RGBM DATA BANK AND RISK ANALYSES FOR SELECT DIVE TABLES, METERS, AND PROFILES

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RISK BASICS

Introduction

Linking model (RGBM) with data (RGBM Data Bank), we have further correlatedmodel parameters with diving profiles. The full analysis will be published in the Annals Of Biomedical Engineering, but we would like to pass back salient aspects, particularly aspects impacting the RGBM Tables, in this special *ADM* article. Much ground is covered, but the most interesting aspects likely reside in various risk estimates deduced for tables, meters, and profiles. The RGBM Data Bank, unlike previous profile compilations, incorporates deep stop data for correlation with a deep stop diving paradigm. This is important, since earlier compilations impose shallow stop staging, a built in bias for any model correlation.

At the outset, we should point out some often misquoted and misunderstood information (even from people who should know better) about DCS risk and underlying DCS incidence in the data structures from which risk is deduced. Risk and incidence are NOT the same thing. Incidence in a data bank is just the number of DCS hits divided by the number of entries. Risk is the statistical estimate of DCS probability for a given dive profile (mix, descent rate, bottom depth and time, decompression stops, mix switches, ascent rate, and altitude). The estimated incidence rate across all recreational diving, for instance, is something like 1/50,000 across all profiles. However, the risk associated with diving air to

popular NDLs is near 1.2%, considerably higher than the incidence rate. This is seen later. The incidence rate across technical diving is estimated to be 10 times greater, yet the risk associated with diving to helitrox NDLs is in the 1.6% range. With that in mind, let's first take a look at the RGBM Data Bank, a data bank providing profile information useful for statistical analysis and related risk estimates, and a data structure with an incidence rate below 1%.

RGBM Profile Data Bank

Divers using bubble models are reporting their profiles to a Data Bank, located at LANL (also NAUI Technical Diving Operations). The profile information requested is simple, but very important. It is the only technical diving data bank presently existing.

Dive Data Structure

Information is both invited and tendered, but always filtered for reliability. Input information is the usual dive profile:

1. bottom mix/ppO_2 , depth, and time (square wave equivalent);
2. ascent and descent rates;
3. stage and decompression mix/ppO_2 , depths, and times;
4. surface intervals;
5. time to fly;
6. diver age, weight, and sex;
7. outcome (health problems), rated 1 - 5 in order of poor to well.

This information aids validation and extension of model application space. Some 2,823 profiles now reside in the RGBM Data Bank. There are 19 cases of DCS in the data file. The underlying DCS incidence rate is, $p = 19/2823 = 0.0067$, below 1%. Stored profiles range from 150 *fsw* down to 840 *fsw*, with the majority above 350 *fsw*. All data enters through the authors (BRW and TRO), that is, divers, profiles, and outcomes are filtered. A summary breakdown of DCS hit data consists of the following:

1. OC deep nitrox reverse profiles – 5 hits
2. OC deep nitrox – 3 hits
3. OC deep trimix reverse profiles – 2 hits
4. OC deep trimix – 2 hits
5. OC deep heliox – 2 hits
6. RB deep nitrox – 2 hits
7. RB deep trimix – 1 hit
8. RB deep heliox – 2 hits

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*. Heavyto-light gas switches occured in 2 cases, violating contemporary ICD (isobaric counterdiffusion) protocols . None of the set exhibited full body nor CNS (central nervous system) oxygen toxicity. The 19 cases come *after the fact*, that is diver distress, most with, but some without, chamber treatment following distress. The next section describes many of the profiles in the RGBM Data Bank, as well as broader field testing reported to us. Profiles come from seasoned divers using wrist slate decompression tables with computer backups. Some profiles come to us directly as computer downlaods, which we transcribe to the requisite format.

Profiles come from the technical diving community at large, essentially mixed gas, extended range, decompression, and extreme diving. Profiles from the recreational community are not included, unless they are involve extreme exposures on air or nitrox (many repetitve dives, deeper than 150 *fsw*, altitude exposures, etc). This low rate makes statistical analysis difficult, and we use a global approach to defining risk after we fit the model to the data using maximum likelihood. The maximum likelihood fit links directly to the binomial probability structure of DCS incidence in divers and aviators. It is a powerful, and time tested statistical technique.

Field Testing And Profile Data Entries

Models need validation and field testing. Often, strict chamber tests are not possible, economically nor otherwise, and models employ a number of benchmarks and regimens to underscore viability. The following are some supporting the RGBM phase model and (released) nitrox, heliox, and trimix diving tables and meters. Profiles are recorded in the RGBM Data Bank, and are representative of entries in terms of dive counts and technical diving applications.

