PROCEEDINGS

DECOMPRESSION AND THE DEEP STOP

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DECOMPRESSION AND THE DEEP STOP WORKSHOP OVERVIEW

Theoretical and practical solutions as to how to ascend or decompress after diving have been considered since Haldane some 100 years ago, yet decompression sickness (DCS) still occurs. The traditional "Haldanian" approach to planning decompression has been to limit supersaturation (the difference between tissue inert gas tension and ambient pressure) according to empirically derived rules that purportedly maximize gradients for inert gas washout and therefore provide a low risk of DCS. The use of Doppler to monitor the central venous circulation, however, shows this approach still frequently results in bubble formation. Other more recent decompression theories have relied on so called "bubble models" which focus on prevention of such bubble formation. To do this, the algorithms limit supersaturation more aggressively and typically result in the imposition of deeper decompression stops. These have been used quite successfully for many years by technical divers for deep diving. In recent years, the utilization of a deep stop by recreational scuba divers at depths less than 130 fsw (41 m) also has been proposed. This is now appearing in dive computers using "bubble models" such as Varying Permeability or the Reduced Gradient Bubble Model or the Half the Depth Model. Some training agencies have also incorporated deep stops into their training regimens. However, there is debate as to when to stop, for how long and how often in regard to whether such a deep stop does limit bubble growth or ameliorate the risk of DCS. This workshop has brought together the most active international individuals with practical human data, animal research and theoretical concepts to help clarify the role of "deep stops" in contemporary recreational scuba and technical diving, and to point out what we know as well as indicate future research needs.

INTRODUCTION TO THE PROGRAM

Peter B. Bennett

By way of starting, we have three chairs -- co-chairs, Bruce Wienke, Simon Mitchell, and myself. We'll each take different sections of the program. I want to, first of all, explain why we're having the workshop.

The workshop on decompression and deep stop came about really as a result of my going to the Navy review and hearing what was going on with the Navy deep stop and being aware of our own work with the Italian divers, with IDAN, and also aware of the French work and other deep stop work.

I felt that deep stop actually is many things. Quite a lot of people, with the controversy surrounding deep stop, say, "I don't believe in the deep stop." I would say, "Which deep stop?" Because deep stop is many things. We will hear over the next two days that there are, in fact, at least three types of deep stop which will be discussed. We will see where we come to a conclusion. I hope for a definition of the deep stop for those three so that we don't get confused in the future and use "deep stop" as a word meaning many things which, in fact, is not quite true.

Decompression sickness remains a problem in diving. Theoretical and practical solutions for decompression have been considered over 100 years, but decompression sickness still occurs. This workshop has brought together the most active international individuals with theoretical, animal and human data to help understand deep stop decompression methods towards reduced risk of decompression sickness and point to future research.

The workshop allows comparison of theoretical and practical data from three major groups with different content; that is, technical diving use of the deep stop, naval use of the deep stop, recreational diving use of the deep stop and research projects.

Technical divers tend to dive very deep and calculate their own deep stop decompression procedures, apparently with little or no decompression sickness. The Navies have tested deep stop decompression procedure in divers with decompression sickness.

The recreational diving researchers have tested human divers at less deep depths, indicating very low Doppler bubble scores, with the deep stop and low decompression stress.

The U.S. and French Navies use of a deep stop during decompression has produced some severe decompression sickness. Technical diving groups have been very successful with this method of decompression and from deep dives. The recreational diving research has shown very low Doppler bubble scores with deep stop, indicating low decompression stress.

These conflicting results have resulted in a consensus of Navy and technical diving and recreational diving organizations to clarify use of a deep stop. For example, the U.S. Navy research had to stop expensive research on the deep stop due to severe decompression sickness.

Technical divers maintain they have no problems, and IDAN recreational diving research has led to major recreational diving agencies adopting a deep stop for all recreational divers worldwide.

After this workshop, these organizations will have the best available information on the use of a deep stop. This may help to explain the Navy problems and point to the evidence in support of a deep stop for technical and recreational divers. Overall, this should help reduce the incidence of decompression sickness in divers and more information on its mechanisms.

To that end, I'd like to thank our supporters of the workshop, the Office of Naval Research of the U.S. Navy (ONR), the Divers Alert Network (DAN), National Association of Underwater Instructors (NAUI worldwide), International Association of Nitrox and Technical Divers (IANTD), Professional Association of Diving Instructors (PADI) and you, the attendees. Any individuals who have a financial relationship, which may provide a conflict of interest, have been disclosed in the program abstracts for CME Accreditation.

This workshop is going to be recorded, so, be careful what you say. This is a controversial area, don't get carried away. Kim Farkas, the court reporter, is very skilled as you know from the technical diving workshop and she will record everything that you say. We hope to have the proceedings published within six months or less, including the discussions.

Please try to keep to your times. We do have a lot of discussion time, so we do have some leeway, but we won't be too severe on you if you have a really long paper. Please try to keep to your time where you can. In the discussions, please use the microphone. Don't stand up from the floor. And, please, I know it's very difficult, this is very important, state your name clearly and where you come from every time you speak. Kim needs to know who you are and who you're representing when you speak.

I think we will then move to the first speaker, which is Tom Neuman. We selected Tom because he had been inadvertently looking at the deep stop for some Navy research, quite a long time ago. It was an indicator perhaps that something had to be done to look at deep stop in the future, which has been done, as we will hear.

EARLY OBSERVATIONS ON THE EFFECT OF "DEEP" DECOMPRESSION UPON DOPPLER ULTRASONIC BUBBLE SIGNALS FOLLOWING 210/50 AND 170/30 DIVES

Tom Neuman

ABSTRACT:

The problem of whether "deep" decompression stops add significantly to the safety of a given decompression profile is a difficult one. Ultimately of course, this is a question that must be addressed empirically; however any studies involving decompression sickness are fraught with a variety of problems. Control groups, blinding, and the selection of an appropriate endpoint are some of the difficulties confronting any group attempting to address these issues.

In the middle 1970's the US Navy had specific operational objectives that required a number of dry chamber dives to 210 FSW for 50 minutes on air and to 132 FSW for 30 minutes, using a normoxic nitrogen/oxygen mixture. At that time, we were able to make some unique observations concerning the decompression profiles used for those dive. The original intent of these experiments was to validate the reliability of Doppler ultrasonic bubble detection methods; however we were also able to make observations relating to the effect of "deeper" decompression stops upon bubble scores. For these dive profiles there was a significant reduction in bubble score associated with a short "deeper" stop, independent of overall decompression time. It is however premature for these results to be extrapolated across the continuum of diving exposures or across the range of decompression algorithms that currently are used to calculate decompression tables. These results may be solely a consequence of the use of the model that generated the decompression profiles used in these dives.

PAPER:

Since the publication of our paper relating to the effect of "deep" decompression stops upon the efficiency of decompression and the changes in Doppler Bubble Scores associated with those stops[1] a great deal has been learned about decompression sickness, bubble detection and the diagnosis of decompression sickness. It is therefore appropriate that the results of those studies (now more than 30 years old) are put into the context of more modern understanding of decompression sickness, bubble detection and the diagnosis of decompression sickness.

Before we begin to work on some of the scientific problems associated with any study concerning decompression sickness and specifically the role that deeper stops may play in its prevention, we must discus terminology briefly. Over the past several years, there has been a trend to use a descriptive nomenclature to describe dysbarism. This nomenclature is symptom based and describes all forms of decompression disorders as decompression illness. The different disorders are not classified by the underlying physiological process that produce the symptoms, but rather by the actual symptoms produced. For the purposes of this workshop, this nomenclature is not only not useful it is misleading and counter productive. When one is trying to evaluate the effect of any intervention on the incidence of DCS, a case of barotraumatic AGE is "noise" since it is unrelated to the exposure profile. Therefore we must be quite careful with terminology and make sure we understand that the only clinical entity of significance to this workshop is DCS or a surrogate for DCS.

In order to assess the efficacy of any intervention upon the incidence of decompression sickness, one first must be able to diagnose decompression sickness. This unfortunately is not as easy as it may at first appear. Aches and pains unassociated with DCS are a common occurrence in every day life. It is therefore always a possibility that a given ache or pain is due to the exertion of a dive rather than from decompression sickness. Thus in any study that purports to have an incidence of DCS, a certain percentage of the cases will be unrelated to DCS at all. Similarly vague "tinglies" are also common complaints in the every day practice of medicine. Patients are often seen in the Emergency Room complaining of numbness in this part of their body or that. Then of course there are the individuals that one could refer to as the "worried well." These are divers who violated one inconsequential rule or another and are manifesting symptoms (often vague neurologic symptoms) that have no basis in neuro-anatomy and simply cannot be an organic problem. Thus every time the diagnosis of DCS is made there is a finite probability of unknown magnitude that the diagnosis will be in error and that the individual has something else entirely. In the jargon of "med speak" these cases are called "false positives". (False negatives on the other hand are individuals who do have DCS but in whom some other diagnosis is made. For the purposes of evaluating decompression tables this is much less of a problem than the problem of false positives.). The percentage of false positives is of course not based upon the "severity" of a dive profile or for that matter any pathophysiologic process related to decompression or decompression sickness. It is noise that always exists in background when a physician is trying to make a diagnosis. False positives are particularly troubling in the setting of a low overall incidence of disease. For example, let's assume that a stress EKG is associated with an incidence of false positives on the order of 1%. That may seem like a low number, but if the population that is being screened has a prevalence of disease on the order of .01%, then a stress EKG is not really a useful test. A fighter pilot getting a stress EKG's (as a routine test, without symptoms) to rule out occult coronary artery disease is a perfect example of this kind of problem. Assuming those numbers are correct (they are not but rather just examples), for every 100 "positive" stress EKG's you would only find one person who really did have occult CAD. On the other hand if you use that test as a screening device for 55 year old males with exertional chest pain, where the prevalence of CAD is high (say 50%), then a false positive rate of 1% is quite acceptable.

Fortunately for our subjects, when we actually do manned tests of decompression tables, the incidence of DCS is quite low and hence real consideration must be made to the effect of "false positives" upon the interpretation of our data. There are two general ways to account for the effect of false positive diagnoses. The scientifically best way to deal with the problem is by the use of a methodology called a double-blinded prospective trial. So, for example, if one were to try to examine the effect of oxygen pre-breathing on the incidence of DCS associated with a decompression equivalent to an EVA from the space shuttle, the best way to "test" the effect of false positives on the data set would be to run both a control group and an experimental group. The experimental group would pre-breathe oxygen and then be taken to the "exposure" altitude. The MD's running the test and responsible for making the diagnosis of DCS would be unaware of the altitude to which the subjects were being taken, as would the tenders and the subjects. The control group would also pre-breathe in exactly the same manner, but they would be taken to an altitude unassociated with DCS. Once again they would be unaware of the altitude to which they were being taken and the MD's supervising the diagnosis of cases of DCS would also be unaware of the actual altitude. The number of times the diagnosis of DCS was made in the experimental group would then be compared to the number of diagnoses made in the control group and in that way the "true" incidence of DCS could be better ascertained. The problem with this approach of course is that if the incidence of DCS is low, then it will take very large numbers to determine whether or not a given protocol confers a functionally adequate safety margin.

It is now important to go over the meaning of the terms "specificity" and "sensitivity" in the setting of a medical experiment. Sensitivity is the ability of a test to find individuals in a population with a given condition. Thus one way to find all cases of colon cancer in a population would be to take out everyone's colon. This is a highly sensitive method of testing for colon cancer, but in most circumstances not very useful. Specificity is the ability to correctly identify an individual with a given condition in a population. Sensitivity and specificity are "yin and yang." As one goes up, the other goes down. This is not Burger King and you can't "have it your way."

Now let's get back to the problem at hand. An alternative method of dealing with the problem of false positives would be to define the symptoms that would produce a diagnosis of DCS before the study began. Such a definition, of course, would best be highly specific. Unfortunately as specificity goes up, sensitivity goes down and we would by necessity then miss a number of borderline cases. That may or may not be an acceptable situation depending upon the risks of the operational development of DCS. This underscores to a small degree the difficulties associated with either creating a case definition of DCS or trying to study DCS without a suitable control group.

Unfortunately, no sizable studies have been done in either of these fashions and thus you must be extremely suspicious of the true incidence of disease whenever anyone reports an incidence of DCS that is relatively low if the impact of false negative diagnoses have not been factored into the analysis. You must also be careful of any study that has a high incidence of DCS when the degree of exposure (i.e. "decompression stress") is low.

If assessing the incidence of DCS in a given series is fraught with either insurmountable theoretical or practical problems, is there then a surrogate that one could use to assess whether a dive produces more or less decompression stress than another dive. Immediately Doppler bubble detection leaps to mind. But Doppler detection is also a methodology that has its limitations. First and foremost there is no clear-cut predictive value to a given Doppler score. Clearly the higher the bubble grade the greater the likelihood of DCS, but a grade of IV on the Spencer scale does not mean that DCS will occur and a grade of 1 does not mean that DCS will not occur. Whether this just is a manifestation of the lack of a true relationship between bubble scores and DCS, whether it is a sampling error, or whether it represents an error of interpretation is not clear. An additional issue with the interpretation of bubble scores is the inter-person (will two different people get the same result listening to the same event?) variability in grading as well as the intra-person variability (will the same person get the same result at different periods of time?). Finally will knowledge of the dive profile by the interpreter influence the interpretation?

Recording the Doppler signals and having them evaluated at a different time by an interpreter unaware of the profile or the time in the profile from which the recordings were made easily deal with the latter problem. The former problems are not as easily dismissed.

Thus at the present time there is no simple way to easily define the effect of any given intervention on the incidence of DCS and therefore it is important for the diving community not to get prematurely enamored with a methodology that ultimately may not turn out to be useful. All too often scientists have made pronouncements about this or that only to be forced to retract those edicts when a better study refuted their work.

This of course brings us to the study that is to be presented at this workshop. It too is limited by some of the difficulties alluded to previously. On the other hand, some of the problems were lessened by the dive profiles we used and others were mitigated by the use of blinding. First and foremost we were diving people on a schedule that had only been calculated and had never been tested. At the time we did the work, the Naval Experimental Diving Unit estimated the incidence of DCS on these tables that would approach 30%. Thus a small percentage of false positive diagnoses of DCS should not have influenced our results in a quantitatively important fashion. More to the point however was that the measurement of interest that we were making was that of Doppler signals and not clinical DCS. For this study we did blind the interpreter of the Doppler recordings to the profile, the point in the profile and whether in fact a given subject was diving or a topside tender. To put it in it's simplest terms, we coded each recording and then interspersed divers with tenders and divers in their decompression phase with the same person a day later or a day previously. Thus the interpreter of the Doppler signals had to take each individual recording in an isolated fashion and interpret the signal without any external clues concerning what he "thought" the signal should be based upon the place or time of the dive or the previous signal.

With that rather lengthy preamble, let us now discuss the study published previously and it's possible meaning to this group.

Because of some very specific operational needs, the Navy was in a situation where some rather deep and somewhat lengthy dives had to be made. We decided that these dives would be an excellent opportunity to see if blinded Doppler interpretations correlated well with the stage of decompression.

The first series were dives to 210 FSW for 50 minutes. These dives had a compression rate of 75 feet per minute, a bottom time of exactly 50 minutes and an ascent rate of 60 feet per minute. They were performed in a dry chamber environment. There was minimal physical work associated with the time on the bottom. Three different decompression profiles were used. The majority of the subjects were decompressed on a US Navy Extreme Exposure 210/50. This schedule provided 175 minutes of decompression starting at 60 FSW. The second group (three subjects) received an extra 3 minute stop 10 FSW deeper than the initial 60 foot stop for a total of 178 minutes of decompression time. The final group (also of three subjects) was decompressed on a 220/50 which provided 190 minutes of decompression also beginning at 60 FSW. This occurred because at the time of the initial compression of this group an inlet valve on the chamber froze open. As a result these individuals were compressed for 10 seconds to 215 FSW before being returned to 210 FSW. According to the Navy requirements the deeper schedule was required in these circumstances. Thus we had three groups of divers, all making essentially the same dive. One group received exactly the decompression required by the model, another group received three minutes of extra decompression time at an initial depth deeper than required by the decompression algorithm, and the third group received 15 minutes of additional decompression time at the same depths required by the model. The decompression times for the different groups are shown in Table 1.

Table 1
Decompression Times from 210/50

		Depth of Decompression Stop from 210 FSW							**TDT**
Group		**70**	**60**	**50**	**40**	**30**	**20**	**10**	
		Minutes of Decompression							
A			1	9	17	19	45	80	175
B		3	1	9	17	19	45	80	178
C			3	12	17	18	51	86	190

Before, during, and after these diving evolutions all the subjects were monitored with a Doppler bubble detector. Recordings of these monitoring episodes were made and then coded in a random fashion. The recordings were then shipped to the Institute for Applied Physiology in Seattle, where Dave Johansson interpreted the recordings. He had no knowledge of where in the profile the recordings were taken, whether the recordings were from control periods or dive periods, which subject was involved or which decompression profile was used. The results of the interpretations of the recordings were then returned to us and the results were decoded.

The bubble scores of the 210 foot dive series are represented graphically in Figure 1 and can be seen as raw data in Table 2

Figure 1
Bubble Scores During Decompression from 210/50

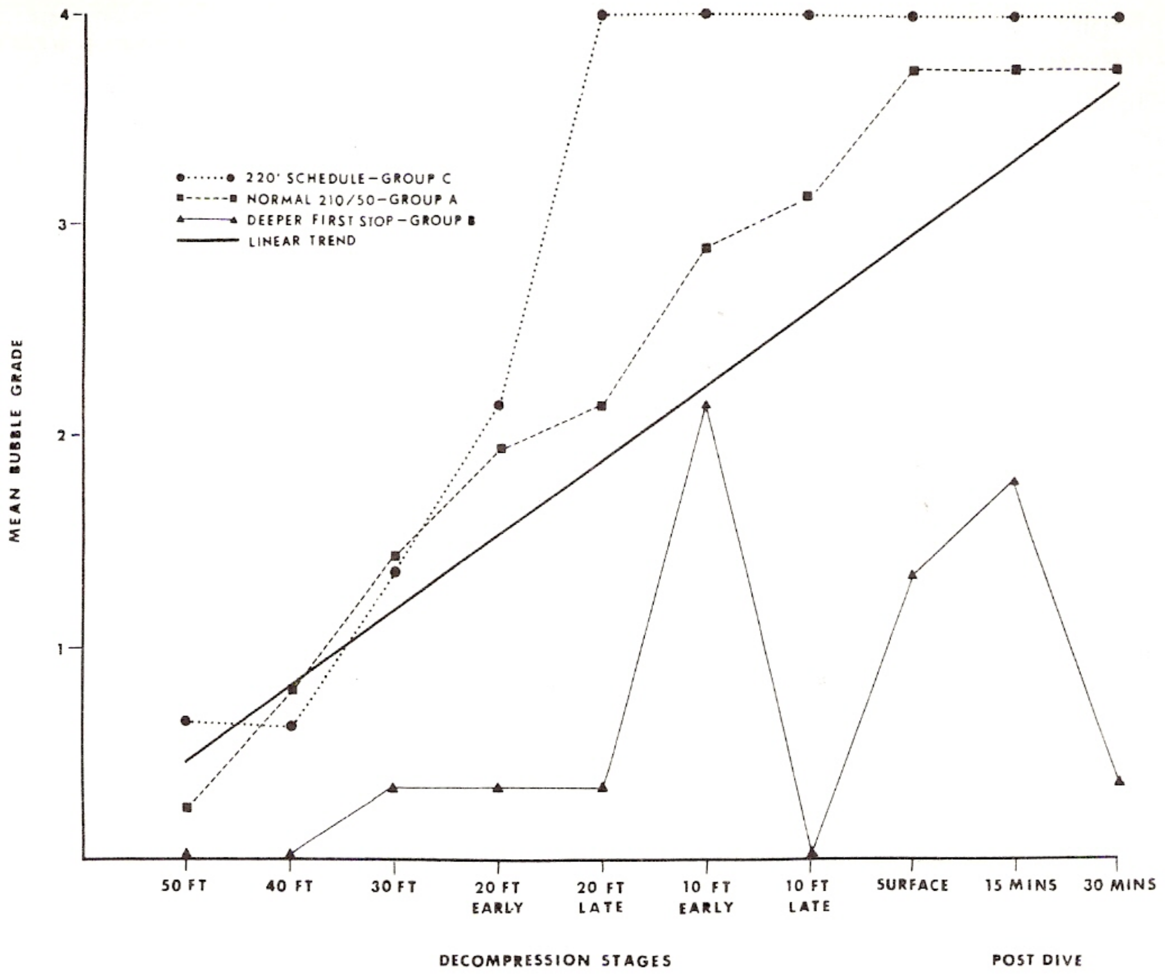
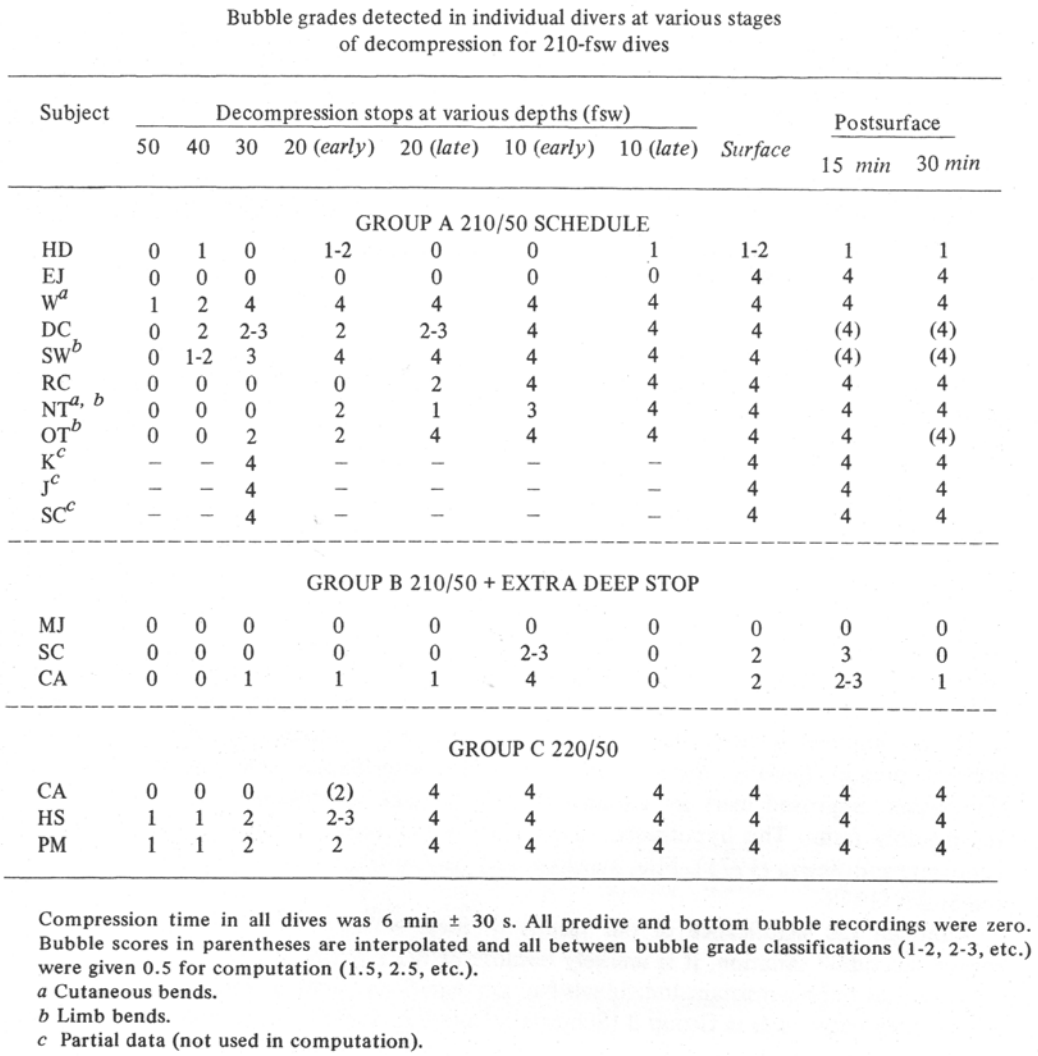


Fig. 1. Mean bubble grades during decompression and postdecompression for three groups following a 210-ft dive.

Table 2
Raw Bubble Scores During Decompression from 210/50



Bubble grades detected in individual divers at various stages of decompression for 210-fsw dives

Subject	Decompression stops at various depths (fsw)							Surface	Postsurface	
	50	40	30	20 (*early*)	20 (*late*)	10 (*early*)	10 (*late*)	*Surface*	15 *min*	30 *min*
				GROUP A 210/50 SCHEDULE						
HD	0	1	0	1-2	0	0	1	1-2	1	1
EJ	0	0	0	0	0	0	0	4	4	4
W[a]	1	2	4	4	4	4	4	4	4	4
DC	0	2	2-3	2	2-3	4	4	4	(4)	(4)
SW[b]	0	1-2	3	4	4	4	4	4	(4)	(4)
RC	0	0	0	0	2	4	4	4	4	4
NT[a, b]	0	0	0	2	1	3	4	4	4	4
OT[b]	0	0	2	2	4	4	4	4	4	(4)
K[c]	–	–	4	–	–	–	–	4	4	4
J[c]	–	–	4	–	–	–	–	4	4	4
SC[c]	–	–	4	–	–	–	–	4	4	4
				GROUP B 210/50 + EXTRA DEEP STOP						
MJ	0	0	0	0	0	0	0	0	0	0
SC	0	0	0	0	0	2-3	0	2	3	0
CA	0	0	1	1	1	4	0	2	2-3	1
				GROUP C 220/50						
CA	0	0	0	(2)	4	4	4	4	4	4
HS	1	1	2	2-3	4	4	4	4	4	4
PM	1	1	2	2	4	4	4	4	4	4

Compression time in all dives was 6 min ± 30 s. All predive and bottom bubble recordings were zero. Bubble scores in parentheses are interpolated and all between bubble grade classifications (1-2, 2-3, etc.) were given 0.5 for computation (1.5, 2.5, etc.).

a Cutaneous bends.
b Limb bends.
c Partial data (not used in computation).

In addition to the above series a second series of dives was conducted. In this second series subjects breathed air for compression to 132 FSW. When the subjects reached the bottom, the breathing mix was changed to normoxic nitrox for a total bottom time of 30 minutes. For approximately ½ of the bottom time of this dive, light to moderate physical exertion took place. Decompression was accomplished on air using a 170/30 schedule, which was the equivalent air depth for this dive. Once again two divers received an additional 2 minutes of decompression time 10 feet deeper than required by the standard air 170/30 table. The decompression times for the two groups can be seen in Table 3.

Table 3
Decompression Times from 170/30

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		Depth of Decompression Stop from 170 FSW				TDT
Group		**40**	**30**	**20**	**10**	
		Minutes of Decompression				
D			4	13	26	46
E		2	4	13	26	48

The bubble scores of the 132 foot dive series can are represented graphically in Figure 2 and the raw data are seen in Table 4.

Figure 2
Bubble Scores During Decompression from 170/30

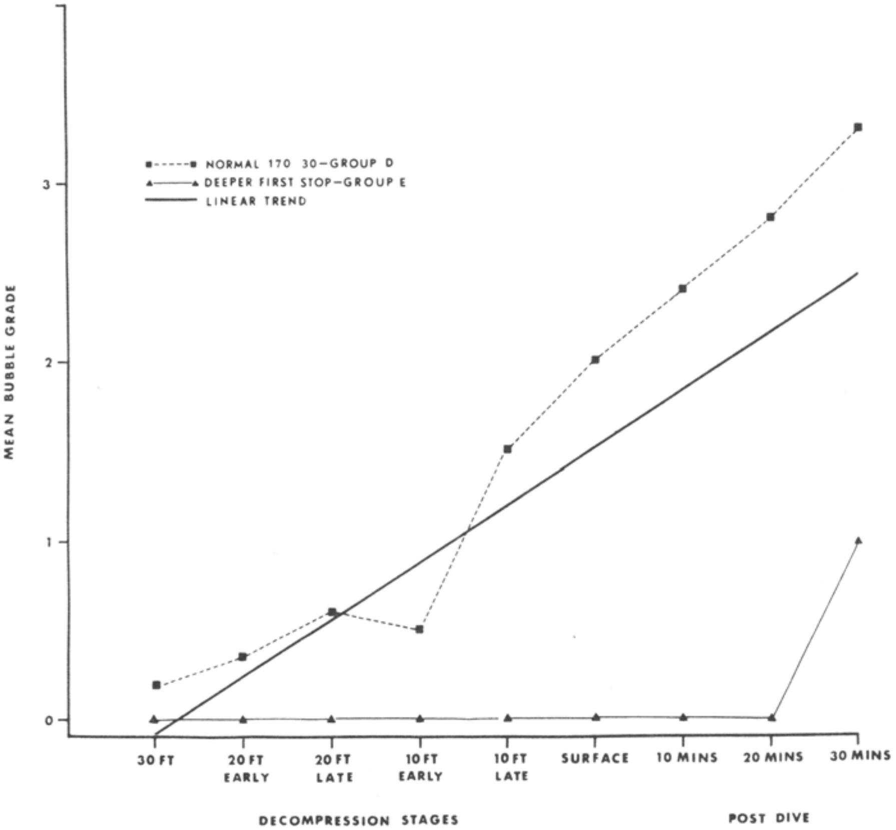
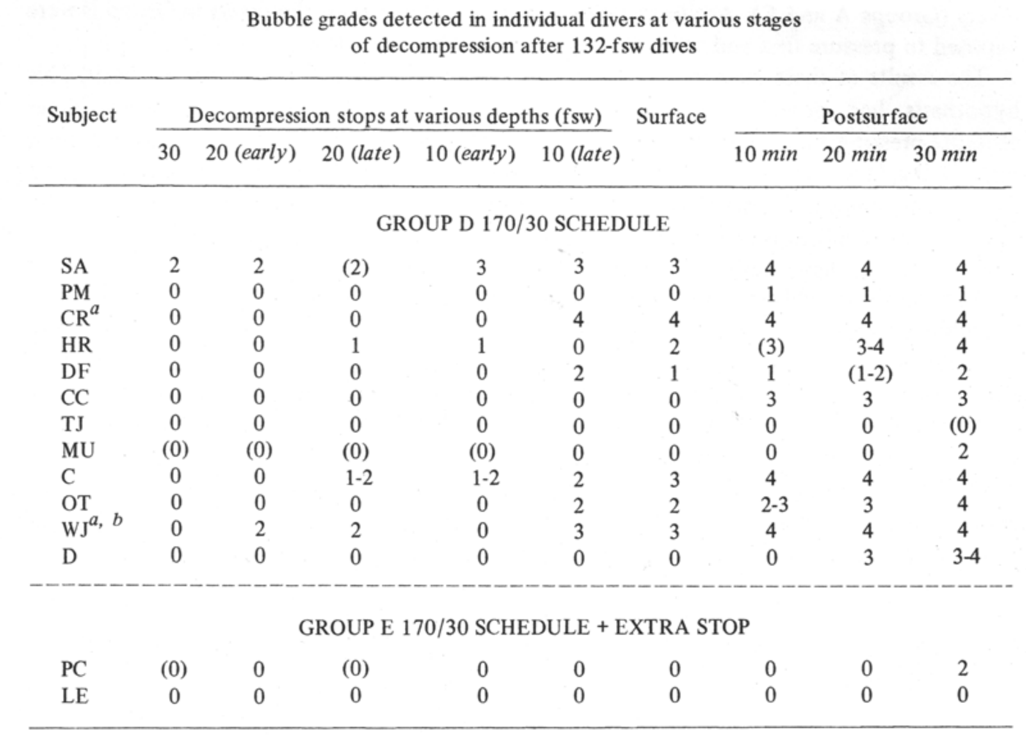


Fig. 2. Mean bubble grades during decompression and postdecompression for two groups following a 132-ft dive.

Table 4
Raw Bubble Scores During Decompression from 170/30



Bubble grades detected in individual divers at various stages
of decompression after 132-fsw dives

Subject	Decompression stops at various depths (fsw)					Surface	Postsurface		
	30	20 (*early*)	20 (*late*)	10 (*early*)	10 (*late*)		10 *min*	20 *min*	30 *min*
GROUP D 170/30 SCHEDULE									
SA	2	2	(2)	3	3	3	4	4	4
PM	0	0	0	0	0	0	1	1	1
CR[a]	0	0	0	0	4	4	4	4	4
HR	0	0	1	1	0	2	(3)	3-4	4
DF	0	0	0	0	2	1	1	(1-2)	2
CC	0	0	0	0	0	0	3	3	3
TJ	0	0	0	0	0	0	0	0	(0)
MU	(0)	(0)	(0)	(0)	0	0	0	0	2
C	0	0	1-2	1-2	2	3	4	4	4
OT	0	0	0	0	2	2	2-3	3	4
WJ[a, b]	0	2	2	0	3	3	4	4	4
D	0	0	0	0	0	0	0	3	3-4
GROUP E 170/30 SCHEDULE + EXTRA STOP									
PC	(0)	0	(0)	0	0	0	0	0	2
LE	0	0	0	0	0	0	0	0	0

As can be seen there are dramatically reduced bubble scores in the groups who received an "extra" deep decompression stop. These differences are statistically significant. In addition there were no cases of DCS in the individuals who received an "extra" deep decompression stop. In the 210 foot series there were no cases of DCS in the group receiving the additional decompression time (i.e. the 220/50 schedule), however their Doppler bubble scores were not significantly different from those on the 210/50 schedule. There also were no statistically significant differences in the bubble scores of the individuals who developed DCS and those that did not in Group A of the 210/50 foot series.

Before immediately concluding that a deeper stop is better for an individual it is worth considering the real limitations of this study. First and foremost one must remember that merely because a "deep" first stop appeared to be beneficial in the setting of these dives, it is by no means assured that such a deep stop would be beneficial in other settings. These dives were decompressed according to a Haldanian "log-in/log-out" model that was calculated but never tested for the 210 FSW series. It is not clear that the results of this study can be extrapolated to shallower (or for that matter deeper) dives of different durations decompressed using a different model. Another limitation of course is that the differences between subjects that were significant were decreases in bubble score. Although it is tempting to assume that such differences can be translated into a decreased incidence of DCS, unfortunately, as likely as that may be, we cannot predict the onset of DCS by bubble scores and as a result that is a piece of the puzzle that is still missing.

What I think can be said, is that seemingly small changes in decompression procedures can have a significant effect upon bubble scores, and by inference, perhaps decompression sickness. Furthermore, where in the decompression these stops are made can also have what appears to be a meaningful effect upon bubble scores and again by inference decompression sickness.

It is on the basis of work like this that the notion of safety stops developed. Although I am a firm believer in the utility of safety stops, I am not sure that the depth of the safety stop plays any role above and beyond the requirement for control of one's ascent and of course the additional decompression time. Ultimately the final analysis of whether a deeper decompression stop offers more protection to a diver from DCS than merely prolonging the decompression for a similar amount of time will require much more manned testing, however for these deep and moderately long air dives, a deeper stop than those mandated by the US Navy, Haldanian, "log-in/log-out" model appears to offer the likelihood of reduced bubble scores and possibly decompression sickness. One must be careful not to extrapolate the results of these studies to different profiles (using this model of decompression) or to extrapolate these findings to different decompression profiles that are developed by using different models.

Reference

1. Neuman TS, Hall D, Linaweaver PG: Gas phase separation during decompression in man: Ultrasound monitoring. Undersea Biomed Res 1976;3(2):121-130

LANL DEEP STOP DATA BANK AND DUAL PHASE BUBBLE MODEL FOR PROFILE ANALYSIS AND RISK

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ABSTRACT:

Linking model and data, we detail the LANL reduced gradient bubble model (RGBM), dynamical principles, and correlation with data in the LANL Data Bank. Table, profile, and meter risks are obtained from likelihood analysis and quoted for air, nitrox, helitrox no-decompression time limits, repetitive dive tables, and selected mixed gas and repetitive profiles. Applications include the Bennett and Marroni 2.5 minute recreational deep stop, early Duke experiments with helium and deep air switches, 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 rebreather (RB) exploration dive, world record open circuit (OC) dive, andWKPP extreme cave exploration profiles. The algorithm enjoys extensive and utilitarian application in mixed gas diving, both in recreational and technical sectors, and forms the bases for released tables and decompression meters used by scientific, commercial, and research divers. The LANL Data Bank is described, and the methods used to deduce risk are detailed. Risk functions for dissolved gas and bubbles are summarized. Parameters that can be used to estimate profile risk are tallied. To fit data, a modified Levenberg-Marquardt routine is employed with $L2$ error norm. Appendices sketch numerical methods, and list reports from field testing for (real) mixed gas diving. A Monte Carlo sampling scheme for fast numerical analysis of the data is also useful, as coupled variance reduction technique and additional check on the canonical approach to estimating risk. Supercomputing resources are used. This work attempts a (needed) correlation between global mixed gas diving, specific (bubble) model, and (deep stop) data. The whole issue of deep stops and staging is one of timing, with questions of time and depth at deep stops possibly addressed optimally within consistent model and ranging data frameworks.

PAPER:

Introduction

Within model and data parameters, we sketch the LANL reduced gradient 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. Application 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*, 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 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 is employed for application and correlation of model and data.

The systematics of gas exchange *[11,14,39,45,59,79]*, nucleation *[3,4,14,29,31,42,71]*, bubble growth *[7,11,28,66,71,90]* and elimination *[22,26,50,54,55]*, counterdiffusion *[40,45,46,82,89]*, oxygen impact *[10,16,34,35,51,52,72]*, and adaptation *[12,13,22,29,30,36,41,48]* upon diving decompression staging *[9,15,19,21,23-27,30,34-36,39,44,49,57,61-64,68-70,86,90]*, and attendant altitude modifications *[5,16,27,39,70,77]* are so complicated that theories only reflect pieces of the puzzle. Computational algorithms, tables, and manned testing are, however, requisite across a spectrum of activities. And the potential of electronic devices to process tables of information or detailed equations underwater is near maturity, with virtually any algorithm amenable to digital implementation. Pressures for even more sophisticated algorithms are expected to grow.

Still computational models enjoy varying degrees of success or failure. More complex models address a greater number of issues, but are harder to codify in decompression tables. Simpler models are easier to codify, but are less comprehensive. Some models are based on first principles, but most are not. Application of models can be subjective in the absence of definitive data, the acquisition of which is tedious, sometimes controversial, and often ambiguous. If deterministic models are abandoned, statistical analysis can address the variability of outcome inherent to random occurrences, but mostly in manner indifferent to specification of controlling mechanisms. The so called dose-reponse characteristics of statistical analysis are very attractive in the formulation of risk tables *[5,69,70,73-75]*. Applied to decompression sickness incidence, tables of comparative risk offer a means of weighing contributing factors and exposure alternatives.

With quantitative relationships, we underscore the reduced gradient bubble model *[76-79]* on dynamical principles, and then its statistical correlations. Both dissolved gas and bubble risk functions are described and parameterized from data in the LANL Data Bank. 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 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, Zeagle, Steam Machines, Underwater Technologies, Mares, Dacor, Suunto, Plexus, and other players. Commercial RGBM software includes GAP, ABYSS, and HydroSpace EXPLORER Simulator. All have exhibited safe and efficient operation from diving perspectives.

Our intent is to cover aspects of the RGBM not detailed in earlier publications. To this end, we have been collecting mixed gas, deep stop, decompression data in the technical diving arena. This is necessary for model and data correlation, that is, most existing data is based on the shallow stop paradigm required by dissolved gas (tissue content) models, thus predominant versus deep stop data. Deep stop data is valuable, within the RGBM, as well as all other bubble (dual phase) models requiring deep stops algorithmically. While our data is broadbased, we have been able to extract correlation parameters, plus estimate some table, meter, and profile risks. Data collection continues across the gamut of technical, scientific, and research diving.

The breakdown of topics in order is:

Conventions
Reduced Gradient Bubble Model Synthesis
LANL Profile Data Bank
Probabilistics
LANL Data Correlations And Risk Estimators
Logarithmic Likelihood And Significance
Nonstop And Repetitive Air Diving
Recent Doppler And Wet Test Analyses
    Bennett And Maronni 2.5 Minute Recreational Deep Stop
    C & C Team 450/20 Multiple RB Dive Sequence At 1.4 atm
    NEDU Deep Air Stop Air Tests
    French Navy Deep Stop Schedules
Gas Transport Analysis
Table, Meter, And Profile Risk Analyses
    UW Seafood Diver Air Tables
    NAUI Air And Nitrox Recreational Tables (sea level - 10,000 ft)
    Helitrox Nonstop Limits (NDLs)
    Comparative Helium And Nitrogen Staging And Risk
    WKPP Extreme Exploration Dives
    Record OC Trimix Dive
    HydroSpace EXPLORER Extreme RB Profile
    USS Perry Deep RB Wreck Dives
RGBM User Overview And Statistics
    Decompression Meters
    Software
    Training Agencies
    Tables

Conventions

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,

$$10\ msw = 33.28\ fsw = 1\ atm$$

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 precentage 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.

Reduced Gradient Bubble Model Synthesis

The RGBM employs a phase volume *[38,85,90]* constraint across the dive profile, tracking excited bubble volumes over the dive. Bubble structures are represented by flexible seed skins with appropriate material properties, permeable to gas diffusion at all pressures and temperatures. Gas diffuses across the bubble interface, and the bubble is subject to Boyle expansion-contraction. The phase volume is an estimate of the cumulative volume of bubbles left at the surface after arbitary depth-time exposures on any diving breathing mixture. Mixtures can be nitrox (oxygen and nitrogen, including air), heliox (oxygen and helium), and trimix (oxygen, helium, and nitrogen). These bubbles can expand and contract during the dive, and are assumed to be excited off an exponential distribution that decreases in number as the radius of the excited bubbles increases. The material properties of these bubbles determine their response to pressure changes, inert gas (nitrogen, helium) diffusion across their interfaces, and the excitation radii for growth. Collectively, material properties are tabulated within equations-of-state (EOS) for lipid and aqueous bubble coatings.

The phase volume constraint equation is written in terms of a phase function, $\dot{\phi}$, varying in time, for τ_{ex} the bubble excitation time, across a distribution of excited bubble seeds, n,

$$\int_{\tau_{ex}}^{\tau} \frac{\partial \phi}{\partial t} dt \ \leq \ \Phi$$

with, tagging the three bubble processes of excitation, interface gas diffusion, and Boyle expansion-contraction,

$$\dot{\phi} = \frac{\partial \phi}{\partial t}$$

for Φ the separated phase, and τ some (long) cutoff time. More particularly, for Π the total gas tension, taking $\tau \rightarrow \infty$, with V the separated phase volume, P the pressure, and T the temperature,

$$\dot{\phi} = \left[\frac{\partial V}{\partial t}\right]_{diffusion} + \left[\frac{\partial V}{\partial t}\right]_{Boyle/Charles} + \left[\frac{\partial V}{\partial t}\right]_{excitation}$$

for,

$$\left[\frac{\partial V}{\partial t}\right]_{diffusion} = 4\pi\beta \; exp \; (\beta\epsilon) DS \int_{\epsilon}^{\infty} nr \left[\Pi - P - \frac{2\gamma}{r}\right] dr$$

$$\left[\frac{\partial V}{\partial t}\right]_{Boyle/Charles} = 4\pi\beta \; exp \; (\beta\epsilon) \int_{\epsilon}^{\infty} nr^2 \left[\frac{\partial r}{\partial P}\frac{\partial P}{\partial t} + \frac{\partial r}{\partial T}\frac{\partial T}{\partial t}\right] dr$$

$$\left[\frac{\partial V}{\partial t}\right]_{excitation} = 4\pi \frac{\partial}{\partial t}\left[\theta(t - \tau_{ex}) \int_{\epsilon}^{\infty} nr^2 dr\right]$$

and,

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

with quantities as noted, and seed density, n, normalized to the excited phase volume, V,

$$4\pi \int_{\epsilon}^{\infty} nr^2 dr = exp \; (-\beta\epsilon) \; [8\pi\beta^{-3} + 8\pi\epsilon\beta^{-2} + 4\pi\epsilon^2\beta^{-1}] = V$$

for ϵ the seed excitation radius, r the bubble radius, γ the surface tension, D the diffusivity, S the solubility, and the step (heaviside) function, θ, defined for seed excitation at time, τ_{ex},

$$\theta(t - \tau_{ex}) = 0, \quad t \leq \tau_{ex}$$

$$\theta(t - \tau_{ex}) = 1, \quad t > \tau_{ex}$$

with the time derivative of the heaviside function a delta function,

$$\frac{\partial \theta(t - \tau_{ex})}{\partial t} = \delta(t - \tau_{ex})$$

In the integrals over time, we do not consider flying-after-diving scenarios.

In lowest order, number densities of nitrogen and helium bubble seeds are comparable *[90]*. Experiments suggest that helium bubbles are smaller but more numerous than nitrogen bubble seeds in the same substrate measurements, but differences are small. In zeroth order,

$$n_{He} \simeq n_{N_2} = n$$

In higher order, helium and nitrogen seed densities are averaged over breathing mixture fractions, f_{He} and f_{N_2}, for an effective number density, n,

$$n = \frac{f_{He} n_{He} + f_{N_2} n_{N_2}}{f_{He} + f_{N_2}}$$

The skin equation-of-state (EOS) quantifies the response of bubble films under changes of pressure, P, and temperature, T. An EOS is complicated, often only tabular, or implicitly defined as function of seed volume. To simplify bubble skin EOS lookups, Boyle factors, ξ, are used, so that,

$$\xi PV = nRT$$

as codified in Table 2. For mixed gas diving, Π is the sum of nitrogen and helium dissolved gas loadings, and the dissolved gradient, G, is,

$$G = \Pi - P$$

Thus the phase function, $\dot{\phi}$, depends on the number of bubbles, n, stimulated into growth by compression-decompression, the supersaturation gradient, G, seed expansion-contraction by radial diffusion, $\partial r/\partial t$, Boyle expansion-contraction with pressure changes, P, and inside temperature, T, in general. The excitation radius, ϵ, depends on material properties *[4,28,86-88]*, and is taken for nitrogen (μm),

$$\epsilon_{N_2} = 0.007 + 0.016 \left[\frac{T}{P}\right]^{1/3} + 0.041 \left[\frac{T}{P}\right]^{2/3}$$

and for helium,

$$\epsilon_{He} = 0.003 + 0.015 \left[\frac{T}{P}\right]^{1/3} + 0.025 \left[\frac{T}{P}\right]^{2/3}$$

for T measured in absolute ^oK, and P given in fsw, with ranges for virial coefficients, aqueous to lipid material, ξ,s, varying by factors of 0.76 to 4.86 times the values listed above *[14,47]*. Both expression above represent fits to RGBM mixed gas data across lipid and aqueous bubble films *[4,60]*, and are different from other phase models *[32,92]*. Values of excitation radii, ϵ, above range from 0.01 to 0.05 μm for sea level down to 500 fsw. This is compared to excitation radii in other models, varying permeability model *[90,91]* and tissue bubble diffusion model *[32]*, which vary in the 1 μm range. In the very large pressure limit, excitation radii are in the 1/1,000 μm range. Table 1 lists excitation radii (air) according to the RGBM.

