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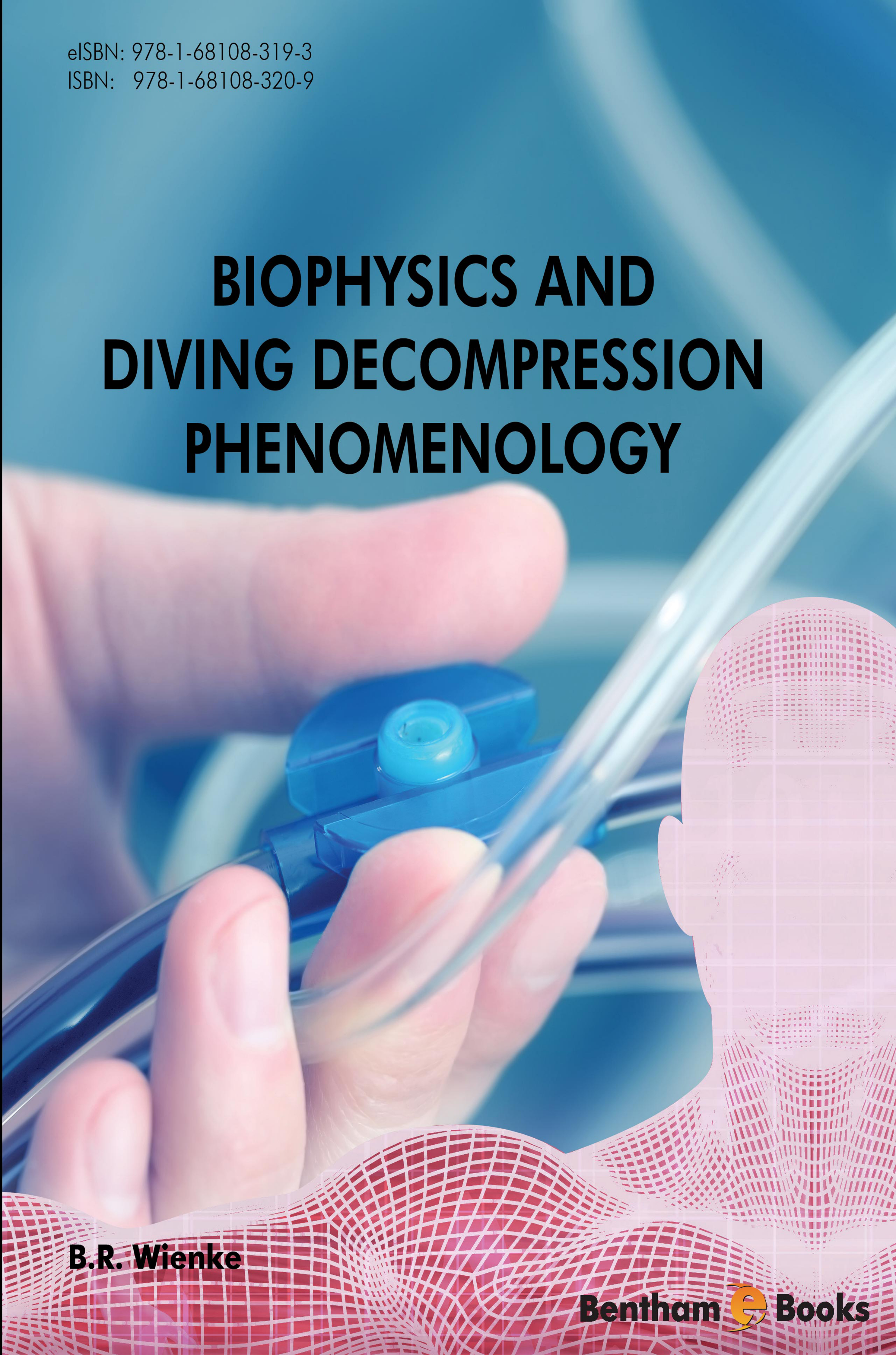
BIOPHYSICS AND DIVING DECOMPRESSION PHENOMENOLOGY



B.R. Wienke

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CONTENTS

FOREWORD

This book has a singular focus and intent and is a necessary addition to the library of any modeler, dive computer engineer, software designer, or table fabricator working in the diving arena. It is well written, concise, and probably the only full reference today on the extensive literature of applied decompression theory. Equations and models are complete and applications are keyed to the content of the book. The References are also extensive. The book follows up a number of earlier publications of the Author, and adds new material in the computational synthesis. Models, mathematical methods, statistical correlations, and wide ranging applications are the mainstay of presentation. Thumbs up all around on this timely and needed publication.