1. Counterterror and Countermeasures Team (C & C) RB and OC exercises have used the RGBM (iterative deep stop version) for a number of years, logging some 2245 dives on mixed gases (trimix, heliox, nitrox) with 0.4% incidence of DCS – 85% were deco dives, and 55% were repets with at least 2 hr SIs, with most in the forward direction (deepest dives first). Some 9 cases of DCS were logged by the Team, mainly in the deep reverse profile category on nitrox and trimix, plus RB hits on heliox;

2. NAUI Technical Diving has been diving the deep stop version for the past 9 yrs, some estimated 22,000 dives, on mixed gases down to 300 *fsw*, with 2 reported cases of DCS, both on trimix. Some 15 divers, late 1999, in France used the RGBM to make 2 mixed gas dives a day, without mishap, in cold water and rough seas. Same thing in the warm waters of Roatan in 2000 and 2001;

3. NAUI Worldwide released a set of no-group, no-calc, no-fuss RGBM Tables for air, EAN32, and EAN36 recreatational diving, from sea level to 10,000 ft, a few years ago. Minimum SIs of 1 hour are supported for repetitive diving in all Tables, and

safety stops for 2 *min* in the 15 *fsw* zone, plus 1 min deep stops at half bottom depth, are required always. Tables were tested by NAUI Insructor Trainers, Instructors, and Divemasters over a 2 year period without mishap, and continue so today as the the mainstay teaching Tables in NAUI basic air and nitrox courses;

4. Modified RGBM recreational algorithms (Haldane imbedded with bubble reduction factors limiting reverse profile, repetitive, and multiday diving), as coded in Suunto, Mares, Dacor, UTC, Zeagle, Steam Machines, GAP, ABYSS, HydroSpace, Plexus decometers, maintain an already low DCS incidence rate of approximately 1/50,000 or less. More RGBM decompression meters, including mixed gases, are in the works;

5. A cadre of divers and instructors in mountainous New Mexico, Utah, and Colorado have been diving the modified RGBM at altitude, an estimated 1,200 dives, without peril. Again, not surprising since the altitude RGBM is slightly more conservative than the usual Cross correction used routinely up to about 8,000 ft elevation, and with estimated DCS incidence less than 1/10,000;

6. Within decometer implementations of the RGBM, only a few scattered DCS hits have been reported in nonstop and multidiving categories, beyond 1,300,000 dives or more, up to now, according to statistics furnished the author (BRW) by meter vendors;

7. Extreme chamber tests for mixed gas RGBM protocols are in the works, and less stressful exposures will be addressed shortly – extreme here means 300 *fsw* and beyond;

8. As seen, probabilistic decompression analysis of selected RGBM profiles, calibrated against similar calculations of the same profiles by Duke, help validate the RGBM on computational bases, suggesting the RGBM has no more theoretical risk than other bubble or dissolved gas models (Weathersby, Vann, Gerth methodology at USN and Duke);

9. All divers and Instructors using RGBM decometers, tables, or Internet software have been advised to report individual profiles to DAN Project Dive Exploration (Vann, Gerth, Denoble and others at Duke), plus to the RGBM Data Bank (Wienke, O'Leary at LANL and NAUI);

10. GAP, HydroSpace RGBM Simulator, and ABYSS are NET software packages that offer the modified RGBM (folded Buhlmann ZHL) and, especially, the full up, deep stop version for any gas mixture, have a fairly large contingent of tech divers already using the RGBM and have not received any reports of DCS to date. The EXPLORER RGBM Simulator is furnished to meter owners of the HydroSpace EXPLORER;

11. Outside of proprietary (commercial) and RGBM Tables, mixed gas tables are a smorgasboard of no longer applicable

Haldane dynamics and discretionary stop insertions, as witnessed by the collective comments of a very vocal and extremely competent, experienced technical diving community;

12. Extreme WKPP profiles in the 300 *fsw* range on trimix were used to calibrate the RGBM. WKPP profiles are the most impressive application of RGBM staging, with as much as 12 hours less decompression time for WKPP helium based diving on RGBM schedules versus Haldane schedules, with estimated 200 dives;

13. Ellyat, a TDI Instructor, dived the Baden in the North Sea to 540 *fsw* on RGBM Tables on two different occasions, and 3 hours were shaved off conventional hang time by RGBM application. Unfortunately, with diver error and mismatched gas switching strategies from helium to nitrogen, dives to 840 *fsw* resulted in vestibular DCS;

