Yet Another Benchmark - Part III
By Albrecht Salm
This is short dive into the world of statistical modeling of dive tables. But before we submerge with pure numbers, read the short motivation from the Intro. This may tell you that concerning decompression sickness you should not rely on your intuition but look only for the real data, i.e. the outcomes of the dives (i.e.: YOUR dives!).

**Intro**

To put it bluntly, the occurrence of decompression sickness (DCS) in man (or girls) is:

- a random event
- not reproducible
- violating a deco table or a no-decompression limit (NDL) does not guarantee DCS (Source: [1])

And: more the worse, even the pure contrary of the last statement is valid! Let’s take a look at the ca. 70 dives with healthy US Navy divers, done in the 50’s (Source: [2] & [3]). These have been controlled chamber dives with the divers resting or exercising afterwards. The ascent rate was always uniform and prescribed with the then usual 25 feet/min (7.6 meters/min). There have been no decompression stops made.

Now: 4 men dived to 150 feet (45 meters) for 36 min on air, surfaced with these 25 feet/min (7.6 meters/min) and made no decompression stops.

**Q:** how many suffered DCS?

**Remember the time-to-surface (TTS) of the two military decompression tables:**

USN Air Table (2008) calls for ca. 128 min TTS, whereas; USN Air Table (1957) calls for ca. 60 min TTS.

**A:** the result is: none! That is: no cases of DCS for these 4 men!

Now another one: more men to a shorter dive to the same depth: 11 men, 150 feet (45 meters) for 30 min on air, surfaced with 25 feet/min (7.6 meters/min) and no decompression stops.

**Q:** how many suffered DCS?

USN Air Table (2008) called for ca. 59 min TTS, whereas; USN Air Table (1957) called for ca. 35 min TTS.

**A:** all! I.e.: 11 cases of DCS (5 cases of mild DCS, 6 cases of bends).

**Basics and difficulties**

There is a wealth of literature on the statistical formulation of decompression tables. We should not repeat that here, but have a look at the basic sources ([4] and [5]) and the 11-volumes series from NMRI / NEDU: “Statistically Based Decompression Tables: I -> XI” from 1985 – 1999, ca. 1,000 pages with short comments from my side at the end of this paper.

In a nutshell, it works like this: we collect not only hundreds but thousands of (very) well-documented dives. Well documented means here: there is a controlled and reproducible environment (breathing gas composition including humidity and CO2, water and air temperatures, workload, ascent and descent rates) and as well the controlled biometrics of the divers. Then we group them together per procedures: say, saturation dives in one group, EAN dives another, Heliox or constant pO2 the next ones, repetitive or multi-level in others and so on. As well the inert gas dose (time, depth combinations) should be comparable. The rationale for this is that it is very probable that no “unified deco theory” would allow for an explanation of all these phenomena.
The next step is to collect the outcomes of these dives. Either in scales of Doppler bubble grades (I to IV or so) or in a more digital black-and-white manner: DCS YES / NO.

Here starts, btw, one of the first difficulties of assessing DCS: how about vanishing niggles, a little skin rash or a short period of migraine? Does it count, or not at all? Do we attribute 10, 25 or 50% of a DCS case? Well: this is called the “pink noise” within the measurement.

And, there is another difficulty: in the past, much effort has been done to assess the relationship between age, gender, BMI (body-mass-index) and DCS or Doppler-bubbles. The relationship was found to be positive. The underlying statistical problem, which rendered the masses of papers more or less useless, was the so-called “multi co-linearity”, which was not corrected in these publications. I.e. the real underlying parameter for the Doppler-bubbles was (probably) the aerobic capacity, which is the “fitness”. Multi co-linearity describes the fact that a couple of parameters, like increasing age and increasing BMI go in the same direction as decreasing fitness. So the data was biased. And so were the conclusions drawn.