Table 1. RGBM Excitation Radii

pressure P (fsw)	excitation radius ϵ (μm)	pressure P (fsw)	excitation radius ϵ (μm)
13	0.174	153	0.033
33	0.097	183	0.029
53	0.073	283	0.024
73	0.059	383	0.016
93	0.051	483	0.011
113	0.046	583	0.009

To track Boyle bubble expansion-contraction easily, a set of multipliers, ξ, is tabulated in Table 2 reducing EOS data for just pressure changes. For changes in pressure, we have, for bubble assemblies of volume, V, at ambient pressure, P,

$$\xi_i P_i V_i = \xi_f P_f V_f$$

simply, with i and f denoting initial and final states. Multipliers represent a 50/50 lipid-aqueous skin, following Sears *[58]* and Blank *[7]*. These multipliers represent a simplification of extensive EOS data for lipid and aqueous materials, condensed into the simpler pressure-volume form above. Obviously, under these multipliers, bubbles are not ideal gases following pressure changes.

Table 2. RGBM Boyle Multipliers

depth (fsw)	EOS multiplier ξ
30	0.610
90	0.732
150	0.859
210	0.939
270	1.032
330	1.119
390	1.169
450	1.183
510	1.203

To track gas transfer across bubble boundaries, we need mass transport coefficients, DS, for inert gases. Table 3 lists DS for the same 50/50 lipid-aqueous surface, using Frenkel *[31]*, Lango *[7]*, and Batchelor *[2]*. Mass transfer coefficients are just phenomenological diffusion coefficients for complex gas transport across lipid and aqueous bubble surfaces in tissue and blood. They are a combination of measurements and data extrapolation of gas transfer estimates for inert gases.

Table 3. RGBM Mass Transfer Coefficients

gas	DS $(\mu m^2/sec\ fsw)$
H_2	72.5×10^{-6}
He	18.4×10^{-6}
Ne	10.1×10^{-6}
N_2	56.9×10^{-6}
Ar	40.7×10^{-6}
O_2	41.3×10^{-6}

Notice that helium has a low mass transport coefficient, some 3 times smaller than nitrogen.

Three parameters, closing the set, are nominally,

$$\Phi = 596. \pm 210\ \mu m^3$$

and, for nitrogen and helium,

$$\beta_{N_2} = 0.68 \pm 0.28\ \mu m^{-1}$$

$$\beta_{He} = 0.57 \pm 0.19\ \mu m^{-1}$$

with,

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

with material property, σ,

$$0.10 \leq \sigma \leq 0.85$$

moving from lipid to watery tissue. Later in this analysis, we take $\sigma = 0.5$. The first two parameter sets were obtained from fitting the algorithm to published no decompression time limits (NDLs) for air, nitrox, trimix, and heliox *[15,20,52,64,86]*. The third parameter follows from EOS estimates of surface tension, as with excitation radii. Tissues and blood are undersaturated with respect to ambient pressure as far as inert gas partial pressures (tensions). This produces the necessary ingradient for oxygen and outgradient for carbon dioxide in metabolic processes. The difference is termed the inherent undersaturation. The inherent unsaturation (or oxygen window), ψ, takes the form, *[39,90]* (fsw),

$$\psi = f_{O_2}P - 2.04(1 - f_{O_2}) - 5.47$$

a linear function of oxygen partial pressure up to 2.0 atm and then constant beyond that, near 70 fsw, with P ambient pressure, and f_{O_2} oxygen fraction. Under compression-decompression, some of this window likely takes up inert gases, denoted, ζ,

$$\zeta = f_{O_2}P - \psi$$

and is added to the inert gas tension. In time, it is assumed, for inert gas, k,

$$\zeta_k = \left[\frac{f_k}{1 - f_{O_2}}\right][f_{O_2}P - \psi]\left[1 - exp\ (-\lambda_k t)\right]$$

for λ_k a decay constant, f_{O_2} again the oxygen fraction, and f_k the inert gas mixture fraction (same across all compartments). Inert gas fractions, f_k, plus oxygen fraction, f_{O_2}, sum to 1,

$$f_{O_2} + \sum_{k=1}^{K} f_k = 1$$

where, $K = 2, k = N_2, He$, that is, mixed gas diving. Tissue tensions (partial pressures), p_k, for ambient partial pressure, p_{ak}, and initial tissue tension, p_{ik}, evolve in time, t, in usual fashion in compartment, τ_k, according to, given v the (linear) ascent or descent rate between stages,

$$p_k - p_{ak} + \frac{v}{\lambda_k} = vt + \left[p_{ik} - p_{ak} + \frac{v}{\lambda_k}\right]\ exp\ (-\lambda_k t) + \zeta_k$$

for,

$$\lambda_k = \frac{0.693}{\tau_k}$$

for τ_k tissue halftime, and ambient pressure, P, as a function of depth, d, in units of fsw,

$$P = \eta d + P_h$$

for surface ambient pressure, P_h,

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

given h in multiples of 1,000 ft elevation, $\eta = 1$ for salt water, and $\eta = 0.975$ for fresh water. For any gas with mixture fraction, f_k, obviously,

$$p_{ak} = f_k P$$

and total tension, Π, is the sum of component tensions,

$$\Pi = \sum_{k=1}^{K} p_k$$

Nitrogen halftimes, τ_{kN_2}, are taken to be 2.5, 5, 10, 20, 40, 80, 120, 180, 240, 320, and 480 min. Helium halftimes, τ_{kHe}, are 2.65 times faster for the same nitrogen compartments,

$$\tau_{kHe} = \frac{\tau_{kN_2}}{2.65}$$

The bubble dynamical protocol in the RGBM algorithm amounts to staging on the seed number averaged, free-dissolved gradient across all tissue compartments, G,

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

so that,

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

for ϵ the excitation radius at P and T. 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 commercially. Stops are computed in 10 fsw increments. An important feature of the iterative process is noted:

1. separated phase volume, Φ, is the same for all inert gases;
2. the gradient, G, is slowly varying as seeds are excited into growth, expand or contract as gas diffuses across bubble films, and expand or contract as ambient pressure changes.

The combination of the two produces dramatically different staging regimens than classical dissolved gas protocols. This (new) staging protocol has been in use for the past 8 - 12 years, data is being collected from divers, and the process of evaluation and updating is a continuous one.

LANL 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:

1. bottom mix/pp_{O_2}, depth, and time (square wave equivalent);
2. ascent and descent rates;
3. stage and decompression mix/pp_{O_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 (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 authors (BRW and TRO), that is, divers, profiles, and outcomes are filtered. A summary breakdown of DCS hit (bends) data consists of the following:

1. OC deep nitrox reverse profiles – 5 hits (3 DCS I, 2 DCS II)
2. OC deep nitrox – 3 hits (2 DCS I, 1 DCS II)
3. OC deep trimix reverse profiles – 2 hits (1 DCS II, 1 DCS III)

4. OC deep trimix – 2 hits (1 DCS I, 1 DCS III)
5. OC deep heliox – 2 hits (2 DCS II)
6. RB deep nitrox – 2 hits (1 DCS I, 1 DCS II)
7. RB deep trimix – 2 hits (1 DCS I, 1 DCS III)
8. 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 (-to-light) gas switches occured in 4 cases, violating contemporary ICD (isobaric counterdiffusion) protocols *[35,40,44-46]*. 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 full body nor CNS (central nervous system) oxygen toxicity. The 20 cases come after the fact, that is diver distress with hyperbaric chamber treatment following distress. The Appendix describes many of the profiles in the LANL 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 downloads, 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 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. Consider it briefly, and the likelihood maximization technique *[8,43,53]*.

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. Specifically, the probability, P, in a random sample of size, N, for n occurrences of decompression sickness and m non-occurrences, takes the form,

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

with,

$$n + m = N$$

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

$$q = 1 - p$$

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

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

Table 4a 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) average of hits.

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 4a 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 4a. Probabilities Of Decompression Sickness For Underlying Incidences.

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

One constraint usually facing the statistical synthesizer is a paucity of data, that is, number of trials of a procedure. Data on hundreds of repetitions of a dive profile are virtually nonexistent, excepting bounce diving perhaps. As seen, some 30-50 trials are requisite to ascertain procedure safety at the 10% level. But 30-50 trials is probably asking too much, is too expensive, or generally prohibitive. In that case, the designer may try to employ global statistical measures linked to models in a more complex trial space, rather than a single profile trial space. Integrals of risk parameters, such as bubble number, supersaturation, separated phase, etc., over exposures in time, can be defined as probability measures for incidence of decompression sickness, and maximum likelihood methods used to extract appropriate constants. Such an approach has been developed by Weathersby *[72-74]*, plus others *[68-70]*, and we adopt it for this analysis.

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

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

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

$$n + m = N$$

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

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

and is maximized when,

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

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

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

satisfied when,

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

In application, such constraints are most easily solved on computers, with analytical or numerical methods. For RGBM analysis, the likelihood, Ψ, is typically a function of 2 - 3 parameters over the whole set of profiles. This requires extensive computing power coupled to sophisticated numerical techniques and software.

A global statistical approach to table fabrication consists of following a risk measure, or factor p, throughout and after sets of exposures, tallying the incidence of DCS, and then applying maximum likelihood to the risk integral in time, extracting any set of risk constants optimally over all dives in the maximization procedure. In analyzing saturation air and helium data, Weathersby *[74]* assigned risk as the difference between tissue tension and ambient pressure. One tissue was assumed, with time constant fixed by the data in ensuing maximum likelihood analysis. Another suggested measure of nonincidence, q, is the exponential of risk integrated over exposure time, for every compartment, τ,

$$q(\kappa, \tau) = exp \left[- \int_0^\infty \zeta(\kappa, \tau, t) dt \right]$$

$$\zeta(\kappa, \tau, t) = \kappa [\Pi(\tau, t) - P]$$

with κ a constant determined in the likelihood maximization, P ambient pressure, and $\Pi(\tau, t)$ the instantaneous total tension for tissue with halftime, τ. corresponding to arbitrary tissue compartments for the exposure data. More complex likelihood functions can also be employed, for instance, excess bubble risk according to the varying permeability model *[90-92]*,

$$\zeta(\mu, \alpha, \tau, t) = \mu \Lambda(t) G(\tau, t)$$

$$\Lambda(t) = [1 - \alpha \epsilon(t)]$$

with Λ the permissible bubble excess, ϵ the excitation radius, G the bubble diffusion gradient (dissolved-free gas), and μ and α constants determined in the fit maximization of the data. Another risk possibility is the tissue ratio *[70]*,

$$\zeta(\kappa, \tau, t) = \kappa \; \left[\frac{\Pi(\tau, t)}{P} \right]$$

a measure of interest in altitude diving applications. An excited seed volume risk function in the reduced gradient bubble model *[75-81]*, is given by,

$$\zeta(\gamma, \beta, \tau, t) = \gamma \Lambda(t) G(\tau, t)$$

$$\Lambda(t) = 4\pi \int_{\epsilon(t)}^{\infty} exp\ (-\beta r) r^2 dr$$

with γ and β minimization constants. In the following RGBM analysis, we will use variants of the above.

Hundreds of air dives were analyzed using this procedure, permitting construction of decompression schedules with 95% and 99% nonincidence (5% and 1% bends incidence). Tables were published by US Navy investigators *[5,73]*, and Table 4b tabulates the corresponding nonstop time limits ($p = 0.05, 0.01$), and also includes the standard US Navy (Workman) limits *[21,23,86]* 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.

Table 4b. 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

LANL Data Correlations And Risk Estimators

To perform risk analysis with the LANL Data Bank, an estimator need be selected. For diving, dissolved gas and phase estimators are useful. Two, detailed earlier, are extended here. First is the dissolved gas supersaturation ratio, historically coupled to Haldane models, ρ, written in modified ratio form,

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

and second, ψ, is the separated bubble volume, invoked by dual phase models,

$$\psi(\gamma, \mu, t) = \gamma \left[\frac{\phi(t)}{\phi_i(t)} \right] - \gamma\ exp\ (-\mu t)$$

with $\phi(t)$ the bubble volume due to excitation, diffusion, and Boyle expansion-contraction, and ϕ_i the initial bubble excitation volume. The exponential terms in both risk functions merely insure data smoothing for short dives, that is, as $t \rightarrow 0$, then $r \rightarrow 0$, too. For long dives, $t \rightarrow \infty$, the exponential terms vanish. Physically, the exponential terms also link to bubble extinction, not discussed herein. Both risk functions vary in time, exposure, and staging. For simplicity, the asymptotic exposure limit is used in the likelihood integrals for both risk functions, r, across all compartments, τ,

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

$$1 - r(\gamma, \mu) = exp\left[-\int_0^\infty \psi(\gamma, \mu, t)dt\right]$$

with $hit - no\ hit$, likelihood function, Ω, of form,

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

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

and logarithmic reduction, Ψ,

$$\Psi = ln\ \Omega$$

where, $\delta_k = 0$ if DCS does not occur in profile, k, or, $\delta_k = 1$ if DCS does occur in profile, k. To estimate κ, λ, γ, and μ in maximum likelihood, a modified Levenberg-Marquardt *[6,43]* algorithm is employed ($SNLSE$, Common Los Alamos Applied Mathematical Software Library) *[84]*, a nonlinear least squares data fit (NLLS) to an arbitrary logarithmic function (minimization of variance over K data points with $L2$ error norm). The same technique was applied to estimating separated phase volume and inert gas densities. The mathematical approach is well known. To estimate a function Φ, using a fit set, Υ, that is,

$$\Phi = \frac{1}{2}\sum_{m=1}^{M}\left[\Upsilon_m(x_m)\right]^2$$

or, in vector notation,

$$\mid \Phi \mid = \frac{1}{2}\Upsilon(x) \cdot \Upsilon(x)$$

a solution vector, $\mathbf{p}$, is found satisfying,

$$\left[\mathbf{J}^\dagger\mathbf{J} + \chi\mathbf{I}\right]\mathbf{p} = -\mathbf{J}^\dagger\mathbf{f}$$

with $\mathbf{J}$ the Jacobian (derivative determinant) of Υ,

$$\mathbf{J} = \frac{\partial\Upsilon}{\partial\mathbf{x}}$$

$\mathbf{J}^\dagger$ the hermitian inverse (transpose) of $\mathbf{J}$, and $\mathbf{I}$ the identity operator. The χ are positive constants, and $\mathbf{p}$ is the approximation to Φ. Numerically, all Jacobian derivatives are estimated and used in the minimization fit. Functions are generally nonlinear in form and behavior, and the error is $L2$ (variance in fit to exact values)). The process is iterative, with each update, $\mathbf{q}$, of $\mathbf{p}$, obtained from the Jacobian differential expansion,

$$\Upsilon(\mathbf{p} + \mathbf{q}) = \Upsilon(\mathbf{p}) + \mathbf{J}\mathbf{q}$$

The likelihood maximization technique amounts to numerically determining κ, γ, λ, and μ according to,

$$\frac{\partial\Psi}{\partial r} = \frac{\partial\Psi}{\partial\kappa}\frac{\partial\kappa}{\partial r} + \frac{\partial\Psi}{\partial\lambda}\frac{\partial\lambda}{\partial r} = 0$$

for the dissolved gas gradient ratio estimator, ρ, and,

$$\frac{\partial\Psi}{\partial r} = \frac{\partial\Psi}{\partial\gamma}\frac{\partial\gamma}{\partial r} + \frac{\partial\Psi}{\partial\mu}\frac{\partial\mu}{\partial r} = 0$$

for the phase estimator, ψ.

We assign numerical tasks to processors on the LANL Blue Mountain Machine, a massively parallel processor (MPP) with 2,000 nodes according to:

1. each tissue compartment, τ, then, within each compartment;
2. only nitrox data points;
3. only trimix data points;
4. only heliox data points;
5. both nitrox and trimix data points;
6. both nitrox and helium data points;
7. both heliox and trimix data points;
8. all heliox, nitrox, and trimix data points.

estimating κ, λ, γ, and μ across all domains. The last case, all data, is the full set employed in risk analysis, but there wasn't much difference in the estimators, seen in mean error estimates across the partitioned data structures. For 11 tissue compartments, and 7 data sets, 77 risk estimates emerge. Only maximum tissue risks are finally averaged and variance computed. In diver staging, certain tissue compartments control the exposure, This is true within dissolved gas algorithms, as well as bubble algorithms. Finally, we find across the partioned data structures, 2-8 above:

$$\kappa = 0.91 \pm 0.14 \ min^{-1}$$

$$\lambda = 0.28 \pm 0.11 \ min^{-1}.$$

and, similarly.

$$\gamma = 0.09 \pm 0.07 \ min^{-1}$$

$$\mu = 0.88 \pm 0.46 \ min^{-1}$$

For notational shorthand, we abbreviate supersaturation and bubble risk functions,

$$\sigma = r(\kappa, \lambda)$$

$$\beta = r(\gamma, \mu)$$

Logarithmic Likelihood And Significance

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 not meaningful yet, so we breakout data into gas categories (nitrox, heliox, trimix), as tabulated earlier. Table 5a indicates the breakdown.

Table 5a. Profile Data

mix	total profiles	DCS hits	incidence
OC nitrox	344	8	0.0232
RB nitrox	550	2	0.0017
all nitrox	894	10	0.0112
OC trimix	656	4	0.0061
RB trimx	754	2	0.0027
all trimix	1410	6	0.0042
OC heliox	116	2	0.0172
RB heliox	459	2	0.0044
all heliox	575	4	0.0070
all	2879	20	0.0069

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.

The logarithmic likelihood (LL), Ψ, is a rough metric for fits to bubble and supersaturation risk estimators. The canonical value, Ψ_6, is the LL for the 6 RB/OC control data set. No fit value, Ψ, will better the canonical value, Ψ_6, that is,

$$\Psi_6 = -112.9$$

$$\Psi \leq \Psi_6$$

meaning all fits will be more negative (smaller LL). Results are tabulated as follow in Table 5b.

Table 5b. Logarithmic Likelihood And Logarithmic Likelihood Ratio

estimator	LL	parameters	LLR	α
6 step set	$\Psi_6 = -112.9$	$p = 0.0232, 0.0061, 0.0172,$ $0.0036, 0.0027, 0.0044$		
3 step set	$\Psi_3 = -118.4$	$p = 0.0112, 0.0042, 0.0079$	$\Gamma_3 = 11.0$	0.013
full set	$\Psi_{full} = -119.2$	$p = 0.0069$	$\Gamma_{full} = 12.6$	0.033
σ	$\Psi_{sat} = -210.6$	$\kappa = 0.91 \pm 0.14\ min^{-1}$ $\lambda = 0.28 \pm 0.11\ min^{-1}$	$\Gamma_{sat} = 92.2$	0.001
β	$\Psi_{bub} = -113.3$	$\gamma = 0.09 \pm 0.07\ min^{-1}$ $\mu = 0.88 \pm 0.46\ min^{-1}$	$\Gamma_{bub} = 0.8$	0.933

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

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

for Ψ the bubble and supersaturation estimators in Table 5b. The percentage point, α, is the area under the χ^2 curve, from $\chi^2_{\alpha,\nu} = \Gamma$ to ∞,

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

for ν the degrees of freedom (6 - the number of bubble, supersaturation, 3 step, or full fit degrees of freedom). The $hit - no\ hit$ criteria for the bubble estimator is the phase volume, Φ, while standard USN $M - values$ are the criteria for the supersaturation estimator. Deep stops clobber $M - values$.

Clearly, the supersaturation risk function does not correlate well, compared to the bubble risk function. It does not work here in the deep decompression arena, but others *[73,74]* have shown it correlates in the nonstop and light decompression limits. In those limits, bubble models and supersaturation models tend to converge, simply because phase growth is minimal.

This analysis suggests that deep stops are both safe and compact statistically for the LANL model and set. Coupled gas transport analysis suggests that deep stops and shallow stops can both be staged safely, but deep stops are more efficient in controlling bubble growth and are usually shorter in overall dive time duration.

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. Listed in Table 6 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 6. Risk Estimates For Standard Air NDLs.

	USN NDL	risk	PADI NDL	risk	NAUI NDL	risk	ZHL NDL	risk
d	t_n	β	t_n	β	t_n	β	t_n	β
(fsw)	(min)		(min)		(min)		(min)	
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 *[Gerth, priv comm, 2001]* within data sets at Duke both in Table 6 and Table 7.

Next, the analysis is extended to profiles with varying ascent and descent rates, safety stops, and repetitive sequence *[53,78-80,82]*. Table 7 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 7. Dissolved And Separated Phase Risk Estimates For Nominal Profiles.

profile	descent rate	ascent rate	safety stop	risk	risk
$(depth/time)$	(msw/min)	(msw/min)	$(depth/time)$	β	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 $msw/32\ min$	18	9	5 $msw/3\ min$		
SI 176 min					
13 $msw/37\ min$	18	9	5 $msw/3\ min$		
SI 174 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 *[75]* 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 $p = 0.0069$, and much evidence suggests $p < 0.0001$, 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.

Recent Doppler And Wet Test Analyses

Recent Doppler and wet tests are interesting, including our recorded CCR 16 dive sequence to 450 fsw. Gas transport *[13,84]* analysis of these applications follows, along with bubble risk estimates.

1. **Bennett And Maronni 2.5 Minute Recreational Deep Stop**

   Deep stops are already mainliners in some training agency protocols for no and light decompression diving on air and nitrox. The prescription is to make a deep stop at half depth for 1 - 3 min, followed by a shallow stop in the 15 fsw zone for 1 - 2 min. In Table 8a, we cite bubble surfacing risks for a deep stop at half depth for 1 min, 2.5 min, and 4 min, the middle case suggested by Bennett and Maronni from Doppler scoring *[Bennett, priv comm, 2008]*, followed by direct ascent to the surface. Surfacing supersaturation risks are tabulated in Table 8b for comparison. Dives are carried out to the (old) US Navy NDLs for easy reference. Deep stops for less than 2.5 min reduce recreational risk out to the Navy NDLs in all cases. Bubble risks decrease for short deep stops and then increase as stop times increase. As stop times continue to increase, the dives will require decompression. In other words, with increasing deep stop time, the dives become multilevel decompression dives. Obviously, the playoff of deep stop time against bottom time is a minimax problem. This is traced to bubble behavior with increased gas tensions for increasing deep stop time. In all cases, stop time in the shallow zone was 1 *min*. Longer stop times in the shallow zone had little effect on surfacing risks. Shallow stops in training regimens probably serve better to teach buoyancy control to neophytes.

Table 8a. Comparative Bubble Risks For Recreational Deep Stops

depth	time	no stop	1 *min* stop	2.5 *min* stop	4 *min* stop
(*fsw*)	(*min*)	β	β	β	β
80	40	2.10%	1.93%	1.90%	1.91%
90	30	2.10%	1.87%	1.83%	1.84%
100	25	2.10%	1.74%	1.71%	1.72%
110	20	2.20%	1.65%	1.61%	1.62%
120	15	2.00%	1.50%	1.46%	1.47%
130	10	1.70%	1.29%	1.25%	1.26%

Ascent and descent rates were standard in the analysis, that is, 30 fsw/min and 60 fsw/min respectively. The small risk spread for 1 - 4 *min* accommodates recreational deep stop training regimens, that is, 1 - 3 *min* deep half stop for many agencies.

Corresponding supersaturation risks in Table 8b are seen to increase montonically with length of deep stop. This is to be expected in dissolved gas models, with exposures at increasing depths for increasing times cascading tissue tensions, oblivious to any bubble-dissolved gas interactions tracked in Table 8a.

Table 8b. Comparative Supersaturation Risks For Recreational Deep Stops

depth	time	no stop	1 *min* stop	2.5 *min* stop	4 *min* stop
(*fsw*)	(*min*)	σ	σ	σ	σ
80	40	2.10%	2.12%	2.18%	2.26%
90	30	2.10%	2.13%	2.20%	2.29%
100	25	2.10%	2.15%	2.23%	2.34%
110	20	2.20%	2.24%	2.32%	2.41%
120	15	2.00%	2.10%	2.20%	2.38%
130	10	1.70%	1.78%	1.91%	2.13%

2. C & C Team 450/20 Multiple RB Dive Sequence At 1.4 *atm*

Details of a 16 dive sequence by members of the C & C Team to 450 *fsw* for 20 *min* at 1.4 *atm* follow. Dives were successfully completed in tandem without mishap, and are included in the LANL Data Bank. All dives follow the same schedule, as given in Table 9. Oxtox (both CNS and full body) metrics are included. Diver Tags and Outcomes are tabulated, according to the LANL Data Bank profile schema described previously. Diver Tag 1 is one of the authors (BRW). Risk estimates (both bubble and supersaturation) are noted, along with binomial probabilities for 16 tandem dives within a LANL Data Bank underlying incidence rate of 0.69%. Four additional dives in the same sequence were also performed without mishap, but are not included because of larger fluctuations about 450 *fsw*. Bottom fluctuations in the 16 dive sequence were ±5 *fsw* maximum for longer than a minute.

Diluent is 10/80 trimix with a pp_{O_2} setpoint of 1.4 *atm*. The cumulative CNS clock fractions exceed a (traditional) limit of 1.0, while OTU uptake remains below a (traditional) limit of 650 *min*. There is likely greater variability in oxtox limit points than decompression limit points. Descent and ascent rates are standard, except in the 30 *fsw* zone where the ascent rate is 1 fsw/min. The binomial probability of no hits is $P(0)$, while the probability of 1 hit is $P(1)$. The probability of 2 or more hits is vanishingly small for underlying incidence of 0.69%.

Table 9. RB 16 Dive Sequence At 1.4 *atm*.

Dive Tags = 2042 - 2058
Diver Tags = 3,20,5,**1**,9,6,10,2,14,4,15,7,8,11,16,12
Diver Outcomes = 3,4,3,**3**,4,3,4,3,4,3,3,3,4,3,4,3
Underlying Incidence = 20/2879

depth	time	CNS clock	OTU uptake
(*fsw*)	(*min*)	(*fraction*)	(*min*)
450	20	.17	32.6
360	0.5	.01	0.8
350	0.5	.01	0.8
340	0.5	.01	0.8
330	0.5	.01	0.8
320	0.5	.01	0.8
310	0.5	.01	0.8
300	1.0	.02	1.6
290	1.0	.02	1.6
280	1.0	.02	1.6
270	1.0	.02	1.6
260	1.0	.02	1.6
250	1.0	.02	1.6
240	1.0	.02	1.6
230	1.5	.03	1.8
220	1.5	.03	1.8
210	2.0	.03	4.1
200	2.0	.03	4.1
190	2.0	.03	4.1
180	2.0	.03	4.0
170	2.0	.02	4.0
160	2.5	.02	4.0
150	2.5	.02	3.9
140	3.5	.03	5.7
130	5.0	.05	9.0
120	5.0	.04	8.5
110	5.0	.04	8.4
100	5.5	.04	9.0
90	6.0	.05	9.8
80	8.0	.07	13.0
70	8.0	.07	12.5
60	9.5	.08	15.5
50	11.0	.10	17.9
40	12.0	.10	19.5
30	8.5	.07	13.8
20	10.5	.09	17.1
10	17.0	.11	25.2
	211.5	1.38	262.2

$$\beta = 4.27\%, \quad \sigma = 12.67\%$$
$$P(0) = 89.4\%, \quad P(1) = 10.4\%$$

Computed bubble risk, β, is below the binomial probability, $P(1)$.

3. NEDU Deep Stop Air Tests

The Navy Experimental Diving Unit recently tested their version of air deep stops *[NEDU, priv comm, 2007]* with a moderate DCS rate. Profiles tested are given in Table 10, along with a suggested LANL deep stop profile. Profile NEDU 1 incurred a 5.5% DCS hit rate, while NEDU 2 1 incurred a lower 1.5% DCS hit rate.

Table 10. Comparative NEDU Air Deep Stop Schedules

depth fsw)	NEDU 1 time (min)	NEDU 2 time (min)	LANL time (min)
170	30	30	30
120			0.5
110			1.5
100			2.5
90			3.5
80			4.5
70			5.0
70	12		5.0
60	17		7.0
50	15		11.0
40	18	9	14.5
30	23	23	22.0
20	17	52	28.5
10	72	93	59.9
	206	207	195
σ	5.6%	2.4%	3.4%
β	10.6%	3.2%	2.6%

Bubble risk is higher in both NEDU 1 and NEDU 2, but large in NEDU 1. NEDU 1 is a multilevel decompression dive with inadequate treatment in the shallow zone. Initial deep stops in NEDU 1 did not control bubble growth, and the length of the stay in 70, 60, and 50 fsw builds up dissolved gas in the middle range tissues, which then diffuses into bubbles causing them to grow. NEDU 2 is classic with no deep stops, and very long times in the shallow zone to effect decompression. The LANL schedule has deeper stops, shorter midzone times, and then shorter times in the shallow zone compared to both NEDU 1 and NEDU 2. One important factor here is the shape of the decompression schedule, that is the LANL profile is shorter overall, with NEDU 1 and NEDU 2 profiles exhibiting supersaturation staging with shallow belly and tail, while the LANL profile is steeper exhibiting bubble staging with deeper stops and steeper ascent rate. Both NEDU profiles are not of the genre typically dived by users of modern deep stop tables, software, and meters.

Gas transport *[13,84]* analyses on both NEDU schedules suggests that NEDU 1 produces 15% - 30% larger bubble volumes on surfacing, due to the longer stay in the mid zone, while NEDU 2 produces surfacing bubble volumes 3% - 5% larger than surfacing bubble volumes in the LANL profile. Surfacing bubble volumes in the LANL profile were close to the staging limit point.

4. French Navy Deep Stop Schedules

The French Navy also tested deep stop air schedules *[Blatteau, priv comm, 2008]*. Three protocols on deep air were employed and none exhibited Grade 4 Doppler bubbles. Analysis centered on just Grade 3 bubbles. For purposes of deep stop analysis, Protocol 1, a dive similar to NEDU 1, is interesting. Protocol 1 is a deep air dive to 200 fsw for 20 min, with ascent staging according to Table 11. Contrasting staging strategies are denoted MN90, the standard French Navy dissolved gas regimen, and LANL. Outside of World Navies, few diving sectors today even contemplate air decompression diving to 200 fsw. Risks in air dives beyond 150 fsw are known to increase by factors of 10 over similar dives at shallower depth *[65,86]*. This is, of course, one major reason why trimix and heliox become mixtures of choice for deep and decompression diving worldwide, across commercial, scientific, exploration, and research sectors.

Table 11. French Navy Air Deep Stop Schedules At 200 fsw

	Protocol 1	MN90	LANL
ascent rate fsw/min starting at 90 fsw	10	20	30
depth (fsw)	time (min)	time (min)	time (min)
200	20	20	20
130			0.5
120			0.5
110			1.0
100			1.0
90			1.0
80	1		1.5
70	1		2.0
60	2		2.0
50	2		2.5
40	4		3.0
30	6	3	6.0
20	9	8	7.0
10	22	32	8.0
	78	68	65
β	3.9%	2.2%	2.1%

By contrast, LANL staging starts deeper, is shorter overall, and has smaller bubble risk than Protocol 1. Protocol 1, however, tracks more closely with LANL than NEDU 1, and exhibits lower risk than NEDU 1. However, run time for Protocol 1 versus MN90 is longer, unlike conventional bubble model run times. Estimated bubble risks, β, are tabulated at the bottom of Table 11.

Gas Transport Analysis

With regard to the preceeding dives and schedules, a couple of points are interesting. These follow from a closer look at dissolved and bubble gas phases across the profiles, using LANL tools and selected way points on the dives. These comments also apply to deep and decompression staging using traditional dissolved gas models and tables *[13,78,89]*. Remember these comments are made within the LANL model framework and attendant data correlation:

1. bubble growth in the deep zone of decompression profiles NEDU 1 and Protocol 1 is not constrained in their version of deep stop air tests;
2. deep stops are not deep enough in NEDU 1 and Protocol 1, nor are follow stops;

3. critical phase volume limit points are exceeded in NEDU 1 and Protocol 1 even before the diver exits, in other words, along the decompression glide path underwater;
4. the recreational 2.5 *minute* stop at 1/2 depth within the NDLs of even the old USN tables maintains the phase volumes below limit points;
5. the LANL 450/20 profiles also surface below the phase volume limit point, no surprise because profiles were designed to meet that constraint;
6. supersaturation profiles MN90 and NEDU 2 also do not control bubble growth in the deeper zones, but the separated phase volume is below model limit points, with pressure in the shallow zone sufficient to constrain bubble growth and maintain adequate dissolution, but time consuming because bubbles are now larger in the shallow zone.

Much the same can be said of supersaturation versus bubble staging strategies in general.

Table, Meter, And Profile Risk Analyses

To finish up analysis, consider other applications across tables, meters, and software, focusing on shallow stop versus deep stop profiles, risk, and data. The time span of these applications is the past 3 - 5 *yrs*, and they represent real mixed gas diving across many venues.

1. **UW Seafood Diver Air Tables**

   As another application of the LANL 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 12 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 half 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 12. RGBM Repetitive Risks For Air Dives

depth (fsw)	β 5.14% maximum time (min)	β 3.29% maximum time (min)	β 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.

2. **NAUI 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 13a through 13c, risks are tabulated at the end of the 3 or 2 dive sequence, for just 3 Tables (air at 6,000 - 10,000 ft, EAN32 at 2,000 - 6,000 ft, and EAN36 at 0- 2,000 ft). Risks decrease at any elevation as the oxygen fraction increases, while elevation increases risk for any mixture of nitrogen and oxygen. 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 - 2 min, plus a shallow stop in the 15 fsw zone for 2 min. The shallow stop mostly serves to control ascent speed. Maximum risk is seen in the air tables at 10,000 ft elevation, and minimum risk in the EAN36 tables at sea level.

Table 13a. NAUI RGBM Air Tables (6,000 - 10,000 ft)
Maximum Risk After Dive 2, $\beta = 2.36\%$

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 13b. NAUI RGBM EAN32 Tables (2,000 - 6,000 ft)
Maximum Risk After Dive 2, $\beta = 1.65\%$

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 13c. NAUI RGBM EAN36 Tables (0 - 2,000 ft)
Maximum Risk After Dive 3, $\beta = 1.12\%$

Dive 1		Dive 2		Dive 3	
$depth$	$time$	$depth$	$time$	$depth$	$time$
(fsw)	(min)	(fsw)	(min)	(fsw)	(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

These air and nitrox tables have been backbones in NAUI training regimes. They are simple to use, and easy to teach, avoiding USN Group tags.

3. 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 14 are nonstop time limits and corresponding risks, β, for exposures at that depth-time. The mixture is helitrox (enriched 26/17 trimix), sometimes called triox.

Table 14. Helitrox NDLs And Risk

depth	time	risk
d (fsw)	t_n (min)	β
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.

4. 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 by seasoned professionals. Table 15 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, β, 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.

Table 15. Comparative Helium And Nitrogen Gas Switches

	$\beta = 6.42\%$	$\beta = 6.97\%$
depth (fsw)	time (min)	time (min)
	10/65 trimix	10/65 trimix
400	10.0	10.0
260	1.5	1.5
250	1.0	1.0
240	1.0	1.0
	18/50 trimix	18/50 trimix
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
	40/20 trimix	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
	123.0	116.0

5. 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 in Florida. Table 16 summarizes the ascent and decompression profile. The risk is 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.

Table 16. WKPP Extreme Trimix Dives
Surfacing Risk, $\beta = 13.67\%$

depth (fsw)	time (min)	trimix (fsw)	depth (min)	time	trimix
270	360	11/50	140	5	
260	1		130	6	
250	1		120	7	35/25
240	1	18/40	110	8	
230	2		100	9	
220	2		90	10	
210	2		80	12	
200	3		70	16	50/16
190	3		60	34	
180	3	21/35	50	41	
170	4		40	49	
160	4		30	60	pure O_2
150	5		20	90	

6. 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 hyperbaric 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. One attempt ended in the Phuket hyperbaric chamber, as reported by a hyperbaric specialist and support team. Earlier dives to 540 fsw using RGBM schedules are recounted in trade magazines and at Internet sites. Dives like these with deep stops are becoming more common these days, both on OC and CCR systems.

Table 17 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 16. Stops are made in 10 fsw increments all the way to the surface.

Table 17. Trimix Dive To 1040 fsw And Risk
Surfacing Risk, $\beta = 26.13\%$

depth (fsw)	time (min)	trimix	depth (fsw)	time (min)	trimix
1049	0.5	5/67	380	3.0	
750	0.5		370	3.0	
740	0.5		360	3.0	
730	0.5		350	3.0	
720	0.5		340	3.5	
710	0.5		330	3.5	
700	0.5		320	3.5	
690	0.5		310	3.5	
680	0.5		300	3.5	
670	0.5		290	2.5	14/56
660	0.5		280	3.0	
650	0.5		270	3.5	
640	0.5		260	3.5	
630	0.5		250	3.5	
620	0.5		240	3.5	
610	0.5		230	4.0	
600	0.5		220	4.0	
590	0.5		210	5.0	
580	0.5		200	6.0	
570	1.0		190	6.5	
560	1.0		180	6.5	
550	1.0		170	6.5	
540	1.0		160	7.5	
530	1.0		150	9.0	
520	1.5		140	9.5	
510	1.5		130	8.0	27/56
500	1.5		120	8.5	
490	1.5		110	9.0	
480	1.5		100	13.0	
470	1.5		90	13.5	
460	1.5		80	14.0	
450	1.5		70	15.5	
440	2.0		60	16.0	
430	2.0		50	17.5	
420	2.5		40	21.0	
410	2.5		30	22.0	EAN80
400	2.5		20	24.5	
390	3.0		10	31.0	pure O_2

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.

7. HydroSpace EXPLORER Extreme RB Profile

Table 18 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 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 comparative pp_{O_2} RB calculations, as well as in OC versus RB risk estimates.

Table 18. Extreme RB Dive And Risk
Surfacing Risk $\beta = 5.79\%$

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

Risk associated with this 444 fsw dive is less than a similar dive on trimix to roughly the same depth for a shorter period of time, that is, Table 15.

8. 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 19. 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 pp_{O_2} setpoint of 1.3 atm.

Table 19. USS Perry RB Repetitive Decompression Dives And Risk
Surfacing Risk After Dive 1, $\beta = 5.32\%$
Surfacing Risk After Dive 2, $\beta = 5.89\%$

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

RGBM User Overview And Statistics

Training Agencies, particularly NAUI, ANDI, Finnish Diving Federation (FDF), and Irish Diving Federation (IDF) employ both RGBM Tables and dive planning software in their formal course structures, as part of standards and procedures and extended range training. Commercial operations in the Gulf and elsewhere are eyeing RGBM trimix and heliox tables for deep work, and air tables for shallow activities (less than 140 fsw). Many RGBM table dives are stored in the LANL Data Bank, coming from diverse sectors. Tables enjoy a safe and utilitarian record across mixed gas diving. Though not recorded directly in the LANL Data Bank, save a few select technical, mixed gas, decompression profiles, meter vendor reported usage statistics on both recreational and technical RGBM decompression meters also underscore safe application and utility. On the recreational side, Suunto, Mares, Dacor, UTC, Plexus, and Zeagle market RGBM meters. On the technical side, HydroSpace, Steam Machines, and Atomic Aquatics market, or will shortly market, RGBM meters. Commercial RGBM software includes ABYSS, GAP, and EXPLORER RGBM Simulator. Upgrades to technical RGBM are in the works for these manufacturers, and other new recreational and technical meters are in development and planning stages. Here at LANL, we use special decompression modules in conjunction with dive planning software incorporating the LANL bubble model. Commercial implementations of the RGBM tend to be more conservative than the LANL inhouse version. Consider some usage statistics furnished by vendors and Training Agencies. The compilation only includes respondents at writing. Across this spectrum of recreational and technical diving, less than 20 cases of DCS have been reported or noted. Certainly, and based on observations of many in the diving community, many cases of DCS go unreported.

1. **RGBM Decompression Meters**

   In recreational circles, computers are mainstay diving tools. In technical mixed gas diving, computers are usually backup or bailout for tables or dive planning software schedules:
   Suunto – recreational and light deco air and nitrox meters, 9,200,000 dives;
   Mares – recreational and light deco air and nitrox meters, 2,200,000 dives;
   Dacor – recreational and light deco air and nitrox meters, 450,000 dives;
   HydroSpace – technical mixed gas OC and RB deco meters, 45,000 dives;
   UTC – recreational and light deco air and nitrox meters, not available at writing;
   Plexus – recreational and light deco air and nitrox meters, not available at writing;

Steam Machines – constant pp_{O_2} deco meters, not available at writing;
Zeagle – recreational and light deco air and nitrox meters, not available at writing;
Atomic Aquatics – technical mixed gas OC and RB deco meters, under development.

2. **RGBM Software**

   ABYSS, GAP, ANDI GAP, NAUI GAP, Ocean Concepts, and HydroSpace RGBM Simulator are dive planning software packages used mainly by technical divers across commercial, research, and exploration sectors. Combined estimates of packages marketed by the six is presently 12,000+. Only a few scattered reports of DCS have been reported or noted among diver users of these software packages. These modules run on desktop and laptop computers, which in the latter case, are often taken to, and used at, the dive site.

3. **RGBM Training Agencies**

   NAUI, ANDI, FDF, and IDF formally incorporate RGBM schedules, software, and tables into their training regimens. Rough statistics suggest:
   NAUI – recreational and light deco air and nitrox tables, 514,000 dives;
   NAUI – technical mixed gas decompression tables, 26,000 dives;
   NAUI – NAUI GAP dive planner, 5,700 dives;
   ANDI – ANDI GAP dive planner, 5,000 dives;
   FDF – recreational and light deco air and nitrox tables, not available at writing;
   IDF – recreational and light deco air and nitrox tables, under analysis.

4. **RGBM Tables**

   RGBM Tables for air, nitrox, helitrox, trimix, and heliox are used by Training Agencies, technical, commercial, scientific, and exploration divers, and span OC to RB mixed gas diving. These tend toward the conservative side of the LANL model. In addition to the 2,000,000+ Training Agency dives on RGBM Tables, another 20,000 - 30,000 dives might be expected from trained divers. The use of GAP software by NAUI and ANDI is a recent development over the past 3 - 4 years.

Capsule Summary

The LANL reduced gradient bubble model (RGBM) has been detailed, including correlations and data linkage within the LANL Data Bank. The Bank stores technical, mixed gas diving profiles with outcomes. Some 2800+ deep stop profiles reside within the Bank, with 20 cases of DCS. Parameters within the RGBM have been extracted from the LANL Data Bank using maximum likelihood techniques, and a Monte Carlo-like sampling technique was employed to accelerate likelihood analysis. Risk estimates for select NDLs, tables, meter algorithms, tests, and diver profiles in the LANL Data Bank were tabulated, using a bubble phase volume estimator integrated over the whole profile. Model, data, and operational diving are congruent, providing a useful and safe platform. Widespread usage statistics for meters, tables, software, and Training Agency protocols underscored safe and consistent application of the LANL model across diverse sectors. All of the above represent an ongoing testing and validation effort which so far surpass scattered clinical tests, wet and dry, numberwise.

In addition to the gas transport comparison of dissolved gas staging versus bubble staging, analysis suggests broadly:

1. deep stop data is intrinsically different from data collected in the past for diving validation, in that previous data is mainly based on shallow stop diver staging, a possible bias in data collection;

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 cases covered, dissolved gas risk estimates will be usually higher than those computed herein;
4. bubble risks estimated herein are higher than risk estimates in other analyses, perhaps a conservative bias;
5. data entry in the LANL Data Bank is a ongoing process of profile addition, extended exposure-depth range, and mixed gas diving application.

Data specifically underscores technical diving trends:

1. pure O_2 or $EAN80$ are standard OC switch gases in the 20 fsw zone;
2. deep stops are standard across mixed gas diving, and DCS spikes are nonexistent;
3. deep switches to nitrogen mixes off helium mixes are avoided by technical divers, instead oxygen fraction is increased by decrease in helium fraction;
4. deep stop dive computers serve mostly as backup or bailout, with tables and dive planning software the choice for deep stop diving;
5. DCS spikes across mixed gas, decompression, and deep stop diving are non existent using deep stop tables, meters, and software;
6. DCS incidence rates are higher for technical diving versus recreational diving, but still small;
7. RB usage is increasing across diving sectors;
8. wrist dive computers possess chip speeds that allow full resolution of even the most extensive bubble models;
9. nitrox diving in the recreational sector is exploding;
10. technical diving data is most important for correlating models and data;
11. technical divers do not dive air, particularly deep air, with trimix and heliox the choices for deep excursions;
12. released deep stop tables, software, and meters enjoy extensive and safe utility among professional divers;
13. technical diving is growing in leaps and bounds, with corresponding data accessible off computers and bottom timers;
14. more cross talk across military, scientific, research, exploration, and commercial diving is desirable.

This work establishes needed correlation between global mixed gas diving, specific bubble model, and deep stop data. The objective is operational diving, not clinical science. The operational issue of deep stops and staging is one of timing, with questions of time and depth at all stops only addressed within consistent model and ranging data frameworks. To that end, we find deep stops are not riskier than shallow stops, that both can accomplish the same end, and that deep stops are more efficient timewise than shallow stops.