14. NAUI Worldwide released sets of deep stop RGBM nitrox, heliox, and trimix technical and recreational Tables that have been tested by NAUI Technical Diving Operations over the past 9 years, with success and no reported cases of DCS, for open circuit regulators and rebreathers,

15. Doppler and imaging tests in the laboratory, and analyses by Bennett, Marroni, Brubakk and Wienke, and Neuman all suggest reduction in free phase counts with deep stop staging;

16. deep air RGBM Tables with surface oxygen decompression are employed by American oil patch diving companies;

17. Scorese, a NAUI instructor, and his students made a total of 234 dives on the Andrea Doria using rebreathers and RGBM (constant *ppO2*) RB Tables, and various nitrogen and trimix diluents. Dive abortions off rebreathers employed ranged RGBM (open circuit) Tables as bailouts, and witnessed no mishaps;

18. Freauf, a Navy SEAL in Hawaii, logged 20 trimix decompression dives beyond 250 *fsw* on consecutive days using RGBM Tables (pure oxygen switch at 20 *fsw*);

19. Gerth, a US Navy researcher at NEDU, suggested that deep stops are necessary and cost effective for air and nitrox Navy divers, that is, risk versus decompression time;

20. Melton, owner of HydroSpace Engineering and developer of the RGBM EXPLORER (OC plus RB) dive computer reports 100s of dives in the 400 *fsw* range on the RGBM EXPLORER;

21. GAP, Gas Absorption Program, an RGBM software product out of the Netherlands, supports brisk and sustained use of the RGBM within the tec and rec diving community;

22. NEDU in Panama City is performimg deep stop man trials in open water using a US Navy bubble model;

N (dives)	n (hits)	P(n) p = 0.01 q = 0.99	P(n) p = 0.10 q = 0.90
5	0	0.95	0.59
	1	0.04	0.33
	2 or more	0.01	0.08
10	0	0.90	0.35
	1	0.09	0.39
	2 or more	0.01	0.26
20	0	0.82	0.12
	1	0.16	0.27
	2 or more	0.02	0.61
50	0	0.61	0.01
	1	0.31	0.03
	2 or more	0.08	0.96

Table 1. Probabilities Of Decompression Sickness For Underlying Incidences.

23. heliox RGBM Tables are being used by a commercial diving operation in Argentina;

24. Raine, a wreck diver in California, reports 100s of RGBM dives in the 250 *fsw* range with low Doppler counts;

25. The RGBM site, *RGBMdiving.com*, receives 100s of hits weekly, and provides custom RGBM Tables;

26. ANDI, a training agency, has adopted a custom version of GAP for diver training on mixed gases, OC and RBs;

27. NAUI similarly employs a custom version of GAP for dive planning, with nominal GAP parameter settings recovering released and published NAUI RGBM Tables;

28. O'Leary, Director NAUI Technical Operations, has made over 70 dives on OC and RB systems using RGBM Table and the Hydrospace EXPLORER to depths beyond 250 *fsw*, with anywhere from 6 - 9 other divers during NAUI Technical Instructor Training Courses;

29. O'Leary, Sharp, Scorese, Bell, Hunley, and 6 other NAUI Instructors used RGBM OC and RB Tables to dive the USS Perry in Anguar in very strong currents, down to 260 *fsw*, logging 2 repetitive deco dives a day for a week or so.

With DCS binomially distributed in incidence probability, many trials are needed (or other close profiles) to fully validate any model at the 1% level. Additionally, full validation requires DCS incidences, the higher the number, the better, contrary to desired dive outcomes. While the foregoing list of field tests and profiles are not controlled scientific experiments with attendant data collection, the shear number of diving events and diversity of exposure spectrum might not be discounted nor treated lightly. The collective information has been dubbed the *living laboratory* by segments of the technical, scientific, and operational diving community.

Probabilistics

Decompression sickness is a hit, or no hit, situation. Statistics are binary, as in coin tossing. Probabilities of occurrence are determined from the binomial distribution, which measures the numbers of possibilities of occurrence and non-occurrence in any number of events, given the incidence rate. **Table 1** lists corresponding binomial decompression probabilities, *P*(*n*), for 1% and 10% underlying incidence (99% and 90% nonincidence), yielding 0, 1, and 2 or more cases of decompression sickness. The underlying incidence, *p*, is the (fractional) hit rate. The non-incidence, *q*, is just 1Å*lp*, or the (fractional) non-hit rate.