Tim O'Leary
NAUI Technical Diving Operations
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PREFACE

This monograph covers a body of biophysics, gas transport, bubble studies and attendant models used for diving and hyperbaric applications, and divides into three Parts, namely; Biophysics And Models, Correlations And Validation, and Applications. Parts are all inter-connected by analysis. The biophysics of diving and decompression in the human body is extremely complex. More needs be learned to safely and routinely stage divers. The physics, biology, engineering, physiology, medicine, and chemistry of diving center on pressure, and pressure changes. The average individual is subject to atmospheric pressure swings of 3% at sea level, as much as 20% a mile in elevation, more at higher altitudes, and all usually over time spans of hours to days. Divers and their equipment can experience compressions and decompressions orders of magnitude greater, and within considerably shorter time scales. While effects of pressure change are readily quantified in physics, chemistry, and engineering applications, the physiology, medicine, and biology of pressure changes in living systems are much more complicated. Caution is needed in transposing biological principles from one pressure range to another. Incomplete knowledge and biophysical complexities often prevent extensions of even simple causal relationships in biological science. Gas exchange, bubble formation and elimination, and compression-decompression in blood and tissues in diving are governed by many factors, such as diffusion, perfusion, phase separation and equilibration, nucleation and cavitation, local fluid shifts, and combinations thereof. Owing to the complexity of biological systems, multiplicity of tissues and media, diversity of interfaces and boundary conditions, and plethora of bubble impacting physical and chemical mechanisms, it is difficult to solve the decompression problem *in vivo*. And equally difficult and elusive are direct measurements of bubbles, bubble sites, and effective transport properties of tissues and blood in living human systems. Early decompression studies adopted the medical supersaturation viewpoint. Closer looks at the physics of phase separation and bubbles in the mid-1970s, and insights into gas transfer mechanisms, culminated in extended kinetics and dissolved-free phase theories. In both cases, models are employed to stage divers as safely as possible to the surface. Optimally, these models ought be correlated with existing diving data and linked to the most current biophysics. So, the monogram describes underlying biophysics, connectivity to macroscopic models, and correlation with real diving data, with correlations as important as models. Applications to mixed gas, decompression, open circuit (OC), and rebreather (RB) diving are linked to a correlated bubble model for comparisons and risk analyses. Applications focus mainly on deep diving where risks increase and statistical collections and tabulations of data are very important.

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Special thanks to diving confidants, gurus, and researchers, namely Jim Joiner (Best Publishing), Dick Vann (Duke), Charlie Lehner (Wisconsin), Alf Brubakk (Trondheim), Brian Hills (Adelaide), Mike Powell (NASA), Bill Hamilton (Hamilton Research), Dave Yount (Hawaii), Tim O'Leary (NAUI Technical Diving), Alessandro Marroni (DAN), and Peter Bennett (UHMS).

CONFLICT OF INTEREST

The author confirms that author has no conflict of interest to declare for this publication.

CHAPTER 1

Biophysics and Models

Abstract: The biophysics of pressure changes in diving and decompression is extremely complex. Fundamental notions of underlying mechanisms of bubble formation and gas transport are presented. Models are discussed for staging diver ascents focusing on dissolved gas perfusion, bubble formation, and coupled mechanics. Oxygen toxicity is also quantified and detailed. The focus is computational models that have been encoded into underwater computers, tables, and dive planning software. There are some 11 models that have been implemented and safely used by divers, though not all have been tested nor validated.

Keywords: Bubbles, Dissolved gases, Models, Oxygen toxicity, Transport.