References

1. Adamson A.W., 1976, The Physical Chemistry Of Surfaces, New York: John Wiley And Sons Incorporated.
2. Batchelor G.K., 1953, Theory Of Homogeneous Turbulence, New York: Cambridge University Press.
3. Bateman J.B. and Lang J., 1945, Formation And Growth Of Bubbles In Aqueous Solutions, Canad. J. Res. E23, 22-31.
4. Becker R. and Doring W., 1965, The Kinetic Treatment Of Nuclei Formation In Supersaturated Vapors, Ann. Phys. 24, 719-752.
5. Berghage T.E. and Durman D., 1980, US Navy Air Recompression Schedule Risk Analysis, Nav. ed. Res. Bull. 1, 1-22.
6. Bevington P. and Robinson D.C., 2003, Data Reduction And Error Analysis For The Physical Sciences, New York: McGraw-Hill Book Company.
7. Blank M., 1979, Monolayer Permeability, Prog. Surface Mem. Science, 13, 87-139.
8. Bowker A.H. and Lieberman G.J., 1964, Engineering Statistics, Engelwood Cliffs: Prentice-Hall.
9. Boycott A.E., Damant G.C.C., and Haldane J.S., 1908, The Prevention Of Compressed Air Illness, J. Hyg. 8, 342-443.
10. Bradley M.E., 1984, Commercial Diving Fatalities, Aviat. Space Environ. Med. 55, 721- 724.
11. Brennen C.E., 1995, Cavitation And Bubble Dynamics, Oxford: Oxford University Press.
12. Brubakk A.O. and Neuman T.S., 2003, Physiology And Medicine Of Diving (5th Edition) Edinburgh: W.B. Saunders.
13. Brubakk A.O., Arntzen A.J., Wienke B.R. and Koteng S., 2003, Decompression Profile And Bubble Formation After Dives With Surface Decompression: Experimental Support For A Dual Phase Model Of Decompression, Undersea Hyper. Med. 30, 181-193.
14. Buckles R.G., 1968, The Physics Of Bubble Formation And Growth, Aerospace Med. 39, 1062-1069.
15. Buhlmann A.A., 1984, Decompression/Decompression Sickness, Berlin: Springer Verlag.
16. Buhlmann A.A., 1966, Saturation And Desaturation With N2 And He At 4 Atmospheres, J. Appl. Physiol. 23, 458-462.
17. Butler F.K. and Southerland D.K., 2001, The US Navy Decompression Computer, Undersea Hyper. Med. 28, 213-228. Circuit Scuba Divers, Undersea Biomed. Res. 13, 193-223.
18. Campbell J., 1968, The Tribonucleation Of Bubbles, Brit J. Appl. Phys. 1, 1083-1088.
19. Conkin J. and Van Liew H.D., 1991, Failure Of The Straight Line Boundary Between Safe And Unsafe Decompressions When Extraoplated To The Hypobaric Regime, Undersea Biomed. Res. 18, 16.
20. Des Granges M., 1957, Repetitive Diving Decompression Tables, USN Experimental Diving Unit Report, NEDU 6-57, Washington DC. Decompression Sickness, J. Appl. Physiol. 94, 2145-2150.
21. Duffner G.J., Synder J.F., and Smith L.L., 1959, Adaptation Of Helium-Oxygen To Mixed Gas Scuba, USN Experimental Diving Unit Report, NEDU 3-59, Washington, DC
22. Dunford R., Wacholz C., and Huggins K., 1993, DCS Risk And Doppler Bubbles In Sport Divers, Undersea Hyper. Med. 20, 80.
23. Dwyer J.V., 1956, Calculation Of Repetitive Diving Decompression Tables, USN Experimental Diving Unit Report, NEDU 1-57, Washington DC.
24. Eckenhoff R.G., Olstad C.E., Parker S.F. and Bondi K.R., 1986, Direct Ascent From Shallow Air Saturation Exposures, Undersea Biomed. Res. 13, 305-316.
25. Eckenhoff R.G. and Vann R.D., 1985, Air And Nitrox Saturation Decompression, Undersea Hyper. Med. 12, 41-52.
26. Eckenhoff R.G., 1985, Doppler Bubble Detection, Undersea Biomed. Res. 12, 485-489.
27. Egi S.M. and Brubakk A.O., 1995, Diving At Altitude: Review Of Decompression Strategies, Undersea Hyper. Med. 22, 281-300.
28. Epstein P.S. and Plesset M.S., 1950, On The Stability Of Gas Bubbles In Liquid-Gas Solutions, J. Chem. Phys. 18, 1505-1509.

29. Evans A. and Walder D.N., 1969, Significance Of Gas Macronuclei In The Aetiology Of Decompression Sickness, Nature 222, 251-252.
30. Farm F.P., Hayashi E.M., and Beckman E.L., 1986, Diving And Decompression Sickness Treatment Practices Among Hawaii's Diving Fisherman, University of Hawaii Sea Grant Report, UNIHI-SEAGRANT-TP-86-01, Honolulu.
31. Frenkel J., 1946, Kinetic Theory Of Liquids, New York: Oxford University Press.
32. Gernhardt M.L., Lambertsen C.J., Miller R.G., and Hopkins E., 1990, Evaluation Of A Theoretical Model Of Tissue Gas Phase Growth And Resolution During Decompression From Air Diving, Undersea Biomed. Res. 17, 95.
33. Goldstein H., 1969, Mechanics, Reading: Addison Wesley Publishing Company.
34. Hamilton R.W., 1989, Tolerating Exposure To High Oxygen Levels, REPEX And Other Methods, Marine Tech. Soc. J. 23, 19-25.
35. Hamilton R.W. and Turner P., 1988, Decompression Techniques Based On Special Gas Mixes For Deep Exploration, Undersea Biomed. Res. 15, 70.
36. Hempleman H.V., 1957, Further Basic Facts On Decompression Sickness, Investigation Into The Decompression Tables, Medical Research Council Report, UPS 168, London.
37. Hempleman H.V., 1952, A New Theoretical Basis For The Calculation Of Decompression Tables, Medical research Council Report, UPS 131, London.
38. Hennessy T.R. and Hempleman H.V., 1977, An Examination Of The Critical Released Gas Concept In Decompression Sickness, Proc. Royal Soc. London B197, 299-313.
39. 39. Hills B.A., 1977, Decompression Sickness, New York: John Wiley And Sons Incorporated.
40. Hills B.A., 1976, Supersaturation By Counterdiffusion And Diffusion Of Gases, J. Appl. Physiol. 43, 56-69.
41. Hills B.A., 1968, Variation In Susceptibility To Decompression Sickness, Int. J. \Biometeor. 12, 343-349.
42. Ikels K. G., 1970, Production Of Gas Bubbles In Fluids By Tribonucleation, J. Appl. Physiol. 28, 524-527.
43. Kahaner D., Moler C., and Nash S., 1989, Numerical Methods And Software, Englewood Cliffs: Prentice Hall.
44. Keller H. and Buhlmann A.A., 1965, Deep Diving And Short Decompression By Breathing Mixed Gases, J. Appl. Physiol. 20, 1267.
45. Lambertsen J.L. and Bornmann R.C., 1979, Isobaric Inert Gas Counterdiffusion, Undersea And Hyperbaric Medical Society Publication 54WS(IC)1-11-82, Bethesda.
46. Lambertsen C.J. and Idicula J., 1975, A New Gas Lesion Syndrome In Man Induced By Isobaric Gas Counterdiffusion, J. Appl. Physiol. 49, 1070-1082.
47. Lango T., Morland T., and Brubakk A.O., 1996, Diffusion Coefficients And Solubility Coefficients For Gases In Biological Fluids, Undersea Hyper. Med. 23, 247-242.
48. Lehner C.E., Lin T.F., Taya F., Wienke B.R., Nordheim E.V., Cuddon P.A., and Lanphier E.H., 1994, Acclimatization Reduces The Incidence Of Decompression Sickness: A Sheep Model, Undersea Hyper. Med. 21, 22.
49. Le Messurier D.H. and Hills B.A., 1965, Decompression Sickness: A Study Of Diving Techniques In The Torres Strait, Hvaldradets Skrifter 48, 54-84.
50. Neuman T.S., Hall D.A. and Linaweaver P.G., 1976, Gas Phase Separation During Decompression In Man, Undersea Biomed. Res. 7, 107-112.
51. Nishi R.Y., 1991, Development Of Surface Decompression Tables For Helium-Oxygen Diving To Depths Of 100 msw, Undersea Biomed. Res. 18, 66-67.
52. Nishi R.Y., 1989, Development Of New Helium-Oxygen Decompression Tables For Depths To 100 msw, Undersea Biomed. Res. 16, 26-27.
53. Parzen E., 1970, Modern Probability Theory And Its Applications, New York: John Wiley And Sons Incorporated.

54. Pilmanis A.A., 1976, Intravenous Gas Emboli In Man After Compressed Air Ocean Diving, Office Of Naval Research Contract Report, N00014-67-A-0269-0026, Washington, DC
55. Powell M.P.and Rogers R.E., 1989, Doppler Ultrasound Monitoring Of Gas Phase Formation And Resolution In Repetitive Diving, Undersea Biomed. Res. 16, 69.
56. Rogers R.E. and Powell M.R., 1989, Controlled Hyperbaric Chamber Tests Of Multiday Repetitive Dives, Undersea Biomed. Res. 16, 68.
57. Schreiner H.R. and Hamilton R.W., 1987, Validation Of Decompression Tables, Undersea And Hyperbaric Medical Society Publication 74 (VAL), Bethesda.
58. Sears F.W., 1969, Thermodynamics, Reading: Addison Wesley Publishing Company.
59. Shapiro A.H., 1958, Dynamics And Thermodynamics Of Compressible Fluid Flow, New York: Ronald.
60. Skripov V.P., 1974, Metastable Liquids, New York: John Wiley And Sons Incorporated.
61. Smith K.H. and Stayton L., 1978, Hyperbaric Decompression By Means Of Bubble Detection, Office Of Naval Research Report, N0001-469-C-0402, Washington DC
62. Spencer M.P., 1976, Decompression Limits For Compressed Air Determined By Ultrasonically Detected Blood Bubbles, J. Appl. Physiol. 40, 229-235
63. Thalmann E.D., 1989, Testing Of Revised Unlimited Duration Upward Excursions During Helium-Oxygen Saturation Dives, Undersea Biomed. Res. 16, 195-214.
64. Thalmann E.D., 1985, Air Tables Revisited, Undersea Biomed. Res. 12, 54.
65. Van Liew H.D. and Hlastala M.P., 1969, Influence Of Bubble Size And Blood Perfusion On Absorption Of Gas Bubbles In Tissues, Resp. Physiol. 24, 111-121.
66. Van Liew H.D., Bishop B, Walder P.D., and Rahn H., 1975, Bubble Growth And Mechanical Properties Of Tissue In Decompression, Undersea Biomed. Res. 2, 185-194.
67. Vann R.D. and Uguccioni D.M., 2001, DAN Report On Decompression Illness, Diving Fatalities, And Project Dive Exploration, Durham: Divers Alert Network.
68. Vann R.D., Gerth W.A., and Charlton W.A., 1999, Operational Testing Of Air And Nitrox Dive Tables, Undersea Hyper. Med. 26, 48.
69. Vann R.D. and Gerth W.A., 1997, Probabilistic Gas And Bubble Dynamics Models Of Decompression Sickness Occurrence In Air And Nitrogen-Oxygen Diving, Undersea Hyper. Med. 24, 275-292.
70. Vann R.D., Gerth W.A., and Leatherman N.E., 1987, A Likelihood Analysis Of Experiments To Test Altitude Decompression Protocols For SHUTTLE Operations, Aviat. Space Environ.Med. 58, A106-A109.
71. Ward C.A., Balakrishnan A., and Hooper F.C., 1979, On The Thermodynamics Of Nucleation In Weak Gas Solutions, J. Basic Eng. 92, 695-704.
72. Weathersby P.K., Hart B.I., and Flynn E.T., 1987, Role Of Oxygen In The Production Of Human Decompression Sickness, J. Appl. Physiol. 63, 2380-2387.
73. Weathersby P.K., Survanshi S. and Homer L.D., 1985, Statistically Based Decompression Tables: Analysis Of Standard Air Dives, 1950-1970, Naval Medical Research Institute Report, NMRI 85-16, Bethesda.
74. Weathersby P.K., Homer L.D., and Flynn E.T., 1984, On The Likelihood Of Decompression Sickness, J. Appl. Physiol. 57, 815-825.
75. Wienke B.R. and O'Leary T.R., 2008, Statistical Correlations And Risk Analysis Techniques For A Diving Dual Phase Bubble Model And Data Bank Using Massively Parallel computers, Comp. Biol. Med. 38, 583-600.
76. Wienke B.R., 1992, Numerical Phase Algorithm For Decompression Computers And Application, Comp. Biol. Med. 22, 389-406.
77. Wienke B.R., 1991, Bubble Number Saturation Curve And Asymptotics Of Hypobaric And Hyperbaric Exposures, Int. J. Biomed. Comp. 29, 215-225.
78. Wienke B.R., 1990, Reduced Gradient Bubble Model, Int. J. Biomed. Comp. 26, 237-256.

79. Wienke B.R., 1990, Modeling Dissolved And Free Phase Gas Dynamics Under Decompression, Int. J. BioMed. Comp. 25, 193-205.
80. Wienke B.R., 1989, Equivalent Multitissue And Thermodynamic Decompression Algorithms, Int. J. BioMed. Comp. 24, 227-245.
81. Wienke B.R., 1989, Tissue Gas Exchange Models And Decompression Computations: A Review, Undersea Biomed. Res. 16, 53-89.
82. Wienke B.R., 1989, N2 Transfer And Critical Pressures In Tissue Compartments, Math. Comp. Model. 12, 1-15.
83. Wienke B.R., 1987, Computational Decompression Models, Int. J. BioMed. Comp. 21, 205- 221.
84. Wienke B.R., 1986, DECOMP: Computational Package For Nitrogen Transport Modeling In Tissues, Comp. Phys. Comm. 40, 327-336.
85. Wienke B.R., 1986, Phenomenolgical Models For Nitrogen Transport In Tissues, Il Nuovo Cimento 8D, 417-435.
86. Workman R.D., 1965, Calculation Of Decompression Schedules For Nitrogen-Oxygen And Helium-Oxygen Dives, USN Experimental Diving Unit Report, NEDU 6-65, Washington DC
87. Yang W.J., 1971, Dynamics Of Gas Bubbles In Whole Blood And Plasma, J. Biomech. 4, 119-125.
88. Young F.R., 1989, Cavitation, New York: McGraw-Hill Book Company.
89. Young C. and D'Aoust B.G., 1981, Factors Determining Temporal Patterns Of Isobaric Supersaturation, J. Appl. Physiol. 51, 852-857.
90. Yount D.E. and Hoffman DC, 1986, On The Use Of A Bubble Formation Model To Calculate Diving Tables, Aviat. Space Environ. Med. 57, 149-156.
91. Yount D.E., 1982, On The Evolution, Generation, And Regeneration Of Gas Cavitation Nuclei, J. Acoust. Soc. Am. 71, 1473-1481.
92. Yount D.E., 1979, Skins Of Varying Permeability: A Stabilization Mechanism For Gas Cavitation Nuclei, J. Acoust. Soc. Am. 65, 1431-1439.

Appendix A: Software And Parallel Implementation

A rundown of the LANL (data correlation) software configuration of the RGBM used in analyses is tabulated. The package is under constant refinement and updating, and can be used on open circuit (OC) or rebreather (RB) systems. It has been a mainstay in dive planning and operations here at LANL. Parameters in the model and software have been calibrated against profile outcomes in the LANL Data Bank. The same module is used to generate bubble and dissolved gas risk functions employed in likelihood analysis of data. The package has been licensed commercially, put into decompression meters, and tailored for individual needs:

1. Module: integrated bubble excitation, dissolved gas and bubble gas transfer, material equations of state for surfactants, Boyle expansion and contraction, and staging routines, with waypoints prior to ascent, for nitrox, heliox, and trimix.
2. Source Code: 1640 Lines.
3. Language/Compiler: FORTRAN 77/90, BASIC.
4. CRAY YMP Running Time: 1 *sec* for deep trimix profile with 5 gas switches on way up.
5. Input: altitude, bottom mixture/pp_{O_2}, ascent/descent rate, switch levels and gas mixtures/pp_{O_2}s, predive breathing gas, safety knobs, previous dive history.
6. Output: controlling tissue compartments, stop depth and times, supersaturation gradient, permissble supersaturation, effective bubble and gas parameters, critical phase volume, dive profile.

Commercial versions are marketed by GAP, ABYSS, and HydroSpace Engineering. Meter implementations are marketed by Suunto, Mares, HydroSpace, Dacor, Plexus, Zeagle, Steam Machines, UTC, and others in the works.

The enormous computing power and lightning speed of the LANL Blue Mountain MPP (massively parallel processor) permits fast and compute intensive numerical experiments with data. So as a variance reduction technique across the full canonical data set, using a random number generator for profiles across 2,000 parallel SMP (Origin 2000) processors at LANL, we construct 2,000 subsets, with $K = 750$ across $p \leq 0.0069$, for separate likelihood analysis, weighting each processor κ, λ, γ, and μ by the number of sample hits divided by the number of population hits. This cuts run and analysis time, plus numerical roundoff errors implicit to likelihood analysis for small r, and large K. The sorting continues through all possible profile combinations, χ, roughly,

$$\chi \propto \frac{2879!}{750!2109!}$$

which is a very large set of calculational samples for any computer, save massively parallel, very fast, large core machines available at select locations in the world. Processors with zero DCS hits in the sample contribute nothing to the total tally. Such a weighting technique has tremendous advantages in Monte Carlo applications, providing fast and reliable estimates of statistical quantities over condensed event space. At LANL, major gains are seen in particle transport, hydrodynamic, and plasma applications of Monte Carlo techniques. The method is similar to roulette, biasing, importance sampling, splitting, and other variance reduction techniques utilized in transport phenomenology. Recall that the Blue Mountain MPP boasts overall processor speeds in the teraflop range (10^{12} *binary operations/sec*). The massively compute intensive program above takes some 30 - 40 *sec*.

Appendix B: Field Data

Models need validation and field testing. Often, strict hyperbaric 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 LANL 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 RGBM Tables for air, EAN32, and EAN36 recreational 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 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 hyperbaric chamber tests for mixed gas RGBM protocols are in the works, and less stressful exposures will be addressed also – extreme here means 300 fsw and beyond;

8. as seen, probabilistic decompression analysis of selected recreational air 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 methodology at USN and Duke);

9. all divers and Instructors using RGBM decometers, tables, or Internet software have been asked to report individual profiles to DAN Project Dive Exploration (Vann, Denoble at Duke), plus to the LANL 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. 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 6 hours less decompression time for WKPP helium based diving on RGBM schedules versus Haldane schedules, with estimated 200 dives;
12. 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;
13. 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,
14. Doppler and imaging tests in the laboratory, and analyses by Marroni, Bennett, Brubakk and Wienke, and Neuman all suggest reduction in free phase counts with deep stop staging;
15. deep air RGBM Tables with surface oxygen decompression are employed by American oil patch diving companies;
16. Scorese, a NAUI instructor, and his students made a total of 234 dives on the Andrea Doria using rebreathers and RGBM (constant pp_{O_2}) RB Tables, and various nitrogen and trimix diluents. Dive abortions off rebreathers employed ranged RGBM (open circuit) Tables as bailouts, and witnessed no mishaps;
17. 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);
18. 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;
19. 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;
20. heliox RGBM Tables are being used by a commercial diving operation in Argentina;
21. the RGBM EXPLORER is also employed in scattered commercial diving operations;
22. Raine, a wreck diver in California, reports 100s of RGBM dives in the 250 fsw range with low Doppler counts;
23. ANDI, a training agency, has adopted a custom version of GAP for diver training on mixed gases, OC and RBs;
24. the Israeli Navy utilizes the ANDI GAP RGBM dive planner;

25. NAUI similarly employs a custom version of GAP for dive planning, with nominal GAP parameter settings recovering released and published NAUI RGBM Tables;
26. O'Leary, Director NAUI Technical Operations, has made over 170 dives on OC and RB systems using RGBM Tables and the HydroSpace EXPLORER to depths beyond 250 fsw, with anywhere from 6 - 9 other divers during NAUI Technical Instructor Training Courses;
27. 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;
28. the Finnish Diving Federation (FDF) has adopted RGBM Tables for recreational air and nitrox diver training, as well as light decompression exposures down to 130 fsw;
29. the Irish Diving Federation is inspecting RGBM recreational and light decompression air and nitrox tables.

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 ought not be discounted nor treated lightly. Collective information has been dubbed a *living laboratory* by segments of the technical, scientific, and operational diving community. Concurrently, it is noted that DCS spikes among table, meter, and software users have not been seen nor reported by divers, meter vendors, training agencies, and commercial operations using RGBM scheduling, nor any other deep stop algorithm.

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DISCUSSION: EARLY OBSERVATION, LANL DEEP STOP

DR. PETER BENNETT: I think the two speakers have really framed what is going to come because you will hear, certainly from the French, you'll hear from Wayne Gerth about the Navy, and you'll hear from us about half the deep stop. They're all a little different, but I think that Doppler, as pointed out by Tom, has some problems. It does not reflect necessarily always decompression sickness itself. On the other hand, the analysis by Bruce shows that in terms of risk, it does have a considerable benefit. So I would like to throw the meeting open for discussion of both Tom and Bruce's talks. Are there any questions?

DR. DAVID DOOLETTE: I have one comment and then a question. Both of you, Peter and Bruce, have talked about how NEDU has been closed down, which is kind of an unfortunate choice. Our incidence of DCS was pretty much what we predicted, and we terminated the trial as planned. I just want to clarify that. I have a question for Bruce about his databank. The 2,800 dives, are those all electronically recorded? You said somewhere that it was equivalent.

DR. BRUCE WIENKE: That's a good question, and I'm sorry I didn't bring it up. All of our stuff from the dive team is downloaded. There's still data files. We have our own bottom timers and computers that we interface.

DR. DAVID DOOLETTE: That's the data you did your problematic data on. The other data that you talked about, the other 500 dives, that's a separate set of data, is it?

DR. BRUCE WIENKE: No. That's essentially the same data. I would say -- Tim may address this later on. I would say that of those 550 dives, 300 of those are also computer downloads. The other 200 are from people that we trust to faithfully follow our tables. You would argue that doesn't always happen, and I appreciate that, but the 200 dives that were not computer downloads come from people that we have tremendous amount of respect for their reporting and their diving, and that includes one of our operators in Hawaii. Also -- I'm drawing a blank. There are also other -- training dives, you know, some really interesting training dives. Actually, I've been there when they've been doing them. These were table dives that we know that the people followed the training regime and the table very well.

DR. DAVID DOOLETTE: So the majority of the dives actually are electronically recorded?

DR. BRUCE WIENKE: Electronically recorded. Then we dump it out from a processor. We take the download from our computers. Other computers, it's a download, and then we have to transcribe it and put it into our computers for analysis.

DR. DAVID DOOLETTE: The 19 DCS is a fairly small number. Most people would say you need a minimum of 10 positives for every parameter.

DR. BRUCE WIENKE: This is not a repeated test. This is across all of diving. So I don't know what the accept/reject statistics are.

DR. DAVID DOOLETTE: Well, that's not what I mean. As far as model fitting, looks like you've got an over fit model there with having three to seven parameters.

DR. BRUCE WIENKE: No. We don't do three to seven all at once. Okay. We do -- to fit the three main constants, we do one analysis. Then we do the risk analysis on three or four parameters. If we go to the six-step null set, if you call it that -- if I go to that, then I have 6 degrees of freedom, and then in the set I may have two or three. So my effective new is two or three. So it works out pretty well. For our very, very best fit, the statistical time periods for deep are at .9. I didn't show you that.

DR. NEAL POLLOCK: Bruce, I was curious about your case counts. Can you give us some information on how you collected those? How firm are those estimates of the DCS? Where do they come from?

DR. BRUCE WIENKE: Well, I'd have to go back in the data files. Our stuff is generally --

DR. NEAL POLLOCK: Bruce, you gave numbers that were not just yours. You had estimates out of 20,000 exposures. I'm curious where those counts came from.

DR. BRUCE WIENKE: I'd have to go to the slide, but those accounts came from meter folks, from training agency folks, software folks. I think three or four. Tim may have more statistics. As far as cave diving goes, I'd have to go look to see what the cave diving feedback is. I don't have a lot of cave diving. We do have some of the WKPP profiles, and Jarrod will talk about that. But outside of that, I'd have to go look. Are you interested in cave diving statistics?

DR. PETER BENNETT: Would you say those symptoms or signs were more oxygen toxicity than decompression sickness?

DR. BRUCE WIENKE: No. Of the 20 cases and across the profiles, we don't -- I don't really know and whether it's -- oxygen toxicity is a complicating effect. All I know, Peter, is that for the kinds of data in our databank, on the hits, it's always DCS, okay. We don't have convulsions under water. We don't have passouts under water. It's always pain, one, two or three and as I said, we do -- the profiles that we dive violate all of the traditional clocks, CNS clocks, OTU, 650 OTU requirements and things. The OTUs were generally always under, but the CNS clock, the oxygen toxicity clock, were generally over. We're in the 1.5 to 1.8 range on a lot of our dives. I don't recall on any of these dives that we ever had an ox-tox problem.

DR. NEAL POLLOCK: My interest was in how much confidence we could put in those estimates. It seemed like they were fairly modest numbers and I was just curious what kind of structure there was in trying to collect those counts.

DR. BRUCE WIENKE: Well, you know, they're computer downloads. That's the data. I don't know -- I guess I don't understand -- the confidence that you put into them? I don't know. I'd put the same confidence in those numbers that -- yet, some people are shooting over to DAN for the recreational diving.

DR. NEAL POLLOCK: Again, I'm not really talking about the profiles. It's when you have the estimate saying that there were 300,000 dives done on this model, and they're saying they have 20 cases of DCS reported, I'm wondering how they collected those cases. Are those underestimates?

DR. BRUCE WIENKE: Yes, that's anecdotal. As I said, I pulsed meter folks, pulsed the dive agencies who are using these protocols and I asked for their best estimates. That's to give you. Now, you can take it or leave it, okay, as far as the estimates, these anecdotal estimates go. You may have experience with very honest people who furnish you statistics. Maybe we don't have that.

DR. PETAR DENOBLE: My question refers to the same set of data. All of his data, I have about 100 times less incidence. Your LANL database has incidence of DCS about 1 percent.

DR. BRUCE WIENKE: It's .06.

DR. PETAR DENOBLE: This data here, they have incidence of 1 per 100,000 or 1 per 20,000, so it's 100 times less incidence. So how do you relate that to your data?

DR. BRUCE WIENKE: We're looking at that. Look, we have some analysis that Biometrica has asked us to furnish to them. Those types of questions, the significance between the classes we hope will address. But, yes, you're right. If you're saying that the statistics are scarce, you're right. We have 20 cases in 2,800 dives. The risk is certainly higher by a factor of 10 overall in that database versus what, for instance, you might see in your DAN databases, where it might be a hundred or a tenth less than what we get.

DR. KEITH GAULT: Bruce, with the slides you had with our two schedules, these slides you have the two NEDU schedules with your own, there are two 70-foot stops for your schedule. Does that indicate a gas change? On your slide, where you have the numbers with the two 170 for 30 dives, and you've got your own schedule.

DR. BRUCE WIENKE: Oh, no, no. Those were strictly air dives.

DR. KEITH GAULT: Is the 70-foot stop just repeated then? You've got two 70-foot stops.

DR. BRUCE WIENKE: Oh, you mean there's a typo in that table?

DR. KEITH GAULT: I'm just wondering if that indicated that you had to do something –

DR. BRUCE WIENKE: No. I'm sorry. That's a typo and I'm sorry I missed that. I was in a hurry.

DR KEITH GAULT: Before that, your model indicates that our profile has a 10.5 percent risk.

DR. BRUCE WIENKE: Yeah. The risk that we get is higher than what you observed in yours -- what did you have?

DR. KEITH GAULT: 5.5 percent.

DR. BRUCE WIENKE: You had 198 dives with 11 cases. I mean, our risk may be overestimates that you really see. That's okay for us, may not be okay for you.

DR. KEITH GAULT: In some of your literature, you indicated you had used that as calibration data. Were the NEDU dives used?

DR. BRUCE WIENKE: No. We're not using the NEDU in any of the stuff that we have shown here. Your information -- I asked years ago, and we had a miscommunication between Wayne and myself. He never got my email. I asked him for the data, but I didn't get it. So when we did all this, I didn't have the data. But the profile I showed for NEDU I believe you guys have published. At least we pulled it off of some source.

DR. KEITH GAULT: That was UHMS last year in a poster. It was displayed in a poster last year?

DR. BRUCE WIENKE: Either that or somebody sent me an abstract or something.

DR. ALF BRUBAKK: I have a comment that relates both to what Tom said and what you've just presented. I mean, the whole analysis here relates to the fact that you describe decompression sickness or decompression incidence in the correct way. And it was commented here about the false positives. I maintain that the problem with false negatives is a much bigger one. The study that we did about 10 years ago showed that for the most experienced divers, if you asked them details about their experience or what symptoms they have experienced as divers, you'll find that something in the order of 70 percent of the most experienced divers have had problems that would have led to treatment had it been reported. So, actually, using that kind of data to judge if a procedure is better or worse or more successful, I don't think you can do that because you do not know exactly what people call decompression sickness, and there's a lot of not reporting. So there are errors both in the positive and the negative way, but I maintain that the negative false positive -- negatives are larger than the positives.

DR. TOM NEUMAN: Let me hit that one because that has to do with the clinical aspects of the diagnosis of decompression sickness. I did not mention false negatives at all because there is no way to assess them in the setting of what we're doing. What Alf has described raises a potential issue. However, everybody, again, has to be careful with the methodology that's being used. What Alf is describing is classic error of what's called "study bias." And there are all sorts of errors that go into diagnostic and medical experiments. And we call these errors, when they're systematic, "bias." You don't realize that you've got it when you do it, but this description, Alf, is a classic study bias. The more you look for something, the more you find it. And so you have to be very careful in defining what you're talking about, which brings us back to the point that I made: The right way to do this is with double-blinded controlled trials with an a priori definition. Anything off of that is going to produce difficulties on each side. So that's why a surrogate becomes probably the best way to do things, where you can quantitate it, although there are problems with it, but at least you can define an end point with a Doppler score. I mean, you can just say, we're not going to accept Doppler scores greater than two or pick a number.

You can do it in a variety of different ways. Now, the one other thing I have to say is it was pointed out to me there's a typo in my presentation on the graph, where it says 210 for 50 series, where it says Group B, that should be Group C. And where it says Group C, that should be Group B. The table does not correlate with the figure. If you look at these two slides, you should be able to figure it out pretty easily, and I'm sorry for the typo. I'll correct it for the presentation.

DR. BRUCE WIENKE: Speaking of Doppler, I think Alf asked me if we were ever wired in our CC operations. And the answer to that is, no. We are burdened with a lot of other things in operational sense.

KARL HUGGINS: Just relating to Tom's talk, one of the things that we found back at the University of Michigan, when we were doing 165-foot dives on the Navy schedule, was a large amount of skin itches and throwing in a one-minute stop at 40 feet pretty much eliminated that. That was just sort of anecdotal, that we just threw in. That was chamber dives. Then on Bruce's talk, the question on the anecdotal data on the dive computers and the software, the question with that data, it's going to be real soft, if any value at all, but how many of those people in that database actually went to the limits of the models? And you can't pull anything out of that unless you have that data where, I'm assuming, Bruce, your group were diving right up to the limits of the model you calculated.

DR. BRUCE WIENKE: Well, for the decompression part, we certainly were diving out to what our schedules predicted, but I think what you're saying is certainly true. It underlines a fact that not all divers, particularly in the recreational regime, dive out to the limits of the NDL tables. You know, the risk associated with going to 80 feet for 40 minutes, might be 1.4 or 1.3, whatever. Most divers don't go that far, so their risk is certainly below that. But, the point that I like and the point that I make about global data is that you get a mix of what's going on and in the decompression arena, it's nice to have a lot of data from a lot of sources, nonanecdotal. I still value the anecdotal data in the sense that it is -- whether it's inflated or deflated, it is a measure of the fact that people are using these things and there are no DCS spikes. Believe me, in the meter business, and you can talk to some of the folks who are here, if there's DCS spikes, that meter and that algorithm gets trashed as fast as possible because of liability issues, marketability. So we don't see DCS spikes in a bubble model like this. Just like with most meter implementations of standard recreational diving, we don't see DCS spikes either. You may see -- the incidence rate may be a little higher from people who don't know how to use computers, but just in general, like Ed Lanphier once said, tables are validated by users, not by scattered tests. Scattered tests are necessary. But in the case of the U.S. Navy repetitive dive tables -- and some of the Navy guys here may want to correct me -- Ed told me years ago, he said, you know, we did one or two dives, repetitive dives, and we signed off on it. You know, if you're doing testing and you're rejecting or accepting, you don't have any type of statistical basis at all there. But yet the Navy tables with repetitive groups for light decompression diving made it out there, and they were diving for a long time. We found problems for deeper exposures. I think the same kind of metamorphosis has been going on here in the bubble model stuff. So, thanks.

DR. WAYNE GERTH: First of all, I have to make an apology to Dr. Neuman for interrupting his talk. He saw me listening rather animatedly to his speaking and had the grace to acknowledge me there. I'm sorry, Tom, I didn't mean to interrupt.

DR. TOM NEUMAN: If I was offended, I would let you know.

DR. WAYNE GERTH: We will show this afternoon, the kind of stop you added was one that would correct for an excessively fast decompression rate to your first stop. This would reflect probably what you did more accurately; the total decompression times that you have tabulated here don't show the impact of that faster ascent rate. You do show, in fact, that you had an ascent rate, in any case, whether you had your deep stop -- in those five-man dives, whether you had that deep stop or not, you showed a 60-foot-a-minute ascent rate, when, in fact, it was a much faster for those cases where you had the added extra stops.

DR. TOM NEUMAN: I'd have to check. I don't remember.

DR. WAYNE GERTH: So, I'm not surprised that you found what you did in your case. Now, the other ones, where Bruce was so nice to review our talk before we had a chance to do it, we'll have a chance to address that later.

DR. BRUCE WIENKE: I'm really sorry, Wayne. I don't think, though -- knowing you and knowing your talk, I don't think I've stolen your thunder whatsoever.

DR. PETER BENNETT: As a matter of fact, he gave a very good paper because it's a stepping stone to where we're going. There's no doubt that you can see by the controversy already going on that he set the scene very well before we step into each of these categories and get into more depth. I think it was a good move, and I think Bruce did a good job. There's going to be plenty more controversies.

DR. CHRISTIAN GUTVIK: I have a question regarding the RGBM implementation. In one of those slides you mentioned that you have kind of two versions for your model, algorithm and ones that reduce to the sole gas mode. Is that the simple version or the full algorithm?

DR. BRUCE WIENKE: The present version in SUNTO -- and the SUNTO people are here -- is what we call "a modified RGBM." It is the full model, the full bubble model, fitted to very, very light decompression as far as the parameter space and the M values are concerned. What we do is look at full-up RGBM profiles and then we look at what the SUNTO M values are, then we would adjust those for different kinds of diving. So what's in the SUNTO computer right now is what we call "the modified approach." It's for light recreational air and nitrox, very, very light decompression diving. On the other hand, you have full-up RGBM in, for instance, the HydroSpace computer. You have it also going to be coming out -- I'm not revealing anybody's marketability because it's already out there. You're going to have a full-up RGBM in the Atomic Aquatics model. And there are other places that I can't talk about that are also going to bring it up.

DR. PETER BENNETT: The last question.

DR. GEORGE PERDRIZET: I'm amazed at the elegant modeling and mathematics, but I think this is a question for Bruce, and then one for Tom. One of the things that I would like to push more into is the biology behind what's happening here. Bruce, your database, do you control for the variable of time between exposures by your individuals?

DR. BRUCE WIENKE: We don't control it. It's computed. What we do is -- during surface intervals, if that's what you meant, we would continue -- in other words, the dive -- it's a dive from the time you go underwater until out. In between exposures, we're still -- the computer is still computing bubble diffusion and things like that. So that hopefully during most of the time, some of the bubbles are outgassing at a faster rate than others. But we look at the whole bubble distribution. The bubble distribution goes from the excitation radius out to very large bubbles, maybe 4- or 500 microns.

DR. GEORGE PERDRIZET: I'm referring to a simpler level. In other words, these are stressful events. And your host, your diver, is going to respond in an adaptive way to those stresses. It will dramatically alter their resistance to a hit, and I think, you know, there's data -- the data that I like best is from Lager, in the 1800's, looking at caisson divers, and how he described acclimatization or an acclimatization phenomenon. I think with these types of rare events, the host resistance to the hit, if you will, has to be controlled for.

DR. BRUCE WIENKE: No. I mean, there's no doubt of that.

DR. GEORGE PERDRIZET: This is a time period of about a week to 14 days.

DR. BRUCE WIENKE: You're talking about adaptation?

DR. GEORGE PERDRIZET: Yeah. So we're not controlling for that. I have a question for Tom, you know, I'm a physician. I don't think you can diagnose this condition yet and so we've got a real problem here. The analogy that I will give you, is I come from Connecticut, the land of lyme disease and if you just want to do an interesting analogy, I think if we were to have a discussion about lyme disease, we would have a discussion about DCI. Until you develop a way to diagnose it, I think we're going to continue to argue back and forth. Our state is embroiled in a huge conundrum of whether the patient has chronic lyme disease or not simply because we lack a gold standard to diagnose it. Furthermore, just like DCI, your symptomatology is very nonspecific and so people get aches and pains and whatnot, just as you point out. So I think you're right on in terms of applying rigorous testing methodology, but I would go further and say that we don't have causality here. It seems to me -- and I'm a newcomer to this -- but bubbles are sufficient, but not the only story. They're necessary, but not sufficient to cause the disease, but I don't think we have a good way to diagnose it and until that happens, I think we're going to be like the lyme disease population.

DR. TOM NEUMAN: I couldn't agree with you more and this is one of the reasons that I've stressed over and over again what I believe is necessary in this arena, which is an a priori definition. Now, just because things are subjective and difficult, it does not mean that you cannot create a definition for the process you're looking for. Acute rheumatic fever is a subjective disease. We have a definition for it. It's called "the Jones criteria." The American Rheumatism Association has a definition for systemic lupus erythematosus. Talk about a disease that is hard to diagnose. Now, we can disagree with aspects of the definition, but at least we're all talking about the same thing once we have a definition. The definition won't be perfect, but at least once we have one, we're not talking about where one person diagnoses decompression sickness because somebody's teeth itch, and in other case, we're talking about decompression sickness where somebody has transverse myelitis. And so this is the absolute critical reason that we need an agreed-upon, an a priori definition of what we're talking about. Will it be perfect? No, but it is a step that will go long way to solving the problems that we're trying to talk about. It will not, however, solve the problem that Alf brought up, which is a real one, of false negatives. So we need to think about that at the same time that we're creating the definition.

DR. PETER BENNETT: With that, we have to close because we have the coffee break at 10 o'clock. We'll have a chance to have more discussions. We're going to come back to these topics again and again.

DR. PETER BENNETT: We're about to move into the technical session. They dive anyway, and it works. But before that, I think it would be useful to have a technical overview. And I've asked Simon Mitchell, Department of Anesthesiology, Auckland City Hospital, to give us a technical overview before the technical guys talk about deep stop.

DR. SIMON MITCHELL: I suppose if we're going to talk about technical diving, it's incumbent on us to define it.

TECHNICAL DIVING OVERVIEW

Simon J. Mitchell

ABSTRACT:

There is no universally agreed definition of technical diving, but it is characterized by decompression diving, the utilization of gases other than air, and equipment configurations other than single cylinder open circuit scuba in order to visit deeper depths or extend underwater duration or both. The adoption of these techniques which in the past have been more commonly associated with occupational or military diving has been driven largely by wreck and cave divers wishing to explore deeper wrecks and deeper and /or longer caves respectively.

The operating depth and duration of single cylinder scuba air is limited by the small amount of gas that is carried, and the unfavorable characteristics of air as a deep diving gas including its high density, and high nitrogen and oxygen fractions which at sufficient depth predispose to narcosis and oxygen toxicity respectively. Technical divers utilize complex multiple open circuit cylinder configurations or rebreather devices to extend duration. Helium is lighter and non-narcotic, and is substituted partly or wholly for nitrogen in deep diving gases. The oxygen fraction is also tailored to the depth being visited. Multiple gas mixes with progressively increasing oxygen fractions are frequently utilized during decompression to optimize inert gas elimination.

Using these methods recreational technical diving exponents have extended “bounce dive” depths and durations well beyond limits adopted by the more conservative occupational and military groups. Technical divers have visited depths exceeding 300m and open ocean wrecks as deep as 200m. Caves as deep as 280m have been dived, and a cave system 90m deep and 11 kilometers long was recently traversed over 7 hours of bottom time followed by 15 hours of decompression. Although these examples represent current boundaries established by cutting edge exponents, there is a vastly greater number of participants who are “routinely” diving to depths between 60 and 100m.

Although there are no definitive figures, limited data and anecdote shared by diving physicians and divers seem to indicate that technical diving is hazardous. There is reason to believe that fatality rates are much higher than for scuba air divers, particularly among rebreather users. Moreover, there are numerous episodes of “unexpected” decompression sickness associated with these dives, and this has given impetus to improvement of decompression algorithms for deep “bounce” diving.

Reference

1. Mitchell S. Technical Diving. In: Moon RE, Piantadosi EM (eds). Dr Peter Bennett Symposium Proceedings. Durham, NC: Divers Alert Network, 2007:55-70.

PAPER:

INTRODUCTION AND DEFINITION OF "TECHNICAL DIVING"

One of the most significant trends in recreational diving practice over the last 15 years is growth in the use of so-called "technical diving" methods. These methods have been adopted mainly to facilitate one or both of two goals: to extend dive duration, and to facilitate dives deeper than the conventional "recreational limit" of 40m.

There has been much debate over which diving methods should be referred to as "technical diving" and which should not. This is because techniques such as nitrox diving have now become so mainstream that some no longer consider they deserve the "technical" designation. Partly because of this "shifting definition", it may be that the term has outlived its usefulness. Nevertheless, for the purposes of this paper, technical diving is defined in keeping with its goals as stated above. Thus, it includes diving that *intentionally breaches no-decompression limits, utilizes gases other than air, or equipment other than single-cylinder open circuit scuba*. This broad definition embraces equipment applications such as multiple cylinder configurations or rebreathers, and techniques such as decompression diving, and diving using nitrox or gas mixes incorporating helium.

The term "bounce diving" must also be defined and distinguished from "saturation diving". In recent years, most very deep dives performed by occupational divers have been "saturation dives" involving long bottom times (often days or weeks spent living in a pressurized habitat) followed by long slow decompressions. After a certain period under pressure the diver's tissues become "saturated" with as much inert gas as can be absorbed at that pressure and so extending the period at depth for longer incurs no extra decompression obligation. This is an efficient way to conduct deep working dives, and though long, the decompression protocols are well tried, well understood, and conducted with dry comfortable divers in pressurized chambers which allows rapid effective responses to any symptoms or signs of decompression sickness (DCS).

Technical divers do not stay at pressure long enough for saturation of all tissues and so their decompressions are much shorter, and rarely employ chambers or dry environments. This approach involving relatively short bottom times and decompressions is frequently referred to as "bounce diving". It is an inefficient approach to deep diving because even short bottom times still obligate the diver to significant periods of decompression. Moreover, although it is almost counter-intuitive, bounce dive decompressions are almost certainly less safe than saturation decompressions. They are less controlled, conducted wet, associated with greater compulsion for expediting completion (because the diver is tired, cold, wet, thirsty and hungry), and they involve less precise assumptions about inert gas uptake by tissues prior to starting the decompression.

The primary aim of the decompression and deep stop workshop is to critically review the optimal means of decompressing from deep bounce dives. However, the co-chairs recognize that there will be attendees whose familiarity with the broader technical diving field is limited. The aim of this paper is to provide an overview of technical diving for such participants, to better place the issue of decompression in context. The paper is based largely around one written by the same author for the Peter B. Bennett symposium hosted by The Divers Alert Network, and Duke University in 2004.[1] We will discuss the factors that limit the duration and depth of recreational scuba air dives, and describe the technical diving methods that have evolved to overcome those limitations. A summary of the current boundaries of technical diving will be presented, along with some commentary on the safety of technical diving practices.

THE LIMITATIONS OF RECREATIONAL SCUBA AIR DIVING.

The limitations of recreational scuba air diving can be considered under the subheadings of limitations on duration, and limitations on depth.

The limitations on duration during recreational scuba air diving

There are a number of factors that limit the amount of time that the scuba air diver can spend underwater.

Breathing gas supply

Perhaps the most intuitively obvious limitation on the duration of a scuba dive is the amount of breathing gas that can be carried. Conventional scuba diving is conducted with a single cylinder of air. There are many options, but typically these cylinders have an internal volume of around 12 L and they are filled to pressures around 200 bar. By way of example, if we assume a surface air consumption rate of 20 L/min and a requirement to plan a dive leaving a 25% reserve (50 bar), we can calculate the duration of this cylinder at 50m (6 bar ambient pressure) as follows:

$$([200 \text{ bar} - 50 \text{ bar}] \times 12) \div (20 \text{ L/min} \times 6 \text{ bar}) = 15 \text{ minutes}$$

Moreover, though obvious, it must be pointed out that while this indicates potential duration at depth, the gas supply must also last for the descent, ascent, and any decompression time required during the latter. It follows that the actual duration available at depth using a typical single cylinder of gas is considerably shorter.

No decompression limits (NDLs)

Conventional scuba diver training teaches “no decompression diving” in which divers limit their underwater duration to avoid exceeding so-called “no decompression limits” and the need for obligatory decompression stops. These limits vary according to the dive table or computer used, but all become increasingly restrictive at deeper depths (see Table 1). Indeed, as depth approaches the recommended recreational limit of 40m there is very little time allowed at depth before the diver is subject to an ascent ceiling, and the dive becomes a “decompression dive”.

Table 1. No decompression limits (minutes) from 3 commonly used dive tables. Note, DCIEM refers to the Canadian Navy Tables, and RDP refers to the PADI Recreational Dive Planner.

Depth (m)	US Navy	DCIEM	PADI RDP
9	310	300	219
12	200	150	147
15	100	75	72
18	60	50	56
21	50	35	37
24	40	25	29
27	30	20	25
30	25	15	20
33	20	12	16
36	15	10	13
39	10	8	9

Cold
Depending on the water temperature, and the quality of the thermal protection employed, cold may become the limiting factor in the dive duration.

The limitations on depth during recreational scuba air diving
Recreational scuba diver training organizations have set a maximum recreational scuba depth limit of 40 m. This maximum is somewhat arbitrary, but a “limit” was undoubtedly necessary in recognition of the increasing influence of various factors that are more likely to complicate an air dive as depth increases.

Nitrogen narcosis
The narcotic effect of the nitrogen in air becomes significant at depths beyond 30 – 40 m. Despite some divers’ claims to the contrary, this occurs in everyone, and it is progressive as depth increases. Narcosis has an insidious onset, and may provoke accidents by causing divers to make mistakes. At extreme depths cognitive function can become dangerously impaired and unconsciousness may result.

Oxygen toxicity
The inspired PO_2 increases linearly with depth, and excessive PO_2 can lead to oxygen toxicity whose first manifestation may be unconsciousness and seizure. The recommended “safe” threshold for PO_2 is somewhat arbitrary, varies between diving organizations, and the risk of toxicity is also time dependent (see later). Nevertheless, many recreational organizations recommend 1.4 bar as an absolute exposure limit irrespective of duration. We can calculate the ambient pressure at which an air-breathing diver ($FO_2 = 0.21$) will be breathing 1.4 bars of oxygen:

$1.4 \div 0.21 = 6.7$ *bars*

Since each 10 metres of seawater exerts 1 bar of pressure, 6.7 bars corresponds to:

(6.7 – 1 bar [for the atmosphere above the water]) x 10 = 57 metres depth.

Thus, if the absolute maximum PO_2 is 1.4 bar, then the "maximum operating depth" or "MOD" for air is 57 m.

Work of breathing

At all depths, air must be supplied by the regulator at ambient pressure in order to facilitate breathing. Air supplied at these greater pressures is denser, and there is greater resistance to flow through both the orifices of the regulator and the airways. It follows that the work required of the respiratory muscles in order to initiate and maintain normal air flow (the "work of breathing"), increases as depth increases. Since air is a "heavy" gas this can become very noticeable at extreme depth. Indeed, it would become exhausting to perform significant work at extreme depths breathing air.