As the number of trials increases, the probability of 0 or 1 occurrences drops, while the probability of 2 or more occurrences increases. In the case of 5 dives, the probability might be as low as 5%, while in the case of 50 dives, the probability could be 39%, both for $p = 0.01$. Clearly, odds even percentages would require testing beyond 50 cases for an underlying incidence near 1%. Only by increasing the number of trials for fixed incidences can the probabilities be increased. Turning that around, a rejection procedure for 1 or more cases of decompression sickness at the 10% probability level requires many more than 50 dives. If we are willing to lower the confidence of the acceptance, or rejection, procedure, of course, the number of requisite trials drops. **Table 1** also shows that the test practice of accepting an exposure schedule following 10 trials without incidence of decompression sickness is suspect, merely because the relative probability of nonincidence is high, near 35%.

Table 2. Nonstop Time Limits For 1% and 5% DCS Probability.

depth d (*fsw*)	nonstop limit t_n (*min*) $p = .05$	nonstop limit t_n (*min*) $p = .01$	nonstop limit t_n (*min*) US Navy
30	240	170	
40	170	100	200
50	120	70	100
60	80	40	60
70	80	25	50
80	60	15	40
90	50	10	30
100	50	8	25
110	40	5	20
120	40	5	15
130	30	5	10

RGBM Data Correlations And Risk Estimates

For the past 10-15 years, a probabilistic approach to assessing risk in diving has been in vogue. Sometimes this can be confusing, or misleading, since definitions or terms, as presented, are often mixed. Also confusing are risk estimates varying by factors of 10 to 1,000, and distributions serving as basis for analysis, also varying in size by the same factors. In a word, the probabilistic approach amounts to defining a risk function for diving, and then fitting the risk function to the data using a statistical method called maximum likelihood. Risk functions might be supersaturations, Doppler bubble counts, bubble formation and growth rates, separated bubble volumes, and combinations thereof. For our RGBM analysis, the risk function is bubble growth rate over number of bubbles initially excited into growth under compression-decompression.

Years ago, hundreds of air dives were analyzed using this procedure, yielding decompression schedules with 95% and 99% non-incidence (5% and 1% incidence). Tables were published by US Navy investigators, and **Table 2** tabulates the corresponding nonstop time limits ($p = 0.05, 0.01$), including standard US Navy (Workman) limits for comparison. Later re-evaluations of the standard set of nonstop time limits estimate a probability rate of 1.25% for the limits. In practice, incidence rates are below 0.001%, and most divers do not dive to the limits. The risk function used in **Table 2** is the dissolved gas oversaturation, that is, the difference between tissue tension and ambient pressure.

SIMPLE DIVING RISKS
RGBM Single And Repetitive Air Dive Risks

To perform risk analysis with the RGBM Data Bank, a risk estimator need be selected. For diving, dissolved gas and bubble estimators are useful. For recreational diving, all estimators are

roughly equivalent, because little dissolved gas has likely separated into free phases (bubbles). Analysis shows this true for all cases examined. The only case where dissolved gas and phase estimators differ (slightly here) is within repetitive diving profiles. The dissolved gas estimator cues on gas buildup in the slow tissue compartments (staircasing for repets within an hour or two), while the phase estimator cues on bubble gas diffusion in the fast compartments (dropping rapidly over hour time spans). This holding true within all recreational diving distributions, we proceed to the risk analysis.

Nonstop limits (NDLs), denoted *tn*, from the US Navy, PADI, NAUI, and ZHL (Buhlmann) Tables provide a set for comparison of relative DCS risk. Listed in Table 3 are the NDLs and corresponding risks for the profile, assuming ascent and descent rates of 60 *fsw/min* (no safety stops). Dissolved gas, *s*, and phase, *r*, estimates vary little for cases, and only the phase estimates are included.

Table 3. Risk Estimates For Standard Air NDLs.

d (*fsw*)	USN NDL t_n (*min*)	risk r	PADI NDL t_n (*min*)	risk r	NAUI NDL t_n (*min*)	risk r	ZHL NDL t_n (*min*)	risk r
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 2. 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 also independently corroborated *[Gerth,priv comm, 2001]* within USN and DAN data sets at Duke, both in Table 3 and Table 4.

Next, the analysis is extended to profiles with varying ascent and descent rates, safety stops, and repetitive sequence. Table 4 lists nominal profiles (recreational) for various depths, exposure and travel times, and safety stops at 5 *msw*. Mean DCS estimates are tabulated for both dissolved gas supersaturation ratio (ZHL), *s*, and excited bubble volume (RGBM), *r*, risk functions, with nominal variance, $r\pm = r \pm 0, 004$, across all profiles.

Table 4. 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 *r*	risk *s*
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 174 *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 .