As was the case with the PFO, the patent foramen ovale, a little hole between the atria, the antechambers of the human heart, which approx. 30% of the population has. There was a famous study, technically brilliantly designed to check for brain lesions (that is, little defects in your brain) with ca. 215 divers. The sensational result was, that if you do a lot of repetitive (more than 100 a year), Tec-like dives (deeper than 40 meters, decompression, cold fresh water lake) you are really prone to DCS-related brain impairment. But there has been no check for a PFO in these divers; to put it mildly, this little procedural error left the whole study open for controversy.

The point here to make is: if the biometrics of the guinea pigs (our divers) are not carefully screened, it may render a whole research-study useless.

After the assessment you have a numerical scale. Now you have to fit that to your gas kinetics model. Be it a dissolved gas-phase, a bubble-volume model or whatever combination thereof. The measurement of the goodness of a “fit” is usually done with the logarithmic scale of likelihood. The result is either a “label” for your dives, being, for example in the 1, 2 or 5% probability of DCS, the \( P(DCS) \). \( P(DCS) \) is the probability \( P \) of contracting a decompression sickness DCS. It follows usually a so-called dose-response curve, what is already well-known from drugs, O2 and antibiotics. In our case the dose is either depth \( d \), time \( t \), a combination thereof like \( d \times \text{square root} \left( t \right) \) or another measure for a compartment saturation / supersaturation. The formula for this “Hill Dose Equation” looks like that:

\[
P(DCS) = \frac{\text{Dose}^a}{\text{Dose}^a + b}
\]

Or you tabulate like a standard decompression table, giving it the sobriquet of the predicted \( P(DCS) \) outcomes. So it may look like that:

![Table](https://www.techdivingmag.com/image.png)

No-Stop Bottom-Time Limits from 3 Sources; Table 3, p.28; Excerpt taken from: A SIMPLE PROBABILISTIC MODEL FOR ESTIMATING THE RISK OF STANDARD AIR DIVES. Van Liew, Flynn: TA 01-07 NEDU TR 04-41[6].

www.techdivingmag.com
Let’s have a look at the 100 feet entry: the old USN table gave 25 min as a No-Stop limit, putting it near a P(DCS) of 2% with 26 min. This is quite a lot: it would imply that approx. out of 50 such dives we would have one guy (or girl) ending up in the deco-chamber. The 1% P(DCS) would yield a reduced No-Stop time of 17 min.

And, there is another problem, intrinsic to the very nature of DCS: it is the fact of small numbers. In the average, we have one case of DCS per 10,000 recreational dives. This is not much, and it is quite OK. Or as our friend Paul K. W. put it: “If you want to do research on DCS: you have to have it!”

For example, there have been publications in the past, telling that the use of dive computers is much safer than the use of the traditional dive tables. The story here is that we do not know how closely the dive computer users followed the profiles from the table users...

And this is the next problem: if your dive was safe, you do not know how closely you have been to DCS. To put it the other way around: a useful contribution to DCS research is only a validated case of DCS! The real endpoint of DCS is death: a point, clearly not so desired for human experiments. This is the rationale, why millions of small and not-so-small guinea-pigs have been sacrificed on the lord’s table of the cruel mistress of science for the welfare of divers.

Concerning P(DCS) we normally speak about the dive profile, fO2, skin temperature and workload. We did not speak so far about: blood chemistry, the so-called “MPs” (micro particles) and the lining of the blood vessels. But this is where topical DCS-research is aimed at.

Results
So what is it now all about this statistical modeling when we have so many variables to control? Wasn’t that ole’ Haldane model not much more simple and didn’t it work? Well, it did, really. Up to a certain extent. But if the dive was very short or very deep, it didn’t! As well Haldane himself was already aware about the limitations and the problems with age and adiposity (old and fat divers). Nowadays we have a lot more models, a couple of them dealing not only with the dissolved gas phase, as Haldane did, but also with the free gas phase, the bubbles. And subsequently started a sometimes heated debate, which of the models is now better. And the down side of this debate is that it leaves the diver completely in the dark: have a look at the tables with the big variations in the TTS for our “test dive” (pls. cf. the “Yet Another Benchmark” Parts I & II in Tech Diving Mag Issue 11, p. 6 & 7; and Issue 12, p. 4 & 5). But the proponents of each of these models forgot a basic wisdom: all of these models are wrong, basically! And there is an elegant way out of this debate: these kinds of traditional models try to predict the outcome of the dive before, based on the model assumptions. This is why these are sometimes called: “deterministic”. The statistically based models avoid this and work the other way around: in hindsight the outcomes of the dives are analyzed. And based on this analysis there is an interpolation or extrapolation for similar dives.
A generic plot of a P(DCS) resp. the risk versus a dose looks like that (Source: [8], p. 89):