Gas exchange, bubble formation and elimination, and compression-decompression in blood and tissues are governed by many factors, such as diffusion, perfusion, phase separation and equilibration, nucleation and cavitation, local fluid shifts, and combinations thereof [17, 28, 31, 37, 44, 47, 48, 57, 61, 69, 87]. Owing to the complexity of biological systems, multiplicity of tissues and media, diversity of interfaces and boundary conditions, and plethora of bubble impacting physical and chemical mechanisms, it is difficult to solve the decompression problem *in vivo*. Early decompression studies adopted the supersaturation viewpoint. Closer looks at the physics of phase separation and bubbles in the mid-1970s, and insights into gas transfer mechanisms, culminated in extended kinetics and dissolved-free phase theories. Integration of both approaches can be useful. Phase and bubble models are more general than supersaturation models, incorporating their predictive capabilities as subsets. Indeed, for most recreational and nonstop diving, bubble and dissolved gas models collapse onto themselves, that is, they suggest similar staging regimens. Having said all that, data still plays the crucial role in model determination and

B.R. Wienke

applicability. Dive modeling is often more of an artform than science, and experiments directed at one or another aspect of unanswered diving questions can often produce divergent conclusions, further caveats, null results, and scattered-beyond-use data. Plus, macroscopic models cannot always cover all important aspects of microscopic phenomena. We cannot cover all model data correlations herein. Instead we indicate range of model use, sector use, history, and some sources for data correlation. We focus on just 11 models. There are more, but they do not enjoy the utility and range of applicability of the 11 discussed. This is not a critical review of models, as all models are incomplete today, but all herein enjoy varying degrees of success and utility. That is, these models with data modifications form the underpinnings of current diving tables, decompression computers, software, and associated protocols. The intent here is to present a working view of physical phase mechanics, then followed by a summary of working models in diving. Such discussion is neither medical nor physiological synthesis. Such aspects are omitted, and, for some, certainly oversimplified.

The physics, biology, engineering, physiology, medicine, and chemistry of diving center on pressure, and pressure changes. The average individual is subject to atmospheric pressure swings of 3% at sea level, as much as 20% a mile in elevation, more at higher altitudes, and all usually over time spans of hours to days. Divers and their equipment can experience compressions and decompressions orders of magnitude greater, and within considerably shorter time scales. While effects of pressure change are readily quantified in physics, chemistry, and engineering applications, the physiology, medicine, and biology of pressure changes in living systems are much more complicated. Caution is needed in transposing biological principles from one pressure range to another. Incomplete knowledge and biophysical complexities often prevent extensions of even simple causal relationships in biological science. With this, models of bubble formation in the body face a tough task.

For sake of connectivity to the medical-biological diving community. mixed (diving) units are employed. In such system pressure and depth are used interchangeably, that is, 1 *atm* = 33 *fsw*, with *fsw* denoting feet-of-seawater (pressure and depth).

CAVITATION AND NUCLEATION

Simply, *cavitation* is the process of vapor phase formation [5, 16, 29, 45, 58] of a liquid when pressure is reduced. A liquid cavitates when vapor bubbles are formed and observed to grow as consequence of pressure reduction. When the phase transition results from pressure change in hydrodynamic flow, a two phase stream consisting of vapor and liquid results, called a cavitating flow [3, 25, 63]. The addition of heat, or heat transfer in a fluid, may also produce cavitation nuclei in the process called boiling. From the physico-chemical perspective, cavitation by pressure reduction and cavitation by heat addition represent the same phenomena, vapor formation and bubble growth, usually in the presence of seed nuclei. Depending on the rate and magnitude of pressure reduction, a bubble may grow slowly or rapidly. A bubble that grows very rapidly (explosively) contains the vapor phase of the liquid mostly, because the diffusion time is too short for any significant increase in entrained gas volume. The process is called vaporous cavitation, and depends on evaporation of liquid into the bubble. A bubble may also grow more slowly by diffusion of gas into the nucleus, and contain mostly a gas component. In this case, the liquid degasses in what is called gaseous cavitation, the mode observed in the application of ultrasound signals to the liquid. For vaporous cavitation to occur, pressure drops below vapor pressure are requisite. For gaseous cavitation to occur, pressure drops may be less than, or greater than, vapor pressure, depending on nuclei size and degree of liquid saturation. In supersaturated ocean surfaces, for instance, vaporous cavitation occurs very nearly vapor pressure, while gaseous cavitation occurs above vapor pressure.