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 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 only at the 0.25% to 0.5% level in relative surfacing risk. Safety stops at 5 *msw* for 3 *min* lower relative risk an average of 0.3%, while reducing the ascent rate from 18 *msw/min* to 9 *msw/min* reduces relative risk an average of 0.35%. Staging, NDLs, and contraints imposed by decometer algorithms are consistent with acceptable and safe recreational diving protocols. Estimated absolute risk associated across all ZHL NDLs and staging regimens analyzed herein is less than 2.32%, probably much less in actual practice. That is, we use $p = 0.0067$, and much evidence suggests incidence $p < 0.0001$, some ten times safer.

Implicit in such formulations of risk tables are assumptions that given decompression stress is more likely to produce symptoms if it is sustained in time, and that large numbers of separate events may culminate in the same probability after time integration. Though individual schedule segments may not be replicated enough to offer total statistical validation, categories of predicted safety might be grouped within subsets of corroborating data. For instance, risks on air dives might be estimated from just nitrox data, risks on trimix from just trimix data, risks on heliox just from heliox data, etc. Since the

method is general, any model parameter or meaningful index, properly defined, can be applied to decompression data, and the full power of statistical methods employed to quantify overall risk. While powerful, such statistical methods are neither deterministic nor mechanistic, and cannot predict on first principles. But as a means to table fabrication with quoted risk, such approaches offer attractive pathways for analysis.

Questions of what risk is acceptable to the diver vary. Sport and research divers would probably opt for small risk (1% or less), while military and commercial divers might live with higher risk (5%), considering the nearness of medical attention in general. Many factors influence these two populations, but fitness and acclimatization would probably play strategically.

UW Seafood Diver Air Tables

As another application of the RGBM Data Bank to table construction and analysis, we detail a set of tables of interest to the University of Wisconsin (UW), along with estimated risk for various nonstop limits gleaned from the data. These Tables have no groups, and simple rules. Released mixed gas RGBM Tables resulted from similar analyses across both the technical and recreational segments. Such Tables are certainly useful for a broad spectrum of diving, and are easy to use. **Table 5** lists the maximum NDLs for any series of dives (up to 3) with 60 *min* SIs between dives. Divers need make a deep stop at 1/2 the maximum bottom pressure for 1 *min*, plus a shallow safety stop in the 15 *fsw* zone for 2 *min*. Descent rate is 60 *fsw/min*, and ascent rate is 30 *fsw/min*. The NDLs are listed for maximum risk after 3 repetitive dives to the (same) depth indicated, or to a lesser depth.

Table 5. RGBM Repetitive Risks For Air Dives

depth (*fsw*)	r 5.14% maximum time (*min*)	r 3.29% maximum time (*min*)	r 1.37% maximum time (*min*)
100	24	20	14 deep stop 60/1 shallow stop 15/2
80	38	32	24 deep stop 50/1 shallow stop 15/2
60	50	42	32 deep stop 40/1 shallow stop 15/2
40	130	120	100 deep stop 30/1 shallow stop 15/2

Tables like these are of interest to Puerto Rican diving fishermen, and fishing sport divers. NAUI uses a variant, detailed next, for training. Technical Training Agencies also employ mixed gas tables for decompression diving, as well as dive planning software, all based on the RGBM algorithm. Some risk estimates of profiles in these RGBM Technical Tables also follow.

RGBM Air And Nitrox Recreational Tables (sea level - 10,000 *ft*)

For comparison, consider similar RGBM Tables employed by NAUI for air and nitrox diver training, sea level up to 10,000 *ft*. They are basically the same as the Puerto Rican seafood diver tables above, except that successive dives must always be shallower than the previous. Descent and ascent rates are 75 *fsw/min* and 30 *fsw/min*, and SIs are 60 *min*. At sea level to 2,000 *ft* elevation, three dives may be made in a day on air or nitrox. At elevations above 2,000 *ft*, only two dives are sanctioned. There are 9 RGBM Tables in all, 3 for air, 3 for EAN32, and 3 for EAN36, ranging in altitude, 0 - 2,000 *ft*, 2,000 - 6,000 *ft*, and 9,000 - 10,000 *ft*. In Tables 9a through 9i, risks are tabulated at the end of the 3 or 2 dive sequence. Moving from left to right (first dive through last permitted dive) successive decrements in permissible depths are seen. Safety stops at half the bottom depth are required for 1 *min*, and an additional safety stop in the 15 *fsw* zone for 2 *min* is part of the protocol. Maximum risk is seen in the air tables at 10,000 *ft* elevation, and minimum risk in the EAN36 tables at sea level.