TECHNICAL DIVING METHODS

Individual technical diving techniques have evolved to address one or more of the above limitations. Some are primarily intended to enhance duration, while others are specifically targeted at extending the depth range. Most commonly, several of the techniques discussed below are combined to facilitate longer dives beyond the recreational depth range. Such dives would be dangerous at best, or simply impossible if performed using conventional single tank scuba air diving.

Nitrox diving

The term "nitrox" refers to mixtures of oxygen and nitrogen in which there is more oxygen than found in air. For this reason, nitrox is often referred to as "enriched air" or "enriched air – nitrox" (EANx). By convention, the mix is described by reference to its oxygen content. Thus, if a nitrox mix contains 36% oxygen, then it is referred to "nitrox 36" or "EANx36". Literal application of this nitrox classification system would designate air as "nitrox 21" but air is never referred to in this way.

The advantages of nitrox diving

Reduced uptake of nitrogen

Since the amount of nitrogen taken up into the diver's blood and tissues during a dive is proportional to the inspired partial pressure of nitrogen, any reduction in the inspired fraction of nitrogen will reduce the amount of nitrogen absorbed. This can be illustrated by consideration of Table 2, which compares the approximate pressures of nitrogen breathed by an air diver and a diver using nitrox 40 over a range of depths.

Table 2. Inspired pressures of nitrogen at various depths when breathing air and nitrox 40. Note 1: for simplicity, the % of nitrogen in air is rounded to 80% and the fraction of nitrogen (FN_2) in air therefore equals 0.8. Note 2: Some technical diving agencies would consider the use of nitrox 40 at 30m to be unwise because this gives a PO_2 of 1.6 bar. It is cited here as a convenient illustration of the potential effect of different nitrox mixes on the PN_2 breathed at depth.

Depth	Ambient pressure (bar)	PN_2 in air (bar) ($FN_2 = 0.8$)	PN_2 in nitrox 40 (bar) ($FN_2 = 0.6$)
Surface	1	0.8	0.6
10 m	2	1.6	1.2
20 m	3	**2.4**	1.8
30 m	4	3.2	**2.4**

A striking feature of these data is that the nitrox 40 diver is breathing the same pressure of nitrogen (2.4 bar) at 30 m as the air diver at 20 m (see shaded cells). It follows that the nitrox diver at 30m will be absorbing the same amount of nitrogen as an air diver at 20 m. Put another way, with respect to nitrogen absorption, the nitrox 40 diver at 30m is at an “equivalent air depth” (EAD) of 20 m.

This reduction of nitrogen absorption during nitrox diving is an advantage that can be utilized in several ways.

Firstly, the nitrox diver can use the reduced absorption of nitrogen to increase allowable dive time. The equivalent air depth can be used in calculation of no decompression limits (NDLs) (either using a dive table or nitrox dive computer), and since the EAD is always shallower than the actual depth, there will be an advantage in terms of allowable bottom time. In the example given in Table 2, the diver using nitrox 40 at 30 m has an EAD of 20 m. Using the US Navy standard air tables (see Table 1), this diver is theoretically limited by a NDL of 50 minutes (the air diving NDL for 20 m) instead of 25 minutes (the air diving NDL for 30 m).

Alternatively, the nitrox diver can ignore this potential for increasing duration, and assume that he or she is using air for the purposes of bottom time calculation. In other words, the diver would use air diving NDLs. This has the advantage of widening the safety margin for avoiding decompression sickness.

Finally, nitrox is frequently utilized for the purpose of accelerating decompression from deeper air or mixed gas dives (see later). In this context, the relatively low nitrogen content minimizes further absorption of inert gas, while the high oxygen content maximizes the gas partial pressure vacancy in tissues and venous blood (frequently referred to as the “oxygen window”) that promotes the out-gassing of helium absorbed during time at greater depth. The choice of nitrox for this purpose is based on the mix that will give the maximum inspired fraction of oxygen considered safe for the depth of use.

Other putative benefits

Since the inspired PN_2 is lowered during nitrox diving, it is often claimed that nitrox reduces nitrogen narcosis. A counter argument based on the relative physical properties of nitrogen and oxygen holds that oxygen is just as narcotic as nitrogen, and that nitrox diving merely shifts the mix's narcotic potential from nitrogen to oxygen. However, at the inspired PO_2s allowed in diving, it is very unlikely that PO_2 at the cellular level will change significantly, and there must therefore be doubt that oxygen narcosis would be significant. No matter what the reality, any reduction of narcosis by using nitrox is likely to be small, and for dives to significant depths the best way to reduce narcosis is to introduce helium into the mix.

There is also prevalent anecdote which holds that nitrox diving reduces post dive fatigue. The rationale for this claim is beyond the scope of this review, and it has certainly never been demonstrated objectively. Indeed, in the only double blinded evaluation of the phenomenon, no difference in fatigue could be demonstrated.[2]

The disadvantages of nitrox diving

Oxygen cleanliness

Since oxygen promotes combustion, all materials that come into contact with oxygen-rich mixtures must be more rigorously cleaned to remove any flammable contaminants. It is generally agreed that if mixes containing more than 40% oxygen are used, then all equipment including cylinders and regulators must be "oxygen clean" and dedicated for nitrox use only. Many believe that all cylinders for nitrox use must be dedicated and oxygen clean, no matter what mixes are used, because the most frequently utilized method of making nitrox involves first bleeding pure oxygen into the cylinder, and following this with air.

Oxygen toxicity

Perhaps the most important "disadvantage" of nitrox is that the use of oxygen-rich mixes increases the potential for cerebral oxygen toxicity, especially if appropriate precautions are not strictly followed. A PO_2 of 1.4 bar is widely considered a safe limit for underwater use, though most agencies consider brief exposures to 1.6 bar to be tolerable. Much beyond this and the risk of toxicity begins to rise precipitously. In this regard, it should be obvious that the use of nitrox is not a technique that facilitates deeper diving, quite the opposite in fact. Its advantage lies in prolongation of "shallow" dives, and acceleration of decompression from deep dives.

Clearly, one of the key issues in nitrox diving (or in its use during long decompressions) is correct planning to avoid exceeding either absolute or time weighted exposure limits[3] such as those published by NOAA. As the depth and time range of technical dives has been extended over the years, this has become a problematic issue. Indeed, exceeding conventional time weighted limits has become almost unavoidable during decompression from typical deep bounce dives, especially during the shallowest stop (eg 3m) when the diver is frequently breathing 100% oxygen rather than nitrox. There are no definitive data describing the risk of such situations, though anecdotally at least, seizures seem very rare in resting divers breathing oxygen at $\leq$ 1.4 bar on their final decompression stop, irrespective of their prior oxygen exposure.

Configuration of equipment for longer dives

Both nitrox diving and the other technical diving methods that are yet to be discussed may involve much longer underwater durations than would be possible with the equipment configuration employed by conventional recreational scuba divers. Therefore, before moving on to a discussion of other techniques, it is logical to briefly consider the changes in equipment configuration used by technical divers to extend their underwater duration.

Increasing gas supply

If we ignore the possibility of using rebreather technology (which is discussed later) then the obvious way of increasing gas supply is to carry more gas using larger cylinders, more cylinders, or more large cylinders!

Cylinder size and pressure

High capacity steel cylinders with a slightly higher pressure rating than the most frequently encountered aluminum recreational cylinders are popular with technical divers. Steel cylinders with a working pressure of 232 bar and water capacity of up to 18 L are readily available. The compressed gas capacity of such cylinders is therefore 232 bar x 18 L = 4176 L. This compares with the aluminum cylinders most frequently encountered in recreational diving (working pressure of 207 bar and water capacity of 11.2 L) which hold 2318 L of compressed gas. DIN ("Deutsche Industrie Norme") couplings that have a screw-in male fitting on the regulator that completely traps the O ring inside the female fitting on the tank valve are considered standard in technical diving.

Twin sets

Technical divers frequently utilize two back mounted cylinders instead of the conventional single cylinder. Each cylinder has its own regulator and independent submersible pressure gauge, and the cylinders are usually "manifolded" to potentially form one large common gas supply. There are 3 isolation valves in the system: a pillar valve on each cylinder and an isolation valve in the middle of the manifold. In this arrangement, turning off the pillar valve on one of the cylinders isolates the regulator on that side, not the gas in the cylinder. Thus, if the left hand pillar valve is turned off, the left hand regulator is isolated and cannot be used, but the right hand regulator still draws gas from both cylinders. If the manifold isolation valve is closed, then the system is effectively reduced to two separate scuba sets. The reason for this arrangement is to maximize redundancy while coping with common scuba system failures such as a free flowing regulator. One of the regulator second stages in a manifolded twin set typically has a long hose for the purpose of air sharing.

Sling tanks

Twin sets effectively double the volume of gas that can be carried conveniently on the diver's back. In many technical diving situations this is still not sufficient, or alternatively, different nitrox mixtures might need to be carried to allow accelerated decompression. With the capacity for carrying back-mounted gas fully utilized, the next option is to use sling tanks.

Sling tanks are usually single scuba cylinders, each with its own regulator and submersible pressure gauge. Sling tanks are usually attached to either or both sides of the diver using snap clips to D rings on the diver's harness or BCD. Cylinders of any size can be used, depending on the diver's gas requirements and ability to cope with the extra equipment bulk. Perhaps the most important issue with respect to the use of sling tanks is clear labeling and consistent positioning, especially where they are used to carry different gasses for different purposes.

Rebreather diving

While it is true that the above strategies do extend the gas supply, none address the inherent inefficiency of open circuit systems that vent exhaled gas to the water. Open circuit scuba is a very inefficient system, particularly when expensive gas mixes containing helium are being used at deeper depths. With a surface air consumption of 20L/min the diver at 90m will breathe 200L/min surface equivalent of gas just to extract 0.5 – 1.5L/min of oxygen. Rebreathers recycle the breathing gas so that much less gas is used, and the cost of expensive gases like helium is vastly reduced.

A *breathing loop* with a collapsible bag (“*counterlung”*), *CO_2 scrubber* and *gas addition system* are the fundamental constituents of all rebreather systems. Several compounds will react with and remove the CO_2 in the expired gas, with soda lime (a mixture of sodium hydroxide and calcium hydroxide) the most commonly used. The reaction liberates heat, and the consequent warming of the breathing gas is one clear advantage of diving a rebreather in temperate water. Effective scrubber duration is influenced by a variety of factors, not the least of which is the amount of scrubber material contained in the canister. In addition, the reaction is inhibited at cold temperature, and scrubber duration is reduced when diving in very cold water. It will also be reduced if the diver is indulging in a pattern of hard underwater work and is therefore producing more CO_2. Some rebreathers incorporate devices that use temperature sensors to measure progression of the reaction front through the scrubber material. These give some indication of remaining scrubber life, and possibly, of imminent breakthrough of CO_2 into the inspiratory side of the loop. There are still no rebreathers that analyze the loop gas for CO_2.

The basic components (listed above) of a rebreathing loop are common to all types. It is essentially the gas addition system that distinguishes and classifies them. There are two types available to the recreational technical diver: “semi-closed circuit” rebreathers and “closed circuit” rebreathers.

Semi-closed circuit rebreathers (SCRs):

The vast majority of applications for SCRs are in the recreational depth range, and these devices are usually seen as tools for extending gas supplies on “shallow” dives rather than tools for deep diving.

Most SCRs use a relatively simple gas addition system that feeds nitrox into the loop at a fixed rate. The use of a constant mass flow regulator ensures that the same number of molecules of gas enter the loop no matter what the ambient pressure. The task of calculating nitrox flow rates is usually undertaken by the SCR manufacturers who provide preset rates for various nitrox mixes. The higher the fraction of oxygen in the nitrox, the lower the flow rate required and the longer the duration of the nitrox supply. However, the trade off when using very oxygen-rich mixes is a shallower maximum depth. The rate of fresh gas addition is calculated to be more than enough to maintain an appropriate fraction of oxygen (FO_2) in the loop at the level of work anticipated (and this inevitably results in frequent liberation of bubbles from the loop), however, the FO_2 will vary with the workload (and oxygen consumption) of the diver. The consequent uncertainty over the exact oxygen content in the loop may be of concern when using those SCRs that lack an oxygen monitoring system. A stylized design for a SCR is given in Figure 1.

Closed-circuit rebreathers (CCRs):

Figure 1. stylized layout of a semi-closed circuit rebreather showing the essential components common to all systems.

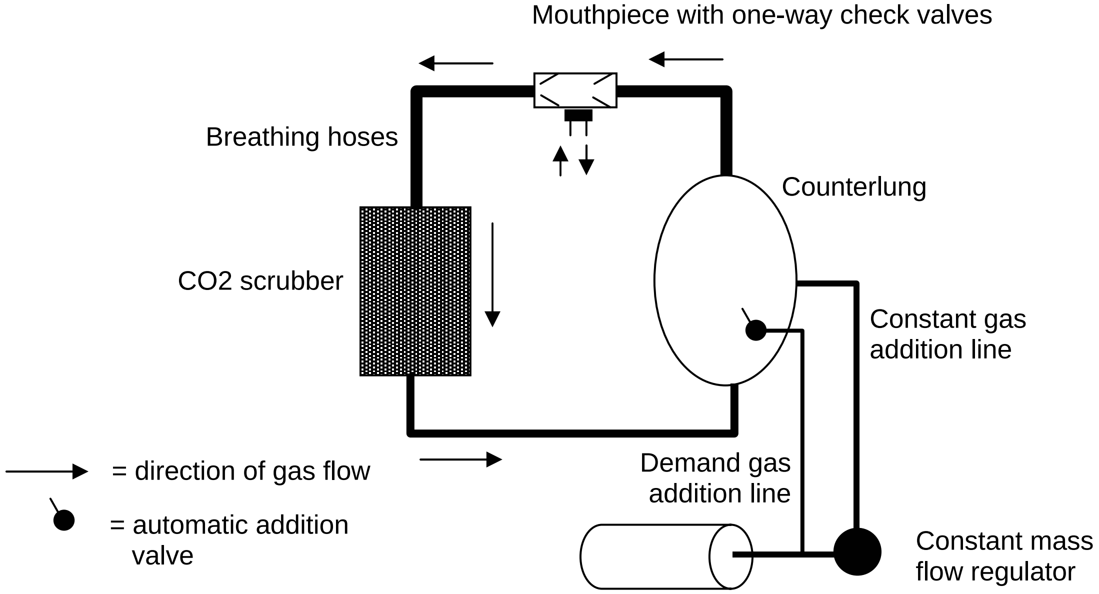
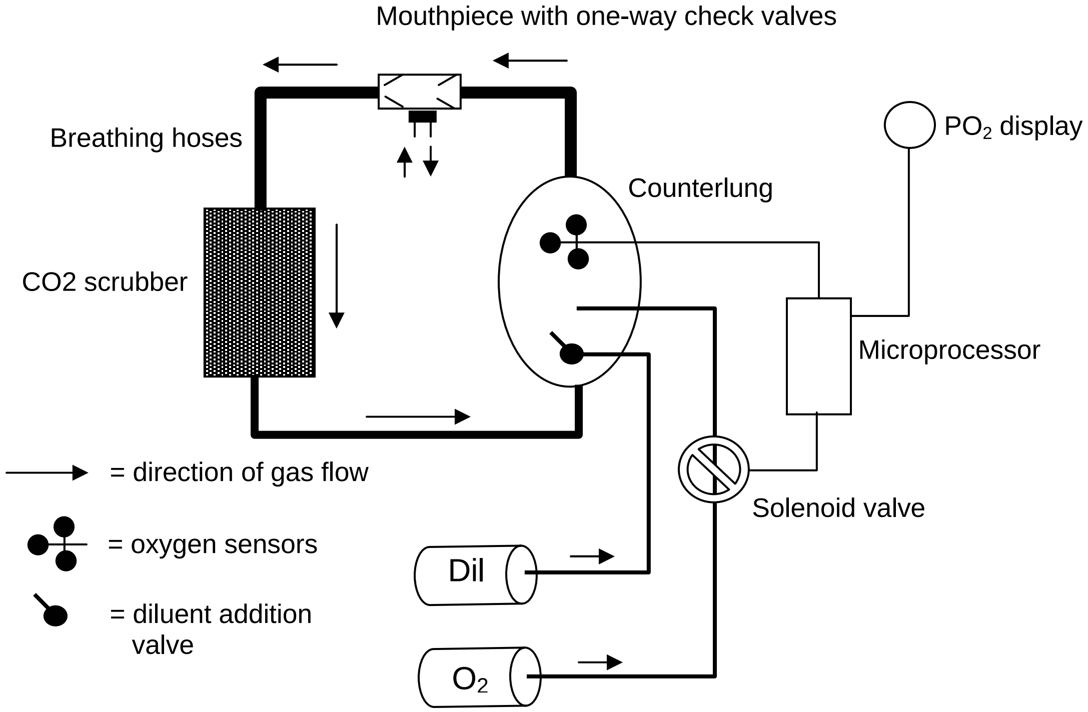


Figure 2. Stylized layout of a closed circuit rebreather showing the essential components common to all systems. For simplicity, the manual gas addition bypasses that allow the diver to common to all CCRs are not shown.



The basic rebreather loop is much the same in a CCR as any other rebreather, but the gas addition system is unique. CCRs utilize independent cylinders of two gases: pure oxygen and a *diluent gas* (named so because it is used to dilute the oxygen in the loop) (see Figure 2). Oxygen and the diluent are added to the breathing loop separately (see below) to form an appropriate mix. The diluent gas is chosen according to the nature of the dive. If a dive within the normal recreational diving range (< 40m) is planned, then it is very common to use air as the diluent. In this setting, the rebreather blends air and oxygen in the loop to make nitrox. For a deep dive the diluent cylinder is charged with either heliox or trimix, and the rebreather will blend it with oxygen to produce an appropriate mixed gas. Military divers often choose heliox (no nitrogen) because they will tolerate no narcosis in their operations. Technical divers often choose trimix because of the shorter decompressions that usually result, rather than any concerns over consumption and cost of helium.

Some might question why oxygen is included in the diluent at all given that the CCR will automatically blend it with oxygen in the loop. Indeed, a CCR could be dived with pure helium, pure nitrogen, or a mixture of nitrogen and helium in the diluent cylinder. However, certain emergency procedures may involve breathing the diluent in a semi-closed circuit mode, or even directly from the cylinder via a demand valve. Clearly, this would be of little use if it contained no oxygen at all. Thus, the presence of some oxygen in the diluent is a safety feature rather than a necessity. The fraction of oxygen in the diluent must be carefully chosen with regard to the planned depth of the dive so as not to exceed the chosen maximum safe PO_2 in the loop.

The key feature of CCR operation is a gas addition system that blends the diluent and oxygen to maintain a constant pressure of oxygen (PO_2) in the loop. The expression "constant PO_2" is used a little reservedly because it is not quite constant during all phases of the dive; especially the descent. However, for the most part, the CCR maintains the PO_2 in the loop at a "set point" that is selected by the diver. In most CCRs this is achieved by mechanical addition of diluent in response to changes in the volume of the counterlung, and microprocessor-controlled addition of oxygen in response to the actual PO_2 in the loop.

In all CCRs diluent is added to the loop when the counterlung volume falls. The most obvious and important requirement for diluent addition is during the descent when the counterlung is compressed and gas must be added to restore its volume. Most CCRs have an automatic diluent addition valve, and in some the diver must manually operate the valve when he or she feels the counterlung "bottoming out" during inhalation.

Oxygen is added through an electronically operated solenoid valve when the PO_2 in the loop falls below the set point selected by the diver. Typically there are 3 oxygen sensors of the galvanic fuel cell type in the loop. The CCR microprocessor averages the readings from all 3 (unless one deviates by more than a certain threshold, in which case it is ignored). When addition of diluent or consumption of oxygen causes the averaged PO_2 reading to fall below the set point, the microprocessor operates a solenoid valve, letting oxygen into the loop until the PO_2 set point is restored. The maintenance of a "constant PO_2" is a huge advantage because it ensures that the diver is breathing close to the ideal gas mix at every depth they visit.

All CCRs have at least one display that allows the user to read the actual PO_2 in the loop. Usually these displays will allow the user to read each oxygen sensor individually. In addition, all CCRs have a visual and / or audible alarm system which will warn the user if the loop PO_2 is too low or too high. The layout of the gas addition system in CCRs that facilitates these functions is shown in Figure 3.

Availability of CCRs

At the time of writing the most prevalent CCR in use among recreational technical divers is the Inspiration manufactured by AP valves in the UK. This situation seems unlikely to change within the next few years. Other models that are readily available include the Megalodon (Inner Space Systems), the Optima (Dive Rite), and the Oroborous (Ambient Pressure Diving). There are a number of ex US Military rebreathers in the Mark 15 and 15.5 family used by recreational technical divers. These are popular with serious technical divers because of their large CO_2 scrubber capacity, but they are hard to obtain. Finally, there are several rebreathers such as the KISS and Halcyon RB80 that utilize hybrid designs with some features common to both SCR and CCR devices (but usually without active electronic control systems).

Extending thermal duration

There is little use in carrying sufficient gas for prolonged dives if thermal protection is inadequate to allow that gas supply to be fully exploited. While such issues are fairly obvious in temperate and many fresh water situations, cold can be a problem even in the tropics during deep dives when thermoclines may be encountered. The anticipated temperature and selection of appropriate thermal protection is an important aspect of technical dive planning. Wetsuits may be adequate in some tropical situations, but dry suits coupled with an appropriate undergarment are frequently used for long technical dives. Gas for dry suit inflation must be drawn from one of the cylinders carried by the diver. Air is a reasonable choice, and some divers even carry a small cylinder of argon for dry suit inflation since argon has good insulating properties. Interestingly, the only controlled and blinded evaluation of argon (versus air) as a dry suit inflation gas showed no advantage.[4]

Decompression diving

Recreational diving training agencies emphasize "no decompression diving"; that is, the planning of dives so that a direct ascent to the surface (without decompression stops) is an option at all stages of the dive. Appraisal of Table 1 reveals that at depths below 40m it becomes virtually impossible to perform meaningful dives that do not exceed the no decompression limit. In addition, even at the shallower depths, there are many reasons why an extended bottom time might be desirable, and this may require performing a "decompression dive" involving decompression stops during ascent. Not surprisingly, decompression diving is an obligatory technique for those wishing to explore deep wrecks and long and / or deep caves.

Though self-apparent, it must be emphasized that the moment decompression stops become necessary the option of safe direct ascent " to the surface in a reasonably timely manner has been removed. It follows that the essence of decompression diving is the planning and safe execution of decompression stops. If these stops are not conducted properly, the risk of decompression sickness rises in proportion to the degree of omitted decompression. In electing to perform decompression dives, the diver must therefore commit him or herself to a new level of meticulous planning and preparation to minimize the chances of complications.

Planning decompression dives

Arguably the most vexing problem facing modern technical divers is that which this workshop has in large part been convened to address: the choice of an appropriate decompression algorithm. In virtually all the contexts in which technical diving takes place there are significant disadvantages in staying in the water longer, so the solution to the problem of reliably avoiding decompression sickness is not as simple as making the decompression longer and more conservative. Indeed, there is an inherent tension between the concurrent goals of exiting the water as quickly as practicable, and conducting a safe decompression.

The various algorithms utilized in decompression planning can be broadly categorized as derived from mathematical models of decompression that focus on either tissue gas content ("gas content models" such as that proposed by Buhlmann) or the mechanics of bubble formation ("bubble models" such as the Varying Permeability Model or Reduced Gradient Bubble Model).[5] The bubble models typically impose deeper initial decompression stops and there is a widespread perception among technical divers that this is a superior decompression strategy to the faster initial decompressions typically imposed by gas content models. The reasons why this might be so (or not) will be extensively discussed by other presenters at this workshop. Some algorithms based on gas content models now incorporate empiric "deep stops" to compensate for this perceived insufficiency. Indeed, the original intent of the term "deep stops" was to refer to the practice of empirically imposing early stops at deeper depths than predicted by the gas content models utilized.

The divers' perceptions on this issue owe more to propagation by internet than to definitive data. Despite some compelling theoretical arguments there is no definitive proof of the superiority of a "deep stop" approach to decompression from deep bounce dives. There are animal and human experimental studies which support both sides of the argument,[6] but all have their strengths and weaknesses, and none can be considered definitive. These issues will be extensively reviewed and debated over the course of this workshop, and are not discussed further here.

Whatever decompression algorithm is chosen, decompression diving involves comprehensive planning that includes selection of a bottom gas and ensuring that its PO_2 (absolute and time weighted limits) and PN_2 (narcotic potential) are acceptable for the planned depth. Typically, ascent from a decompression dive, even using air at modest depths, will involve switches to one or more "decompression gases" during ascent. This is because one of the significant advantages of nitrox or the use of higher fractions of oxygen in other gas mixes is the acceleration of decompression. Breathing a mix with a higher oxygen content during decompression increases the gradient for diffusion of nitrogen or helium out of tissues, into the blood, and to the lungs for elimination. The steeper this gradient, the more rapid the elimination of the inert gas, and the faster the decompression. Modern technical divers almost invariably utilize gas mixes that are progressively richer in oxygen as their decompression progresses into shallower depths, in order to maximally accelerate inert gas elimination. This is achieved automatically in electronic closed circuit rebreathers (see above) but must be achieved by the open circuit scuba diver by carrying or staging a variety of gas mixes in separate cylinders.

Once the dive plan is established in this way, the gas requirements must be calculated and the amounts to be carried determined with reference to an appropriate reserve regimen. One such regimen that widely pervades the cave diving world is the so-called "Rule of Thirds" and dictates that the diver should use one third of the gas supply heading into the cave, one third coming out, leaving one third in reserve. It is less clearly applicable in decompression diving in deep caves or open-ocean because the long slow ascent means that the dive is not symmetrical. Nevertheless, the notion that you should end your dive with a significant proportion of your gas in reserve has carried over into many technical diving activities.

D. Mixed gas diving

In order to minimize the debilitating effects of nitrogen narcosis and the toxicity of oxygen associated with the use of air at extreme depths a less narcotic gas must be replace at least some of the nitrogen, and the amount of oxygen in the mix must be reduced below that found in air. This is the essence of "mixed gas diving".

Using helium to replace nitrogen

Mixed gas diving usually involves the introduction of helium into the breathing gas. Helium has some very relevant properties. First, it is much less narcotic than nitrogen and can be breathed at extreme depths with almost no narcotic effect at all. Second, it is very light, and becomes much less viscous than nitrogen when breathed at high pressures. The work of breathing is markedly reduced by helium at extreme depths.

Helium may be used to completely replace the nitrogen, leaving helium and oxygen only ("heliox"). Heliox is used most commonly by the military and commercial sectors because the complete absence of nitrogen narcosis means that delicate tasks (like defusing a mine) can be completed safely.

In deep recreational diving it is more common to replace only some of the nitrogen leaving a mix of helium, nitrogen, and oxygen; commonly known as "trimix". The nitrogen fraction of trimix is planned with consideration of the resulting "equivalent narcotic depth" (END); the air diving depth that would produce the same amount of narcosis as the trimix at its target depth. There is no consensus on an acceptable END. Some agencies suggest 30m, but others are prepared to tolerate greater ENDs. By convention, trimix is designated by its oxygen and helium content. Thus, a mixture of 10% oxygen, 50% helium and 40% nitrogen would be "trimix 10:50".

There are three reasons deep technical divers are prepared to tolerate some narcosis by using trimix. First, helium is very expensive, and so using no more than necessary makes economic sense. Second, helium is a rapidly diffusing gas and is absorbed quickly. The corollary is also at least partly true (it is outgassed quickly), and this will result in shorter decompressions from very long "saturation dives" where the rate of in-gassing is largely irrelevant because sufficient time is spent at depth for all tissues to be saturated with whatever inert gas is being breathed. However, for the type of short "bounce" dives performed by deep recreational divers, a pure helium-oxygen mix will usually result in a longer decompression requirement than a trimix with less helium and some nitrogen. Finally, beyond depths where the high pressure neurological syndrome (HPNS) may occur (the threshold is frequently considered to be 150m) some extreme deep divers utilize nitrogen for its known ability to ameliorate the HPNS effects.

Reducing the fraction of oxygen below that found in air

It was previously pointed out that to comply with an absolute PO_2 limit of 1.4 bar, the maximum operating depth (MOD) for air would be 57m. It follows that to "safely" proceed to depths beyond 57m the fraction of oxygen in the breathing mix must be reduced below the 21% found in air. Thus, most trimix dives involve the use of so-called "hypoxic" mixes. In this regard, it is notable that the minimum fraction of oxygen in a mix that can be breathed at the surface is around 16% (a PO_2 of 0.16 bar), and even this might make the diver feel slightly light headed. Any less than this and the diver risks becoming unconscious. It would be usual to plan the oxygen content of all mixes breathed through the dive to produce a PO_2 as high as tolerable, but with due consideration to absolute and time weighted limits for oxygen toxicity (see earlier).

Planning and execution of mixed gas dives

Deep mixed gas dives rapidly accumulate a significant decompression obligation. Such dives must be approached with great care and due respect to the potentially disastrous consequences of unplanned premature ascent. Accidents that might result in only minor embarrassment in conventional air diving are likely to be fatal in deep mixed gas diving.

The methods of mixed gas diving are not greatly different to those outlined for decompression diving. Gas switches to mixes with less helium and progressively more oxygen are virtually always used during decompression in mixed gas diving. As previously mentioned, it is common for nitrox and finally 100% oxygen to be used in the shallower stages of these decompressions. Not surprisingly, trimix divers will spend much time in the planning stages working out which combinations of gases give them the most rapid decompression.

PRACTICAL APPLICATION AND CURRENT BOUNDARIES OF TECHNICAL DIVING TECHNIQUES

There are no statistics to describe the activities of technical divers, so there is much reliance on anecdote and personal experience for the following comments.

Technical diving does not mix well with "standard" recreational diving if conducted from the same surface support platform, so most technical diving is undertaken by small focus groups on field trips to caves and charter trips on boats specifically for that purpose. Technical diving "operations" vary in levels of organization. "Routine" dives to well known targets in the shallower depth range are often made on a "free for all" basis in which a group of divers all enter the water at once. Targets that are very deep or unexplored or both are often approached in a more organized "expedition style", with designated surface crew, support divers, and "bottom divers". Some technical dives of this nature are major logistic exercises involving massive quantities of equipment and huge support crews.

John Bennett from the UK was the first scuba diver to break the 1000' mark (actual depth 308m) in 2002. This "record" has subsequently been broken several times and it now sits around 318m. These were dives in which depth of itself was the goal; the divers simply descended down and back up a shot line suspended in very deep water. Dives to such depths are impractical because of the extraordinary rate at which a decompression obligation is accumulated with every minute that passes at depth. In the opinion of this author, the pursuit of record depth for its own sake is a dangerous (see below) and largely pointless exercise that should be discouraged. In fact, the vast majority of technical dives with a practical goal are performed in the 30 – 100m depth range. Open-ocean wrecks as deep as 200m and caves as deep as 280m have been visited, but the more complicated logistics and hazards associated with dives deeper than 100m reduce enthusiasm for visits to the more extreme depths. Caves can pose challenges in respect of length (distance) as well as depth. In this regard, it is notable that technical divers recently traversed a cave system 90m deep and 11 kilometers long over approximately 7 hours of bottom time followed by 15 hours of decompression.

Some perspective on adverse events surrounding these "extreme" technical diving achievements is necessary. Many of them have been associated with accidents or mishaps of varying severity. John Bennett suffered inner ear decompression sickness on his depth record dive. He recovered fully from this, but tragically died on a subsequent dive which was much less ambitious. The two subsequent holders of the "depth record" have suffered serious decompression sickness, either as a result of their record dives, or work-up dives to similar depth. It is a similar story for extreme depth record cave dives which have resulted in severe decompression sickness and several deaths. The inescapable fact is that these dives at the extreme end of technical diving appear highly dangerous.

SAFETY OF TECHNICAL DIVING

Accident data

Unfortunately, there are no properly gathered data describing the demographics, activities and accidents of any discrete technical diving population, and it is therefore difficult to draw firm conclusions about safety.

There is one statistically crude exception to this in the form of Inspiration rebreather users. This group is relatively readily identifiable, and members of the rebreather community have kept track of accidents on a world wide basis. There have now been approximately 60 deaths among Inspiration users since the device was introduced in 1999. The exact number of units sold is not known, but various commentators estimate that it is somewhere between 6000 and 8000. It is difficult to draw meaningful conclusions from these numbers (especially without some knowledge of the number of dives performed with the devices), but the apparent rate of 1 death per 100 units in the community to date seems high. This is most definitely not to say that the Inspiration *per se* is an inferior or inherently dangerous device. Indeed, few of the deaths thus far can be clearly attributed to device failure. In the opinion of this author, the Inspiration (and particularly the newer "Vision" iteration) is well thought out and manufactured. However, it has become a victim of its own success in as much as it is widely used in what appears to be an inherently dangerous activity, and the deaths therefore continue to mount.

The only other relevant data comes from the DAN database. For example, the DAN 2003 report on decompression illness and dive fatalities (based on 2001 data) records that 10% of all decompression sickness cases and 20% of diving fatalities in the USA occurred in technical divers. There is no denominator against which to compare these event data, but in the opinion of this author, it is extremely unlikely that technical divers are performing anything like 9.8% of all dives in the USA, let alone 20%. It therefore seems very likely that technical divers are over-represented in these accident data.

Added to these considerations, there is abundant anecdote shared among diving physicians regarding the occurrence of serious neurological decompression sickness among technical divers. It stands to reason that a technical dive might predispose to this by generating a large decompression obligation which is then not completed for some reason. However, more disturbing are those cases that occur despite the diver having faithfully followed the decompression regimen prescribed by their chosen algorithm. Such cases reveal the imprecision of these algorithms and exemplify the need for workshops such as this in which different approaches to decompression are critically examined.

Accident scenarios

There are a number of clearly identifiable predispositions to accidents and poor outcomes in technical diving.

Firstly, the combination of human fallibility and the complexity of the techniques and equipment of technical diving provide fertile ground for error. This is particularly true for rebreather diving. The task loading for a CCR diver during a critical phase of the dive (such as the descent) is greater when compared to the use of open circuit scuba equipment. Whereas the open circuit diver would have to monitor depth, adjust buoyancy and clear the ears during a descent, the CCR diver would have to monitor depth, adjust buoyancy, clear the ears, inflate the dry suit, monitor loop PO2, and possibly adjust counter lung volume in the same phase of the dive.

Second, circumstances of the diving such as the extreme depths, large decompression obligations, and isolated locations mean that any errors or omissions are likely to have much worse consequences than in normal recreational diving.

Third, there is a macho and competitive culture that pervades technical diving, and this appears to have played a role in causation of some technical diving accidents.

There are a number of "classic" errors that have repeatedly caused accidents in technical diving. These include:

a. Incorrect gas switches in open circuit diving which might, for example, result in breathing an oxygen-rich mix whilst still deep;

b. Having an incorrect gas in a cylinder resulting in hypoxia, hyperoxia, or inadequate decompression. This usually arises when divers become lazy and fail to measure the oxygen content of all their mixes;

c. Incorrect gas consumption calculations coupled with a failure to recognize this and change plans during the dive itself;

d. Losing staged decompression gas. This usually occurs when decompression gas is cached (to lighten the swimming load) to be picked up later, and then the pick up does not occur for some reason.

Rebreathers deserve special mention. Closed circuit rebreathers in particular are complex devices and their use introduces a number of hazards that are either absent or less likely to arise in the use of open circuit scuba equipment. Most prominent among these hazards is the development of an excessive or insufficient PO_2 in the loop. There are numerous ways either state can be induced. A comprehensive discussion of the failure modes of rebreathers is beyond the scope of this paper, but it is worthwhile to consider the following examples.

In a semi-closed circuit rebreather hypoxia could arise because the wrong gas (air for example) is mistakenly pumped into the loop supply cylinder. It could also in occur because the diver works too hard for a long period, or works hard just before an ascent. For the latter reason, SCR divers are advised to manually flush the loop with fresh gas just before making an ascent. In contrast, an excessively high PO_2 could occur, as with any other nitrox dive, if the diver ventured too deep for the nitrox mix being used.

In a closed circuit rebreather hypoxia could arise because the diver exhausts the oxygen supply, forgets to turn the oxygen cylinder or rebreather on, makes an ascent at sufficient speed that the solenoid valve cannot add oxygen quickly enough to maintain the PO_2, or because of a solenoid failure or electronics failure. An excessively high PO_2 could occur if an oxygen rich mix was mistakenly added to the diluent cylinder, the solenoid or manual oxygen injection valves jammed open, or if the diver made a rapid descent when diving at an established high PO_2 set point (such as 1.4 bar). It should be noted that none of the currently available CCRs automatically add diluent to lower the PO_2 if it rises above the set point during a descent.

Both types of rebreather are subject to the possibility of CO_2 scrubber failure if the scrubber material is incorrectly packed, used for too long, or if there is a flood of the loop. Both types are also prone to catastrophic loop floods, for example, induced by ripping of one of the breathing hoses. If the loop floods, the rebreather is completely unusable.

In recognition of these various problems (and there are many more), most technical divers using rebreathers for deep diving carry open circuit bail out gas supplies so that if the rebreather fails for any reason the diver can surface safely on open circuit. Whilst the necessity to carry this open circuit bailout gas negates some of the advantages of the rebreather, the risk of not doing so is widely considered too high.

Conclusions

Technical diving methods have evolved to overcome the limitations of conventional scuba air diving in deeper and longer dives. These techniques and the associated equipment are, of necessity, more complex and error prone than those associated with recreational air scuba. Moreover, technical dives frequently take place under more dangerous circumstances and the consequences of an error are magnified. Not surprisingly, there are some signs that technical divers are over-represented in accident statistics, and that one particular facet, closed circuit rebreather diving, may come to be recognized as highly dangerous. Nevertheless, technical diving has established itself as a gratifying and challenging activity, and a niche area in the diving industry. It is probably too expensive and challenging to become truly mainstream, but it represents a highly rewarding extreme sport for those properly motivated, appropriately experienced and properly trained.

References

1. Mitchell S. Technical Diving. In: Moon RE, Piantadosi EM (eds). Dr Peter Bennett Symposium Proceedings. Durham, NC: Divers Alert Network, 2007:55-70.
2. Harris RJ, Doolette DJ, Wilkinson DC, Williams DJ. Measurement of fatigue following 18msw dry chamber dives breathing air or enriched air nitrox. Undersea Hyperb Med 2003;30(4):285-91
3. Lippmann J, Mitchell SJ. Deeper into Diving (2nd ed). Melbourne 2005, Submariner Publications: p 401
4. Risberg J, Hope A. Thermal insulation properties of argon used as a dry suit inflation gas. Undersea and Hyperbaric Medicine 2001;28(3):137-143
5. Doolette DJ. Gas-content versus bubble decompression models. SPUMS J 2005;35(2):71-5
6. Fock A. Deep decompression stops. Diving Hyperbaric Med 2007;37:125-32

TECHNICAL DIVING:
USE OF THE DEEP STOP

A DECADE OF DEEP STOP TRAINING WITH THE REDUCED GRADIENT BUBBLE MODEL

Timothy O'Leary

ABSTRACT:

Linking a dual phase decompression model to mixed gas training operations, I will recount and detail protocols and diver training data from 1998 to the present. The diver data and training protocols described will be selected helium based dives and variable mixes with both open circuit and closed circuit in the 150 fsw to 300 fsw zones along with repetitive profiles as used in the technical diver programs. The algorithm and published groupless, no fuss, NAUI mixed gas decompression tables with repetitive dive protocols have seen extensive application in the technical diving sectors from a wide array of mixed gas instructors and divers in a variety of countries and is currently extending to dive meters in the training field.

PAPER:

A Decade of Deep Stop Training

These are very exciting times for both divers and agencies, when cutting edge technology and ideas can be transmitted to minimize risk in such a high risk arena. It seems like only yesterday that nitrox was first spoken in Key Largo, trimix in Key West and today deep stops have revolutionized the way we look at decompression physiology regardless of gas mixture or training agency loyalty.

Where did deep stops begin in the technical diving world? Frankly, in the closet as early as 1992 and shortly after Dr. Wienke began to write his monographs, circa 1992, on Diving Topics for the Fearless. The seed, when first planted, directed that perhaps we should look at controlling the bubble size in lieu of allowing the bubble to grow and then treating the bubble. From this juncture the living laboratory spawned a plethora of deep divers that began to experiment in parallel with deep stop injection into their ascent profiles. Frankly, without guidance, a long look back indicates how dangerous our methodology was. We were simply injecting deep stops into existing ultra conservative profiles which required lengthy shallow zone stops.

We left ourselves with a hodgepodge of tables all of which required lengthy shallow stops. Yet factoring the deep stops and shortening the shallow stops by a 20 to 30 percent factor appeared to work on some level and brought us out of the water on a much more efficient manner. It seemed to work and what works, works.

In 1997, Dr. Wienke agreed to assist NAUI Technical Diving Operations in creating hard tables based on the Reduced Gradient Bubble Model. Immediately there was such a high demand, within a small cadre of extreme divers, for these original beta tables that some selected highly skilled divers were given specific profiles to use on their specific dives. For example and to recant some specific dive profiles I would have to look towards the Andrea Doria dives in late summer of 1997 that were renowned for deep air diving to 250 feet using Haldanean style profiles while exposing the diver to the harmful effects of oxygen CNS, in the range of 140% to

150%. 1997, enter deep stops on beta RGBM, the most pronounced effect of the deep stop ascent was the acute reduction of oxygen exposure as well as the efficiency of decompression in colder water with both the deep stops and the use of helium.

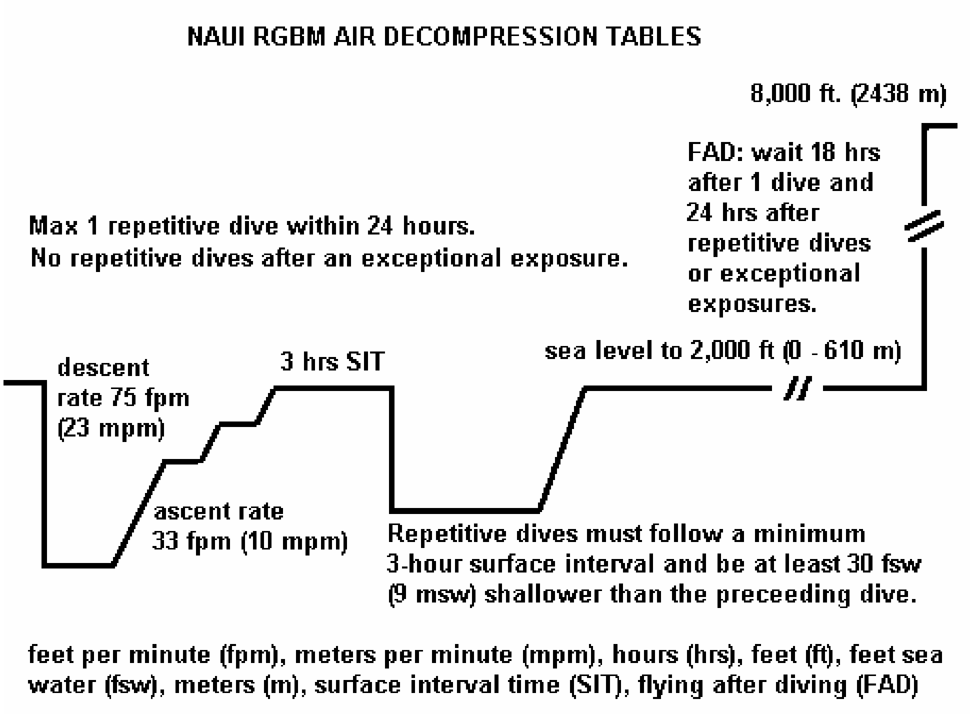
A symbiotic relationship began in 1998 between the modeler, Dr. Wienke, and the divers of our living laboratory. It might also be noted that it was of extreme importance to those of us that were diving the tables to have a modeler that was an extreme exposure diver that dived these new tables with us.

During the early development of NAUI RGBM decompression tables, we realized that we would likely need, for simplicity sake in worldwide diving scenarios, decompression tables that could be ranged in gas mixtures as well as an array of possible gas mixtures to choose from. The choice to range tables was made on the premises that exact mixtures would likely be very difficult to target in worldwide field operations.

Development of RGBM decompression tables were developed for both repetitive dives as well as the single exceptional exposure dives over a wide array of tables. Tables were developed for air, air with oxygen decompression, Nitrox 28 through 50, ranged Helitrox (hyperoxic trimix), ranged Trimix, ranged hypoxic trimix, Constant PO2 tables with a plethora of diluents as well as set points. Also set forth were a series of exceptional exposure tables to be used only as a single dive day for exploration style diving.

The tables as set forth in charts below will give the reader an idea as to the extent of the NAUI RGBM deep stop tables that have been distributed and used by divers worldwide in the last decade.

Table 1



NAUI RGBM AIR DECOMPRESSION TABLES

Max 1 repetitive dive within 24 hours.
No repetitive dives after an exceptional exposure.

FAD: wait 18 hrs after 1 dive and 24 hrs after repetitive dives or exceptional exposures.

Repetitive dives must follow a minimum 3-hour surface interval and be at least 30 fsw (9 msw) shallower than the preceeding dive.