In gaseous cavitation processes, inception of growth in nuclei depends little on the duration of the pressure reduction, but the maximum size of the bubble produced does depend upon the time of pressure reduction. In most applications, the maximum size depends only slightly on the initial size of the seed nucleus. Under vaporous cavitation, the maximum size of the bubble produced is essentially independent of the dissolved gas content of the liquid. This obviously suggests different cavitation mechanisms for pressure (reduction) related bubble trauma in diving. Slowly developing bubble problems, such as limb bends many hours after exposure, might be linked to gaseous cavitation mechanisms, while rapid bubble problems, like central nervous system hits and and embolism immediately after surfacing, might link to vaporous cavitation. But it's certainly never been

CHAPTER 2

Correlations and Validation

Abstract: Models used for safely staging divers by computers, software, or tables need correlation and validation against real diving data. The process of correlating diver profiles and DCS outcomes against predictive models and fundamental parameters is presented. Data from computer downloaded profile records is correlated against several well known models, that is, USN, ZHL16, VPM, and RGBM using maximum likelihood statistical techniques. Results are tabulated, LANL DB discussed, risk functions constructed, and implications for diving and divers detailed.

Keywords: Maximum likelihood, Model correlations, Profile data banks, Risk.

To discuss correlations and risk, we want to focus on just one model and its published results. To cover all 11 models is beyond scope of this analysis, and a modern bubble model is preferable. Accordingly, within model and data parameters, we take the LANL bubble model (RGBM), dynamical principles, and correlation with profiles in the LANL Data Bank. Table, meter, and profile risks deduced in likelihood analysis are noted along with risks parameters. The model enjoys safe, widespread, and utilitarian application in mixed gas diving, both in recreational and technical sectors, and forms the bases of software, released tables and decompression meters used by scientific, commercial, and research divers. Supercomputing power [74, 76] is employed for application and correlation of model and data. The methods and approach described are generic to all diving models.

The RGBM uses a bubble volume to limit exposures, not critical tensions. Bubble volumes are estimates of separated gas phases, and the limit point is called the phase volume. Critical tensions are limit points to dissolved gas buildup in arbitrary tissue compartments, and are often called M-values. The approach is

B.R. Wienke

computationally iterative, and though mathematically intensive, diving microprocessors today easily handle calculations in the millisecond processing time frame. The algorithm is the basis of released mixed gas technical tables [NAUI Technical Diving, Tampa, 2002] and simplified recreational air and nitrox tables up to 10,000 ft elevation. Meter implementations of the RGBM are available and under continuing development, specifically HydroSpace, Atomic Aquatics, Steam Machines, Underwater Technologies, Mares, Dacor, Suunto, ConnXcion, LiquiVision, and other players. Commercial RGBM software includes *GAP, ABYSS, Free Phase,* and HydroSpace *RGBM Simulator*. All have exhibited safe and efficient operation from diving reports.

Note so-called diving units are employed herein, that is, standard SI units for depth and pressure are not used. Pressures and depths are both measured in feet-of-seawater (*fsw*) or meters-of-seawater (*msw*). The conversion is standard,

$$10\ msw = 33.28\ fsw = 1\ atm \qquad \textbf{(244)}$$

Breathing mixtures, such as nitrox (nitrogen and oxygen), heliox (helium and oxygen), and trimix (helium, nitrogen, and oxygen), carry standardized notation. If the fraction of oxygen is greater than 21%, the mixture is termed enriched. Enriched nitrox mixtures are denoted EANx, enriched heliox mixtures are denoted EAHx, and enriched trimix mixtures are denoted EATx, for x the oxygen percentage. For other mixtures of nitrox and heliox the convention is to name them with inert gas percentage first, and then oxygen percentage, such as, 85/15 nitrox or 85/15 heliox. For trimix, notation is shortened to list the oxygen percentage first, and then only the helium percentage, such as, 15/45 trimix, meaning 15% oxygen, 45% helium, and 40% nitrogen. Air is interchangeably denoted EAN21 or 79/21 nitrox.