Table 6a. RGBM Air Tables (0 - 2,000 *ft*)
Maximum Risk After Dive 3, *r* = 1.69%

Dive 1		Dive 2		Dive 3	
depth (*fsw*)	time (*min*)	depth (*fsw*)	time (*min*)	depth (*fsw*)	time (*min*)
130	10	80	30	30	150
120	13	75	30	30	150
110	16	70	40	30	150
100	20	65	40	30	150
90	25	60	55	30	150
80	30	55	55	30	150
70	40	50	80	30	100
60	55	45	80	30	150
50	80	40	110	30	150
40	110	35	110	30	150
30	150	30	150	30	150

Table 6b. RGBM Air Tables (2,000 - 6,000 *ft*)
Maximum Risk After Dive 2, *r* = 1.92%

Dive 1		Dive 2	
depth (*fsw*)	time (*min*)	depth (*fsw*)	time (*min*)
110	9	70	28
100	13	65	28
90	17	60	38
80	22	55	38
70	28	50	54
60	38	45	54
50	54	40	85
40	85	35	85
30	125	30	125

Table 6c. RGBM Air Tables (6,000 - 10,000 *ft*)
Maximum Risk After Dive 2, *r* = 2.36%

Dive 1		Dive 2	
depth (*fsw*)	time (*min*)	depth (*fsw*)	time (*min*)
90	11	60	28
80	15	55	28
70	21	50	40
60	28	45	40
50	40	40	64
40	64	35	64
30	103	30	103

Table 6d. RGBM EAN32 Tables (0 - 2,000 *ft*)
Maximum Risk After Dive 3, *r* = 1.44%

Dive 1		Dive 2		Dive 3	
depth (*fsw*)	time (*min*)	depth (*fsw*)	time (*min*)	depth (*fsw*)	time (*min*)
120	20	80	47	40	150
110	25	75	47	40	150
100	30	70	60	40	150
90	38	65	60	40	150
80	47	60	85	40	150
70	60	55	85	40	150
60	85	50	115	40	150
50	115	45	115	40	150
40	150	40	150	40	150

Table 6e. RGBM EAN32 Tables (2,000 - 6,000 *ft*)
Maximum Risk After Dive 2, *r* = 1.65%

Dive 1		Dive 2	
depth (*fsw*)	time (*min*)	depth (*fsw*)	time (*min*)
100	20	65	43
90	26	60	57
80	33	55	57
70	43	50	84
60	57	45	84
50	84	40	120
40	120	35	120
30	150	30	150

Table 6f. RGBM EAN32 Tables (6,000 - 10,000 *ft*)
Maximum Risk After Dive 2, *r* = 1.84%

Dive 1		Dive 2	
depth (*fsw*)	time (*min*)	depth (*fsw*)	time (*min*)
90	17	60	43
80	24	55	43
70	32	50	60
60	43	45	60
50	60	40	96
40	96	35	96
30	140	30	140

Table 6g. RGBM EAN36 Tables (0 - 2,000 *ft*)
Maximum Risk After Dive 3, *r* = 1.12%

Dive 1		Dive 2		Dive 3	
depth (*fsw*)	time (*min*)	depth (*fsw*)	time (*min*)	depth (*fsw*)	time (*min*)
110	31	80	60	50	150
100	35	75	60	50	150
90	46	70	85	50	150
80	60	65	85	50	150
70	85	60	115	50	150
60	115	55	115	50	150
50	150	50	150	50	150

Table 6h. RGBM EAN36 Tables (2,000 - 6,000 *ft*)
Maximum Risk After Dive 2, *r* = 1.24%

Dive 1		Dive 2	
depth (*fsw*)	time (*min*)	depth (*fsw*)	time (*min*)
90	21	60	79
80	39	55	79
70	54	50	114
60	79	45	114
50	114	40	150
40	150	35	150
30	150	30	150

Table 6i. RGBM EAN36 Tables (6,000 - 10,000 *ft*)
Maximum Risk After Dive 2, *r* = 1.66%

Dive 1		Dive 2	
depth (*fsw*)	time (*min*)	depth (*fsw*)	time (*min*)
80	29	55	54
70	37	50	84
60	54	45	84
50	84	40	128
40	128	35	128
30	150	30	150

COMPLEX DIVING RISKS

Helitrox Nonstop Limits (NDLs)

Helitrox is enriched trimix, that is, the oxygen fraction is above 21 % in the breathing mixture. Helitrox is gaining in popularity over nitrox when helium is available for gas mixing. Diving agencies often use helitrox in the beginning sequence of technical diver training. Listed below in **Table 7** are nonstop time limits and corresponding risks, *r*, for exposures at that depth-time. The mixture is helitrox (enriched 26/17 trimix), sometimes called triox.