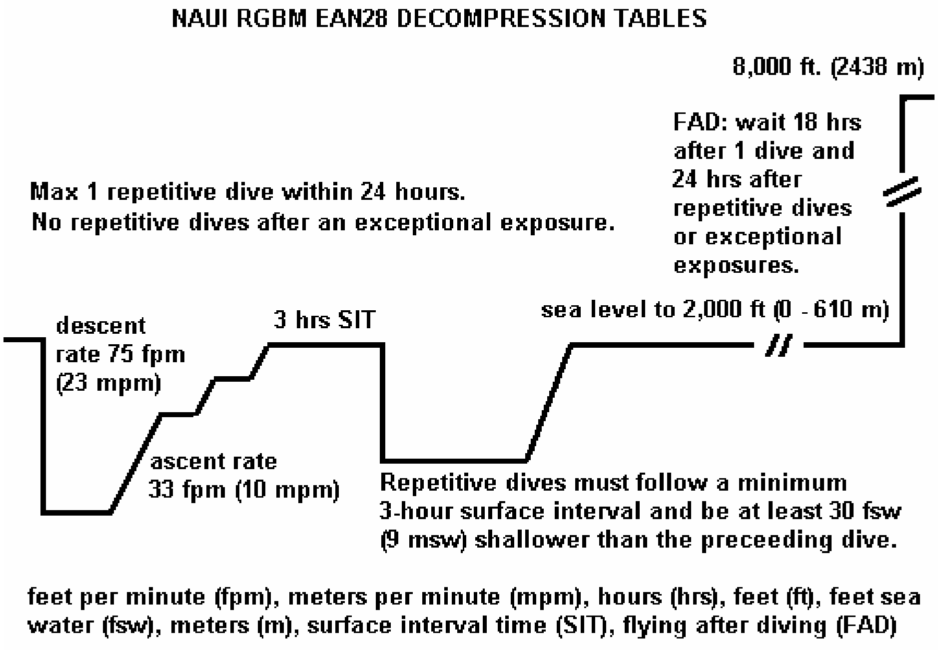
feet per minute (fpm), meters per minute (mpm), hours (hrs), feet (ft), feet sea water (fsw), meters (m), surface interval time (SIT), flying after diving (FAD)

NAUI RGBM AIR NDLs		
(21% Oxygen, 79% Nitrogen)		
msw	fsw	mins
3	10	
6	20	
9	30	720
12	40	185
15	50	95
18	60	60
21	70	45
24	80	35
27	90	20
30	100	15
33	110	12
39	130	10
42	140	8
45	150	6

REDUCED GRADIENT BUBBLE MODEL (RGBM) TABLE INSTRUCTIONS
1. Be properly trained with the breathing gases, equipment and decompression procedures used.
2. Do not exceed a PO2 of 1.4 atm at maximum depth or or 1.6 atm during decompression.
3. Do not descend faster than 75 fpm (23 mpm).
4. Do not ascend faster than 30 fpm (9 mpm).
5. Do not conduct more than one repetitive dive following a decompression dive.
6. Wait a minimum of 3 hours at the surface before conducting any repetitive dive.
7. Repetitive dives must be a minimum of 30 fsw (9 msw) shallower than the previous dive.
8. Wait a minimum of 18 hours after one decompression dive to fly or ascend to 8,000 ft. (2438 m).
9. Wait a minimum of 24 hours after repetitive dives or an exceptional exposure dive to fly/ascend to 8,000 ft (2438 m).
10. No repetitive dives permitted with exceptional exposures, which is any dive with an hour or more of decompression or a maximum depth deeper than 240 fsw (76 msw).

Note: Read all instructions before using these tables.

Table 2



Max 1 repetitive dive within 24 hours.
No repetitive dives after an exceptional exposure.

Repetitive dives must follow a minimum 3-hour surface interval and be at least 30 fsw (9 msw) shallower than the preceeding dive.

feet per minute (fpm), meters per minute (mpm), hours (hrs), feet (ft), feet sea water (fsw), meters (m), surface interval time (SIT), flying after diving (FAD)

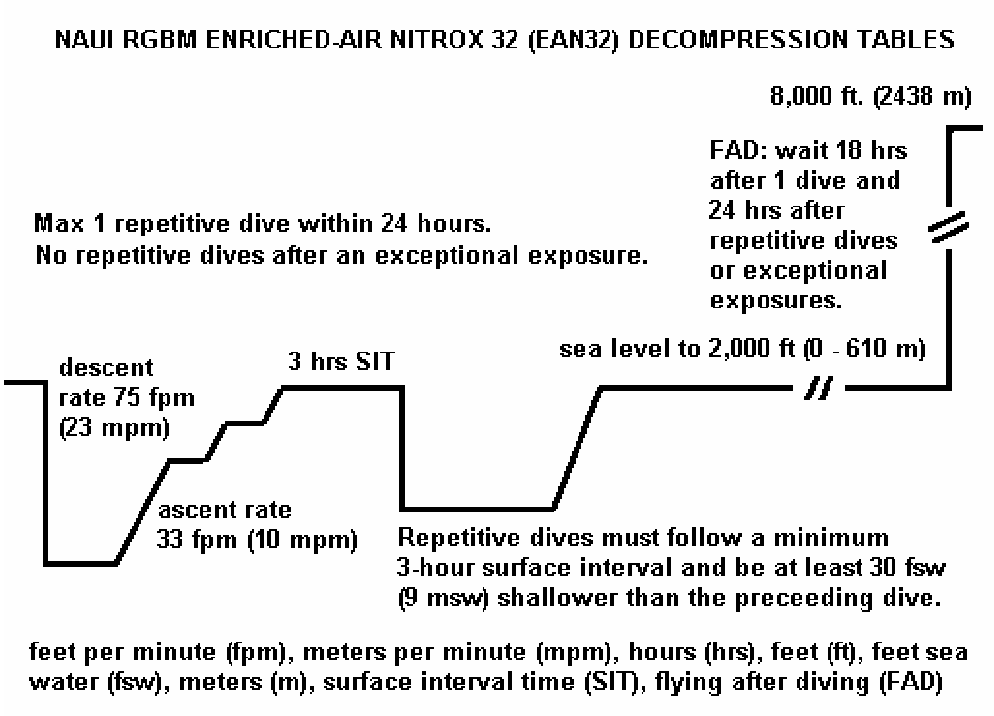
NAUI RGBM EAN28 NDLs (28% Oxygen, 72% Nitrogen)		
msw	fsw	mins
3	10	
6	20	
9	30	220
12	40	160
15	50	100
18	60	80
21	70	60
24	80	40
27	90	30
30	100	25
33	110	20
36	120	17
39	130	15
42	140	12
45	150	10

REDUCED GRADIENT BUBBLE MODEL (RGBM) TABLE INSTRUCTIONS

1. Be properly trained with the breathing gases, equipment and decompression procedures used.
2. Do not exceed a PO2 of 1.4 atm at maximum depth or or 1.6 atm during decompression.
3. Do not descend faster than 75 fpm (23 mpm).
4. Do not ascend faster than 30 fpm (9 mpm).
5. Do not conduct more than one repetitive dive following a decompression dive.
6. Wait a minimum of 3 hours at the surface before conducting any repetitive dive.
7. Repetitive dives must be a minimum of 30 fsw (9 msw) shallower than the previous dive.
8. Wait a minimum of 18 hours after one decompression dive to fly or ascend to 8,000 ft. (2438 m).
9. Wait a minimum of 24 hours after repetitive dives or an exceptional exposure dive to fly/ascend to 8,000 ft (2438 m).
10. No repetitive dives permitted with exceptional exposures, which is any dive with an hour or more of decompression or a maximum depth deeper than 240 fsw (76 msw).

Note: Read all instructions before using these tables.

Table 3



NAUI RGBM ENRICHED-AIR NITROX 32 (EAN32) DECOMPRESSION TABLES

Max 1 repetitive dive within 24 hours.
No repetitive dives after an exceptional exposure.

Repetitive dives must follow a minimum 3-hour surface interval and be at least 30 fsw (9 msw) shallower than the preceeding dive.

feet per minute (fpm), meters per minute (mpm), hours (hrs), feet (ft), feet sea water (fsw), meters (m), surface interval time (SIT), flying after diving (FAD)

NAUI RGBM EAN32 NDLs

(32% Oxygen, 68% Nitrogen)

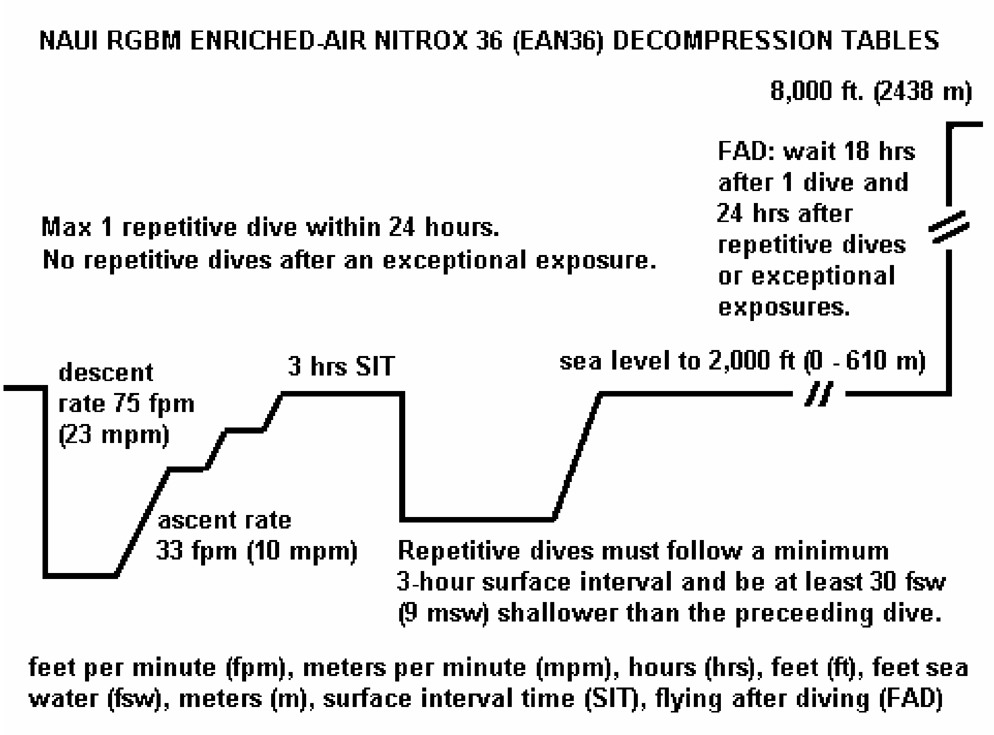
msw	fsw	mins
3	10	
6	20	
9	30	720
12	40	380
15	50	220
18	60	125
21	70	85
24	80	45
27	90	35
30	100	30
33	110	20
36	120	15
39	130	12

REDUCED GRADIENT BUBBLE MODEL (RGBM) TABLE INSTRUCTIONS

1. Be properly trained with the breathing gases, equipment and decompression procedures used.
2. Do not exceed a PO2 of 1.4 atm at maximum depth or or 1.6 atm during decompression.
3. Do not descend faster than 75 fpm (23 mpm).
4. Do not ascend faster than 30 fpm (9 mpm).
5. Do not conduct more than one repetitive dive following a decompression dive.
6. Wait a minimum of 3 hours at the surface before conducting any repetitive dive.
7. Repetitive dives must be a minimum of 30 fsw (9 msw) shallower than the previous dive.
8. Wait a minimum of 18 hours after one decompression dive to fly or ascend to 8,000 ft. (2438 m).
9. Wait a minimum of 24 hours after repetitive dives or an exceptional exposure dive to fly/ascend to 8,000 ft (2438 m).
10. No repetitive dives permitted with exceptional exposures, which is any dive with an hour or more of decompression or a maximum depth deeper than 240 fsw (76 msw).

Note: Read all instructions before using these tables.

Table 4



NAUI RGBM ENRICHED-AIR NITROX 36 (EAN36) DECOMPRESSION TABLES

Max 1 repetitive dive within 24 hours.
No repetitive dives after an exceptional exposure.

FAD: wait 18 hrs after 1 dive and 24 hrs after repetitive dives or exceptional exposures.

Repetitive dives must follow a minimum 3-hour surface interval and be at least 30 fsw (9 msw) shallower than the preceeding dive.

feet per minute (fpm), meters per minute (mpm), hours (hrs), feet (ft), feet sea water (fsw), meters (m), surface interval time (SIT), flying after diving (FAD)

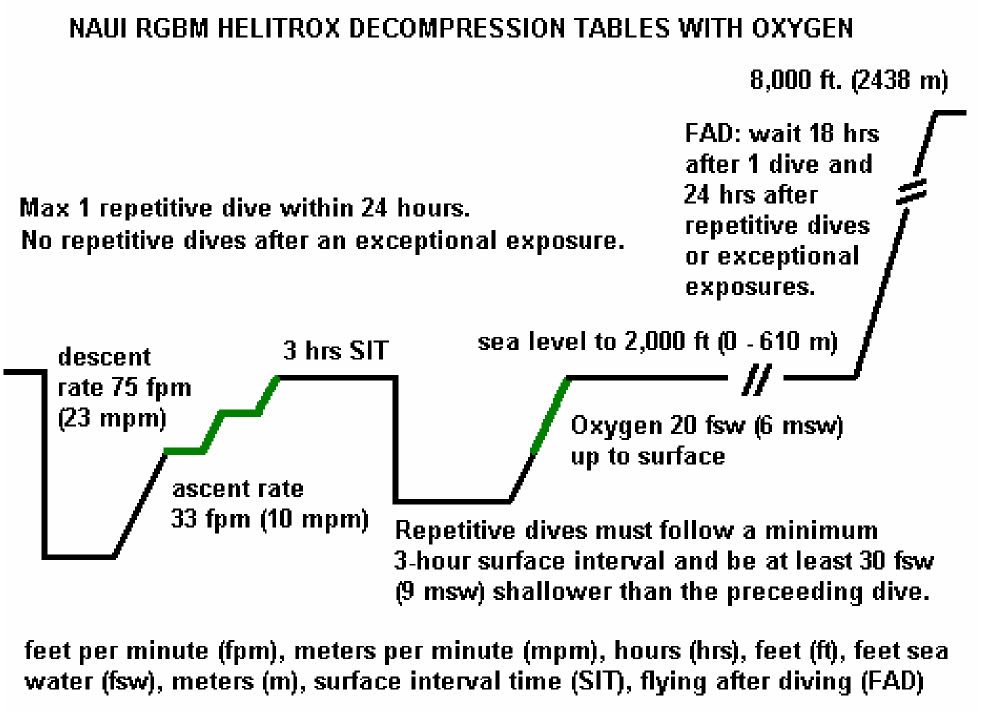
NAUI RGBM EAN36 NDLs		
(36% Oxygen, 64% Nitrogen)		
msw	fsw	mins
3	10	
6	20	
9	30	720
12	40	380
15	50	220
18	60	140
21	70	110
24	80	65
27	90	40
30	100	35
33	110	25

REDUCED GRADIENT BUBBLE MODEL (RGBM) TABLE INSTRUCTIONS

1. Be properly trained with the breathing gases, equipment and decompression procedures used.
2. Do not exceed a PO2 of 1.4 atm at maximum depth or or 1.6 atm during decompression.
3. Do not descend faster than 75 fpm (23 mpm).
4. Do not ascend faster than 30 fpm (9 mpm).
5. Do not conduct more than one repetitive dive following a decompression dive.
6. Wait a minimum of 3 hours at the surface before conducting any repetitive dive.
7. Repetitive dives must be a minimum of 30 fsw (9 msw) shallower than the previous dive.
8. Wait a minimum of 18 hours after one decompression dive to fly or ascend to 8,000 ft. (2438 m).
9. Wait a minimum of 24 hours after repetitive dives or an exceptional exposure dive to fly/ascend to 8,000 ft (2438 m).
10. No repetitive dives permitted with exceptional exposures, which is any dive with an hour or more of decompression or a maximum depth deeper than 240 fsw (76 msw).

Note: Read all instructions before using these tables.

Table 5



NAUI RGBM HELITROX DECOMPRESSION TABLES WITH OXYGEN

Max 1 repetitive dive within 24 hours.
No repetitive dives after an exceptional exposure.

FAD: wait 18 hrs after 1 dive and 24 hrs after repetitive dives or exceptional exposures.

Repetitive dives must follow a minimum 3-hour surface interval and be at least 30 fsw (9 msw) shallower than the preceeding dive.

feet per minute (fpm), meters per minute (mpm), hours (hrs), feet (ft), feet sea water (fsw), meters (m), surface interval time (SIT), flying after diving (FAD)

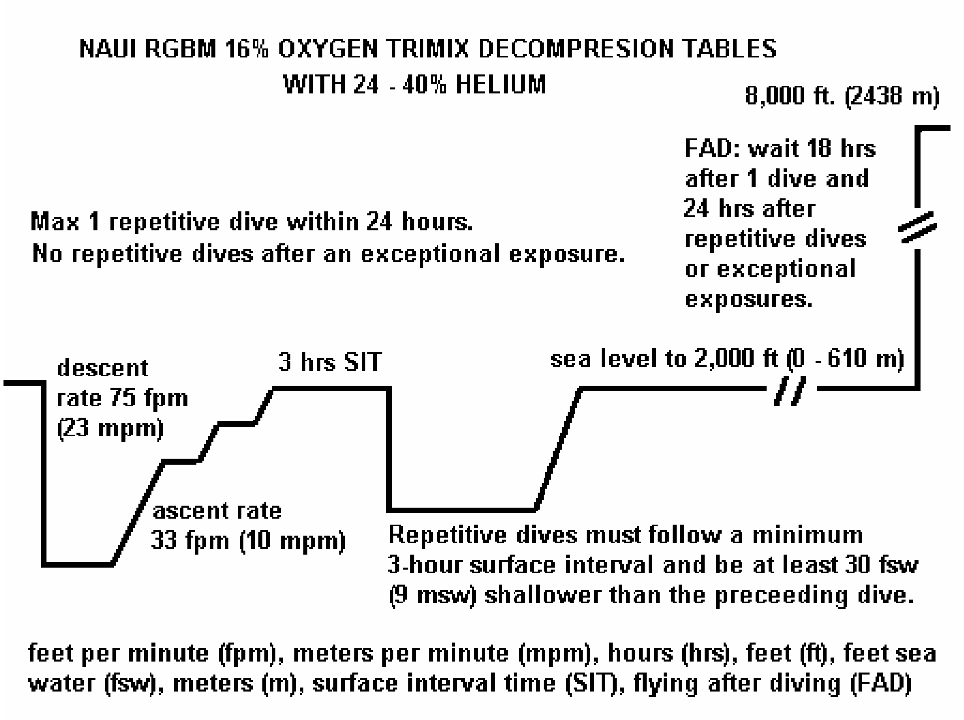
NAUI RGBM HELITROX NDLs		
(26-30% O_2, 13-17% He, Bal N_2)		
msw	fsw	mins
3	10	
6	20	
9	30	
12	40	
15	50	
18	60	
21	70	35
24	80	25
27	90	20
30	100	15
33	110	10
36	120	8
39	130	6
42	140	4
45	150	2

REDUCED GRADIENT BUBBLE MODEL (RGBM) TABLE INSTRUCTIONS

1. Be properly trained with the breathing gases, equipment and decompression procedures used.
2. Do not exceed a PO_2 of 1.4 atm at maximum depth or or 1.6 atm during decompression.
3. Do not descend faster than 75 fpm (23 mpm).
4. Do not ascend faster than 30 fpm (9 mpm).
5. Do not conduct more than one repetitive dive following a decompression dive.
6. Wait a minimum of 3 hours at the surface before conducting any repetitive dive.
7. Repetitive dives must be a minimum of 30 fsw (9 msw) shallower than the previous dive.
8. Wait a minimum of 18 hours after one decompression dive to fly or ascend to 8,000 ft. (2438 m).
9. Wait a minimum of 24 hours after repetitive dives or an exceptional exposure dive to fly/ascend to 8,000 ft (2438 m).
10. No repetitive dives permitted with exceptional exposures, which is any dive with an hour or more of decompression or a maximum depth deeper than 240 fsw (76 msw).

Note: Read all instructions before using these tables.

Table 6



NAUI RGBM 16% OXYGEN TRIMIX DECOMPRESION TABLES
WITH 24 - 40% HELIUM

Max 1 repetitive dive within 24 hours.
No repetitive dives after an exceptional exposure.

FAD: wait 18 hrs after 1 dive and 24 hrs after repetitive dives or exceptional exposures.

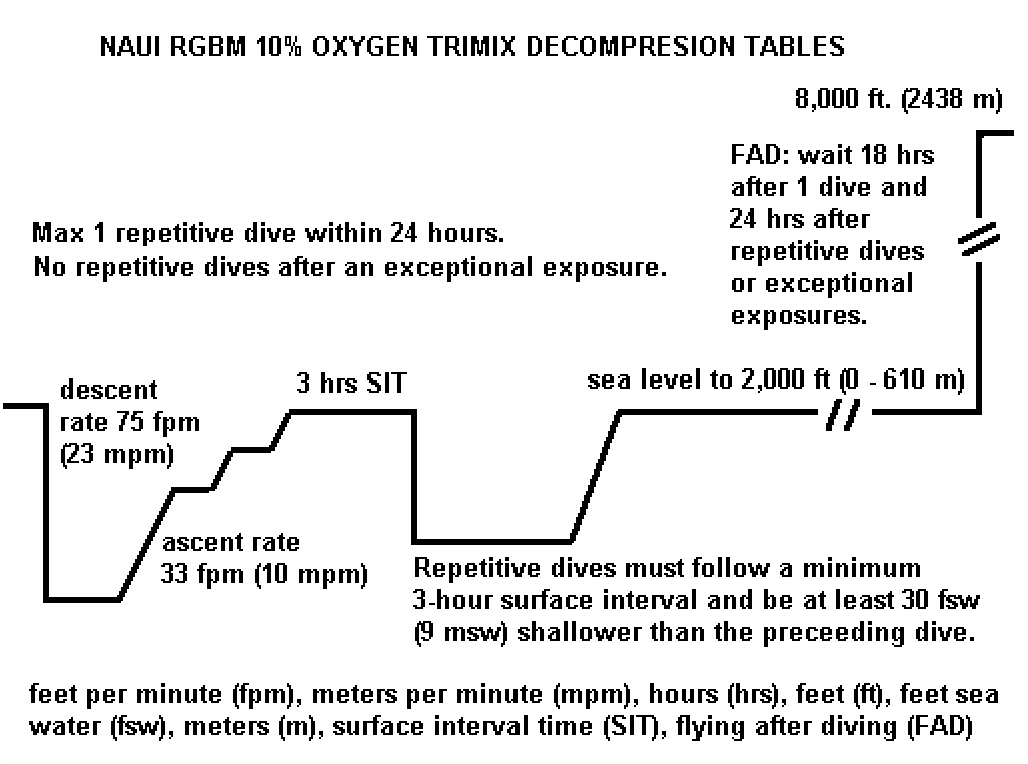
Repetitive dives must follow a minimum 3-hour surface interval and be at least 30 fsw (9 msw) shallower than the preceeding dive.

feet per minute (fpm), meters per minute (mpm), hours (hrs), feet (ft), feet sea water (fsw), meters (m), surface interval time (SIT), flying after diving (FAD)

REDUCED GRADIENT BUBBLE MODEL (RGBM) TABLE INSTRUCTIONS

1. Be properly trained with the breathing gases, equipment and decompression procedures used.
2. Do not exceed a PO2 of 1.4 atm at maximum depth or or 1.6 atm during decompression.
3. Do not descend faster than 75 fpm (23 mpm).
4. Do not ascend faster than 30 fpm (9 mpm).
5. Do not conduct more than one repetitive dive following a decompression dive.
6. Wait a minimum of 3 hours at the surface before conducting any repetitive dive.
7. Repetitive dives must be a minimum of 30 fsw (9 msw) shallower than the previous dive.
8. Wait a minimum of 18 hours after one decompression dive to fly or ascend to 8,000 ft. (2438 m).
9. Wait a minimum of 24 hours after repetitive dives or an exceptional exposure dive to fly/ascend to 8,000 ft (2438 m).
10. No repetitive dives permitted with exceptional exposures, which is any dive with an hour or more of decompression or a maximum depth deeper than 240 fsw (76 msw).

Table 7



NAUI RGBM 10% OXYGEN TRIMIX DECOMPRESION TABLES

Max 1 repetitive dive within 24 hours.
No repetitive dives after an exceptional exposure.

FAD: wait 18 hrs after 1 dive and 24 hrs after repetitive dives or exceptional exposures.

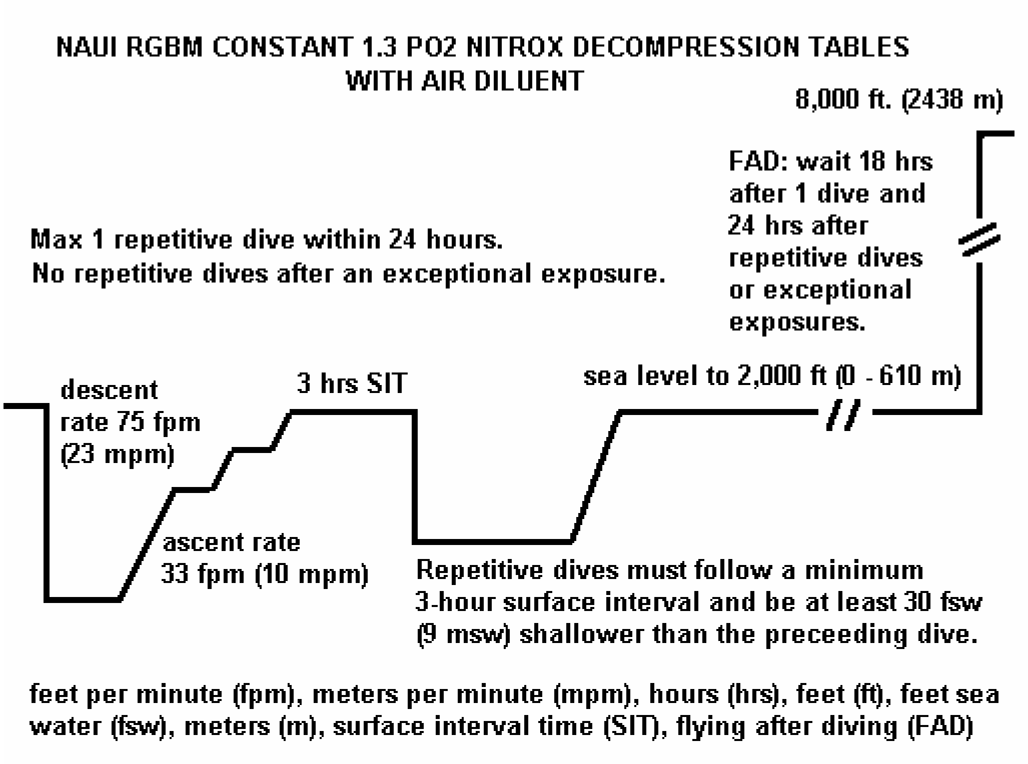
Repetitive dives must follow a minimum 3-hour surface interval and be at least 30 fsw (9 msw) shallower than the preceeding dive.

feet per minute (fpm), meters per minute (mpm), hours (hrs), feet (ft), feet sea water (fsw), meters (m), surface interval time (SIT), flying after diving (FAD)

REDUCED GRADIENT BUBBLE MODEL (RGBM)
TABLE INSTRUCTIONS

1. Be properly trained with the breathing gases, equipment and decompression procedures used.
2. Do not exceed a PO2 of 1.4 atm at maximum depth or or 1.6 atm during decompression.
3. Do not descend faster than 75 fpm (23 mpm).
4. Do not ascend faster than 30 fpm (9 mpm).
5. Do not conduct more than one repetitive dive following a decompression dive.
6. Wait a minimum of 3 hours at the surface before conducting any repetitive dive.
7. Repetitive dives must be a minimum of 30 fsw (9 msw) shallower than the previous dive.
8. Wait a minimum of 18 hours after one decompression dive to fly or ascend to 8,000 ft. (2438 m).
9. Wait a minimum of 24 hours after repetitive dives or an exceptional exposure dive to fly/ascend to 8,000 ft (2438 m).
10. No repetitive dives permitted with exceptional exposures, which is any dive with an hour or more of decompression or a maximum depth deeper than 240 fsw (76 msw).

Table 8



NAUI RGBM CONSTANT 1.3 PO2 NITROX DECOMPRESSION TABLES
WITH AIR DILUENT

Max 1 repetitive dive within 24 hours.
No repetitive dives after an exceptional exposure.

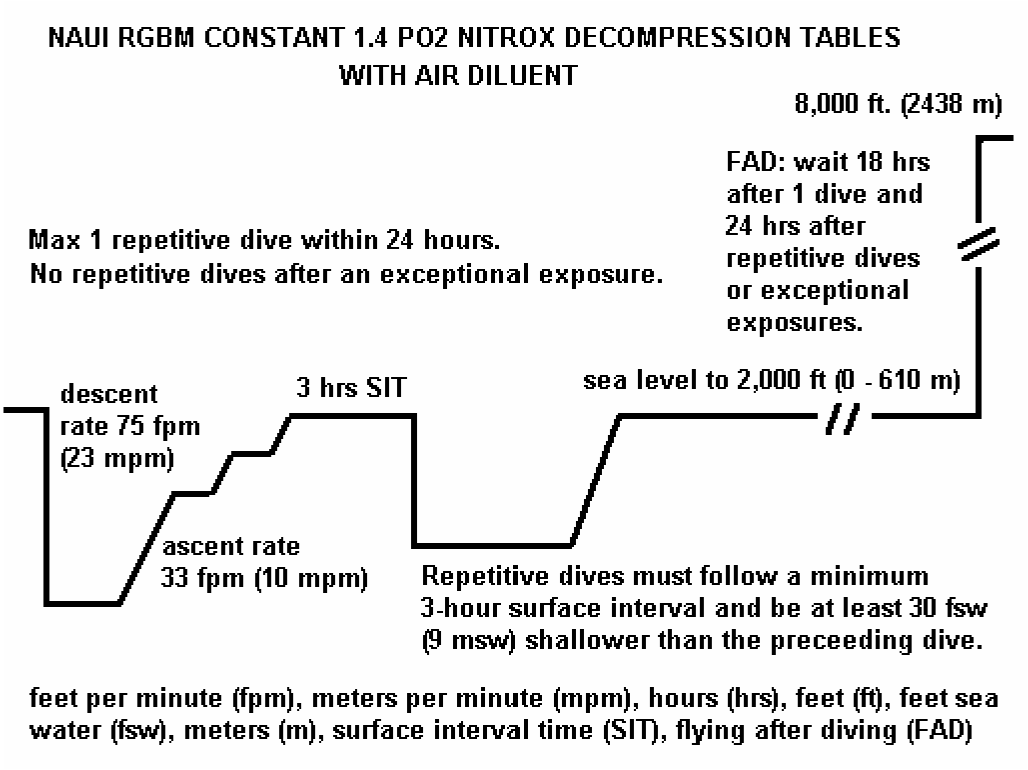
FAD: wait 18 hrs after 1 dive and 24 hrs after repetitive dives or exceptional exposures.

Repetitive dives must follow a minimum 3-hour surface interval and be at least 30 fsw (9 msw) shallower than the preceeding dive.

feet per minute (fpm), meters per minute (mpm), hours (hrs), feet (ft), feet sea water (fsw), meters (m), surface interval time (SIT), flying after diving (FAD)

REDUCED GRADIENT BUBBLE MODEL (RGBM) TABLE INSTRUCTIONS
1. Be properly trained with the breathing gases, equipment and decompression procedures used. 2. Do not exceed a PO2 of 1.4 atm at maximum depth or or 1.6 atm during decompression. 3. Do not descend faster than 75 fpm (23 mpm). 4. Do not ascend faster than 30 fpm (9 mpm). 5. Do not conduct more than one repetitive dive following a decompression dive. 6. Wait a minimum of 3 hours at the surface before conducting any repetitive dive. 7. Repetitive dives must be a minimum of 30 fsw (9 msw) shallower than the previous dive. 8. Wait a minimum of 18 hours after one decompression dive to fly or ascend to 8,000 ft. (2438 m). 9. Wait a minimum of 24 hours after repetitive dives or an exceptional exposure dive to fly/ascend to 8,000 ft (2438 m). 10. No repetitive dives permitted with exceptional exposures, which is any dive with an hour or more of decompression or a maximum depth deeper than 240 fsw (76 msw).

Table 9



NAUI RGBM CONSTANT 1.4 PO2 NITROX DECOMPRESSION TABLES WITH AIR DILUENT

Max 1 repetitive dive within 24 hours.
No repetitive dives after an exceptional exposure.

FAD: wait 18 hrs after 1 dive and 24 hrs after repetitive dives or exceptional exposures.

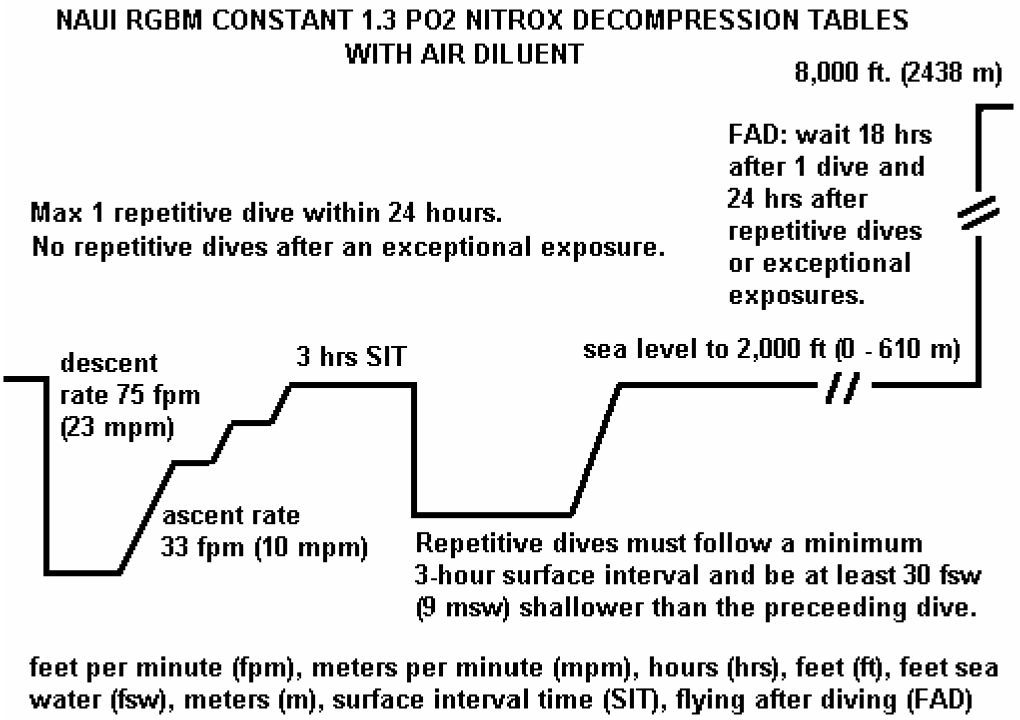
Repetitive dives must follow a minimum 3-hour surface interval and be at least 30 fsw (9 msw) shallower than the preceeding dive.

feet per minute (fpm), meters per minute (mpm), hours (hrs), feet (ft), feet sea water (fsw), meters (m), surface interval time (SIT), flying after diving (FAD)

REDUCED GRADIENT BUBBLE MODEL (RGBM) TABLE INSTRUCTIONS

1. Be properly trained with the breathing gases, equipment and decompression procedures used.
2. Do not exceed a PO2 of 1.4 atm at maximum depth or or 1.6 atm during decompression.
3. Do not descend faster than 75 fpm (23 mpm).
4. Do not ascend faster than 30 fpm (9 mpm).
5. Do not conduct more than one repetitive dive following a decompression dive.
6. Wait a minimum of 3 hours at the surface before conducting any repetitive dive.
7. Repetitive dives must be a minimum of 30 fsw (9 msw) shallower than the previous dive.
8. Wait a minimum of 18 hours after one decompression dive to fly or ascend to 8,000 ft. (2438 m).
9. Wait a minimum of 24 hours after repetitive dives or an exceptional exposure dive to fly/ascend to 8,000 ft (2438 m).
10. No repetitive dives permitted with exceptional exposures, which is any dive with an hour or more of decompression or a maximum depth deeper than 240 fsw (76 msw).

Table 10



NAUI RGBM CONSTANT 1.3 PO2 NITROX DECOMPRESSION TABLES WITH AIR DILUENT

Max 1 repetitive dive within 24 hours.
No repetitive dives after an exceptional exposure.

FAD: wait 18 hrs after 1 dive and 24 hrs after repetitive dives or exceptional exposures.

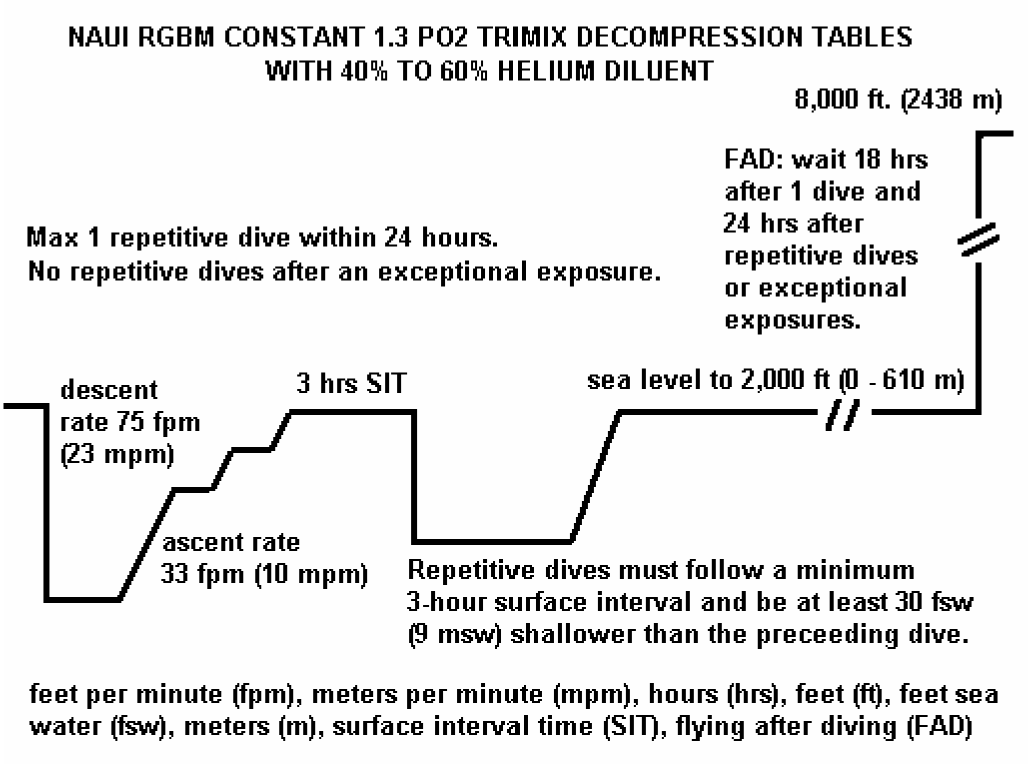
Repetitive dives must follow a minimum 3-hour surface interval and be at least 30 fsw (9 msw) shallower than the preceeding dive.

feet per minute (fpm), meters per minute (mpm), hours (hrs), feet (ft), feet sea water (fsw), meters (m), surface interval time (SIT), flying after diving (FAD)

REDUCED GRADIENT BUBBLE MODEL (RGBM) TABLE INSTRUCTIONS

1. Be properly trained with the breathing gases, equipment and decompression procedures used.
2. Do not exceed a PO2 of 1.3 atm at maximum depth or or 1.6 atm during decompression.
3. Do not descend faster than 75 fpm (23 mpm).
4. Do not ascend faster than 30 fpm (9 mpm).
5. Do not conduct more than one repetitive dive following a decompression dive.
6. Wait a minimum of 3 hours at the surface before conducting any repetitive dive.
7. Repetitive dives must be a minimum of 30 fsw (9 msw) shallower than the previous dive.
8. Wait a minimum of 18 hours after one decompression dive to fly or ascend to 8,000 ft. (2438 m).
9. Wait a minimum of 24 hours after repetitive dives or an exceptional exposure dive to fly/ascend to 8,000 ft (2438 m).
10. No repetitive dives permitted with exceptional exposures, which is any dive with an hour or more of decompression or a maximum depth deeper than 240 fsw (76 msw).

Table 11



NAUI RGBM CONSTANT 1.3 PO2 TRIMIX DECOMPRESSION TABLES WITH 40% TO 60% HELIUM DILUENT

Max 1 repetitive dive within 24 hours.
No repetitive dives after an exceptional exposure.

FAD: wait 18 hrs after 1 dive and 24 hrs after repetitive dives or exceptional exposures.

Repetitive dives must follow a minimum 3-hour surface interval and be at least 30 fsw (9 msw) shallower than the preceeding dive.

feet per minute (fpm), meters per minute (mpm), hours (hrs), feet (ft), feet sea water (fsw), meters (m), surface interval time (SIT), flying after diving (FAD)

REDUCED GRADIENT BUBBLE MODEL (RGBM) TABLE INSTRUCTIONS

1. Be properly trained with the breathing gases, equipment and decompression procedures used.
2. Do not exceed a PO2 of 1.3 atm at maximum depth or or 1.6 atm during decompression.
3. Do not descend faster than 75 fpm (23 mpm).
4. Do not ascend faster than 30 fpm (9 mpm).
5. Do not conduct more than one repetitive dive following a decompression dive.
6. Wait a minimum of 3 hours at the surface before conducting any repetitive dive.
7. Repetitive dives must be a minimum of 30 fsw (9 msw) shallower than the previous dive.
8. Wait a minimum of 18 hours after one decompression dive to fly or ascend to 8,000 ft. (2438 m).
9. Wait a minimum of 24 hours after repetitive dives or an exceptional exposure dive to fly/ascend to 8,000 ft (2438 m).
10. No repetitive dives permitted with exceptional exposures, which is any dive with an hour or more of decompression or a maximum depth deeper than 240 fsw (76 msw).

TRAINING DIVES

In the early fall of 1998, protocols were set forth to train divers for deep open ocean exposures while using a deep stop profile with only one gas switch to oxygen at 20 feet for efficiency of training safety.

Once the disciplines of deep stops protocols with the concomitant emergency and safety skills as well as top side support were instilled in the divers, deep stop helium diving began.

A typical seven (day) training regimen would include the early morning dive to some 200 feet on a 40% helium, 16% oxygen, and 44% nitrogen mix with oxygen in the 20 foot zone. Bottom time was usually in the 25 to 30 minutes range.

Table 12

NAUI RGBM 200 FSW (60 MSW) TRIMIX TABLE WITH OXYGEN							
(16% 0xygen, 24 - 40% Helium, 44 - 60% Nitrogen)							
0xygen required from 20 fsw (6 msw) up to sea level							
msw	fsw	decompression stop times (minutes)					
3	10	13	10	10	5	5	1
6	20	9	7	6	4	3	
9	30	13	11	11	5	6	
12	40	10	9	8	4	4	
15	50	8	5	6	3	2	
18	60	5	4	4	2	3	
21	70	4	4	4	2	1	
24	80	4	2	2	1	1	
27	90	3	2	2	1	1	
30	100	2	2	2	1	1	
33	110	1	1	1	1	1	
36	120	2	1	1	1	1	
39	130	1	1	1	1	1	
42	140	1	1	1			
45	150						
48	160						
51	170						
54	180						
57	190						
60	200	30	25	20	15	10	5
Max descent rate 75 fpm (23 mpm). Max ascent rate 33 fpm (10 mpm).							

After a three to four hour surface interval divers would begin in water training operations again with a minimum delta p of 30 fsw to 60 fsw on a hyperoxic trimix of 26% oxygen, 17% helium , and 57 % nitrogen at 150 fsw with bottom times around 25 to 30 minutes and switching to oxygen at 20 fsw.

NAUI RGBM 150 FSW (45 MSW) HELITROX TABLE WITH OXYGEN							
(26 - 30% 0xygen, 13 - 17% Helium, 53 - 61% Nitrogen)							
0xygen required from 20 fsw (6 msw) up to sea level.							
msw	fsw	decompression stop times (minutes)					
3	10	7	5	4	2	2	1
6	20	4	3	2	2	1	
9	30	6	4	3	1		
12	40	3	2	1	1		
15	50	2	2	1			
18	60	2	1	1			
21	70	1	1				
24	80						
27	90						
30	100						
33	110						
36	120						
39	130						
42	140						
45	150	30	25	20	15	10	5
Max descent rate 75 fpm (23 mpm). Max ascent rate 33 fpm (10 mpm). Max 1 repetitive dive, a min 30 fsw (9 msw) shallower than the prior dive. Min 3 hrs surface interval. Wait 18 hrs to ascend to 8,000 ft (2438 m) after 1 dive and 24 after 2. Read all instructions before using this device. Copyright 2001 NAUI Worldwide.							

With the advent of rebreather technology within the recreational diving manufacturers, we have noted an increase at both the training level as well as the extreme exposure level. Of the most noted may be the cave system explorations by the WKPP in Florida conducting dives of some 300 feet in depth with four to six hour exposures on semi closed rebreather systems incorporating both helium and deep stop technology.

It should also be noted that it is not uncommon for Closed Circuit divers, today, to have exposures of 500 fsw for up to 30 minutes with deep stop ascents.

On a typical training regimen for NAUI Technical Diving Operations, we look at a two week program for deep gas Closed Circuit UBA training as explained below with RGBM ascent profiles.

- Day one through Day six dives are between 60 fsw to 130 fsw and a PO2 of 1.3. Each day is two dives a day and a delta p of 30 to 40 feet on the repetitive dive.
- Day 7 through Day 14 are between 130 fsw and 250 fsw on a 10% oxygen and 50% and 40% nitrogen diluent gas mixture. Repetitive dives are made with a delta p of 40 to 60 fsw. Once the diver is in the exceptional exposure zone only one dive is made per day on the RGBM ascent profiles.

An example of an exceptional exposure training dive on Closed Circuit UBA and a set point of 1.3 would be 240 fsw for 30 minutes with an ascent using RGBM of some 41 minutes.

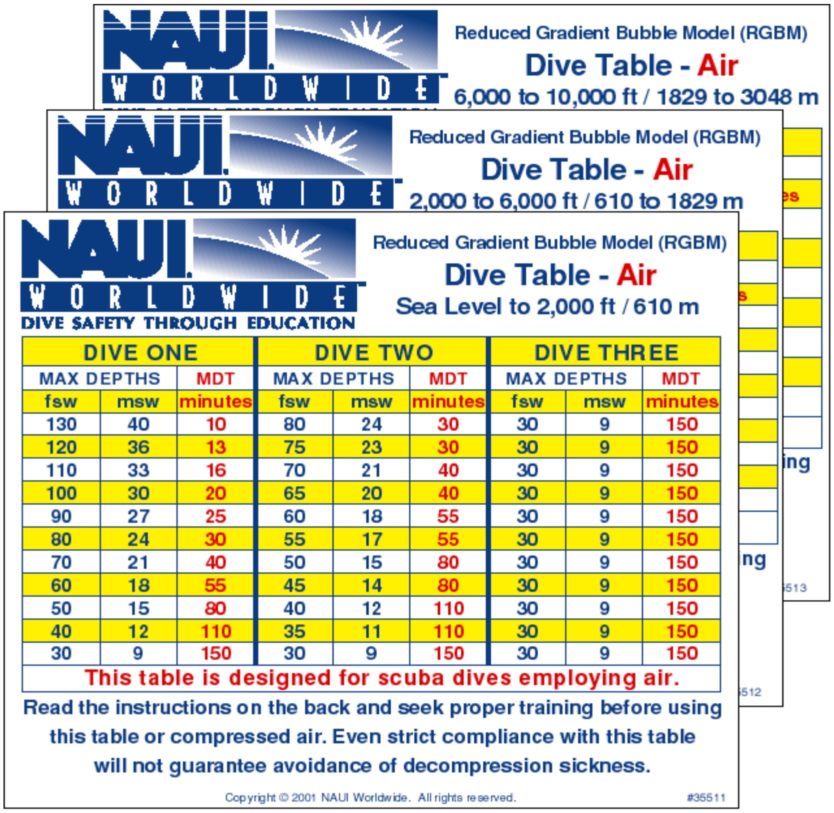
Table 13

EXCEPTIONAL EXPOSURE NAUI RGBM 240 FSW (72 MSW) CONSTANT 1.3 PO2 TRIMIX TABLE							
10% OXYGEN & 40% - 60% HELIUM DILUENT							
msw	fsw	decompression stop times (minutes)					
3	10	9	7	5	4	2	1
6	20	6	5	4	2	2	1
9	30	5	4	3	2	1	1
12	40	4	4	2	2	1	
15	50	4	2	2	1	1	
18	60	2	2	2	1		
21	70	2	2	1	1		
24	80	2	2	1	1		
27	90	2	1	1	1		
30	100	1	1	1	1		
33	110	1	1	1			
36	120	1	1	1			
39	130	1	1				
42	140	1					
45	150						
48	160						
51	170						
54	180						
57	190						
60	200						
63	210						
66	220						
69	230						
72	240	30	25	20	15	10	5
Max descent rate 75 fpm (23 mpm). Max ascent rate 33 fpm (10 mpm). No repetitive dives. Wait 24 hrs to ascend to 8,000 ft (2438 m) after diving. Read all instructions before using this table. Copyright 2001 NAUI Worldwide.							