LANL PROFILE DATA BANK

Divers using modern models are reporting their profiles to a Data Bank, located at LANL (also NAUI Technical Diving Operations). The profile information requested is simple:

- bottom mix/pp_{O2}, depth, and time (square wave equivalent);
- ascent and descent rates;

- stage and decompression mix/pp_{O2}, depths, and times;
- surface intervals;
- time to fly;
- diver age, weight, and sex;
- outcome (health problems), rated 1 - 5 in order of poor (DCS) to well.

This information aids validation and extension of model application space. Some 2,879 profiles now reside in the LANL Data Bank. The are 20 cases of DCS in the data file. The underlying DCS incidence rate is, $p = 20/2879 = 0.0069$, below 1%. Stored profiles range from 150 *fsw* down to 840 *fsw*, with the majority above 350 *fsw*. All data enters through the author (BRW), that is, divers, profiles, and outcomes are filtered. A summary breakdown of DCS hit (bends) data consists of the following:

- 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 – 2 hits (1 DCS I, 1 DCS III)
- OC deep heliox – 2 hits (2 DCS II)
- RB deep nitrox – 2 hits (1 DCS I, 1 DCS II)
- RB deep trimix – 2 hits (1 DCS I, 1 DCS III)
- RB deep heliox – 2 hits (1 DCS I, 1 DCS II)

DCS I means limb bends, DCS II implies central nervous system (CNS) bends, and DCS III denotes inner ear bends (occurring mainly 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. The abbreviation OC denotes open circuit, while RB denotes rebreather. 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 ($heavy - to - light$)

CHAPTER 3

Applications

Abstract: Model applications are important as predictors of comparative diver staging and protocols. Whether by computer, diveware, or tables, planning is requisite for safe diving. Applications following focus on both shallow and deep mixed gas diving on OC and RB systems. Profiles along with estimated risk are tallied. A bubble model correlated with deep stop diver outcomes is used. Profiles and schedules are listed and compared. Many profiles reside as data entries in the LANL DB. So the applications are both data and comparative dive profiles.

Keywords: Comparative gas transport, Real profiles, Risk, Staging.

Applications with model and risk estimates follow. Applications analyses [75, 79] include the Marroni and Bennett 2.5 *min* recreational deep stop, the C & C 450/20 multiple RB dive sequence at 1.4 *stm*, NEDU deep stop tests, French Navy deep stop profiles, EXPLORER decompression meter algorithm, NAUI Tables, University of Wisconsin Seafood Diver Tables, comparative NAUI, PADI, Oceanic NDLs and repetitive dives, comparative nitrogen and helium mixed gas risks, USS Perry deep RB exploration dive, world record OC dive, and WKPP extreme cave exploration profiles. The LANL model enjoys useful, widespread, and prudent application in mixed gas diving, both in recreational and technical sectors, and forms the bases of software, released tables and decompression meters used by scientific, commercial, and re- search divers. Supercomputing power is employed for application and correlation of model and data.

NONSTOP AND REPETITIVE AIR DIVING

Nonstop limits (NDLs), denoted t_{nn}, from the US Navy, PADI, NAUI, and ZHL (Buhlmann) (Tables **15, 16**) provide a set for comparison of relative DCS risk.

B.R. Wienke

Listed in Table **5a** are the NDLs and corresponding risks for the nonstop excursion, assuming ascent and descent rates of 60 *fsw/min* (no safety nor deep stops). Dissolved gas and phase risk estimates vary little for cases, and only the phase estimates are included. Surface intervals (SIs) between dives are time spent at the surface.

Table 5a. Risk estimates for standard air NDLs.

	USN NDL	**Risk**	**PADI NDL**	**Risk**	**NAUI NDL**	**Risk**	**ZHL NDL**	**Risk**
***d* (*fsw*)**	**t_n (*min*)**	**β**	**t_n (*min*)**	**β**	**t_n (*min*)**	**β**	**t_n (*min*)**	**β**
35	310	4.3%	205	2.0%			181	1.3%
40	200	3.1%	140	1.5%	130	1.4%	137	1.5%
50	100	2.1%	80	1.1%	80	1.1%	80	1.1%
60	60	1.7%	55	1.4%	55	1.4%	57	1.5%
70	50	2.0%	40	1.2%	45	1.3%	40	1.2%
80	40	2.1%	30	1.3%	35	1.5%	30	1.3%
90	30	2.1%	25	1.5%	25	1.5%	24	1.4%
100	25	2.1%	20	1.3%	22	1.4%	19	1.2%
110	20	2.2%	13	1.1%	15	1.2%	16	1.3%
120	15	2.0%	13	1.3%	12	1.2%	13	1.3%
130	10	1.7%	10	1.7%	8	1.3%	10	1.7%