A P(DCS) of 0 means you have none whereas a P(DCS) of 1 means you ended up in the deco chamber. But in between is a big gray area of individual and intra-individual susceptibility, where this is not so clear and humans or guinea pigs do not react in a proper digital Yes/No manner on a varying inert gas dose. So, next question.

Q: when you have been bent like a pretzel on your last dive, is it more probable than not, that you may get bend for another time?

A: statistically speaking: yes! Why so? Not speaking about the personal susceptibility for DCS which really plays a dominant role in all these statistics. If you look at the collections of many dive outcomes, preferably with the same subjects (for e.g. from the big offshore diving companies or the organizations for public health), you will see that there are DCS-candidates, divers which will contract DCS more easily than others.

But statistically speaking the story is the following: tossing a coin and betting for head or tail is like getting DCS, a binominal distribution. And it is more likely than not, getting a run of 3 tails (or 3 heads) in a sequence. Here the probability in 10 tosses is 864/1,024, i.e. ca. 82% [7]. So this is more likely than getting a head after a tales, or vice-versa!

Lessons learned for TEC diving
Lesson #1: donate your dive computer log files to DAN’s PDE.
In the first place, the biggest part of dives, being Tec or recreational or whatever, does not match the required basic quality criteria described above: they cannot be used for a proper statistical analysis. This yields even as well for the big DAN PDE database: neither the skin temperature nor the workload, nor complete biometrics are available. As well the DCS assessment is questionable. Normally, if there are Doppler readings these are not taken double-blinded. But, as we pointed out here in “YetAnother Benchmark, Part II” in Tech Diving Mag, Issue 12, p.9:
- It is a good starting point!
- And you have to start somewhere!!
- And you should contribute your log files to DAN’s data base!!!

In any case this is by much better than another data base, very often cited within papers, gloating about a DCS rate of 19 from 2,823 deep and multi-gas TEC-dives and thus trying to insinuate the safety of a certain undocumented decompression algorithm. There are no logfiles for public scrutiny and the input was obviously partly from
“wrist slates of seasoned divers”. This is just scientific garbage! So DAN’s idea to collecting the very details of the profiles via the DLT #7 file format directly converted from the dive computer logfiles is the only way out to get a broad data base where a ballpark of the inert gas dose could be re-evaluated even years later.

Lesson #2: question your extrapolations.  
(pls. cf. as well: Tech Diving Mag Issue 5, p. 41 - 53). What a normal desktop deco software or an implementation into a mixed gas dive computer does outside the safe and proven envelope is standing on statistically relatively thin and fragile leggies: but this is just, how the algorithm works with larger values! Resilient data from longer and deeper mix gas dives with a lot of O2-deco is still missing. And resilient means: not just anecdotal experience from one TEC dive which was successful. But you probably want to know, where along the P(DCS) curve your deco-software or your dive computer puts you! [8]

Lesson #3: monitor your dives / your DCS outcomes.  
That is: do Doppler measurements after all your dives, record the profiles along with your settings (e.g. gradient factors and the like) with your measurements and your self-assessment.

Lesson #4: caveat boundaries!  
There is no way of extracting a useful deco procedure from a pool of data, when yours does not match the decompression procedure or the inert gas dose! Do not even try! Or you have to accept, that doing dives like the record dives Mark Ellyatt once did [9], will put your P(DCS) in close proximity to 1.