RECREATIONAL DIVE TABLES

Since 2001, NAUI has incorporated deep stops RGBM into the recreational training tables with a half stop at half the dive pressure and a shallow stop at the 15 fsw zone. This array of recreational tables were designed for use from sea level to 10,000 feet altitude These tables also incorporate a delta p on repetitive dives within the NDL limits, slower ascent rates, and in quantifiable terms these are very much akin to deep stops though not as pronounced as decompression stops

Table 14



NAUI WORLDWIDE
Reduced Gradient Bubble Model (RGBM)
Dive Table - Air
6,000 to 10,000 ft / 1829 to 3048 m

NAUI WORLDWIDE
Reduced Gradient Bubble Model (RGBM)
Dive Table - Air
2,000 to 6,000 ft / 610 to 1829 m

NAUI WORLDWIDE
DIVE SAFETY THROUGH EDUCATION
Reduced Gradient Bubble Model (RGBM)
Dive Table - Air
Sea Level to 2,000 ft / 610 m

DIVE ONE			DIVE TWO			DIVE THREE		
MAX DEPTHS		MDT	MAX DEPTHS		MDT	MAX DEPTHS		MDT
fsw	msw	minutes	fsw	msw	minutes	fsw	msw	minutes
130	40	10	80	24	30	30	9	150
120	36	13	75	23	30	30	9	150
110	33	16	70	21	40	30	9	150
100	30	20	65	20	40	30	9	150
90	27	25	60	18	55	30	9	150
80	24	30	55	17	55	30	9	150
70	21	40	50	15	80	30	9	150
60	18	55	45	14	80	30	9	150
50	15	80	40	12	110	30	9	150
40	12	110	35	11	110	30	9	150
30	9	150	30	9	150	30	9	150

This table is designed for scuba dives employing air.

Read the instructions on the back and seek proper training before using this table or compressed air. Even strict compliance with this table will not guarantee avoidance of decompression sickness.

#35511

Some numbers to look at:

Since 2001, some 175,000 recreational divers have been trained on the NAUI RGBM recreational tables with half stops incorporated. To date there has not been a single incidence reported of DCS.

Since 1998, there have been some 5750 divers trained on Deep Stop NAUI RGBM Decompression tables and we have had four reported incidents of DCS using these profiles and none of these incidents involved students in training.

The data reliability at NAUI relies on second and third generation data and what really took place during the dive such as:
- Was buoyancy control a factor?
- Are we receiving truthful facts from the diver?

DEEP STOPS WORK

To most of us in the technical diving community we are of the opinion “It Works”. Deep Stop methodology has been implemented in the field with NAUI for over 10 years, tested in the field of the living laboratory as well as laboratories of science and has been a revolution in diving circles. Without a doubt, the deep stop approach has reshaped the horizons of both technical and recreational diving and will likely continue to do so in the foreseeable future.

For the technical diving community of NAUI, deep stops have reduced decompression time and when coupled with helium (trimix) in the breathing mixture to reduce the narcotic effects of nitrogen, our divers report feeling much better physically when they leave the water with a reduction of decompression “hangs” ranging from 10% to as high as 50% and this is certainly a win-win situation for our divers.

THE BOTTOM LINE

To NAUI Technical Diving Operations, the bottom line is very simple.

The technology has developed successfully over the last 16 or so years. Tried and tested in the field, now some in the laboratory and it is certainly backed with diver success, confidence, theoretical and experimental underpinnings and general acceptance by seasoned professionals.

NAUI Worldwide will continue using deep stop technology with our training protocols for the foreseeable future.

Acknowledgments

Much thanks to Bruce Wienke for teaching those of us that are a part of the living laboratory with his patience and mentorship. Additional thank you to Jim Bram and Jed Livingstone at NAUI Headquarters for believing in the cutting edge technology of the deep stops and allowing NAUI Technical Diving Operations to implement them within our training program. And a very special thanks to those that became a very significant part of NAUI RGBM tables by participating in the living laboratory.

References

1. Wienke B.R., 1994, Deep Stops Simplified, Sources Magazine
2. Wienke B.R., 1992, Deep Helium, Sources Magazine
3. Wienke B.R., O’Leary T.R., 2003 NAUI RGBM Deco Tables

A PRACTICAL LOOK AT DECOMPRESSION SURVIVAL ON DIVES DEEPERS THAN 100 METER AND USE OF INTUITIVE DECOMPRESSIONS

Tom Mount

ABSTRACT:

This presentation will address the practical decompression procedures used by some "Technical Divers" and how they evolved. It will describe use of a multi model approach such as advocated by JP Impert and will reflect this to combinations with VPM-RGBM and Gradient Factors.

The process of decompression may be compared to a giant circle, where practice produces consequence, learning, and management of technique interact, creating the foundation of "intuitive decompression."

We will also address some modifications to decompression models used by deep trimix divers. The overall process is to use a model but use it in a manner stated by RW Hamilton, a "What Works-Works" approach. Within this, most of us favor deep stops or very slow ascents, which contradicts the thoughts of many researchers and agree with others. Yet this process is hard to define. We will endeavour to do so.

The paper will also address what the author believes to be the most ideal decompression strategy when using a CCR. This leads us away from the concept of getting off Helium. It maintains the same gas for the duration of CCR decompression as the inert gas volume mixed is reduced due to the constant PO2.

At the end of the presentation an understanding of the apparently "what works decompression process" should be evident. Although subjective, as was the "subjective" feeling of nitrox dives vs. air dives long ago, it does seem to provide better post dive health.

TRANSCRIPT: A PRACTICAL LOOK AT DECOMPRESSION SURVIVAL ON DIVES DEEPERS THAN 100 METER AND USE OF INTUITIVE DECOMPRESSIONS

Presented by: Joseph Dituri

Past years, going back to the '60s, we're talking about those free radicals, you know, the Tom Mounts that were out there, the Billy Deans, the guys that were on a lunatic fringe, if you will.

These guys have survived, have helped this process push, push past where they thought it could go to where it is today. And we owe a lot to them at this point, so I don't want to glossover the history. History winds up being important, and those who don't understand the history are deemed to repeat it. And I think that we are falling into that a little bit here.

So decompression wound up being a big challenge, and Tom wanted me to point on that a little bit. It was the unknown. They didn't know exactly what we were getting into, so they were truly breaking ground.

So a little more into the historical perspective. Gene Melton, instrumental in the '60s and '70s, publishing the extreme exposure tables, combining some of these with the old SOS dive computer.

Now, I'm not quite of this genre so I don't know the Benzomatic, so I guess it shows that I'm not quite that old. But we did do things like decompression using pure oxygen. Even some of us guys that were a little crazier, that took high school chemistry and were diving the Doria, decided to switch gases, not knowing what we were switching to, just trying different gases, if you will. So a little bit of experimentation goes a long way.

Also, in this historical data, the commercial divers followed suit, and it's really important. Why did they follow suit? They're following the buck, the money, because they're trying to expand their knowledge to increase their profitability and their safety.

Okay. So who are the former or current military divers in the room? I know there's a couple of you out there. You guys all know this. This is the history that we've all lived with.

I asked master diver Jerry Dearing, when I was a mud pup diver, I said, "Hey, Master Diver, why do we bring the diver up at 60 feet a minute? Why do we bring him off the bottom so quickly so you stand there and you just watch him?"

"Well, son, it's so you can top side keep a better eye on him from here." Well, we ascended at 60 feet per minute, limited to 300 feet of seawater, except in some rare occasions where you have to get the chief naval operation's approval. And we all know that that's not an easy thing to do.

So for all you divers, you recall the delay in ascent greater than one minute, deeper than 50 feet. Round up to the next table and schedule. Recompute table and schedule. This was the fallacy that we've been living with for all those years. Basically, that's like what Dr. Neuman discussed earlier, the delay in ascent.

Before I get into my 20 cents here or my pair of dimes, what I want to do is -- Jarrod, JJ, where are you? JJ and I, way back in the early '90s, we were communicating a lot. And, you know what, it was over valves. And I distinctly remember this discussion, debate, argument, whatever you want to call it, that a long hose left pose, which one are you breathing.

Finally, I acquiesced and I say, "You know what, I was wrong. JJ, you were right." You know, sometimes it's a hard pill to swallow, if you will. Basically, what we've got here is we've gotten ourselves into a situation where we have a hard pill to swallow. Sometimes you just have to say, "Hey, you know, maybe it's not quite the right thing we did when we were there."

We all did the best, the military and commercial. We all did the best that we could at that point with the knowledge that we had. Now we know a little bit more, so let's change with the changing time. Let's shift our paradigm or our pair of dimes.

So we pushed past the deep stops, and we brought the divers to the surface. We created those symptoms and then we treated those symptoms with long shallow stops. That's basically effectively the pickle that we're in right now, military and commercially.

Divers weren't given enough credit, in my opinion. They're intelligent people. Basically, they derived through the happenstance. They stumbled upon it, the need for these deeper stops. As everybody knows, thanks to Rich Pyle. The fish helped a little bit. You know, we need to perforate the swim bladder and let the air out. We found out that, hey, you know, I feel a little better after that dive. Well, that happened about every atmosphere. So fish were a small part of it.

Tom wanted me to ping on a couple of practical words to live by. Everybody talks about half-times. What you do is you put someone in a chamber, and if they get a niggle, you holler, oh, Jesus, and then you throw some more numbers at it. That's the J factor. Also, he wanted to ping on J.P. Impert. Since the time people have been fiddling with tissue half-life, we have not learned much about the critical issue, which is what is my risk for the next dive? Also, hitting on Dr. Hamilton, where are you, Doc? You see the trend. Everybody has been hitting on it. What works, works.

I wanted to basically touch base on decompression, as I know it today, which has moved beyond the theoretical. The divers have it. It's no longer in the hands of the scientists. The proof is in the pudding. We've got 20 million dives out there, and they're doing it regardless of what the scientists are doing. So I'm not trying to offend the scientists right now, but these guys are in the interest of exploration, the interest of beyond, they're pushing the limits, using scientific knowledge, making good decisions. But they're the ones that are out there doing it.

So I just want to quote Elton John here: “All this science, I don't understand; it's just my job five days a week.” So these guys are just pushing past the technical limit, if you will. But I do want to hit right here. Let's be realistic. Doc Neuman, you talked about double-blind studies and a priori states and figuring out the whole puzzle before we start.

I now am a program manager. So now that I'm a program manager, I'm looking at the bottom line, and the bottom line is the mighty dollar. Nobody is going to pay for double-blind a priori studies, and that's the bottom line. There's not enough people out there diving.

So if there's not enough people out there diving, we need the right mix or the just-in-time-type philosophy of creating decompression tables. So using a little bit of what the divers are building out in the field on their own -- and all you really intelligent scientists are using a bit of that all together.

All right. Now onto IANTD and deep stops. Basically, initially we were impressed with Brian Hill's deco work and followed up by Dr. Fife and his daughter, Carolyn. So early use of the Buhlmann and Pyle micro bubble-type stops. We adapted this in the '92 and '93 timeframe. Some of the tables we have are obviously Buhlmann based. Why? Because it works. And like Dr. Hamilton says, what works, works.

Deeper stops seem to be better for many of us. We do use the VPM B for trimix open circuit and closed circuit as well. And in the future, we're looking into the ABM 2-type models. We certainly believe in deep stops for everything but air and that's only because we don't do deep air anymore. We've stricken it from the records effectively, and we have no knowledge based on it. Basically, I wanted to also hit on the fact that we require tables as backup because, like Tim O'Leary said, yeah, the computers work less than the slate on your wrist.

Okay. So what is a deep stop? Well, the answer is: It depends. Our version of a deep stop is approximately 1 atmosphere off the bottom, give or take, in increments of between 10 and 15 feet depending, on who you talk to, maybe in increments of an atmosphere wholly. One minute of stop depending on the depth. We didn't want to increase too much the on gassing that you would take when you are too slowly ascending.

Also, what we found and what my group, particularly, and the Association for Marine Exploration, has found that slow, gradual ascents and not necessarily stops, decreasing to somewhere on order of between five and ten feet per minute ascent rate from the bottom. That seems to work best for us. Once again, I say that word.

So, like I said, we feel better about it. And this is a subjective thing. And this is part of what Tom's esoteric-type thought process goes into a little more. Subjective, but effective reasoning, based on the factors we have at hand.

So tuning the intuition of the diver. How many people have been diving, and you have the hair stand up on the back of your neck. Something is going to go wrong here pretty soon. Your intuition was probably right. Something was going to go wrong or is about to go wrong. Whether you're driving a car or diving, you know it.

Basically relaxing, slowing your breathing, some pre-dive meditation, some visualization, looking at yourself getting out of the water, all these positive things that they're using in yoga and the real world, they apply to diving and can apply to diving. So we need to trust the feelings that we have, communicate these feelings or allow ourselves to communicate these feelings to ourselves and not just stifle them and push them down.

You see the bottom line, it says, "Be quiet, be still, listen, believe and act." And that kind of sounds a whole lot like stop, think, breathe, act, which is what we learn when we were growing up. The fledgling diver stuff is still there, and it's prevalent.

So some of these adaptations may be on the fly. Like I said, from that feeling that you have, staying longer, ascending slower, staying longer at a specific stop or increasing a stop time. Like I said, it depends on how you feel. It depends on the factors. There's a little bit of current. It's a little colder than I would expect. I had a little more rigorous dive than I expected, so I'm modifying this on the fly. I'm not trying to be cavalier here, but you need to adapt to the situation that you have.

I am a little concerned about the reports of DCS and people not listening to their bodies. When I initially put requests out for dives greater than 350 feet, I got back, "Oh, yeah, I had no hits of DCS." I said, "Really? Tell me a little bit about your dive." I start talking to these people a little more. "Oh, you know. It was great. I felt like crud after the dive and I was lethargic. I slept for a while." "Oh, for goodness sake, you were probably bent." "Oh, no, I wasn't bent. I didn't have simple joint pain or bilateral pain."

Okay, yeah, more the classic symptoms, sure. But the tired and lethargic, the nonstress-type symptoms, I believe that those are potentially prevalent. From the people I talked with, there's a higher incidence of decompression sickness than they are reporting. So I wasn't too happy with the initial reports that we got back from dives deeper than 350 feet.

It's like the doctor from the University of Connecticut said, it's more of a biological function. You're feeling like what's going on inside the body. All right. So where do we need help from the scientific community? Because I'm assisting with the design and the document of the new system on a rebreather. And Niles has a saying, and it's basically YADD, yet another dumb diver.

Basically, the divers are trying to push forth the technology and the engineers are pushing back. So to the scientific community, what us divers need from the scientific community or YADDs need from the scientific community is a number, an ascent rate that we can live with that's going to work for a broad spectrum.

Also, where do we start the stops? Is it 1 atmosphere above the bottom? Is it two? Three? You know, depending on if you go to 500 feet, 600 feet, what is it? So a better table. How long should these stops be? Or should they not be stops? Should they be a slow, continual ascent?

So in the spirit of adventure, the technical divers, these guys are going to wind up getting the number in some way, shape or form if the scientific community doesn't come up with it. As evidenced by the works that they've done so far, they're going to continue pushing the envelope and they're going to come up with a number on their own. Maybe some of them will get a little bent, and they'll fix it and take care of it. But it will come out.

What I do want to focus on is here is the military aspect. What I need from a military commander's aspect is the operational commander's discretion. I need an envelope that's about this wide, you know. If you narrow me down into here, you tell me exactly how much decompression I have. It's not going to help us because, as you guys out in the field know, things happen. Things go sideways. I stayed two minutes longer, the current is stronger. It's hotter. It's colder.

Things happen, and you need to improvise, adapt and overcome. I need a window of operational commander's discretion so that I can go acceptable risk, or unacceptable risk. That's what I think we're going to need as a community as we push forward, not the pinpoint accuracy that I think we're pushing towards.

Okay. Some of the benefits, the overall benefits of deep stops from a commercial, a military and scientific standpoint. Decreased decompression times means an increase in profitability. The all mighty buck. If I can get the guy out of the water, I'm not paying him as much money as I am if he's in the water.

Increasing an on-the-job safety. This applies to instructors as well because they are at a high risk of DCS multiple dives. I know Tim O'Leary is like, oh, man, you guys do those back-to-back dives like that. Those instructors are certainly at risk, and we all know it. So deep stops are helping us, too, not only the commercial divers.

If you require less divers, you require less logistics. Decreased costs. This is all the cost benefit analysis that deep stops are going to help with. Also decreasing that thermal exposure. The long-term reward, the colder you're going to be, the less efficient you're going to be at off gassing. So less decompression stress and, like I said, people just feel better.

Okay. Conclusion. We believe in deep stops. We, IANTD, believe in deep stops. Now, don't shoot me here. Just take a broad look at this next statement. The bottom line is scientific community, commercial and military have lost their competitive edge. Honest to God. They used to be at the forefront. They're no longer there.

The technical divers are pushed into the forefront, and they're using stuff from the scientific community, and it's not bad, but we need to focus and push back and give them a couple of numbers if we're in a scientific community. Now if I could just get the U.S. Military to buy off on the secondhand adaptive idea of getting lighter and faster, maybe we could also break some more ground.

At this point I'd like to take the opportunity to say thank you for allowing me to present Tom's and my paper. I am quite honored to be up here with the greats, as I look through the audience, I mean, Drs. Vann, Bennett, Neuman, Wienke. Tom Mount, who, like I said, sends his regrets, Ed Betts, Doc Richardson, Doc Gerth, Melton and Hamilton. All you guys, I remember coming up and hearing all these names, and now I'm standing in a room with you guys. I'm truly honored, and I appreciate the opportunity to be here.

I would like to put out one disclaimer. While I do not stand before you in a Navy uniform, the opinions are expressed are mine and mine alone, and do not necessarily reflect those of the United States Navy. With that, I'd like to thank you.

WORLD RECORD CAVE DIVE, DEEP STOPS WITHIN THE WOODVILLE KARST PLAIN PROJECT

Jarrod Jablonski

ABSTRACT:

During the late 1980's a non-profit exploration group known as the Woodville Karst Plain Project (WKPP) began steadily expanding the length of their deep cave immersions. By the mid 1990's these divers were experiencing bottom times of about six hours at a depth of 300'. During this period and in the years to come the team would focus considerable energy toward safely reducing total decompression time. This process was primarily a response to the sense that conventional Buhlmann algorithms were not structured with the most favorable arrangement of decompression stop times. Over approximately 7,500 dives spanning nearly 20 years these divers aggressively experimented with a range of decompression profiles, working to support immersions that have reached nearly thirty hours. The divers utilize a similar decompression time for all dives in excess of six hours bottom time where dives average approximately 280 feet. To date ten hours is the longest bottom time obtained, resulting in a decompression of 17 hours.

PAPER:

From the logistics of underwater exploration to the strange malady that became known as decompression illness, divers and scientists have been struggling for decades to successfully explore the underwater world. As early as 1670 Boyle described, with detailed accuracy, bubbles in the blood and body fluids of small animals subjected to low pressures. These bubbles, first located in the eye of a snake, marked more than 300 years of debate about the meaning, repercussions, and logistics of exposure to elevated ambient pressure. The quest for procedures that allowed effective immersion and safe retreat from hyperbaric exposures is dotted with a medley of evolving theories, best-guess practices, and hopeful global conceptualizations.

For individuals engaged in dives that require very limited exposures, these issues are arguably less problematic. The high numbers of diving profiles within "recreational" time/depth ranges establish a low statistical risk. However, variability in decompression risk seems obvious to most seasoned technical divers. For example, divers may follow vastly different profiles on the same dive where the very aggressive diver experiences the same success as divers showing much greater conservatism. Conversely, some divers seem to experience problems with deep dives and/or long bottom times almost regardless of the length of their decompression profile. Predisposing factors such as PFO as well as other variables including poor fitness, high fat content, and dehydration appear relevant. Yet these seem to paint an incomplete picture while trying to explain the variability within decompression illness.

The early years of technical diving found the mysteries of decompression consistently represented, but it was the growing expanse of extreme exposures in technical diving that heavily challenged inconsistencies in decompression knowledge and practice. In some groups this new style of diving rapidly pushed the established decompression envelope. During the late 1980's, technical diving became more common among a very small group of divers. Not until the mid

1990's did the practice of deep and mixed gas diving become solidly entrenched within "recreational" (i.e., non-paid) circles and become acknowledged as technical diving.

For most early technical divers, obtaining deep, mixed gas decompression tables constituted one of many roadblocks to safe deep diving. Available tables tended to come from a hodgepodge of locations and often relied on extreme conservatism as insulation against the lack of detailed experience. Many explorers found that common decompression assumptions subjected divers to extremely long decompression. Some divers noted that very long decompressions seemed inefficient and that including a greater proportion of deeper stops seemed to allow the reduction of shallower decompression stops, reducing total decompression time.

During the late 1980's a non-profit exploration group known as the Woodville Karst Plain Project (WKPP) began steadily expanding the length of their deep cave immersions. By the mid 1990's these divers were experiencing bottom times of about six hours at a depth of 300'. During this period and in the years to come the team would focus considerable energy toward safely reducing total decompression time. This process was primarily a response to the sense that conventional Buhlmann algorithms were not structured with the most favorable arrangement of decompression stop times.

WKPP divers employ progressively deeper stops for varying times while shortening shallow times in pursuit of reducing total decompression obligations. Over approximately 7,500 dives spanning nearly 20 years these divers aggressively experimented with a range of decompression profiles, working to support immersions that have reached nearly thirty hours. The divers utilize a similar decompression time for all dives in excess of six hours bottom time where dives average approximately 280 feet. To date ten hours is the longest bottom time obtained, resulting in a decompression of 17 hours.

One unfortunate aspect of dives conducted within the WKPP is that profiles are not documented with an eye toward establishing scientific validity. Moreover, the limited number of divers utilizing exceptional exposure is limited; this further complicates reliable statistical evaluation. However, the body of subjective evidence points to an interesting strategy whereby successful immersions of more than ten hours at 300 feet are successfully conducted. These divers utilize decompression times roughly 300 minutes less than requested by typical Bühlmann profiles. These profiles utilize stops deeper than called for during Bühlmann profiles while also shortening shallow stops. To date roughly ten divers use these procedures successfully with at least six of these divers sustaining exposures of approximately 20 hours; two of these divers regularly sustain exposures from 20 to 30 hours.

There is little question that one must use great caution while drawing conclusions from data that is subjectively reported. Yet, the divers from the WKPP have a long history of successful immersions that far exceed those historically thought feasible. Therefore, these dives represent one weigh point toward assembling a broader picture of successful decompression strategies. Clearly they point toward the idea that practices deemed historically unconventional may have merit, increasing the burden of responsibility to consider these practices during future research initiatives.

THE APPLICATION OF "DEEP STOPS" IN ANDI'S TECHNICAL DIVER TRAINING AND EXPEDITIONS

Ed Betts

ABSTRACT:

Introduction

The validity and efficacy of the RGBM is an unresolved topic. To some it is controversial. After much discussion and investigation ANDI performed its own trials on two expeditions and recorded all data for our own use. Although no specific case studies and conclusions were offered by others, we decided to conduct our own trials. ANDI has since implemented the use of this methodology by means of the ANDI-Gap software program.

Data Collection

The original "field tests" consisted of 4 series of dives which were performed by groups consisting of 12 males and 2 females with age variations of 23 to 61. The dive planning was completed using the Gap software in RGBM mode and the individual tables were printed including bailout options. Depths ranged from 24m to 156m with bottom times at the deepest depths of 20 to 29 minutes. Several dives made at the shallowest depths exceeded 150 minutes of BT. In 2003, ANDI has trained a team of commercial divers using surface-supplied equipment from pre-mixed gas racks. ANDI methodology was used on their project, the Rio-Andirion Bridge, Europe's largest. Several thousand dives were completed.

Current Usage

ANDI has 4+ years of use throughout our network. With training conducted in over 60 countries by our trainers and instructors in many different languages we require that ANDI-Gap is the only algorithm permitted. We are not scientists, mathematicians or research physiologists. We are engineers, instructors and working divers who are often the test subjects for our own methods. We currently offer students free use of the software and require instructors to purchase it. We have recorded over 2500 free downloads of the trial program from our web-site.

Results of the Dives

Regarding the efficacy of the deep stop method we can only say "what works...works." I am not the expert here. My position is that Decompression is still an art and not yet a science. We are all still learning and especially so at the more extreme exposures. Despite conflicting comments from some colleagues, our experience using this method is as follows. No incidences of DCI occurred during the expeditions and all divers reported no sub-clinical symptoms. We have not one single case ever reported to ANDI of DCI during any training program, nor, any reports of DCI experienced by ANDI-certified divers using this method.

Conclusions

Until contrary data can be offered it is ANDI's decision to continue to recommend the use of this diving methodology and training procedure.

TRANSCRIPT: THE APPLICATION OF "DEEP STOPS" IN ANDI'S TECHNICAL DIVER TRAINING AND EXPEDITIONS

Good morning, everybody. Thank you very much for your attendance. Thanks for giving me the honor, time and courtesy of hearing what we have to say.

I would offer a comment here. Bruce called me up and asked me to speak about this and just share my own experiences and ask questions about validity and efficacy of what we were doing in our ANDI organization. I guess the reason that we're here is because this is still an unresolved topic, and to some there's a strong measure of travesty or controversy, depending upon which side of the pond you're on, but it's still there.

After much discussion and investigation through our own evolution in our training methodology, we've decided to endorse the RGBM model.

I should give you a little background history. In 1990, we were working with a group of people developing rebreather software and at the same time ANDI International was involved in the early stages of technical diving and trimix diving. It was interesting that I, too, called Dr. Hamilton in early '90 and asked him to help me out with some dives that I wanted to do. For us it was a question of decompression. Well, okay, open ocean, high sea conditions, changing environment decompression. On one hand, you want to get out of the water faster, no problem, don't do any decompression. On the other hand, you want to have a zero hit rate. Good, stay in the water for three hours.

We needed a little bit more than that and, of course, Dr. Hamilton did help us out, although he did tell me his computer was crunching away for several hours to produce those tables. Quite a bit different than the powerhouse computers we're using today.

The software that we were working with on the original rebreather was incorporated in deep stop and it was an interesting thing to me because being the novice and amateur, I had no historical references on it. It was very simple. The software mandated the deep stop if the diver was ascending and 50 percent of the maximum depth was reached.

Very simple. Required two-minute stop. The rebreather adjusted your ascent gas into a deco mode, 1.6 ATAs, and it continued towards the surface. Now, today that sounds like standard procedure. In 1989 and '90, when we were working with this, it was kind of weird, certainly not common. The system proved to be more and more valid. We had zero recorded hits and we were doing what was considered at that time extreme exposures. The living laboratory -- and I've seen my other colleagues here all refer to a living laboratory. Interesting that we've all hit on the terminology.

That living laboratory did work because it became part of our protocols and I have to freely admit to you, I didn't understand and still don't understand exactly why it works so well. I'm not a scientist. I'm just an engineer. I'm not able to handle all the research and statistics, but we do balance risk factors with operational necessities.

When the RGBM became a topic of discussion and became available to ANDI, we were receptive and receptive to implementation and did accept it. In 2003, we did some initial evaluations. Our instructor trainer director board did recommend the change. We changed our ANDI dive planner software and we were using a dive planning software as a training agency and I don't know of anybody else that was at the time, but we were using a dive planning software. We called it "the ANDI dive planner" and it was essentially Buhlmann, Haldanian and so on. I mean, it was not as sophisticated as we have today, but we had good results with it. We implemented the ANDI-GAP dive planner into our training methodology 100 percent in February of 2005.

As far as data collection is concerned, all along ANDI has been involved in projects and operations. In 2003, we trained the team of commercial divers that were used to build the Rio-Antirion bridge, which is Europe's largest bridge. These dives were quite effective and both the French government and Greek government did give us some pretty significant compliments as to the results.

The records show that for 72 dives using our safe air nitrox methodology, 11.5 using trimix, zero dives using air, zero DCI. No symptoms. No subclinical. No hits. Zero accidents. I have a complimentary letter from the prime contractor, the diving contractor and both governments. Considering the difficulty of the job, fast moving water, cool water, not cold water, by our standards, zero accidents was impressive in a commercial operation.

2004, we trained the Israeli Army, IDF, Israeli Navy, and they implemented the ANDI methodology and implemented our program 100 percent. The comment that I am able to share with you in written documentation, more than 1,000 dives completed, 60 to 103 meters, zero incidents. I can't give you the details of the dives, but I do have printouts and so forth. These were all computer backed up with black box data recording provided by Cochran, so I have little Cochran black boxes recording the data.

It is an impressive thing that they had approached this so suspiciously, they were being pushed into it because, as one of my colleagues mentioned earlier, technical diving was outpacing the military in every aspect. The tech divers could be deployed faster, deeper and with more effective equipment than the military divers.

And Admiral Suer said to me, "We're not going to let that continue. We want to at least be right with you guys." We are involved in a shipwreck consortium, doing treasure salvage project, and every diver on the team has been trained according to the ANDI methodology. This dive project was halted with the litigation with Odyssey, but I hope to be back to it shortly. But, again, a perfect track record.

Now, 2004 we did our twilight zone expedition, deep diving for the celicant. And although I don't have a lot of dives, it's pretty interesting that we did have depths to 156 feet, 17 dives deeper than 500 feet, and zero incidents completely.

All those dives were done using our ANDI-GAP dive planner. All those dives were done, of course using CCRs. The whole expedition was a huge success, and I feel that that was our test. Not too many people on the other side of 60 do dives deeper than 500 feet and have zero incidents. So I do feel fortunate with that.

Now, essentially, the summary of this is that ANDI has, besides our evolutionary phase, four-plus years of use throughout the network, we do have training conducted in over 60 countries by trainers and instructors. And the only thing I can report to you is what we get back from the instructors who are actually recording and working with the divers in the field.

The issue to the scientists and the statisticians, what you're doing obviously can't work. You guys just don't have your handle on it. Yes, sir, I know I'm the grunt with my boots on the ground, but I have to just report back, this is what I'm seeing, and what's working for us is what we're going to continue to do.

So based on that, I have to say I'm not the expert here. My whole position is that decompression is an art and not a science. At this point it's still an art because we are still modifying and modifying and modifying.

Within the ANDI system, we have implemented it in such a way that all technical training requires the use of standardized preset dive profiles created by ANDI-GAP or at the discretion of the instructor generated on site by ANDI-GAP. This covers all of our default Level 3 technical diving, extended range diving, trimix diving.

The implementation is done in such a way that we offer every single student the opportunity to download a free full function trial of ANDI-GAP. That's what you're going to use during the course. We require the technical divers to use it in our program, and we've got a substantial group, more than 16,000 divers, who are actually using the method that they were trained in.

I have to say that we're just doing what works and I freely admit, I'm not the guy to tell you why, I don't know why. We, as a training agency, have been awfully lucky. We have yet to have a claim made against our insurance policy. So we haven't had any recorded hits during training. So something is working. Whatever it is that we're doing, I'm going to keep doing it until somebody can show me a better way.

Now, we would estimate here in conclusion that although ANDI is certainly operating beyond what people would call the average dive depth in difficulties, our safety record proves that, yes, we are lucky and we're simply going to strive and continue to strive to better understand why it's working, but we're not going to change what is working.

So thank you very much. I appreciate the time and I hope that what I've been able to share has been somewhat informative and enlightening. I'll leave the science to the scientists. I'm just a diver and an engineer. Thanks very much, everybody.

DEEP STOPS: AWARENESS AND CURRENT PRACTICE IN THE TECHNICAL DIVING COMMUNITY

Drew Richardson, Karl Shreeves

ABSTRACT:

The practice of making deep stops began with tec diving more than 10 years ago, with Richard Pyle, Ph.D. primarily credited with raising the question and creating awareness. Decompression models such as the Reduced Gradient Bubble Model (RGBM) and others have also come to the fore with recommendations that it is beneficial to begin decompressing deeper than mandated by conventional Haldanean-type models.

Anecdotally, the approach to deep stops in tec diving includes using deep models like RGBM, adding deep stops to conventional Haldanean-type model predictions and not making deep stops, but there have been no data that reveal which practices are present to what extent. The authors initiated a survey of individuals certified as Technical and Technical Trimix Divers, Instructors and Instructor Trainers to determine an indication of the present state of deep stop awareness and practice in the technical diving community. This paper discusses the findings from the survey.

PAPER:

Introduction

The practice of making deep stops began with tec diving more than 10 years ago, with Richard Pyle, Ph.D. primarily credited with raising the question and creating awareness. (Pyle 1996) Wienke and O'Leary also credit the Woodville Karst Plains Project (WKPP) deep cave dives with contributing to the trend. (Wienke and O'Leary, 2) Decompression models such as the Reduced Gradient Bubble Model (RGBM) and others have also come to the fore with recommendations that it is beneficial to begin decompressing deeper than mandated by conventional Haldanean-type models. (Maiken 1995) (Marroni, Bennett et al 2004) (DSAT 2003, 25-26)

Anecdotally, the approach to deep stops in tec diving include using deep models like RGBM, adding deep stops to conventional Haldanean-type model predictions and not making deep stops at all, but there have been no data that reveal which practices are present to what extent. The authors initiated a survey of individuals certified as Technical and Technical Trimix Divers, Instructors and Instructor Trainers to examine the present state of deep stop awareness and practice in the technical diving community. The study found a universal awareness of deep stops in the tec diving community surveyed, with making deep stops the prevailing practice for technical decompression dives. The study also found that among tec divers, making deep stops is a common, but not universal practice when making no stop dives.

Methodology

The authors initiated a by-invitation electronic survey conducted by PADI to a sample from the DSAT TecRec diver certification pool. The criteria for selection included having an valid email address and a certification of DSAT Tec Diver Level 1 or higher. DSAT Gas Blender certification was excluded from the data pool because it does not require a certification as a technical diver. The survey invitation transmitted by email to 1003 individuals and included a link to a web page for completing the survey.

The survey consisted of 17 questions about diver certification levels, experience, familiarity with deep stops, and application in both decompression and no stop diving. A draft of the survey appears in Appendix I. The flow of questions was written so that certain answers directed respondents to subsequent questions so that they skipped over non applicable questions based on previous questions. Therefore, it was not expected that all questions be answered by all respondents. For added clarity in completing the questions, two minor adjustments were made to Question 6 and Question 8 on the first day of the survey based on some initial comments. It is not thought that these minor changes affected the data significantly, if at all.

Table 1 – Survey Summary

- 1003 invitations to survey
- DSAT TecRec certfication, Tec Diver Level 1 & above
- Valid email address required
- Blender certification excluded (non tec diving qualification)
- International distribution:

79.7%	North America
11.7%	South America
3.9%	Europe
1.8%	Central America
1.3%	Caribbean
0.5%	South Pacific
1.1%	Other

Response Results

The survey initiated 10 April 2008 ath 1:44 a.m. PDST and ended on 18 April 2008 at 6:16 p.m. PDST. There were 234 respondents, or a response rate of 23.3 percent, for a margin of error of 5.6 percent at the 95 percent confidence level, or 7.4 percent at the 99 percent confidence level. The summary of the responses appears in Appendix II.

Diver Profiles

The responding diver data pool included a wide age and experience range. Ages ranged from 22 to more than 60 years old, with 30 to 49 accounting for 65.3 percent of the respondents. Because the survey asked for ages in ranges, there is no meaningful way to calculate a mean age. Answers for years being a diver ranged from one to 52 years, with a mean of 12.5 years diving. The range for years tech diving went from less than a year to 30 years, with a mean of 4 years. (Note: For calculation purposes, responses of <1 years [n=7] were treated as .5 years.) Gender was 93.2 percent male, which compares well within the 99 percent confidence interval against the 91.7 percent male found for this population as a whole in certification statistics. DSAT TecRec instructor-level and higher tec divers accounted for 40.6 percent of respondents, with approximately 65 percent of respondents indicating they have one or more tec diving credential from other training organizations. 75.2 percent rated their decompression practices as conservative; 24.4 percent rated it as neither conservative or liberal, with only a single respondent (.4 percent) rating them as liberal.

Table 2 – Survey Responder Profile

Age Distribution	
22-29	9.0%
30-39	30.3%
40-49	35.0%
50-59	19.2%
60+	6.4%
Mean years diving: 12.5	
Mean years tec diving: 4	
Gender Distribution	
Male	93.2%
Female	6.8%

Deep Stop Awareness and Practice

One hundred percent of respondents indicated that they were familiar with deep stops practice and theory. 80.76 percent said that deep stops were part of their tec diver training, with 61.1 percent saying they read about them in publications, and 50.42 percent said they had learned about deep stops from fellow tec divers. Multiple responses were allowed. Under “other,” respondents cited specific dive computers, Richard Pyle and decompression software as sources of information about deep stops.

The majority (97.9 percent) of respondents said they have made a deep stop. (Those who said they had not were directed to skip to question 11.) For decompression diving, 51.8 percent of those who had made deep stops said their practice is to use a conventional algorithm such as Buhlmann and add one or more deep stops, and to complete any decompression the stops add. 37.7 percent said they use a bubble algorthm that inherently requires deep stops. Only 3.9 percent said they add deep stops to a conventional alorthim and then disregard any addition decompression the deeps stops add. 77.4 percent of respondents who have made deep stops said that they plan deep stops for all decompression dives, with the balance split between those who said they plan or omit stops based on assessed risk factors for each dive, and those who said they did not plan deep stops for dives that require decompression due to duration rather than due to depth.

Table 3 – Survey Responder Deep Stop Practices for Decompression Dives

Have made a deep stop	97.9% (229 of 234 responses)
Plan deep stops for all deco dives	77.4% (175 of 226 responses)
Plan deep stops for deep deco dives	11.5% (26 of 226 responses)
Plan deep stops based on factors	11.1% (25 of 226 responses)
Add deep stops to conventional algorithm & complete added deco	51.8% (118 of 224 responses)
Add deep stops to conventional algorithm & omit added deco	3.9% (9 of 224 responses)
Use bubble algorithm (RGBM, etc.)	40.2% (90 of 224 responses)
Use whatever computer/algorithm teammates use	4.8% (11 of 224 responses)

For no stop (no decompression) diving, respondents were split about 60-40, among those who do and who do not routinely make deep stops when no stop diving, respectively. 59.2 percent said they make deep stops at half the bottom depth and another between 6 metres/20 feet and 3 metres/10 feet when no stop diving, with 33.8 percent indicating they stop between 18 metres/60 feet and 10 metres/30 feet as well as between 6 metres/20 feet and 3 metres/10 feet when no stop diving. Seven percent said they make only the deep safety stop when no stop diving. The majority (56.7 percent) said they don't make deep stops on all no stop dives, but do so for deep no stop dives or depending upon specific risk factors assessed for each dive.

Table 4 – Survey Responder Deep Stop Practices for No Decompression (No Stop) Dives

Routinely make deep stops on no stop dives	59.9% (136 of 227 responses)
Deep stops on all no stop dives	43.3% (68 of 157 responses)
Deep stops on deep no stop dives only	33.1% (52 of 157 responses)
Make or omit deep stops based on risk factors	23.6% (37 of 157 responses)
Stop @ $^1/_2$ bottom depth & between 6m-3m	59.2% (93 of 157 responses)
Stop 18m-10m & between 6m-3m	33.8% (53 of 157 responses)
Stop @ $^1/_2$ bottom depth only	3.8% (6 of 157 responses)
Stop 18m-10m only	3.2% (5 of 157 responses)

Those Who Don't Make Deep Stops

Question 11 was intended specifically for respondents who said they do not make deep stops. Respondents who said they had never made a deep stop (Question 5) and those who said they did make deep stops while decompression diving but did not make them routinely when no stop diving (Question 8) were directed to skip to Question 11. All other respondents were directed past Question 11 on the survey, though this was apparently missed by some respondents who answered it anyway. Fortunately, the data tracking software was able to filter out these not-relevant responses so the intended data were not lost. Understandably, many comments (Question 17) reflect questions from responders who were supposed to skip Question 11 but did not, and ask why Question 11 had no pro-deep stop choices.

Of the five respondents who said they have never made a deep stop, one answered subsequent questions that suggested the person actually does or would make deep stops. The remaining four answered that they believe deep stops have some benefit, but not enough to make them worth the additional planning and time. None of these indicated they believe that deep stops lack theoretical support or add risk.

52 respondents said they did not routinely make deep stops when no stop diving. Examination of the responses for these 52 with respect to decompression stop diving found answer distribution that was similar to the group overall. Based on this, it should be inferred that their responses to Question 11 applied to their beliefs with respect to deep stops while no stop diving only. Of these, the majority indicated that they believe that deep stops have a benefit, but not enough to make them worth the planning and time.

Table 5 – View of Deep Stops for No Stop Dives by Responders Who Do Not Routinely Make Them

Believe deep stops have some benefit, but not enough to make them worth added planning & time	65.4% (34 of 52 responses)
Don't believe evidence supports deep stops	23.1% (12 of 52 responses)
Believe deep stops add risk	11.5% (6 of 52 responses)

Of those who answered "no" to Question 8, 21 answered Questions 9 and 10 instead of skipping to 11. This is at least partially explained by the fact the skip reference was accidentally omitted at first, but corrected before the end of the first day. Interestingly, the answers of the 21 who answered these two questions approximately conform to the distribution of answers from the group overall, so their answers did not affect the data results in any meaningful way (if they had, the software would have been used to filter their responses and examine their views compared to the views of the broad group).

Comments by Respondents

Question 17 allowed respondents to make any comments. These comments appear in the appendix (names, where put in by the respondent, have been removed).

By far the most common comments were those related to Question 11, which, as explained earlier, many respondents would not have been expected to answer. These comments understandably question why there is no pro-deep stops choice.

The majority of comments reflect an attitude supporting deeps stops in general, with some variety of opinion regarding their role in no stop diving. Expressed views ranged from a desire to see deep stops included in recreational diver courses to the opinion that deep stops are unproved theory.

Limitations

There are a few study limitations one must apply to the data and conclusions presented here.

1. Given that the level of commitment, training and experience of the average tec diver is higher than that of the average recreational diver, it cannot be inferred from this data that recreational divers have an equal awareness of deep stops. Also, while gender distribution of the survey approximates that of the TecRec certification base (93.2 percent male survey; 91.7 percent male in TecRec certification data base), it departs from the gender distribution found in the broad PADI recreational diver certification data base, which is approximately 67 percent male. Therefore, it is not reasonable to conclude that the distribution of deep stop awareness, views and behaviors found by this study will necessarily be the same in the broad recreational, non tec diving diving public.

2. As stated previously some of the respondents who answered "no" to Question 8 answered Questions 9 and 10 instead of skipping to Question 11. Software separated these from the rest of the survey respondents and found no meaningful differences in the distribution of answers given to Questions 9 and 10. Their inclusion is therefore not likely a limitation in this study.

3. The survey was conducted in English. There was no examination of English as a primary or secondary language as a factor influencing the survey. While there is no hypothetical reason to suggest a significant difference in the responses of tec divers who don't speak English, nothing in the data excludes the possibility.

4. As mentioned previously, those who answered "no" to Question 8 were those who indicated they don't routinely make deep stops on no decompression dives. It is not specifically stated that Question 11 is specific to deep stops on no decompression dives only, but that is the reasonable inference when looking at the response distribution of those responders to the decompression dive, deep stop questions. Nonetheless, one must point out that this leaves some, albeit minor, question about these responders answers to Question 11.

Conclusions

The data in this survey, as summarized below, suggest that tec divers as a group are almost universally aware of deep stops and make them as common, accepted practice when decompression diving. The high awareness in the sample group isn't surprising, considering that deep stops are part of TecRec training and the selection for participation was a TecRec certification. (DSAT 2000, 226-227) (DSAT 2003, 25-26, 65, 74) But, the high percentage of cited sources for learning about deep stops beyond from outside TecRec training, coupled with the numerous certifications from other organizations, points to a strong community awareness and indicates that TecRec training alone doesn't account for the 100 percent survey response. Indeed, because 100 percent of respondents had TecRec certifications, the actual figure for learning about deeps stops during training should be 100 percent, though only 80.76 percent indicated so.

Table 6 – Responder Non DSAT TecRec Certifications

Certification	Number of Responders
Advanced wreck (no org. listed)	1
ANDI CCR	1
ANDI Nitrox Instructor (all levels)	1
ANDI Technical Advanced Instructor	1
ANDI Trimix Instructor (all levels)	2
ANDI Trimix diver (all levels)	3
CCR Instructor, (no org. listed)	2
CCR diver, (no org. listed)	5
Full cave diver (no org. listed	7
GUE fundamentals	1
GUE wreck	1
IANTD Advanced Nitrox diver	8
IANTD Cave Instructor (all levels)	10
IANTD cave diver (all levels)	16
IANTD CCR Instructor (all levels)	6
IANTD CCR diver (all levels)	6
IANTD Decompression Specialist Instructor	1
IANTD Nitrox Instructor (all levels)	8
IANTD Trimix Instructor (all levels)	18
IANTD Trimix diver (all levels)	26
IANTD Tech Diver Instructor	4
IANTD Technical Diver	5
IANTD Technical Wreck Instructor	1
IANTD Technical Wreck Diver	1
NACD Instructor	2
NACD cave diver (all levels)	13
NAUI cave diver	1
NAUI Heliox diver	1
NAUI Trimix diver	1
NSS-CDS cave instructor	2
NSS-CDS cave diver (all levels)	27
PSA Trimix instructor	1
TDI Advanced Wreck Instructor	3
TDI Advance Wreck Diver	2
TDI Cave Instructor	1
TDI cave diver (all levels)	4
TDI CCR Instructor	5
TDI CCR diver	7
TDI Deco Procedures Instructor	8
TDI Deco Procedures diver	11
TDI Extended Range Instructor	2
TDI Extended Range Diver	8
TDI Nitrox Instructor (all levels)	6
TDI SCR Instructor	3
TDI Trimix Instructor (all levels)	19
TDI Trimix diver (all levels)	22
Trimix instructor (no org. listed)	3

Notes: Multiple answers were permitted and were tallied separately, so that some responders account for more than one certification. Some responses were not tabulated due to inapplicability (non tec) or ambiguity. Not all responders listed non TecRec certifications.