Comparative Helium And Nitrogen Staging And Risk

Consider a deep trimix dive with multiple switches on the way up. This is a risky technical dive, performed only by seasoned professionals. **Table 8** contrasts stop times for two gas choices at the 100 *fsw* switch. The dive is a short 10 *min* at 400 *fsw* on 10/65/25 trimix, 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, the oxygen fractions were the same 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.

Comparative profile reports suggest that riding helium to the 70 *fsw* level with a switch to EAN50 is good strategy, one that couples the benefits of well being on helium with minimal decompression time and stress following isobaric switch 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*, for the helium strategy, 40/20/40 trimix at 100 *fsw*, is slightly safer than the nitrogen strategy, EAN40 at 100 *fsw*, but in either case, the risk is high.

WKPP Extreme Exploration Dives

The Woodville Karst Plain Project (WKPP) has reported a number of 300 *fsw* dives with OC and RB systems on trimix for many hours bottom time, and some 8 *hrs* of deompression. Pure oxygen is employed in the 30 *fsw* zone with the help of an underwater habitat. Successful regimens systematically roll back the helium fraction and increase the oxygen fraction in roughly the same proportions, thus maintaing nitrogen fractions low and fairly constant. Diving starts in the cave systems of Wakulla Springs

Table 7. Helitrox NDLs And Risk

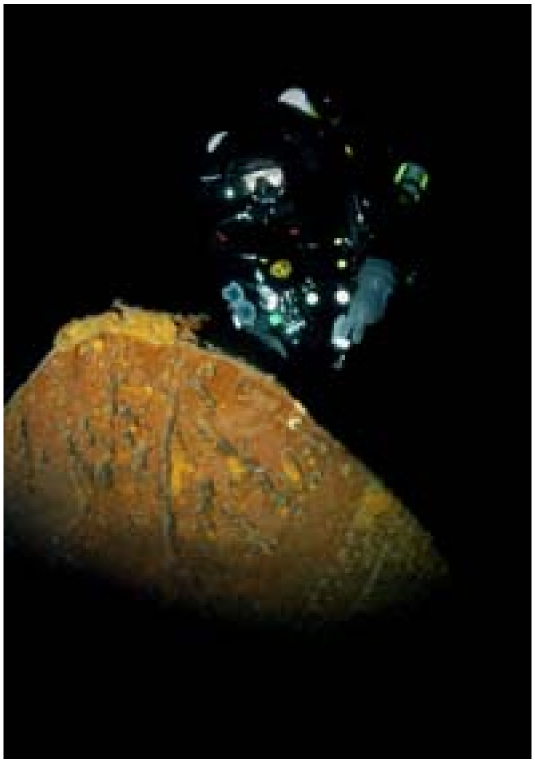
depth *d* (*fsw*)	time *tn* (*min*)	risk *r*
70	35	1.4%
80	25	1.4%
90	20	1.4%
100	15	1.4%
110	10	1.5%
120	8	1.5%
130	6	1.4%
140	5	1.5%
150	4	1.6%

These NDL triox risks track closely with NDL risks for air and nitrox.

Table 8. Comparative Helium and Nitrogen Gas Switches

depth (*fsw*)	r 6.42% stoptime (*min*) Tx10/65/25	r 6.97% stoptime (*min*) Tx10/65/25
400	10.0	10.0
260	1.5	1.5
250	1.0	1.0
240	1.0	1.0
	Tx18/50/32	Tx18/50/32
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
	Tx40/20/40	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
	TDT(min) 123.0	TDT(min) 116.0

Table 9. WKPP Extreme Trimix Dives Surfacing Risk, *r* = 16.67%		
depth (*fsw*)	stop time (*min*)	mixture
270	360	10.5/50 trimix
260	1	
250	1	
240	1	18/40 trimix
230	2	
220	2	
210	2	
200	3	
190	3	
180	3	21/35 trimix
170	4	
160	4	
150	5	
140	5	
130	6	
120	7	35/25 trimix
110	8	
100	9	
90	10	
80	12	
70	16	50/16 trimix
60	21	
50	27	
60	34	
50	41	
40	49	
30	150	100% *O2*



in Florida. **Table 9** summarizes the ascent and decompression profile. The risk is, of course, high, but WKPP professionals continue to attempt and complete such extreme exposures, pushing the exploration envelope. These dives served as calibration points for the RGBM algorithm on whole.