Risks are internally consistent across NDLs at each depth, and agree with the US Navy assessments in Table **4b**. Greatest underlying risks occur in the USN shallow exposures. The PADI, NAUI, and ZHL risks are all less than 2% for this set, and risks for single DCS incidence are less than 0.02. PADI and NAUI have reported that incidence rates (*p*) across all exposures are less than 0.001%, so considering their enviable track record of diving safety, our estimates are liberal. ZHL risk estimates track as the PADI and NAUI risks, again, very safely. Estimates were corroborated [74] within data sets at Duke both in Tables **5a** and **5b**.

Next, the analysis is extended to profiles with varying ascent and descent rates, safety stops, and repetitive sequence [53, 78 - 80, 82]. Table **5b** lists nominal profiles (recreational) for various depths, exposure and travel times, and safety stops at 5 *msw*. Mean DCS estimates, r, are tabulated for both dissolved gas supersaturation ratio and excited bubble volume risk functions, with nominal variance, $r_{\pm} = r \pm 0, 004$, across all profiles.

Table 5b. Dissolved and separated phase risk estimates for nominal profiles.

Profile (*depth/time*)	Descent Rate (*msw/min*)	Ascent Rate (*msw/min*)	Safety Stop (*depth/time*)	Risk β	Risk σ
14 *msw*/38 *min*	18	9	5 *msw*/3 *min*	0.0034	0.0062
19 *msw*/38 *min*	18	9	5 *msw*/3 *min*	0.0095	0.0110
28 *msw*/32 *min*	18	9		0.0200	0.0213
37 *msw*/17 *min*	18	9	5 *msw*/3 *min*	0.0165	0.0151
18 *msw*/31 *min*	18	9	5 *msw*/3 *min*	0.0063	0.0072
	18	9		0.0088	0.0084
	18	18		0.0101	0.0135
	18	18	5 *msw*/3 *min*	0.0069	0.0084
17 *msw*/32 *min* SI 176 *min*	18	9	5 *msw*/3 *min*		
13 *msw*/37 *min* SI 176 *min*	18	9	5 *msw*/3 *min*		
23 *msw*/17 *min*	18	18	5 *msw*/3 *min*	0.0127	0.0232

The ZHL (Buhlmann) NDLs and staging regimens are widespread across decompression meters presently, and are good representations for dissolved gas risk analysis. The RGBM is newer, more modern, and is coming online in decometers and associated software. For recreational exposures, the RGBM collapses to a dissolved gas algorithm. This is reflected in the risk estimates above, where estimates for both models differ little [9, 20, 23, 36, 86].

Simple comments hold for the analyzed profile risks. The maximum relative risk is 0.0232 for the 3 dive repetitive sequence according to the dissolved risk estimator. This translates to 2% profile risk, which is comparable to the maximum NDL risk for the PADI, NAUI, and ZHL NDLs. This type of dive profile is common, practiced daily on liveaboards, and benign. According to Gilliam, the absolute incidence rate [93] for this type of diving is less than 0.02%. Again, our analyses overestimate risk. Effects of slower ascent rates and safety stops are seen

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BIOSKETCH

Bruce Wienke is a Program Manager in the Nuclear Weapons Technology/ Simulation And Computing Office at the Los Alamos National Laboratory (LANL), with interests in hydrodynamics, applied mathematics, particle and nuclear physics, numerical methods, parallel computing, thermonuclear burn, decompression phenomenology and models, radiation and gas transport, bubble dynamics, and phase mechanics, publishing some 240+ technical and research papers in related Journals. He contributes to underwater symposia, educational publications, technical periodicals and decompression workshops, authoring ten monographs *(Computational Decompression Theory And Applications, Science Of Diving, Hyperbaric Physics With Bubble Mechanics And Decompression Theory, Reduced Gradient Bubble Model In Depth, Technical Diving In Depth, Physics, Physiology And Decompression Theory For The Technical And Commercial Diver, High Altitude Diving, Basic Diving Physics And Applications, Diving Above Sea Level, Basic Decompression Theory And Applications)*. Diving experience includes the Caribbean, South Pacific, Asia, inland and coastal United States, Hawaii, and polar Arctic and Antarctic on OC and RB systems in technical, scientific, military, and research exercises. He functions on the LANL Nuclear Emergency Strategy Team (NEST), above and below water, heading up the C & C Dive Team.