Lesson #5: mistrust small numbers!  
That is, do not believe in publications, relying on small numbers of divers / dives. A couple of years ago there have been rumors concerning cancer-markers (biochemical traces in the blood, resulting from growing of ill-behaving cells) found after EAN-dives. Here we had the usual problem, that this study covered only a handful of divers, doing just a couple of dives: the error margins have been exceeding the original values.

Lesson #6: (the bitter pill for people like us).  
We should not sell NDLs. At least not in the careless way it is done by a couple of diver training agencies and dive computer manufacturers.

**Finale furioso**

If the intro did not beam you away, well, then, here is the last, a personal one: during our Guinness world record of underwater indoor cycling (yep, we did that, 12 years ago) we made 9 dives on air to 8.5 meters (ca. 27 feet in warm fresh water) in our diving tower. We stayed in teams of 3 divers there for exactly 60 min cycling on an underwater-ergometer (well, not so much, but ...), surfaced slowly, stayed approx. 3 to 5 min at 3 to 2 meters (10 to 6.6 feet) as a safety stop and had a surface interval of precisely 3 hours. So in the end this was a “near / sub-saturation” dive for 36 hours. In the background at the upper part of the little picture, near my air-bubbles, you could see our “deco-rig” hanging around in our diving-tower:
OK: no deco table and no deco-software from this mean ole’ world did call for these deco stops, not even the DCIEM table with all security features enabled. In the end, that is, around dive #6 and 7, nearly the complete team had various problems. And two divers had niggles and one a serious DCS Type I (me! (Being that time already the old grand-pa of the complete team). I took some normobaric O2 (and a couple of Aspirins®). And then I did something stupid but responded very well to re-compression: I did the dives #7, 8 & 9 with EAN36 and extending the deco stops to 10, then 15 and finally to 20 min with EAN60!).

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So, this is the very end of the series “Yet Another Benchmark” of 3 somewhat lengthy and “dry” articles. If you want to go through the mathematical details of the screen shots in “Yet Another Benchmark, Part II” in Tech Diving Mag, Issue 12, p. 7; pls. cf. as well there the detailed references to these sources. Here we are:

Method I; Southerland, p. 77, 78, 82; with:
Logit (DCS) = ln (P/(1-P)).
Logit (DCS) = -25.95 + 6.64 * Ln(Depth) + β2 * (Ln(Depth))^2 + 5.31 * Ln(Time) - 0.33 * (Ln(Time))^2 + β5 * Ln(Depth) * Ln(Time)
with: β2 = β5 = 0

Method II:
is an expanded PME Model. PME means: “Parallel Mono-Exponential” and has been developed during the middle 80’s based on ca.1,700 air dives. The thus calibrated parameters have been compared to 10,391 well-documented dives in the volume I of the NMRI/NEDU series “Statistically Based Decompression Tables”, p. 5-7 & p. 31. We have taken this thing and expanded it even further to 6 compartments and fitted the parameters to our helium dives.
Method III:
is a simplified integral over a risk function which we took from the
volume VI, “Statistically Based Decompression Tables”, p. 5 & p. 55.
For the fun of it, DIVE calculates the upper & lower error boundary
from the given standard deviations.

Method IV; NEDU TA 01-07 TR 04-41, p.8 & p. 11:
\[ \text{Logit(DCS)} = a + b \times (D - c) \times (1 - \exp(-d \times T \times f)) / (TDT - g) \]
with:
\[ a = -6.022169 \]
\[ b = 86.596315 \]
\[ c = 25.091718 \]
\[ d = 0.002929 \]
\[ f = 0.918547 \]
\[ g = -170.304442 \]
\[ D: \text{Depth (fsw)} \]
\[ TDT: \text{Total Decompression Time (min)} \]