An interesting finding is that despite the popularization of bubble dynamics models that inherently prescribe deep stops (RGBM, HKBM, VPM, etc.), the most common practice found by the survey (55.7 percent of respondents) is to use a conventional (e.g. Buhlmann) algorithm and add deep stops not predicted by the model. This is not likely a result of a TecRec training bias because TecRec courses do not prescribe a particular algorithm, table or computer. Though the course materials have examples in which deep stops have been added to conventional models (DSAT 2000, 226) (DSAT 2003, 29-30), the actual algorithms, computers, etc. chosen for planning dives during training are determined by the instructor and students. The large number of non DSAT tec certifications presents the possibility that other training organizations may influence this choice, though nothing in the data specifically suggests this. Of respondents using conventional models, the overwhelming majority (93 percent) said they complete the extra decompression "tail" that results when they add deep stops to a conventional model.

The respondent's answers regarding no stop diving and deep stops appear to reflect an attitude that within no stop diving, the use of deep stops is more situational than when decompression diving. Although about 60 percent (59.9) of respondents said they routinely make deep stops when no stop diving; only 43.3 percent of these said they plan them for all such dives. About a third of these divers (33.1 percent) said they make deep stops on deep but not shallow no decompression dives ("deep" and "shallow" were not defined). About twice as many respondents said that they omit or make deep stops depending upon specific risk factors for no stop dives as said they do this for decompression dives (23.6 percent versus 11.1 percent).

A minority of responders indicated that they view deep stops as unproven or adding risk (100 percent of responders who have not made a deep stop, and 34.6 percent of responders who do not routinely make deep stops on no decompression dives). These data suggest that there remains a minority of divers who disagree that deep stops have a proven benefit, particularly with respect to no stop diving.

Summary – Statements of Key Findings

- Survey based on n=234 (23.3% response rate)
- Respondent age range 22 to 60+, 65.3% of respondents aged 30-49.
- Mean years diving = 12.5; mean years tec diving = 4
- Predominantly male (93.2%)
- Approx 65% have one or more nonDSAT tec certifications
- There is a nearly complete awareness of deep stops and theory in the tec community. 100% of respondents said they were familiar with deep stops
- 97.9% said they have made a deep stop.
- 51.8% of those who have made a deep stop said that when deco diving they use a conventional algorithm, add deep stops and complete the resulting additional decompression.
- 37.7% of those who have made a deep stop said that when deco diving, they use a bubble algorithm that inherently includes deep stops.
- The survey suggests that deep stops are the prevailing practice in the tec diving community. 77.4% of those who have made a deep stop said that they plan deep stops for all deco dives and only omit them in an unforeseen situation.

- Tec divers make deep stops on no decompression dives, but apply them less routinely than when deco diving. 59.9% of those who have made a deep stop said they routinely make deep stops on no decompression dives. 56.7% of those answering said they don't make deep stops on all no stop dives.
- 65.4% of those who said they don't make deep stops routinely on no stop dives said they believe deep stops have some benefit, but not enough to make them worth the additional planning and time.
- 11.5% (2.6% of the survey respondents, n=6) of those who said they don't make deep stops routinely on no stop dives said they believe deep stops add risk rather than reduce the risk of DCS.

References

1. DSAT, 2000. DSAT Tec Deep Diver Manual, PADI, Rancho Santa Margarita, CA
2. DSAT, 2003. DSAT Tec Trimix Diver Manual, PADI, Rancho Santa Margarita, CA
3. Maiken, E., 1995. Bubble decompression strategies. Presentation tek95 conference, version published in Deep Tech, vol. 6. www.decompression.org/maiken/Bubble_Decompression_Strategies.htm
4. Marroni, A.; Bennett, P.B.; Cronje, F.J.; Cali-Corleo, R.; Germonpre, P.; Pieri, M. ; Bonuccelli, C.; and Balestra, C., 2004. A deep stop during decompression from 82 fsw (25m) significantly reduces bubbles and fast tissue gas tensions. Undersea and Hyperbaric Medicine Journal: 31:2
5. Pyle RL., 1996. The importance of deep safety stops: Rethinking ascent patterns from decompression dives. DeepTech. 5:64
6. Wienke, B. and O'Leary, T, no date, Deep stops and deep helium, RGBM technical series 9, pdf document, www.tek-dive.com/portal/upload/deep.pdf

Appendix I: Survey

Deep Stop Survey 2008

Instructions

Answer questions as they relate to you. For most answers, check the boxes most applicable to you or fill in the blanks.

About You

1. Of the following TecRec certifications, please check the highest level you have?

(Select only one.)

☐ Tec Diver Level I
☐ Tec Deep Diver
☐ Tec Trimix Diver
☐ Tec Deep Instructor
☐ Tec Trimix Instructor
☐ Tec Deep Instructor Trainer
☐ Tec Trimix Instructor Trainer

2. Please list other tec diving certifications (not DSAT TecRec certifications) that you have, if any:

(Provide one response only.)

3. Are you familiar with the concept of deep stops and deep stops theory?

(Select only one.)

☐ Yes
☐ No **(Skip to Q. 12)**

4. Where did you learn about deep stops?

(Select all that apply.)

☐ They were part of tec diver training
☐ From fellow tec divers
☐ Read about them online
☐ Read about them in publications
☐ Other-fill in:

5. Have you ever made a deep stop?

(Select only one.)

☐ Yes
☐ No **(Skip to Q. 11)**

6. Indicate the choice that best completes this sentence of how you determine deep stops on a decompression dive. I use a computer and / or tables with a:

(Select only one.)

☐ Conventional algorithm (Buhlman) add 1+ stops between bottom & 1st req'd stop and COMPLETE any deco the deep stops add
☐ Conventional algorithm (Buhlman) add 1+ stops between bottom & 1st req'd stop and DISREGARD any deco the deep stops add
☐ Bubble algorithm (RGMB, RGBM, HKBM, VPM, etc) that inherently require deep stops
☐ I use whatever computer and / or tables my teammates use

7. Please indicate the choice the that best reflects your practice regarding deep stops on decompression dives:

(Select only one.)

☐ I plan deep stops on all decompression dives, and only omit them if an unforeseen situation calls for it.
☐ I plan deep stops for deep (below 40m/130ft) decompression dives but not dives that require decompression due to duration
☐ I plan to make or omit deep stops depending upon the specific risk factors I assess for each dive

8. Do you routinely make deep stops when making no decompression (no stop required by the model) dives?

(Select only one.)

☐ Yes
☐ No **(Skip to Q. 11)**

9. Indicate the choice that best describes your preferred practice for making deep stops on a no decompression dive:

(Select only one.)

☐ I make a safety stop somewhere between 18m/60ft and 10m/30ft and another between 6m/20ft and 3m/10ft
☐ I make a safety stop somewhere between 18m/60ft and 10m/30ft and no shallower safety stop
☐ I make a safety stop at half the bottom depth and another between 6m/20f and 3m/10ft
☐ I make a safety stop at half the bottom depth and no shallower safety stop

10. Please indicate the choice that best reflects your practice regarding deep stops on no decompression dives:

(Select only one.)

☐ I plan deep stops on all no decompression dives, and only omit them if an unforeseen situation calls for it **(Skip to Q. 12)**
☐ I plan and make deep stops for deep no decompression dives, but not shallow ones **(Skip to Q. 12)**
☐ I plan to make or omit deep stops depending upon the specific risk factors I assess for each dive **(Skip to Q. 12)**

11. Please indicate the statement that best reflects your position on deep stops:

(Select only one.)

☐ I don't believe the evidence strongly supports deep stops
☐ I believe that deep stops add risk rather than reduce risk of DCS
☐ believe that deep stops may have some benefit, but not enough to make them worth the additional planning and time

12. I believe that my decompression practices are:

(Select only one.)

☐ Conservative
☐ Liberal
☐ Neither conservative or liberal

13. What is your gender?

(Select only one.)

☐ Male
☐ Female

14. What is your age?

(Select only one.)

☐ 18 to 21
☐ 22 to 29
☐ 30 to 39
☐ 40 to 49
☐ 50 to 59
☐ 60+

15. How many years have you been tech diving?

(Provide one response only.)

16. How many years have you been scuba diving?

(Provide one response only.)

17. Any additional comments you have about deep stops theory and / or practice? If your comments require a response, please email cheryl.gilmore@padi.com separately for a response:

(Provide one response only.)

Appendix II: Results

Respondent Metrics

Respondents: 234 of 1,003 invitations = 23.3% response rate
First Response: 4/10/2008 01:44 AM
Last Response: 4/18/2008 06:16 PM

Survey Results

The following is a tabular depiction of the responses to each survey question. Additional comments provided by respondents, if any, are included after each table.

Section - About You

1. Of the following TecRec certifications, please check the highest level you have?

32.5%	76	Tec Deep Diver
20.1%	47	Tec Trimix Diver
12.4%	29	Tec Deep Instructor
11.1%	26	Tec Trimix Instructor
9.4%	22	Tec Trimix Instructor Trainer
7.7%	18	Tec Deep Instructor Trainer
6.8%	16	Tec Diver Level I

2. Please list other tec diving certifications (not DSAT TecRec certifications) that you have, if any:

[Multiple responses given.]

3. Are you familiar with the concept of deep stops and deep stops theory?

100.0%	234	Yes

[Note: The survey directed those answering "no" to skip to Question 12, but zero responders answered "no."]

4. Where did you learn about deep stops? (multiple responses)

80.76%	189	They were part of tec diver training
61.1%	143	Read about them in publications
50.42%	118	From fellow tec divers
48,7%	114	Read about them online
17.52%	41	Other-fill in:

Comments/Notes: [Mulitiple responses given.]

5. Have you ever made a deep stop?

97.9%	229	Yes
2.1%	5	No

6. Indicate the choice that best completes this sentence of how you determine deep stops on a decompression dive. I use a computer and / or tables with a:

51.8%	118	Conventional algorithm (Buhlman) add 1+ stops between bottom & 1st req'd stop and COMPLETE any deco the deep stops add
37.7%	86	Bubble algorithm (RGMB, RGBM, HKBM, VPM, etc) that inherently require deep stops
4.8%	11	I use whatever computer and / or tables my teammates use
3.9%	9	Conventional algorithm (Buhlman) add 1+ stops between bottom & 1st req'd stop and DISREGARD any deco the deep stops add
1.8%	4	Bubble algorithm (RGMB) that inherently require deep stops

7. Please indicate the choice the that best reflects your practice regarding deep stops on decompression dives:

77.4%	175	I plan deep stops on all decompression dives, and only omit them if an unforeseen situation calls for it.

11.5%	26	I plan deep stops for deep (below 40m/130ft) decompression dives but not dives that require decompression due to duration
11.1%	25	I plan to make or omit deep stops depending upon the specific risk factors I assess for each dive

8. Do you routinely make deep stops when making no decompression (no stop required by the model) dives?

59.9%	136	Yes
40.1%	91	No

9. Indicate the choice that best describes your preferred practice for making deep stops on a no decompression dive:

59.2%	93	I make a safety stop at half the bottom depth and another between 6m/20f and 3m/10ft
33.8%	53	I make a safety stop somewhere between 18m/60ft and 10m/30ft and another between 6m/20ft and 3m/10ft
3.8%	6	I make a safety stop at half the bottom depth and no shallower safety stop
3.2%	5	I make a safety stop somewhere between 18m/60ft and 10m/30ft and no shallower safety stop

10. Please indicate the choice that best reflects your practice regarding deep stops on no decompression dives:

43.3%	68	I plan deep stops on all no decompression dives, and only omit them if an unforeseen situation calls for it
33.1%	52	I plan and make deep stops for deep no decompression dives, but not shallow ones
23.6%	37	I plan to make or omit deep stops depending upon the specific risk factors I assess for each dive

11. Please indicate the statement that best reflects your position on deep stops: (said no to Question 5)

100%	4	believe that deep stops may have some benefit, but not enough to make them worth the additional planning and time

11. Please indicate the statement that best reflects your position on deep stops: (said no to Question 8)

65.4%	34	believe that deep stops may have some benefit, but not enough to make them worth the additional planning and time
23.1%	12	I don't believe the evidence strongly supports deep stops
11.5%	6	I believe that deep stops add risk rather than reduce risk of DCS

12. I believe that my decompression practices are:

75.2%	176	Conservative
24.4%	57	Neither conservative or liberal
0.4%	1	Liberal

13. What is your gender?

93.2%	218	Male
6.8%	16	Female

14. What is your age?

35.0%	82	40 to 49
30.3%	71	30 to 39
19.2%	45	50 to 59
9.0%	21	22 to 29
6.4%	15	60+

15. How many years have you been tech diving?

- <1 (7 responses tallied)
- 1 (28 responses tallied)

- 10 (17 responses tallied)
- 11
- 12 (5 responses tallied)
- 13 (2 responses tallied)
- 15 (11 responses tallied)
- 16
- 18 (3 responses tallied)
- 2 (31 responses tallied)
- 20 (6 responses tallied)
- 21
- 25
- 29
- 3 (24 responses tallied)
- 30 (2 responses tallied)
- 4 (15 responses tallied)
- 5 (37 responses tallied)
- 6 (14 responses tallied)
- 7 (9 responses tallied)
- 8 (13 responses tallied)
- 9 (5 responses tallied)

16. How many years have you been scuba diving?

- 1 (2 responses tallied)
- 10 (13 responses tallied)
- 11 (6 responses tallied)
- 12 (9 responses tallied)
- 13 (9 responses tallied)
- 14 (6 responses tallied)
- 15 (16 responses tallied)
- 16 (9 responses tallied)
- 17 (5 responses tallied)
- 18 (4 responses tallied)
- 19 (3 responses tallied)
- 2 (2 responses tallied)
- 20 (10 responses tallied)
- 21 (2 responses tallied)
- 22 (12 responses tallied)
- 23 (4 responses tallied)
- 24
- 25 (15 responses tallied)
- 26 (2 responses tallied)
- 27 (6 responses tallied)
- 28
- 29 (2 responses tallied)
- 3 (2 responses tallied)
- 30 (9 responses tallied)
- 31 (2 responses tallied)
- 32 (3 responses tallied)
- 33

- 35 (10 responses tallied)
- 36
- 37 (2 responses tallied)
- 38 (2 responses tallied)
- 39
- 4 (11 responses tallied)
- 40 (6 responses tallied)
- 42
- 5 (3 responses tallied)
- 50
- 51
- 52 (2 responses tallied)
- 6 (5 responses tallied)
- 7 (15 responses tallied)
- 8 (11 responses tallied)
- 9 (6 responses tallied)

17 Any additional comments you have about deep stops theory and / or practice?

- Although there is not a (scientific) evidence, I do believe that DeepStop are good for reduce risk of DCS. As I say: its better to go down from a first floor using a ladder than jumping.
- As the new computers add deep stop technology - such as Suunto Vytec DS - I will make the deeps stops on no deco dives when I dive that computer. I ususally always dive a VR3 now - even on shallow receational dives. That computer adds deep stops and saftety stops only on deco dives - which I follow religiously. SO I tend to "multi-level" my deco dives, which inherently adds a "deep stop" because of the multilevel even though the computer does not prompt for it.
- Is there an "agenda" in Question 11. It seems none of these support my position. I feel deep stops neither add or change risk factors significantly. I do deep stops on my deeper dives as some evidence does support them. (Microbubbles are real) I'm closely watching studies being conducted by DAN for emperical evidence either way.
- concepts of deep stops and ascent rates must go together... and includes comments of the algorythm your choosing... questions just like this don't mean a lot...it must include more parameter...
- deep stops are a very good practice but I always do them on back gas. Some people just consider them their 1st deco stop but I feel that they should be additional
- Deep stops should become a recommeneded part of all dive planning. There are two main reasons I alway do deep stops: 1, Best practice gas profile managment. 2, a deep stop is the perfrect place to collect yourself in preparation for the ascent, are your deco cylinders all OK and ready for use, are your hoses squared away, are you on plan or do you need to make adjustments to your deco/asceent plan, shoot your SMB if using, is everyone on the team ready.... ascend :-)
- Deepstops give you also a moment to stop the ascent, re-check everything and team mates, shoot up lift bags if necesary and continue a controlled ascent... this also answers question 11 for me, since there was a good answer supporting my opinion. I personally, physically, feel the benefit of deepstops, especially with a gas-switch. Feel less tired after a dive...this might be psychological...
- During recreational dives, I use the Suunto D9 dive computer. it gives me the choice between deep stop and safety stop. It is always set to Deep stop. If I can't make it, I will make the regular safety stop.
- Evidence reflects a good practice and a more conservative approach using deep stops. People like Pyle and (my instructor) believe in them, and even go one step more conservative, and have never hasd any incidents reported after thousands of dives... that type of statistics is what i want in my log book

- For deco dives. I plan using the Bulman or VPM algorithm, at max conservitism then add deep stops subtracting from my planned bottom time. That way my plan is more conservative both by running more deco, and adding the deep stops just adds to that. One important note. When diving with open circuit I find they are a lot less conservative due to the gas volume requirements. This obviously requires them to balance risk, when on one of my rebreathers that is never an issue. I find I am doing less and less open circuit tec diving and using the RB instead. That has resulted in my stopping my instructor cert for DSAT courses.
- for deep stops, i typically use Vplanner. i always use them with helium mixes.
- For me it's more easy and better than do a long one at 10ft.
- Great survey!!!
- I always plan deep stops and list them on my dive slate. Using them is determined on the dive and any problems that exist. For example I was working at 200 feet and ran low on trimix so I rolled over to my air back gas and got hit with the effects of narcosis in an instant and started ringing ears and concussion spots in my eyes. I was on air maybe 3 minutes and started up with deep stops on my slate. All deep stops were done on this dive and by the time I was back at 70-50 fsw my head cleared. I added 3 minutes on O2 to the last stop and stayed on O2 on the boat for 30 minutes and all is well. The deep stops did help stabalize the hit I took at depth. Ordinarily I use less helium than most as my body prefers less helium and yet I still maintain the 1.4 for O2 and I use up to 130 feet for narcosis.
- I am also a PADI IDC Staff Instructor, and do talk about the concept of deep stops with students at the AOW and DM levels. I plan my own decompression diving using the V-Planner (VPM-B/E) set at +2 conservatism. I am impressed by this survey and appreciate the opportunity to provide this input.
- I believe deep stops should be a formal part of the recreational Deep Diver Specialty.
- I believe in deep stops and I believe they have saved lives in trimix diving when all or some of the mandatory deco was aborted because of emergency and the deep stops where completed before the emergency occured. I also believe in slow ascents especially the last 10 to 15 feet. I stand by PADI stance that deep stops are not needed in no deco diving but stand by slow ascents instead. be conservative
- I believe in deep stops. When I plan a deco dive I always let the dive planning software (Vplanner - VPM) include deep stops. If I find that my mutli gas switch computer (VR3 - Buhlman & VPM) has a slightly more conservative profile while I am executing the deco/deep stops then I will use that as my guide. If I am executing a non deco dive (recreational dive) and notice that to stay longer will take me into deco I check my air supply and then decide if I have enough to complete the deep stops that my dive computer (Suunto Vytec DS - RGBM) could give to give me along with the required deco obligation. I deliberately bought a Vytec wih the Deep Stop in it. I think that Richard Pyle had a good point and still does!
- I believe its a good tec diver habit,like the safety stops in normal diving
- I believe that deep stop are a safety factor, but allways include the safety stop time in the bottom time.
- I believe that deep stops may have some benefit and I would like to learn more about them.
- I believe that going a little slower than normal to your first required stop would be a suitable practice verses a deep stop.
- I did not submit an answer for question #11 as I don't agree with any of the ones listed. I do think deep stops are valuable and should be made & taught for both tech & NDL diving.
- I didn't understand the responses to question eleven
- I do deep stops on all dives below 120'
- I do deep stops on any dive greater than 80 ft. & alway do 3 to 5 min. @ 15ft.--A MUST- Thanks
- I feel very comfortable with Deep Stops and feel thay should be part of good dive planning. Would like to see DSAT offer an overhead / cave course

- I feel your questions are to vague, I plan deep stops as follows, In the planning process when I add deep stops if it adds to my deco time then I feel this could create a problem and do not do them, ecspecally if multiple deep stops are required. I only do them when they are added to the program and do not create more deco time.
- I find that I feel so much better at the end of Decompression dives when I plan deep stops, as well a hold around 100 feet or so on a Nitrox mix prior to doing my finally decompression. I call it multi level extended range decompression dives.
- I generally feel that deep stops are a great way to slow down the pressure gradient during ascent especially for longer or deeper decompression dives. They give the body a chance to catch up to the pressure gradient before continuing on to the first required deco stop. In recreational diving where there is less tissue loading, I'll typically use a slow ascent (30fpm or less) to keep the delta P between body tissues and ambient minimized.
- I have been doing Deep Stops since I read about them in a NAUI publication on RGBM Models around10 years ago, maybe less. I introduced Deep Stops to my Advanced Scuba Diver students and now as a PADI Instructor I discuss it in the Deep Adventure Dive and the Deep Diver Course.
- I just wanted to make my responses to questions 7 and 11. I did not like the choices you allowed for those 2 questions. For question number 11, my resopnse is "I always plan and complete deep stops, it's built into V Planner and my VR3 requires it, I believe they are a necessary". Question 7 response, "I will always complete a stop at the 1/2 point on non-decompression dives, it is very rare that I do tec dives that are not decompression, but I advocate to my students and instructors to always make deep stops on every tec dive".
- I make a 2 Minute Deep stop on all Decompression Dives and 1 minute on Recreational Dives plus the saftey stop
- I make deep stops on all dives at 1/2 the depth from bottom depth to 20 ft., then 1/2 from 1st stop to 20ft etc. + 3min at 20 ft and 2 min at 10 ft. on no deco dives.
- I my opinion, deep stops DO have benefits, enough to make them worth the additional planning and time
- I only make deep stops because my dive computer (Suunto D9) is programmed to do so and I thought it was more conservative. I have not done any research to determine if deep stops are actually beneficial or not, so I don't actually have an opinion based on any facts.
- I strongly believe in deep stops and use them on all deep dives
- I thing that the theory and the use of Deep Stops will be insert in the Tec Deep Manual and PADI make a Decompression Planner software for sale to the student.
- I think that PADI can include this theory in its advanced dive course, it's very important and is a good tool for prevent DCS.
- I think deep stops are very important on reducing DCS
- I think deep stops should be used in all decompression dives, but are not as important in non decompression dives where just a safety stop will suffice.
- I think that deep stops should be the preferred practice for all PADI Deep Divers who dive deeper than 30' .
- I typically add one or 2 deep stops when doing dives below 160fsw. I stay for one minute per stop the ascend slowly to my first required stop based on what my Cochran Trimix computer tells me. I have made over 50 dives to depths exceeding 150' - 200' range and have never taken a DCI hit. Most often I do 2 deep dives in that range on the same day. I typically deco on 32% and 80% I hope this info has helped. P.S. I beleive the DSAT TEC REC is the best training available for this type of diving and I beleive the training I received has kept me safe and cutting edge. Keep up the good work at DSAT!
- I was taught about oc/deep stops in my DSAT class and follow them as a rule of thumb I follow my dive plan based on table generated by desktop deco software and use a computer as back up

always. Diving CCR is a whole different animal though. Planning deep stops depends on the dive, conditions, depth, time, thermal exposure etc. There are a lot of variables here to consider. Basically, it all ends up evening out I feel. You can do your stops deeper and have short shallow foot deco stops, or vice versa.

- I was working as tech dive guide in a wreckship dive 63 meters deep around the year 2005. In that year some times I did 2 tech dives 63 meters down in a single day almost every day and I am sure that deep stops have saved me loads of times. If I have to chose between a deep or shalow stop for sure I will do the deep priority, the deep ones. Because is quickly and realy important when we are talking about fast tissues like blood and nervous sistem. In question 11, I put the 3rd alternative because I really believe in the importance of this deep stop in deco dives. I am using the algorithm Bulmann ZHL16 with configurations for conservative deep stops but I compare the profile with RGBM and VPM, to have more security.
- I would be interested in deep stops being part of Level II when I take that class in the future.
- I would like the be informed of the purpose for the survey. The recreational inclusion of the deep stop concept seems to be crowding the mooring lines at popular sites in the Florida keys, which are complicating decompression stops. Often tec divers encounter recreational divers making incorrrect deep stops for incorrect lengths of time which throws off the actual deco schedule of the tec divers. This result seems to be perpetuated by the recreational dive industry which encourages deep stops of 1-3 min. Rather than make a 1 min stop, the rec. divers usually opt for 3, which seems to be more conservative at face value, but is actually counterproductive with respect to nitrogen loading of fast tissue compartments. Basically, teach recreational deep stops correctly or don't mention them. And get those lime green split fins off my boat.
- I would like to receive any publications regarding to the deep stops
- I´m agree about deep stops, and considerated that its helped a good descompression dive. I`m 50 years old.
- If using my computer (Nitek He) I add deep stops and then do the additional deco required. However, I plan and try and dive against tables, usually VPM or HKBM using Nautilus, and include deep stops as part of the planning.
- In regard to question 11, I believe deep stops do have benefits but I don't think it's inconvienient to plan for. I think its a good and safe way to allow your body to off gas a little bit and catch up before the rest of your stops. Unless you have encountered an emergency or contingency event, why not include a deep stop? Gas permmitting, of course.
- My recreational deep stop teaching is for anything deeper than 80', cut max depth in half, stop at least one minute, cut in half again, stop at least one minute, and at most one more time until your 3+ minutes at 15-20'. Usually this requires 3 total stops but sometimes only 2.
- Not at this time. It is still theory and not proven fact.
- Number 11 on this survey does not give enough options. Each answer on number 11 is against deep stops, however, the whole survey is asking poeple why they prefer to add in deep stops.
- Personally, I feel less tired after doing deep stops after doing a dive with required deco. Therfore I always try to do deep stops.
- please disregard question 11, as I think that deep stops have enough merit as to incorporate them in my dive plans
- Prepaid for Dive Rite's Nitek X computer due to its deep stop capability.
- Q #11 does not have an option for a positive response. My official answer would be "I believe that deep stops do reduce the risk of DCS". I complete deep stops on all decompression dives however I do not complete them on no decompression dives. I always run tables with my computer used only as a back-up. Deep stops have never shown to add additional time to my regular deco. To me, they are an opportunity to blow off a little nitrogen prior to ascending to a shallower depth.
- Question 11 does not allow for me to support deep stop theory

- Question 11 is bogus. I strongly support deep stops and I have no other choice than responding something that is not what I truly think. How about " Ibelieve that deep stops have some benefits and I promote them routinely" or something like that.
- Question 11 only gives choices which are negative to deep stop. No answer was a good choice for me. I support the practice of deep stops based on statements by many divers that they felt better after using them than when they didin't and that they are required by the decompression programs I have been using.
- Question 11 was answered regarding deep stops on a no stop dive. The question taken out of context is not clear otherwise.
- Ratio deco (i.e. deco on the fly) should be a considered as a topic in PADI tech courses. PADI should also include more information regarding the more popular algorithms in it's courses.
- rgbm computers are standard now a days
- Since neither Padi or DSAT provide ample tables or software to plan your deep decompression dives, one is forced to look elsewhere. PADI provides tables for each and everything dive. Why not for deep decompression dives?
- Thanks for sending this question. I hope more.
- Thanks for the opportunity to partake in this survey. I firmly believe in the concept of theoretical deep stops. I currently teach the DSAT Tec Deep and DSAT Trimix programs to students and instructor candidates. It is encouraging that most new students in the DSAT program embrace the concept of theoretical deep stops and are eager to undertake a research project which includes readings from DAN, Richard Pyle, Suunto, UHMS, and other internet sources. Largely the research project is designed to have students understand the concept of deep stops, research the benfits of theoretical deep stops and reducing gradient bubbles, and understand the principal application of theoretical deep stops to all dives, even those considered recreational dives. Now we also assign a research project associated to the concepts of in water recompression. I know that will raise some eye brows, but the information is out there and we would be remiss not to address the concept. The one single hurdle in this educational and research process is having instructors, who have taught various programs for years, understand that we need to embrace technology and support research that will have a positive impact in their teaching styles and the success of their students. Thanks again for the opportunity.
- This is my concept of deep stops: Deep stop +/- start at 75% of your bottom depth ata until your medium stops, Medium stop, characterizes by bubbles models (eg. 18, 15, 12 , 9 m) And shallow stops. (6, 3m) The deep stops should be shorts and they manage your ascent rate controlling the bubbles grow, but, I believe if you made deep stops to long, will have oppose results. I use VPM-B for plan my dives.
- We have to put it on the recreational deep diver manual, teach and execute it in every dive deeper than 18 meters as a standard practice.
- What works is what works. I suspect that those who answered question 11 did not read enough or understand enough of the ample material available on the subject or simply have not dove enough to fully understand that there is no such thing as a "no decompression dive". So have them dress for the journey not the arrival.
- With deep stops from 150 or 130 feet every 10 feet for one minute to the decompression requirement decreases the bubbles and possibility of DCI.
- With the advent af programs like Vplanner over Zplanner and change in the way decompression is managed, in terms of multiple stops at deeper depths, the benefits are clearly felt upon surface. Physically there is less fatigue and much more energy, I'm a great fan and implement deep stops on recreational dives to depth.
- My tec instructor taught them and recommneded them but my Trimix instructor (Jeff insisted on them.)

DISCUSSION: TECHNICAL DIVING

DR. BRUCE WIENKE: Thanks, Drew. Let's open the session up for discussion. Again, as you ask questions, please state your name for the record and speak into the microphone. Thanks.

DAVID DOOLETTE: I wanted to make one general comment about what we heard. I heard a lot about the use of deep stops from the technical agencies. It was an interesting overview. I'm not telling you anything new. I just want to go on record that the fact that millions of dives have been done with deep stops without a lot of problems is not proof of their efficacy. There's infinite number of ways to decompress from a dive. Deep stop schedules appear to work, but it doesn't mean that they lower risk or can reduce overall decompression time compared to some other strategy. Jarrod pointed out, the only thing that these people have to go on is how they feel after a dive. I've got a bit of experience of measuring health status following decompression. It's notoriously difficult. People don't even remember if they've been to the hospital in the last year, let alone how they felt when doing a shallow dives 20 years ago wearing a cracking wetsuit. We need to be careful in the right hands. There may be some good anecdotal data there, but we haven't got any proof of efficacy from what was discussed in the last couple of hours. Just that it works, not necessarily that it's the best way to do things.

DR. PETER BENNETT: Do any of our technical divers want to take up that comment?

ED BETTS: I certainly appreciate the comment. Of course, there's lots of ways to decompress on a dive and as you get more and more experience, you certainly would employ your bag of tricks. This old guy would rather be cold on the bottom and warm during the deco phase of the dive, and consequently, I try and structure my diving to that. So is that going to change my issue? I hope so. I hope that makes me a little less likely to be one of the negative statistics here, positive hit. But really the comment of the statistical value, well, show me a better way that's going to give us less recorded hits than we've got, I'm ready to change. Just give me the info. That's one of the reasons why I'm here. I'm talking about ANDI's experience in my presentation for doing quite a few years of deep technical diving, which, yeah, I think we're on the limits, but we don't have any recorded hits during training. So I can't say, "Give me something that works better." We're not having a problem with what we're doing. I respect the comment and if I was able to say to you we've got 65 or 70 hits and you can show me a better methodology, I'm going to say -- I'm number one. I'm going to stand here and say, "I'm ready to listen. I'm ready to learn. Give me a better way, and I promise I'll do it tomorrow." Thank you.

JOSEPH DITURI: I just want to make sure that the scientific community doesn't throw the baby out with the bath water. There are some good dives that have been done, some good evidence. It may not be the end story, but let's use that data. Let's not throw it away. Let's move forward with the data that we have. I realize anecdotal proof, that we did some good things, but let's not just throw that away because it's not done scientifically.

KARL HUGGINS: I just want to ask the presenters what their opinions were in terms of this ratio decompression I've been hearing about and how that falls into this kind of practice that they are doing.

DR. BRUCE WIENKE: Well, we've looked at some of the ratio deco protocols that have been submitted as a way to do sort of deco on the fly. There's not just one. There's a bunch of them. Some are okay, in my humble estimation. Some totter on the edge. So to answer that question, I don't think you can give a blanket answer. Some would be okay. Some would not be okay. If I remember correctly, looking at about four or five of these, the ones where you're in the shallow decompression arena, where you're, say, in the 250-foot range and above, the ratio deco stuff, you know, looks a little bit like a deep stop paradigm. It may not be exact, but the numbers are close. You start doing the rules of ratio deco deeper, I would suggest that, from my experiences, that you get into a very gray area, and it's up to you.

DR. DAVID DOOLETTE: Karl, I missed your question a little bit. I didn't hear the whole question. From the little bit I know about ratio deco -- and I've used it myself in some circumstances -- it seems to be the most misunderstood procedure in the world. It's basically a way of memorizing short segments of tables. It's a way of memorizing a procedure and it depends on the procedure that you're memorizing as to how good it is. That's the way I look at it. People may have another opinion about what it is.

KARL HUGGINS: I just heard one protocol.

DR. DAVID DOOLETTE: There are a number of them. I use ratio as a way of memorizing those tables. Use them over a narrow limit way. You can use a ratio as an approximation to the actual numbers.

DR. SIMON MITCHELL: I'll just make a comment. I was quite up front with my co-chairs when I got involved with this meeting that I was really keen that this didn't seem to be a cheerleading session for deep stops, and the last sort of the segment could have been interpreted that way. I might also say that I use a bubble model algorithm for my own diving. I'm not expressing a belief either way here. But my concern is that I totally agree with David Doolette's comments, that we've heard a whole lot of anecdotal talk about large numbers of divers using these algorithms or large numbers of dives being done with no incidents. I don't think we've heard any evidence in either direction here this morning and I think people need to bear that in mind -- Ed, I really don't want to ambush you, but twice now you've stood up and said there's never been an incident using RGBM in training. And that's not true. I know of a guy who was in training, did a dive, it was absolutely perfectly executed, and he died of cardiopulmonary decompression sickness. I'm involved in defending the instructor as we speak. Now, that leads me to my next comment. It's the big problem with all these stories that we've been hearing from the presenters this morning. How do you know what the outcomes of these dives are? You don't. You've got no idea. The ones you're watching, that's fine. No problem. You can see those. But there's dives going on all over the world and you just don't see it. The only sort of program that gets you the kind of evidence that you need to make the statements about efficacy that we all want to hear is the kind of program that DAN is running at the moment with project dive exploration. Everything else is highly substandard and I think we shouldn't lose sight of that fact. Thank you.

(Footnote: Drs Mitchell and Betts followed up on the case cited here by Dr Mitchell. The diver was using ANDI GAP RGBM to control decompression from the dive in question as stated, but

this table had been adopted by an instructor from another agency. Thus, the accident did not occur on an ANDI program, which is why Dr Betts did not know about it).

DR. PETAR DENOBLE: I'm impressed with the data that you've shown here. It seems that DAN gets information about 10 percent of all DCS injuries reported annually who come from technical divers, and these 10 percent that equates to about 100 cases per year. It seems that no major training agency produces these divers, and that is really strange.

DR. PETER BENNETT: Is there any way that these agencies can provide the evidence behind the statements they're making; that is, provide the documentation to us in some way, either to us in this committee, which can start to put it together perhaps in some format for the proceedings. At least have some way to back up the data which was really quite impressive in the numbers, but if it's insecure, then we don't feel we made much progress.

ED BETTS: My comment would be that as far as a training agency is concerned, the only incidences that you can attest to are incidences that are reported to the training agency. Now, my colleague here said he's investigating a case of an accident incident using ANDI-GAP that resulted in a death. Flat out, where is the accident report? If the training agency is never notified, then what else can be said. As far as the Israeli Navy, I can tell you that every single dive is black-boxed, but you're not going to see it. I can also tell you that every single dive on the Rio-Antirion project was intensely recorded. With regard to the twilight expedition every dive was printed out. You know, and there's probably millions of dives being done annually, that there's no way to get any data from other than just subjective commentary. So I'm skeptical of the statistics. But I simply have to share with you what my personal experience is. I can't do more. I said I don't have a methodology for recording all this data. Certainly as head of a training agency, I'm not going to get black box reports dropped off to me. So, granted, the researchers need to have some project, some program, that could get scientific data. And I'm the first to say I would love to have scientific data. But lacking that scientific data, as a personal issue, as an explorer, I'm looking to step towards the edge and do some exploration. On the commercial side of it, I'm looking to produce a training program that gives us an acceptable risk factor. So we have to balance those two issues. That's the real world. Thank you very much.

(Footnote: see the footnote to Dr Mitchell's comment above)

DR. BRUCE WIENKE: Go ahead, Richard.

DR. RICHARD VANN: I think this is great, everybody here getting together and discussing this and having disagreements. When that happens, the reason is because we just don't have enough knowledge. But it's important to discuss it.

ADVANTAGES OF TRIMIX REBREATHERS OVER CONVENTIONAL "BOUNCE" DIVING

Joseph Dituri, K. Parsley, Harry T. Whelan

ABSTRACT:

Background
Conventional commercial and U.S. Navy deep "bounce" diving is generally limited to 300 feet and requires the support of large surface platforms and a minimum of 13 divers. The breathing media generally used is HeO_2 and the diving apparatus is the MK-21 or Superlight 17 style hard hats. This method requires recompression chambers, storage racks and equipment in excess of 50,000 lbs. on site.

Methods
Using trimix rebreathers and portable recompression chambers in lieu of the above mentioned method, deeper dives are being achieved with greater safety.

Results
Incorporating new knowledge of decompression tables and algorithms would allow the depth limit for "bounce" dives to be increased to as much as 600 feet. The use of constant Partial Pressure of Oxygen rebreathers and dive computers can increase safety and decrease required decompression time. The incorporation of inflatable chambers and rebreathers would also reduce the required footprint and weight of a team as well as vessel required.

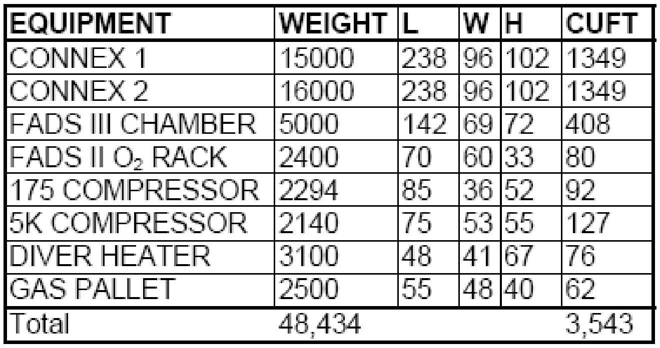
Conclusion
With this proposed—less expensive—system; a team of 12 divers can deploy more rapidly, with 80% less equipment burden, while greatly exceeding the current diving model's capabilities.

PAPER:

Introduction

Commercial and military salvage employ "heavy metal" for bounce dives. Due to the pressure of "right sizing" has been evaluating "alternative approaches" to complete future missions with fewer people and lighter/more mobile equipment, thus providing a more cost-effective service to "customers". Both Mobile Diving and Salvage Units (MDSUs) have championed this effort for the Navy. The commercial divers have been compelled to stay with the "what works, works" philosophy. A concept receiving little attention in the past is the integration of civilian technical diving skills and equipment to enhance specific areas of commercial and military deep diving with the ultimate goal of increasing efficiency—without compromising safety. Incorporating civilian technical diving methods into deep diving would increase overall service capabilities while also fulfilling current shortfalls in the ability to complete strategic mission responsibilities. To illustrate this point this paper will outline a baseline for current Commercial and Military

Diving and demonstrate where the integration of Technical Diving methods could have proven useful on previous missions. The discussion will also include alternative diving equipment and a comparison of newer decompression chambers. Appropriate breathing media, decompression tables and training requirements as well as team outfitting are presented.



EQUIPMENT	WEIGHT	L	W	H	CUFT
CONNEX 1	15000	238	96	102	1349
CONNEX 2	16000	238	96	102	1349
FADS III CHAMBER	5000	142	69	72	408
FADS II O_2 RACK	2400	70	60	33	80
175 COMPRESSOR	2294	85	36	52	92
5K COMPRESSOR	2140	75	53	55	127
DIVER HEATER	3100	48	41	67	76
GAS PALLET	2500	55	48	40	62
Total	48,434				3,543

Table 1: Equipment list for current diving method

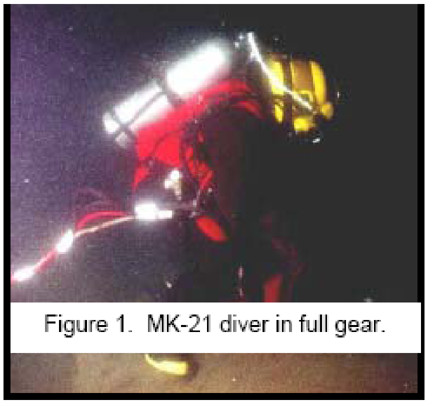


Figure 1. MK-21 diver in full gear.

Background

The primary focus of this proposal is deep diving, but is also applicable to diving in general. The Navy employs the use of surface supplied (tethered) diving for the deep diving range (130-300 feet of seawater (fsw)). Deep diving is accomplished by using the MK-21 diving apparatus (figure 1). Shortcomings of this system include but are not limited to: excessive bulk, intense manning requirements, decreased mobility, high gas usage and slow deployment. Large recompression chambers and numerous mixed gas bottle racks are required to be on site, requiring a diver's deployment platform of at least 200ft. Transport of this system requires significant preplanning and a large cargo transport aircraft, greatly limiting the utility of this valuable "mobile" service from D&S commands. Table 1 shows exact size and weight of the current flyaway mixed gas system.

Total weight to accomplish a Navy dive is approximately 50,000 lbs. plus incidentals and the total space requirement is approximately 3,500 cuft.

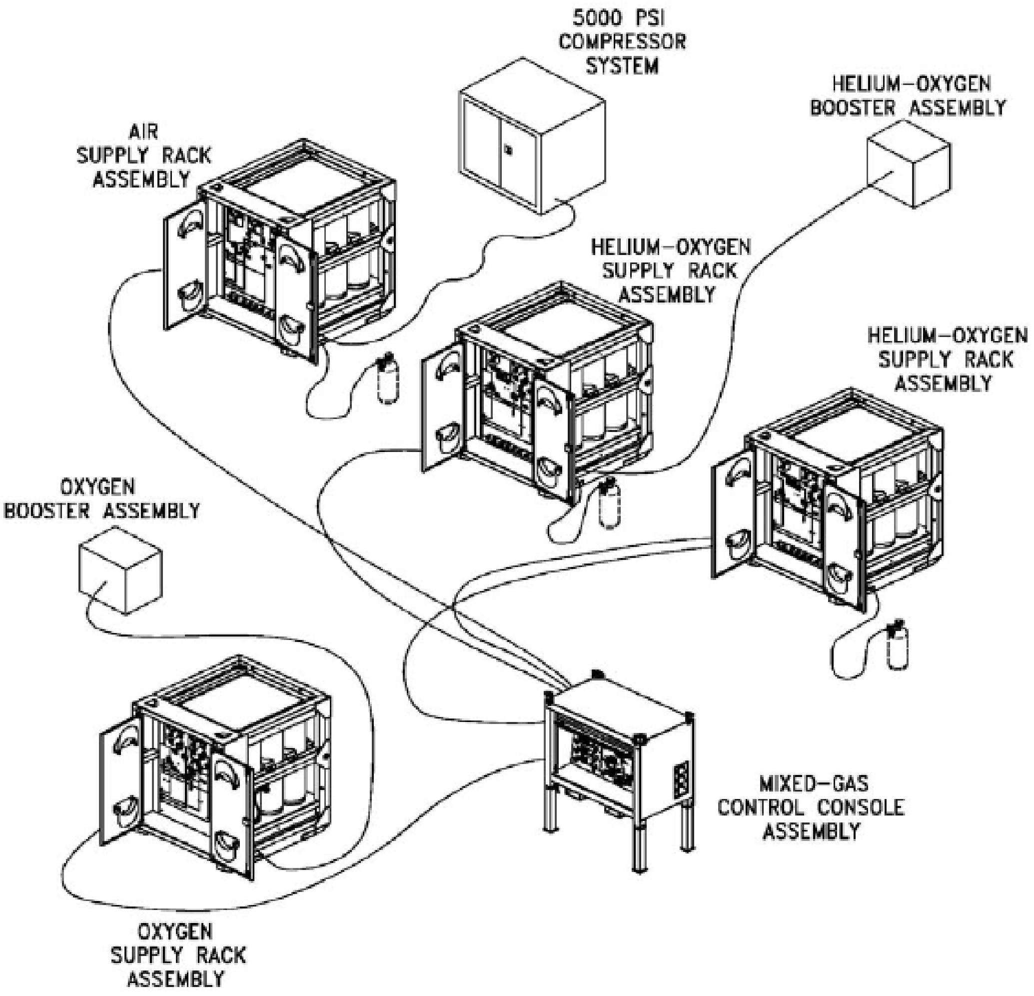


Figure 1-1. Fly Away Dive System III Mixed-Gas System

Figure 1-1 shows the current flyaway mixed gas system the Navy employs.

Equipment	Price
Air Rack	$125,000
Chamber	$200,000
5gas racks	$625,000
Console	$100,000
Hoses	$6,000
Umbilicals	$15,000
Compressor	$30,000
Gas boosters	$75,000
Pers. Dive gear	$10,000
Total	$1,186,000

Table 2: FADS III price

Table 2 illustrates a price breakdown of the current FADS III system.

Discussion

The strategic defense posture has changed from a heavy cold war scenario to a lightweight localized reactionary force. The D&S area must also change to better accommodate the new required mission area. One method of achieving this would be for D&S to emulate EOD in its ability to perform mission areas in a light flyaway mode. The in-water time period can be shortened while not compromising diver safety. The FADS III diving system has several potential failure points and technical complexities, leading to excessively conservative utility. Supporting rapid response capabilities in a light flyaway mode will also promote conservative diving. However, it will also decrease the number of failure points resulting in an overall reduction in the likelihood of a diving accident. This increase in safety would be directly proportional to the reduction in the amount of required equipment., A few examples of how the proposed diving model could have improved the efficiency and out come of the Navy's mission are as follows:

(1)When the Kursk sank to 350 fsw. The proposed method would have allowed more timely response and contact with the vessel.
(2) With the crash of Alaskan Airlines in 500+ fsw, this method would have increased the depth capability of the salvage team.
(3) Another example is the recovery of two marine Lighter Amphibious Re-supply Cargo (LARC 842, LARC 872) from 300+ fsw—longer time at depth for the divers, would almost certainly result in more efficient and timely recovery efforts..
(4) Rebreather use would have doubled performance--by doubling the no-decompression limit--while increasing the safety margins on the salvage operations of the Ehime Maru, TWA flight 800, PBM 5 in Washington State, John F. Kennedy Jr's plane and Swiss Air flight 111.

