weapons Technology/Simulation Office at LANL. He received a BS in physics and mathematics (Northern Michigan), MS in nuclear physics (Marquette) and a PhD in particle physics (Northwestern). He has authored 250+ articles in peer reviewed journals, media outlets, trade magazines, workshop proceedings and has published 12 books on diving science, biophysics and decompression theory. He heads up the C& C Dive Team vested with worldwide underwater search, assessment and disablement of nuclear, chemical and biological WMDs. He is a Fellow of the APS, Technical Committee Member of the ANS, Member of the UHMS and serves as a Consultant to the EPA, DHS, ADA, US Military and Dive Industry. Bruce is an Editor/Reviewer for CBM, PR, TTSP, NSE, JQSRT and CEO of Southwest Enterprises Consulting. He is the developer of the Reduced Gradient Bubble Model (RGBM) implemented in decompression meters, tables and dive software worldwide. Bruce has dived all over the world on OC and RB systems in military, scientific, exploration, testing and training activities. He is a NAUI Tec/Rec Instructor Trainer and Course Director. Interests include USSA Masters ski racing, USTA Seniors tennis, golf and windsurfing. Bruce is a Certified Ski Instructor (PSIA) and Racing Coach (USSCA). He has won Masters National Titles in SL, GS, SG and DH and Quarterbacked the Northern Michigan Wildcats to a NCAA II Title in the Hickory Bowl.

Tim O'Leary heads up NAUI Technical Diving Operations and developed implemented training manuals, support material, tech dive tables, monographs and related media along with Tech Course Standards. He is a practicing commercial diver and CEO of American Diving & Marine Salvage on the Texas Gulf Coast. Tim received a BS in zoology (Texas A&M) and a DMT and CHT from Jo Ellen Smith Medical Center at the Baromedical Research Institute. He was a Commercial Diving and Hyperbaric Chamber Instructor at the Ocean Corporation. Tim is a member of the UHMS, SNAME and NADMT. He is an Admiral in the Texas Navy, a USCG 100 Ton Vessel Master and a Consultant to Texas Parks & Wildlife, Canadian Coporation, Rimkus Group and Offshore Oil Industry. His diving experienc is global on OC and Rb systems in commercial, exploration, training and testing activities. He is a NAUI Tec/Rec Instructor Trainer, Course Director and Workshop Director. Other interests include skiing, deep wreck diving, and dive travel. Tim and NAUI Dive Team are credited with the discovery and exploration of the USS Perry in approximately 250 fsw off Anguar and diving it for a week on RBs.