Wienke is Workshop Director/Trainer with the National Association Of Underwater Instructors (NAUI), and served on the Board Of Directors (Vice Chairman for Technical Diving, Technical and Decompression Review Board Member). Wintertime he hobbies ski racing, coaching, and teaching. As a Racing Coach and Instructor, he is certified United States Ski Coaches Association (USSCA) and Professional Ski Instructors of America (PSIA), and competes in the United States Ski Association (USSA) Masters Series, holding a 8 NASTAR racing handicap while winning NASTAR National Championships in his age class in 2002 and 2011. He quarterbacked the Northern Michigan Wildcats to an NCAA-II National Championship in 1963, garnering All American Honors. Other pastimes include tennis, windsurfing, and mountain biking.

Wienke received a BS in physics and mathematics from Northern Michigan University, MS in nuclear physics from Marquette University, and PhD in particle physics from Northwestern University. He belongs to the American Physical Society (APS), American Nuclear Society (ANS), Society Of Industrial And Applied Mathematics (SIAM), South Pacific Underwater Medical Society (SPUMS), Undersea And Hyperbaric Medical Society (UHMS), and American Academy Of Underwater Sciences (AAUS). He is a Fellow of the American Physical Society, and a Technical Committee Member of the American Nuclear Society.

Wienke advises on decompression algorithms across exploration, recreational, technical, commercial, scientific, and research sectors, and developed the reduced gradient bubble model (RGBM), a dual phase approach to staging diver ascents over an extended range of diving applications (altitude, nonstop, decompression, multiday, repetitive, multilevel, mixed gas, and saturation). Many modern dive computers incorporate the modified and iterative RGBM into staging regimens for OC and RB mixed gas diving. In lock step, computer software and platforms offer RGBM for technical dive planning and profile analysis. A number of Training Agencies employ RGBM tables, software, and meters for hands on training and education within their Standards and Procedures. Wienke also brought the LANL Data Bank online for model and profile analysis and risk assessment. The LANL Data Bank is similar to the DAN PDE Data Bank but focuses on tec diving data. The LANL Data Bank presently (as of 2/16) contains 3023 mixed gas, OC and RB, decompression profiles with 23 cases of DCS. The Data Bank has been instrumental in RGBM success worldwide and a valued component of C&C dive planning over the past 12 years.

Wienke serves as Reviewer Editor for the *Journal of Computational Physics, Physical Review, Transport Theory And Statistical Mechanics, Applied Physics, Nuclear Science And Engineering, Nuclear Fusion, Journal Of Quantitative Spectroscopy And Radiation Transport, Nuovo Cimento, and Journal of Applied Physics.* He is also an Associate Editor for the *International Journal Of Aquatic Research And Education*, a Contributing Editor of Sources, the NAUI training periodical, and a Contributing Editor of *Advanced Diver Magazine*, a trade publication for technical diving.

SUBJECT INDEX

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Bruce Wienke is a Program Manager in the Weapons Technology/Simulation Office at LANL. He holds a degree PhD in particle physics from Northwestern University, has authored 350+ articles in peer reviewed journals, media outlets, trade magazines and has published 12 books on diving science, physics and decompression theory. He heads the C&CDive 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 and serves as a Consultant to the EPA, DHS, ADA, US Military, Oil and Dive Industries. Bruce is an Editor/Reviewer for CBM, PR, TTSP, NSE, JQSRT and is a 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. He is a NAUI Tec/Rec Instructor Trainer and Course Director. His interests include USSA Masters Ski Racing, USTA Seniors Tennis and Windsurfing. Bruce is a certified Ski Instructor (PSIA) and a Racing Coach (USSCA).