Method V; NEDU TR 2009-03, p. 9, 11:
\[ \text{Logit (DCS)} = \beta_0 + \beta_1 \times \text{Ln(fsw)} + \beta_2 \times \text{Ln(Time)} + \beta_3 \times (\text{Ln(Time)})^2 + \beta_4 \times \text{Ln(Ascent Rate)} \]
with:
\[ \beta_0 = -53.0 \]
\[ \beta_1 = 7.97 \]
\[ \beta_2 = 3.32 \]
\[ \beta_3 = 0.04 \]
\[ \beta_4 = -0.03 \]

Literature cited
[1] UHMS ASM 2012, Session D71: Estimating DCS risk for Emergency Conditions; Paul K. Weathersby & Keith A. Gault. Naval Submarine Medical Research Laboratory, Groton CT and Navy Experimental Diving Unit, Panama City FL
For further reading
• the 51st. UHMS workshop: „Survival Analysis and Maximum Likelihood Techniques as applied to Physiological Modeling“, 1989
• „Logistic Regression and Decompression Sickness“, David Graham Southerland, Duke University, 1992
• „Statistical Bubble Dynamics Algorithms for Assessment of Altitude Decompression Sickness Incidence“, Gerth, W. A. & Vann, R.D., July 1995, Duke University Medical Center

Statistically Based Decompression Tables, an 11-volume series of papers from the NMRI
Naval Medical Research Institute, Bethesda, Maryland:
NMRI 85-17, Part II: Equal Risk Air Diving Decompression Schedules
NMRI 86-50, Part III: Comparative Risk using U.S. Navy, British, and Canadian Standard Air Schedules
NMRI 86-51, Part IV: Extension to Air and N2-O2 Saturation Diving
NMRI 89-34, Part V: Haldane-Vann Models for Air Diving
NMRI 91-84, Part VI: Repeat Dives on Oxygen/Nitrogen Mixes
NMRI 92-85, Part VII: Selection and Treatment of Primary Air and N2O2 Data
NMRI 92-73, Part VIII: Linear-Exponential Kinetics
NMRI 96-05, Part IX: Probabilistic Models of the role of Oxygen in Human Decompression Sickness
NMRI 96-06, Part X: Real-Time Decompression Algorithm using a probabilistic Model
NMRC 99-01, Part XI: Manned Validation of the LE Probabilistic Model for Air and Nitrogen-Oxygen Diving

Private comments on the above listed sources I —> XI
Part I:
Table 9 (p. 37) features DCS incidences during operational use of the USN 1957 Table, depths from 100 to 300 feet, bottom times from 10 to 50 min. From 10.391 dives there are 83 cases of DCS. The reported incidence range within the CI goes from 0.1 up to 4.6 (eg. at 200 feet). The problem with “operational use” is that there is only a written log of the dive. So the time & depth recordings in the logs are somewhat “creative” (i.e. irreproducible). Part II:
Fig. 5 (p. 14) features a graph of the “Risk Surface” for a certain dive. The trough of the 3-dimensional hyperbola shows the optimum distribution of stop times at various depths, thus minimizing the calculated P(DCS).
Part III:
states on top of p. 1: “... if no cases (of DCS) were seen in a trial with 10 divers, the 95% confidence limits still allows an actual incidence of 31 % DCS. A single case in a 30 man trial could come from 0.1 to 17 %underlying incidence. Hundreds of replicated dives are needed for greater precision.” Part V:
on p. 3, Table 1, describes their decompression data sets A, B, C, D & L. These are covering 1.835 dives with 101 cases of DCS and a range of 1.3 to 45.7 % DCS.
Part VI:
features a good mathematical overview on the whole subject.
Part VIII:
gives a nice overview on the LE models (linear - exponential), on Table 5 (p. 48) is a summary of the used data sets: 5 risk categories in 2.5 % intervals, for eg. with 2.383 dives and 139 observed cases for DCS for the 0-model. The 0-model comes with a predicted # DCS of 139 cases, but unevenly distributed along these categories. On Table 7 (p. 50) the data sets NOT used for modeling with 1.985 dives and a DCS range from 1.0 —> 21.3 % DCS.