World Record OC Trimix Dive

Consider risk after an OC dive to 1040 *fsw* on trimix, with matched ICD switches maintaining the relative fraction of nitrogen constant as helium is reduced in the same measure as oxygen is increased. Dives without this rather well known strategy ended in some serious chamber time for treatment of vestibular DCS. Reports hint this dive was attempted, maybe accomplished, but contradictions abound. We merely treat it as academic exercise for risk prediction.

Table 10 roughly summarizes the RGBM profile and ascent protocol. Stops range from 740 *fsw* to 10 *fsw* for times ranging 0.5 *min* to 31.0 *min*. Descent rate is assumed to be 60 *fsw/min*, and ascent rate between stages is assumed to be 30 *fsw/min*. Mixes and switch depths are indicated, as in **Table 9.**

Table 10. Trimix Dive To 1040 *fsw* And Risk Surfacing Risk, *r* = 29.24%		
depth range (*fsw*)	stop range (*min*)	mixture
1040	1	5/67 trimix
740 - 530	0.5 - 1.5	
520 - 300	2.0 - 3.5	
290 - 180	4.0 - 6.5	14/56 trimix
170 - 140	7.0 - 9.5	
130 - 70	10.0 - 15.0	27/56 trimix
60 - 40	16.0 - 20.50	
30 - 20	24.5	80/20 nitrox
10	31.0	100% *O2*

The computed risk for this dive is very high, near 30%. Total decompression time is near 415 *min*. Logistics for stage cylinders are beyond formidable, and the risk for deep support divers is also high.

Extreme RB Profile

The following, **Table 11**, 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 10/85 trimix, and *ppO2* setpoint is 1.1 *atm*. From a decompression standpoint, rebreather systems are the quickest and most efficient systems for underwater activities. The higher the *ppO2* , 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 *ppO2* setpoints of 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 comparative *ppO2* RB calculations, as well as in OC versus RB risk estimates.

The risk associated with this 400 *fsw* is less than a similar dive on trimix to roughly the same depth for a shorter period of time, that is, Table 8.

Table 11. Extreme RB Dive and Risk
Surfacing Risk r = 5.79%

depth (*fsw*)	time (*min*)
444	15.0
290	0.5
280	0.5
270	0.5
260	0.5
250	0.5
240	0.5
230	1.0
220	1.0
210	1.0
200	1.0
190	1.5
180	1.5
170	1.5
160	1.5
150	2.0
140	2.0
130	2.0
120	2.5
110	3.0
100	3.5
90	4.0
80	4.5
70	5.0
60	7.0
50	7.5
40	8.0
30	12.5
20	14.0
10	18.5

USS Perry Deep RB Wreck Dives

A team of divers uncovered the wreck of the USS Perry in approximately 250 *fsw* off Anguar, and explored it for a week on RBs. Diving in extremely hazardous and changing currents, their repetitive decompression profile appears in **Table 12**. Profiles and risk for the two dives, separated by 4 *hrs* SI, are nominal, with no accounting of exertion effort in current implied. Diluent is 10/50 trimix, with a *ppO2* setpoint of 1.3 *atm*.

Table 12. USS Perry RB Repetitive Decompression Dives And Risk
Surfacing Risk After Dive 1, r = 7.48%
Surfacing Risk After Dive 2, r = 7.79%

depth (*fsw*)	time (*min*)
260	40
170	1
160	1
150	1
140	1
130	1
120	1
100	2
90	2
80	2
70	3
60	3
50	4
40	5
30	6
20	9
10	12
0	270
210	20
90	1
80	1
70	1
60	1
50	2
40	2
20	4
10	5

Summary

The reduced gradient bubble model (RGBM) has been correlated with profiles housed in the RGBM Data Bank. The Bank stores technical, mixed gas diving profiles with outcome. Some 2800+ deep stop profiles reside in the Bank, with 19 cases of DCS. Parameters in the RGBM are calibrated against data using maximum likelihood. Risk estimates for select NDLs, tables, meter algorithms, and diver profiles in the RGBM Data Bank were tabulated, using a bubble phase volume estimator integrated over the whole profile.

A few points important points need be reiterated here:
1. Deep stop date is intrinsically different from date collected in the past for diving validation, in that previous data is based on shallow stop diver staging, a bias in dissolved gas model correlations;
2. Deep stop data and shallow stop data yield the same risk estimates for nominal, shallow, and nonstop diving because bubble models and dissolved gas models converge in the limit of very small phase separation;
3. If shallow stop data is employed in all the cases detailed, dissolved gas (only) risk estimates will be categorically higher than those computed herein;
4. Data entry in the RGBM Data Bank is a ongoing process of profile addition, extended exposuredepth range, and mixed gas diving application.