Additionally, technical diving has potential benefit in archeological work. One example would be on the Monitor in 240 fsw primarily. Use of a self-contained apparatus would minimize the disruption of the historical site. Finally, given the decline in saturation diving ability within the Navy, technical diving could help bridge the gap for deeper diving without performing costly saturation dives. Although the primary focus of this paper is deep diving, the proposed diving apparatus (appropriately named a rebreather) could also increase the no-decompression limit of shallow water dives.

Dive equipment

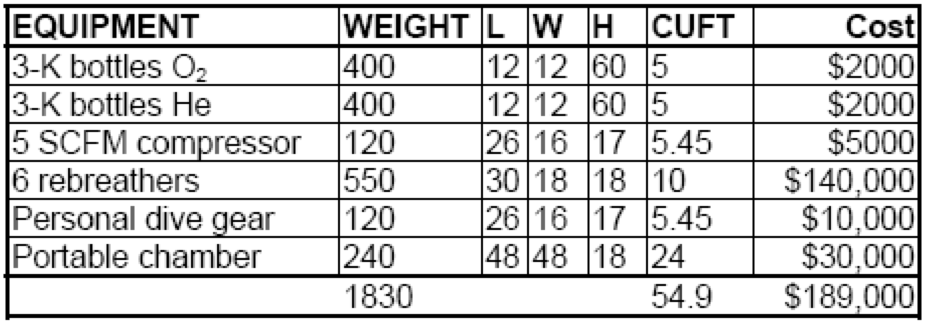
For diver safety and mission success, deep diving/salvage equipment must be rugged, durable, and reliable. These characteristics currently exist in rebreathers commonly categorized as Commercial Off The Shelf (COTS) items. Not only do COTS rebreathers meet the increased durability standard, there is a marked reduction in the amount of costly helium and oxygen required to perform a normal dive. Rebreathers also reduce the amount of gas required--by recycling the expelled gas from a diver's lungs. Unlike surface supplied diving, a rebreather is not limited to the premixed gasses carried because the rebreather creates the mixture. The divers' exhaled gas is chemically scrubbed of the carbon dioxide. An on board computer with three oxygen sensors samples the remaining breathing gas mixture automatically adding oxygen until a predetermined set point is achieved. The units insures an optimized breathing mixture at any depth. Consequently, rebreathers are approximately 100 times more efficient in gas usage than the systems currently in use. An added benefit of chemical removal of carbon dioxide is that the reaction is exothermic. This corrected breathing mixture increases diver safety and decreases required post dive decompression, given that decompression requirements are based on the ratio of inert gas to oxygen in the breathing mixture and the depth.

Divers can tolerate increased stay times in colder water, primarily due to the diver inhaling a warmer and moister breathing media. Leveraging the advantages of the rebreather with the benefits provided by dry suits will extend bottom times and increase diver safety. Rebreathers are also self contained, meaning each diver carries, on his or her back, all required dive equipment.

Figure 2: The author in full rebreather dive gear.

Figure 2 depicts the author equipped with a rebreather returning from a 400-fsw dive for 30 minutes. Despite a total in-water time of five hours the diver exhibited no symptoms of decompression sickness.

Table 3 outlines the equipment load out or “footprint” of a 12-person team with six rebreathers and the cost of each item. The equipment listed is sufficient to support four divers on a 600-fsw dive up to 40 minutes of bottom time and complete all required decompression in the water or in a chamber. This “load out” includes several forms of bailout mixtures carried for use in the event of an emergency. Comparatively the standard storage capacity of a Fly Away Diving System III (FADS III) will support three divers on
Table 4: Weight comparison of required equip
Figure 2: The author in full rebreather dive gear.
a dive 300 fsw dive for 30 minutes and complete all decompression in-water or in a chamber. The rebreather will reduce the overall footprint by 97% and cost by 84% as compared to that required by FADS III. The reduction in the overall support footprint and cost yields a rebreather system that can fit easily on a commercial aircraft as checked baggage. Despite the drastic reduction of the rebreather’s support footprint and cost, the rebreathers will double the current maximum achievable depth, while increasing mobility and safety.



EQUIPMENT	WEIGHT	L	W	H	CUFT	Cost
3-K bottles O_2	400	12	12	60	5	$2000
3-K bottles He	400	12	12	60	5	$2000
5 SCFM compressor	120	26	16	17	5.45	$5000
6 rebreathers	550	30	18	18	10	$140,000
Personal dive gear	120	26	16	17	5.45	$10,000
Portable chamber	240	48	48	18	24	$30,000
	1830				54.9	$189,000

Table 3: Equipment list for new diving method

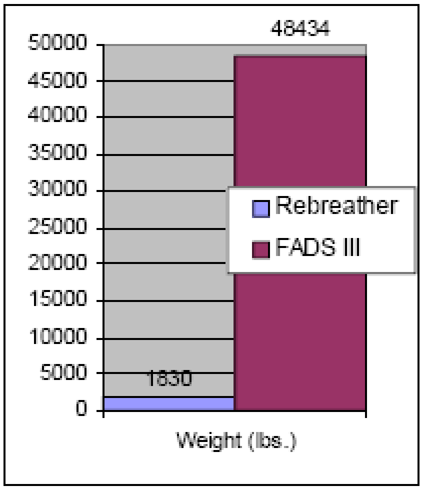


Table 4: Weight comparison of required equip

Decompression Chambers

Decompression chambers are used in emergency situations to treat decompression sickness or for surface decompression. The existing mixed gas protocol consists of a large decompression chamber and sufficient gas to support pressurization for treatment or for surface decompression dives. The 10,000-lb. chamber and ancillary equipment is used less than 1% of the time for the emergent treatment of divers. Given the proposed decompression table generating software, surface decompression duration would decrease and could be accomplished in a significantly smaller chamber with a 90% reduction of drive gas supply or in-water with the rebreather. The author advocates the streamlining and thoughtful reduction of decompression chamber's weight and size. Conveniently portable, COTS portable chambers can be carried by two men while another two can carry the full gas supply for a Treatment Table (TT) 4. A TT4 is the longest table used in the field for recompression of a diver stricken with decompression sickness. The proposed portable chamber is lightweight and is equipped with double locks incorporating the North Atlantic Treaty Organization (NATO) mating flange. It can be loaded on a helicopter and transported to a large hyperbaric facility in the unlikely event a longer treatment table is required. During the flight, the treatment does not have to be interrupted also eliminating the need to have valuable Diving Medical Officers close to the operational area.

Current protocol requires recompression chambers to be on site to recompress a diver who "blows up from greater than 50 fsw" to the surface from a mixed gas dive. These chambers should recompress the diver to the maximum depth of the dive or maximum depth of the chamber.[I] A “blow up” is described as a diver who makes a rapid ascent to the surface from depth and does not complete required decompression. FADS III chambers are limited to 165 fsw. A “blown up diver” is the most critical decompression related situation a diver could encounter and is at the greatest risk of decompression sickness. This requirement existS for an exceedingly rare event (less than .01% of all Navy dives). Blow-ups were more common when divers used the MK-5 breathing apparatus and were able to make themselves “light” enough to lift off the bottom. Comparatively, many mixed gas protocols are completed in the civilian and commercial communities without a chamber on site. The need for a chamber should be reevaluated and if there is still a valid need, COTS portable chambers could be used. The pictures on the following page show a standard Navy decompression chamber as well as a portable COTS recompression chamber. Under current protocol, Navy decompression chambers and COTS decompression chambers would be equal in utility. They are both capable of 165-fsw recompression and have sufficient breathing media to complete a TT 4. Significant differences are primarily fabrication material, size and bulk. Admittedly, the portable COTS chambers may not be as comfortable for the occupant and tender, due to the reduction in size.

Portable chamber size
Standard Navy double lock chamber
Portable chamber inside
Standard Navy decompression chamber inside
Portable chamber shipping size
Standard Navy Transportable
Recompression Chamber shipping size

Breathing media choice & decompression tables

Navy decompression tables are designed to avoid Decompression Sickness (DCS). Although the pathopysiology of DCS is still not completely understood, most credible theories postulate that inert gas bubbles in the blood are involved. It is for this reason that the following theory of DCS is discussed in detail.

Henry’s law governs DCS in divers. The amount of gas capable of absorption into a liquid at a given temperature is inversely proportional to the Partial Pressure (PPxx) of the gas. Since oxygen will be metabolized prior to absorption, only inert gases are of concern to divers with respect to DCS. The leading theories on DCS profess that the physical manifestations of DCS are a result of inert gas being absorbed into the tissues on compression and while at depth during the dive. They in turn do not having sufficient time to escape during the ascent to the surface. At surface pressure, body tissues are saturated with the inert gas being breathed. As pressure is increased with depth, the partial pressure of the gas inhaled increases. Simultaneously, due to the increased pressure, the body’s tissues are capable of absorbing an increased proportion of the inert gas being breathed. While maintaining a constant increased pressure (at depth), the tissues can absorb an amount of inert gas consistent to that pressure. As the external pressure is reduced (at a decreased depth), tissues begin the process of off gassing. The tissues are releasing gases into the peripheral (largely capillary) blood flow (at an increased rate), in order to equilibrate to this new external pressure. The gases are then removed from central blood flow via diffusion within the lungs.

Capillary bed volume is about 5% of the body's total blood volume. The exchange of gases, nutrients, and waste products—between tissues and blood—occurs at the capillary beds. Exchange is limited to this area because this is the only place in vasculature where the endothelial lining is only a single cell thickness, and highly porous. Capillar endothelial cells have a basement membrane which does not interfere with diffusion but serves to hold the capillary together. When the inert gas solubility capability is exceeded such that the gas is forced out of solution, a bubble is formed to transport the gas out of the system. These bubbles can stimulate the antibody mediated immune response. The bubbles are then attacked in the usual fashion (phagocytosis, natural killer cells, and T-cell mediated responses).

Another problem associated with the gas bubble trapped in the bloodstream is that the surface of the gas bubble tends to attract other particles found in the blood stream such as lipoproteins. The result is a large mass consisting of the gas bubble, fat and phagocytes/leukocytes making its way through the blood stream. This process is illustrated in figure 3.

Figure 3: Possible blood vessel and bubble path

A common misconception, concerning gas bubbles trapped in the blood stream, is that the bubbles will necessarily become lodged in the veins and block blood flow. While this may be true in the worst case scenarios, it is not the most common progression. Commonly this mass of gas bubble and solids are small enough to fit through all vessels. The problems arise when the bubble mass moves through the blood stream and bounces off the vessel wall. This can damage endothelial cells, which can then stimulate the coagulation cascade. This response can potentially aggravate the decompression injury. The coagulation cascade can form a clot sufficient to occlude blood flow, thus leading to distal tissue ischemia and possibly necrosis.[II] The manifestation of this damage is generally pain but sometimes more serious symptoms present themselves. Consequently, the objective of most diving physiology study is to minimize the potential of gas bubble formation within the bloodstream.

The choice of breathing media can directly impact the duration of required decompression as well as the formation of gas bubbles in the bloodstream. For instance; helium diffuses 2.67 times faster than nitrogen into the tissues at a given depth, it therefore saturates the tissues more quickly at any given depth. The breathing media of choice for today's Navy deep diving is HeO2 (Heliox). The HeO2 tables are based upon decompression tables that were produced 60 years ago with the Navy's surface-supplied heliox tables being developed in 1939 by LT (later RADM) C.B. Momsen. They are predicated upon Haldanian ratios and the tables were computed using a constant 1.7/1 supersaturation ratio for all tissues and all decompression stops. J.S. Haldane (an English physiologist working for the royal Navy in 1905) attempted to quantify the amount of inert gas dissolved into the body during exposures to high-pressure environments. He used tissue half times of 5, 10, 20, 30, 40, 50, 60, and 70 minutes. Tissue half times are numbers assigned to different tissues in the body indicating the duration of time for them to absorb ½ of their maximum saturation at the given external pressure. To increase the margin of safety, the actual bottom time was doubled in the calculation. The tables also advocate a time at first stop of seven minutes --to allow for the "initial out rush of helium".

As a result of this seven minute first stop being longer than mathematically determined (using Haldanes tissue half time data), the next one to two stops often had zero decompression time.

100% oxygen breathing was initiated at 60 fsw and the diver surfaced after completing the 50 fsw water stop on oxygen.

The heliox tables were modified in the mid-1950's by LCDR Molumphy, reducing the depth of the oxygen breathing stops from 60 and 50 fsw to 50 and 40 fsw. This was at a time when the diving medical community learned that Central Nervous System (CNS) tolerance to hyperbaric oxygen is far less in water than it is in a dry chamber. Additionally, Navy tables had up to a 20% incidence of DCS on some deep salvage jobs. CAPT Flynn modified the tables further in 1991 by converting them from a partial pressure-time format to a depth-time format while also to introducing additional means of safety by switching to 60% helium 40% oxygen at 100 fsw. He put the longer time schedules for a given depth in the shorter bottom time slot in the table to increase the decompression time for a given table. CAPT Flynn modified the tables again in 1999 after five oxygen convulsions occurred in the water during the deep dive testing of the Fly Away Diving System III. The principal objective was to eliminate oxygen breathing in the water without significant increases in decompression time. The final result of all modifications can be seen in Revision 4 of the U.S. Navy Diving Manual. Although the Navy used several probabilistic models to assess the impact that various changes might have on DCS risk for the current tables. These models were not used to re-calculate the decompression times.[III] The derivation of current tables is mostly by trial and error.

However, taking advantage of modern technology, civilian table generating software can quickly calculate dive profiles that take into consideration nearly all data derived from the Navy's 50 plus years of dive table research and design. This author therefore professes that the use of alternate gases should be considered--based on COTS decompression table generating software. Civilian companies have developed this decompression software based on similar decompression models used by the Navy. Although the current Navy tables are useful for general applications, using these COTS programs could increase safety. Many of the commercial decompression table generating software companies have expanded the decompression algorithm to include faster and slower tissue groups within the body based on experiences of several thousand civilian divers. The table generating software can generate tables with the capability of establishing risk factors.

The Bühlmann ZH-L16 algorithm is commonly used as the basis for the table generating software model. A Swiss medical doctor named Albert A. Bühlmann invented this algorithm and is generally thought of as the successor to the Haldanian theory that the Navy still employs. Bühlmann established, by means of many hyperbaric chamber experiments--using volunteers, how much supersaturation the individual tissues (compartments) could tolerate without injury. Appendix A contains further information about the Bühlmann model. Using table-generating software for the depth and duration of 100% of Navy mixed gas dives, the breathing medium that yields the shortest decompression time is N_2HeO_2 (Trimix). The difference in total decompression time for all depths is illustrated in table 5. The use of Trimix can also reduce the probability of High Pressure Nervous Syndrome (HPNS). HPNS is a neurological and physiological dysfunction generally associated with hyperbaric exposure. Since symptoms of HPNS have normally been observed during high partial pressures exposures in HeO_2 atmospheres, this malady has often been referred to as "helium tremors".[IV] Reducing the content of helium by substituting nitrogen will decrease the likelihood of HPNS. Anecdotally, many divers who have experienced dives on both gasses "feel more comfortable" on N2HeO2 than on HeO2. This author speculates that the presence of nitrogen adds a more "normal" feeling.

Table 5: Comparison between total decompression times of dive in minutes.

Perhaps increasing the narcotic (nitrogen) effect to that of normal air (at the surface) makes divers feel more at ease. Even though this improvement of Navy diving advocates the use of dive computers with the rebreathers, dives still must be planned and bailout tables must be carried. This software could be used to generate those tables optimizing safety based on the depth, duration and risk the Navy assesses to the job after an operational risk assessment. These decompression calculators can also provide the ability to complete dives to depths of 600 fsw safely. Table 5 compares profiles of every mixed gas diving depth. A single depth profile comparison is shown in charts 1 and 2 where as much as a 54- minute advantage can be achieved using the COTS software. All of the COTS table generating software profiles were calculated at a very conservative 1.4 PPO2 which eliminates the risk of CNS oxygen toxicity. A significant problem with the current mixed gas protocol is that it advocates the use of 100% oxygen at 50 and 40 fsw. This has been problematic. More divers have suffered the affects of central nervous system (CNS) oxygen toxicity than have suffered decompression sickness problems while diving mixed gas. Similar to DCS, the precise etiology of oxygen toxicity is unknown, but National Oceanographic and Atmospheric Administration (NOAA) have significant evidence that it is very prevalent in dives that have a PPO2 of greater than 1.6. A diver at 50 fsw on oxygen experiences a 2.51 PPO2. The COTS software recommends limiting the PPO2 to 1.6. COTS decompression table generators have been proven to be reliable and very safe. The author has completed several hundred dives using these COTS tables and has collected feedback from over 100 divers who are performing similar dive profiles using the same software. The results were consistent: all divers reported a DCS rate of zero. The specifics of this data is beyond the scope of this paper. However, all data is available upon request. The subject group consists of male and female divers ages 19-60 ranging in fitness level from very fit to marginally fit. This sample represents a larger and more diverse group than any existing Navy table or study. The best protocols include those that incorporate deep stops. Ascents should be gradual in deeper depths, commonly referred to as "Pyle stops". The best results come for not a "stop" per-se, rather a decreased ascent rate to between 10-20 feet per minute. At this point of decompression, the PO_2 should be manually maintained at 1.5 PO_2. Decompression is continued in the usual manner after deep stops emphasizing "active decompression" (movement) as opposed to passive decompression (just hanging). This procedure increases off gassing and warmth. Divers should be careful not to perform too much exercise at depth because it could lead to bubble formation.

Total in water time = 134 min

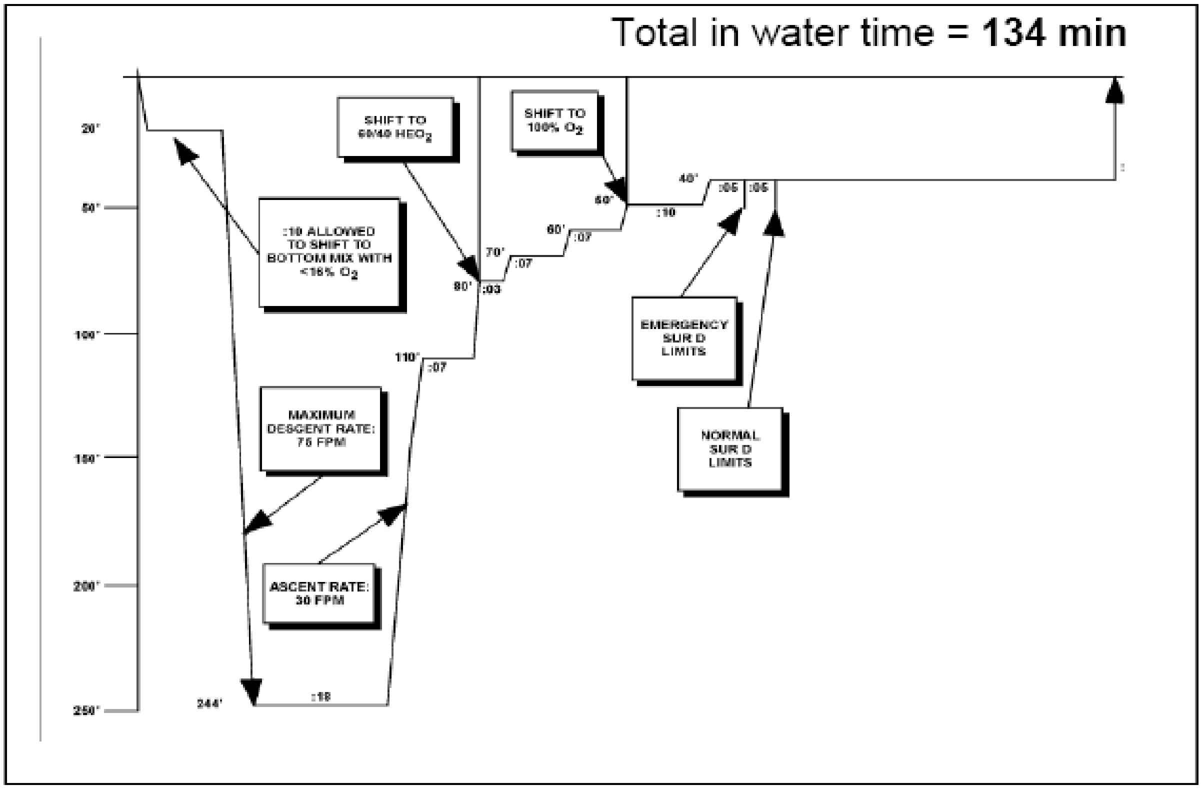


Chart 1. Standard Navy mixed gas decompression profile

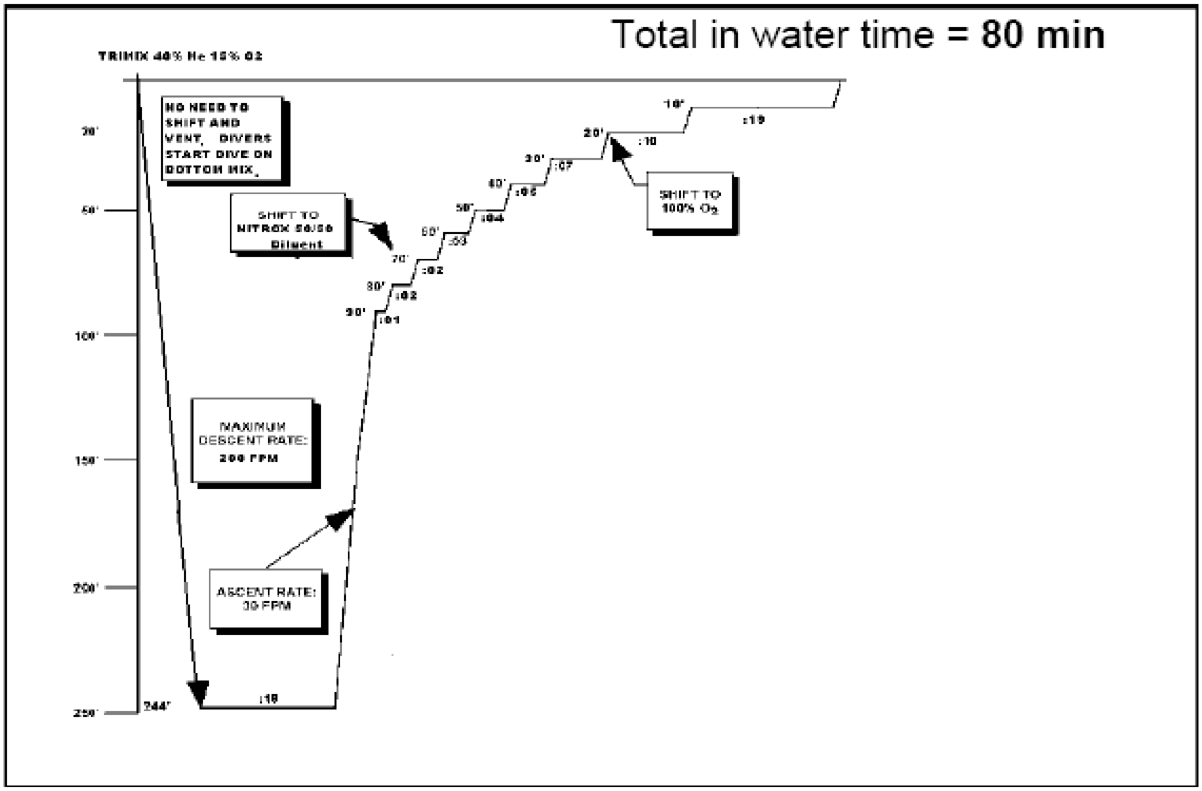


Chart 2. Standard Technical dive decompression profile

Chart 1. Standard Navy mixed gas decompression profile
Chart 2. Standard Technical dive decompression profile
Total in water time = 80 min

Communication

Topside communication is an important part of salvage diving. While in the past, surface supplied diving was the only way to achieve reliable communication underwater communication gear has made significant technological advancements. Today almost any diving unit can be fitted with a communication package to facilitate excellent through-water discussion where surface units can listen and interact with each diver as well as provide a recall signal. Topside can continue to monitor divers and coordinate movement of divers while allowing the diver to manage his own decompression and dive profile. Through water communications provides the advantage of constant contact with all divers without hampering diver mobility due to a tether to the surface that must be carried. A tetherless, free-swimming diver has a decreased likelihood of becoming fouled in wreckage and will not disturb the diver's environment nearly as much. Tetherless diving operations could prove extremely beneficial to the current Monitor expedition supported by MDSU-2.

Training

Training must be looked at in a new light breaking the current paradigm where divers are taught to listen to the supervisor and allow the topside to run the dive. Although this method exerts positive control of the dive, it tends to produce a diver less inclined to think and reason for himself. Placing more of the operational control of the dive with the diver will almost certainly increase productivity. Divers must be taught to manage their entire dive from start to finish and rely upon themselves to plan and complete the mission and survive. Topside's primary function should be assistance and coordination. A similarly equipped diver must still be available topside to act as a safety diver in the unlikely event the working divers have a problem. Training divers to make intelligent decisions yields a more reactive and smarter diver, empowered to make his/her own decisions in an emergency situation. This significant change in philosophy will reduce the overall number of Navy divers required by creating an environment where divers are more inclined to stay in the Navy if they are challenged and trained to commercial diving standards. An increase of retention will provide a commensurate decrease in the cost of continuous training. In light of the large initial training investment it is recommended trainees be assigned to a team of divers for a period of five years, increasing team camaraderie and esprit de corps while decreasing the overall training requirement. Another advantage will be the realization of savings to permanent change of station (PCS) requirements and afford sailors the opportunity to homestead in a geographic location. More so than in other types of diving, these "technical" dives require periodic proficiency dives. A budget for training must be established to support diver proficiency. Budget requirements will be more reasonable than other mixed gas diving because this concept saves costs associated with breathing gas and ship size. A typical rebreather dive with a team of four divers costs $500, including all consumables and the vessel. The associated cost with a typical Navy mixed gas dive for three divers can easily exceed $200,000 when considering the vessel size requirement, fuel, support crew for the vessel, load out time and the breathing gas requirement.

Team outfitting and concept

Team size should be limited to ten divers, one Diving Officer and one Master Diver. Each team should be outfitted with the following off the shelf equipment:

1. Satellite phone for communications
2. Laptop computer with a printer and an e-mail link to the satellite phone
3. Six COTS rebreathers
4. COTS decompression generating software
5. COTS portable decompression chamber
6. Two AN/PQS 2A hand held-underwater sonar
7. Small 600 fsw capable Remotely Operated Vehicle (ROV)

Upon notification of official tasking, the team would pack personal belongings and make arrangements to board the next commercial aircraft to the dive site. Following arrival to the shore nearest the work site, nearly any vessel greater than 40 feet in length could be secured and loaded with their equipment. At the salvage operation scene, the team would deploy the ROV to perform a quick search for hazards and use as a down line. Three divers would deploy as a team with a surface marker buoy allowing the vessel and balance of the team to pinpoint their exact location. Data recorder would be retrieved with the use of the underwater sonar while different colored surface marker buoys would be used to tag and map the location of any large or suspect debris. With continuous ROV use, divers would collect digital video and still pictures capable of being sent via computer and e-mail to NAVSEA for inspection and further clarification as well as redirection. The vessel of opportunity may not be fitted with a crane capable of lifting the pieces thus necessitating a larger Navy asset or lifting craft to rendezvous at the scene to provide additional support to the recovery effort. The entire operation described above is far safer and significantly more efficient with a real time response rather than the current cumbersome alternative which requires deploying on a larger vessel and transporting almost 50,000 lbs. of equipment and 15 personnel. The most strategic locations for these flyaway teams would be as part of the two Mobile Diving and Salvage units (MDSUs) pre-positioning teams on both east and west coats of the continental US facilitating a rapid response to any world crisis. Predeployment teams could also be dispatched to any area of conflict or potential “hotspot”. The funding required for initial establishment and training would be approximately $200,000, allocated by the resource sponsor for the two MDSU’s (N763M). The anticipated annual training and OPTAR budget would be $50,000 per year to include support of training, phased replacement and equipment maintenance. All assignments would be cost reimbursable from the National Transportation Safety Board (NTSB) or other “customers” contracting the service. The objective of this paper is not to advocate a specific rebreather or decompression generating software by manufacturer but to advocate the use of these devices in general with the rebreather possessing the capability to perform real time decompression calculations. Real time decompression calculations bear the most significant contribution to decreasing overall decompression time. [V]

Conclusion

In the early 1900s the MK V diving helmet became the standard commercial and U.S. Navy diving system. It gave them the means to provide submarine rescue and accomplish salvage work. The MK V diving helmet was eventually succeeded. This watershed event signified an end to the “heavy diver” mentality and progressed commercial and Navy diving one hundred years.

Off the shelf procurement aligned Navy diving more similarly with commercial diving contractors. Today's U.S. strategic defense policy has shifted from the bulky cold war mentality to that of lightweight fast reaction response teams for crisis situations. The current Navy diving methodology does not align well with the new U.S. global defense policy. Diving contractors feel the sting of downsizing and feel the profit margin shrinking with the introduction of more contractors. The equipment in most military and commercial diving lockers prohibit fast reaction. Military divers are limited in their participation in exercises and cannot deploy rapidly. Diving contractors who are unable to rapidly respond to the needs of the customer have the potential of loosing money. Their deep diving skills are degrading as a result of missing valuable training opportunities in the military and contractors are loosing money. In today's terroristic threatened environment a significant peril is said to be an attack originating from the water. Current diving methodology could require five to seven days to respond to an enemy strike such as the sinking of a ship to block a strategic channel of water. Similarly a local response to an NTSB tragedy could take three days. Using this proposal's concepts to replace the MK 21 with COTS rebreathers and decompression table generating software, operational commanders would have the flexibility of deploying a lightweight fast reaction team to respond to a mishap in less than 24 hours. The paradigm shift discussed herein is essential for the continued survival of diving contractor and military diving. All of the equipment presented is available and being used comprehensively and safely throughout the civilian sector. Extensive review and experimentation has been accomplished by civilian technical diving organizations. While their procedures are not scientifically derived, their work has led to conservative procedures and safe manipulation of rebreathers in varying conditions. It is time to move forward. The nation cannot afford to wait any longer. The concepts presented in this proposal should be implemented so that we can lead diving into the 22nd century.

Basic Tenants of Lightweight System

- 96% Lighter than current system
- 98% Less cubic space required
- 84% Cheaper than current system
- Doubles the current max depth of dive
- Significantly decreases decompression time while requiring only 10% as much gas as the current system
- All equipment is commercially available
- Requires fewer divers/operators
- Less expensive
- More compact and easier to transport

Advantages of Trimix

- Decrease decompression time
- Decrease risk of High Pressure Nervous Syndrome (HPNS)
- Decrease risk of Oxygen toxicity
- Less thermal losses
- Decrease "Mind race"
- Enables use of drysuit

Requirements for Proposed System

- One Diving Officer
- One Master Diver
- Ten Divers
- Satellite Phone
- Laptop Computer
- Six Rebreathers
- Decompression Software
- One portable Decompression Chamber
- Two AN/PQS 2A Hand-held Underwater Sonar
- One Remotely Operated Vehicle (ROV)

Appendix A: Bühlmann model detailed explanation

Bühlmann expresses the relationship through the following equation:

pamb. tol. = (pt. i.g. - a) ·b (Equation 1)

or

pt. tol. i.g. = (pamb / b) + a (Equation 2)

pamb. tol. - the ambient pressure tolerated by the tissue

pt. i.g. - the pressure of the inert gas in the tissue

pt. tol. i.g. - tolerated (excess) pressure of the inert gases in the tissues

pamb - current ambient pressure

a, b - parameters of the model ZH-L16 for each tissue

a depends on the measure unit of pressure used, while b lacks dimension and represents the steepness of the relationship between the ambient pressure pamb. And the pressure of inert gas in the tissue pt. i.g. Equation 1 shows which lower ambient pressure pamb. tol. will still be tolerated at the actual pressure of inert gas in the tissues pt. i.g. Equation 2 shows which level of supersaturation pt. tol. i.g. can be tolerated at a given ambient pressure pamb for a given tissue. The rate of (de)saturation depends on the gradient of inert gas pressure in the lung and in the tissues. According to Bühlmann, the saturation and desaturation of the various compartments can be calculated as follows:

pt. i.g. (tE) = pt. i.g. (t0) + [pI i.g. - pt. i.g. (t0)] ·[1 - 2-t

E

/ t

1/2] (Equation 3)

pt. i.g. (t0) - pressure of inert gas in the tissue at start of exposure

pt. i.g. (tE) - pressure of inert gas in the tissue at end of exposure

pI i.g. - pressure of inert gas in the breathing mix tE - duration of exposure in minutes

t1/2 - half-time in minutes 30

References

1. Pyle, R.L. 2000. Use of Advanced Self-Contained Diving Technology for Assessing Undiscovered Fish Biodiversity on Deep Coral Reefs. Marine Technology Society Journal, 2000. 33(4).
2. U.S. Navy Diving Manual, Vol. 4 SS521-AG-PRO-010, 0910-LP-708-8000, Revision 4 20 January 1999 Change A dated 1 March 2001.

3. Technical Manual Operation and Maintenance Organization Fly Away Dive System (FADS) III Mixed-Gas System S9592-B2-OMI-010, 0910-LP-721-3500, 30 September 1998.
4. Albert A. Bühlmann und Ernst B. Völlm, Tauchmedizin: Barotrauma, Gasembolie, Dekompression, kompressionskrankheit, 4th edition, Springer press, 1995.

Notes

I. U.S. Navy Diving Manual, Vol. 4, 2001, Chap 14 pgs 14-23, Section 14-4.10.1.
II. Joseph Dituri, Diving Medical Technician Manual, 1999, pgs 25-27.
III. Edward Flynn, (2002 April 11), RE: HeO2 tables, FlynnET@NAVSEA.NAVY.MIL.
IV. M.L. Nuckols, W.C. Tucker, A.J. Sarich, Life Support Systems Design, Simon & Schuster, pg 61.
V. F. Parrish and R.L. Pyle, 2001, Surface Logistics and Consumables for Open-Circuit and Closed-Circuit Deep Mixed-Gas Diving Operations, Proceedings of the MTS/IEEE Oceans 2001 Conference, Volume 3:1735-1737. .

List of acronyms and Abbreviations

EOD – Explosive ordinance disposal
CNS – Central nervous system
COTS – Commercial off the shelf
D&S – Diving and salvage
DCS – Decompression sickness
FADS – Fly away diving system
Fsw – Feet of sea water
HeO2 – Breathing mixture of helium and oxygen (Heliox)
HPNS – High pressure nervous syndrome
PPx – Partial pressure of the gas (x)
PCS – Permanent change of station
MDSU-x – Mobile Diving and Salvage Unit (x) indicates the number
NATO – North Atlantic Treaty Organization
Nitrox – Combination of nitrogen and oxygen. Used as a breathing mixture for shallow diving.
NTSB – National Transportation Safety Board
N2HeO2 – Breathing mixture of nitrogen, oxygen and helium (Trimix)
ROV – Remotely operated vehicle
SW – Special warfare
TT – Treatment table

Some of the following are not cited because I didn't know where to put them.

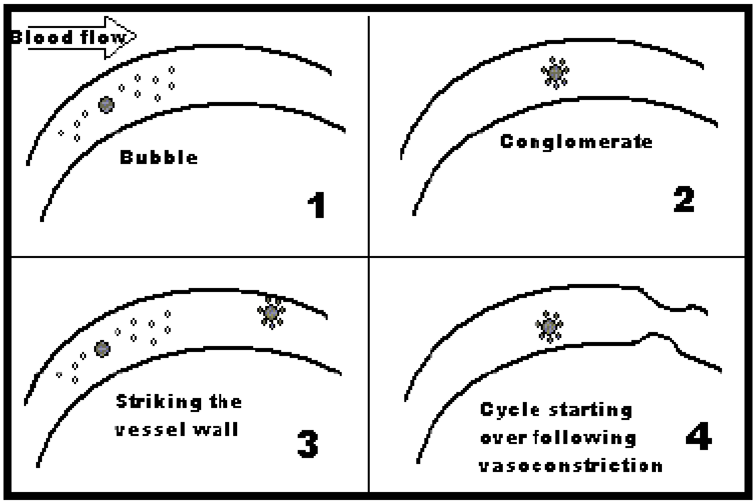


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Figure 3: Possible blood vessel and bubble path

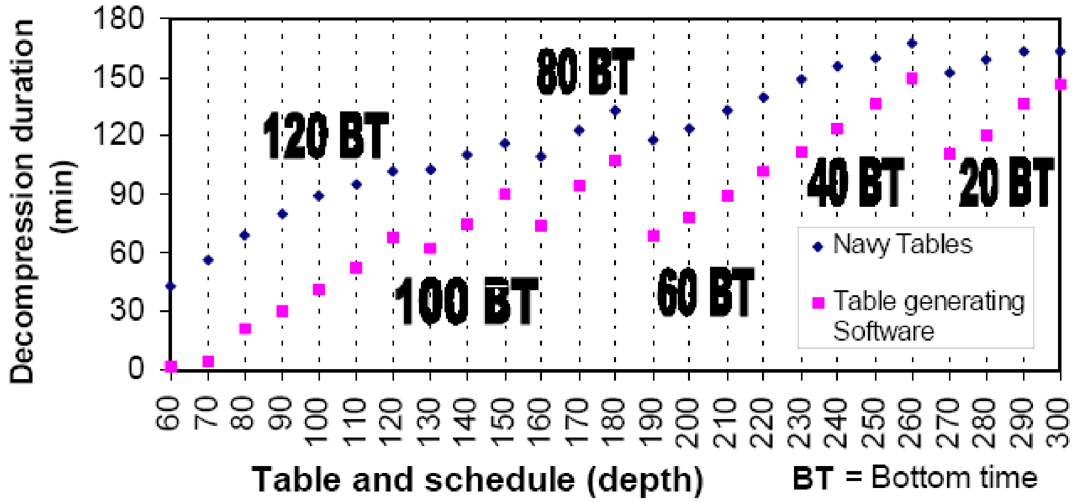


Table 5: Comparison between total decompression times

NOTE: All schedules are for the maximum duration allowed by Navy tables that ARE NOT exceptional exposure dives.

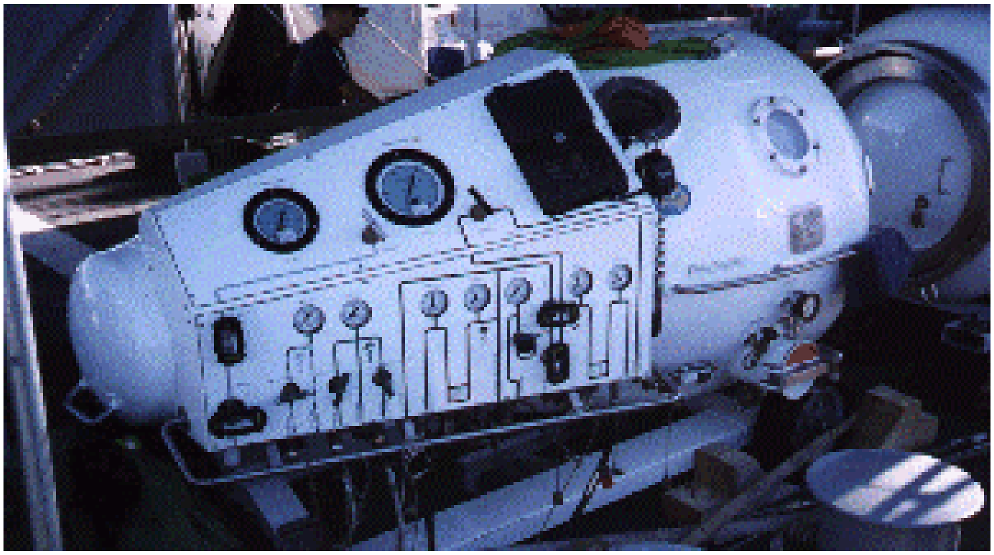
Current Navy Flyaway System

EQUIPMENT	WEIGHT	L	W	H	CUFT
CONNEX 1	15000	238	96	102	1349
CONNEX 2	16000	238	96	102	1349
FADS III CHAMBER	5000	142	69	72	408
FADS II O2 RACK	2400	70	60	33	80
175 COMPRESSOR	2294	85	36	52	92
5K COMPRESSOR	2140	75	53	55	127
DIVER HEATER	3100	48	41	67	76
GAS PALLET	2500	55	48	40	62
Total	48,434				3,543

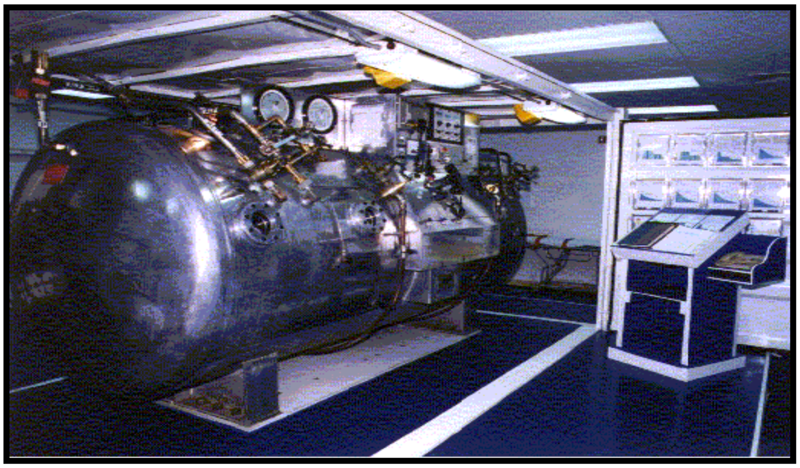
Proposed Flyaway Loadout

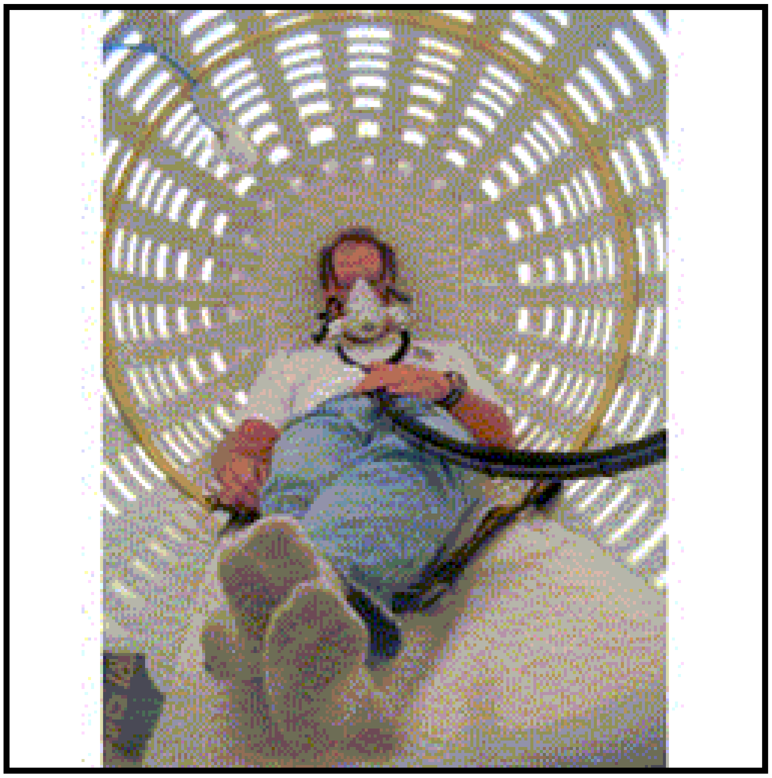
EQUIPMENT	WEIGHT	L	W	H	CUFT	Cost
3-K bottles O2	400	12	12	60	5	$2000
3-K bottles He	400	12	12	60	5	$2000
5 SCFM compressor	120	26	16	17	5.45	$5000
6 rebreathers	550	30	18	18	10	$140,000
Personal dive gear	120	26	16	17	5.45	$10,000
Portable chamber	240	48	48	18	24	$30,000
Total	1830				54.9	$189,000

Proposed Recompression Chamber



Current Recompression Chambers





DEEP STOPS AND THEIR EFFICACY IN DECOMPRESSION: U.S. NAVY RESEARCH

Wayne A.Gerth, David J. Doolette, Keith A. Gault

ABSTRACT:

Introduction

Classical decompression algorithms limit hypothetical tissue gas contents and prescribe decompressions that advance rapidly to shallow stops where most of the total stop time (TST) is scheduled. Recent bubble-based algorithms limit calculated bubble profusion and size and prescribe decompressions with TST skewed toward deeper stops. Navy Experimental Diving Unit (NEDU) has completed a controlled comparative study of these approaches.

Methods

Divers wearing swimsuits and t-shirts, breathing surface-supplied air via full face masks, and immersed in 86 °F water in the NEDU Ocean Simulation Facility wetpot were compressed at 60 fsw/min to 170 fsw. They performed 115 Watt cycle ergometer work during an ensuing 27.2 minutes at bottom and were decompressed at 30 fsw/min with stops prescribed by one of two schedules, each with 174 min TST. Schedule 1, with stops at (fsw/min) 40/9, 30/20, 20/52, and 10/93, was prescribed by the man-tested, deterministic gas content, VVAL18 Thalmann Algorithm. Schedule 2, with stops at 70/12, 60/17, 50/15, 40/18, 30/23, 20/17, and 10/72, was the optimum distribution of TST according to the man-dive calibrated, probabilistic BVM(3) bubble model. Decompression sickness (DCS) incidence with these schedules was compared under the sequential stopping rules of reject-high if DCS risk > 7% or reject-low if DCS risk < 3% with 95% confidence.

Results

The trial was terminated after midpoint interim analysis. Neither schedule was rejected, but DCS incidence in Schedule 2 (deep stops, 11 DCS/198 dives) was significantly higher than in Schedule 1 (3/192, p=0.030, one-sided Fisher Exact). On review, one Schedule 2 DCS was excluded, but the result remained significant (p=0.047). Most DCS was mild, late onset, Type I, but two Schedule 2 cases involved rapidly progressing CNS manifestations.

Conclusions

The deep stops schedule had a greater risk of DCS than the matched conventional schedule. Slower gas washout or continued gas uptake offset benefits of reduced bubble growth at deep stops.

PAPER:

Introduction

Ascent to surface from a dive may require interruption with one or more decompression stops to reduce the risk of decompression sickness (DCS) [1]. During each decompression stop, a period of time is spent at a constant depth to allow “safe” washout of inert gas from body tissues before resumption of the ascent. A “deep stop” is a decompression stop at a depth deeper than that of the first stop prescribed for the ascent by a decompression algorithm. This definition of a deep stop is inherently relative because the distinction of a deep stop from any other depends on the algorithm used to compute the decompression schedule. For ascent from a given dive, a deep stop in a schedule prescribed by one algorithm may be a normal stop in another schedule computed with a different algorithm.

In a recent workshop [2], we categorized what are colloquially called deep stops into two distinct classes. Deep stops of the first class are those that are inserted into a schedule ostensibly to make the ascent safer, shorter, or both, compared to the schedule originally prescribed by a given algorithm. Two types of deep stop were identified within this class. Deep stops of the second class are one or more initial stops that are deeper in a schedule prescribed by one algorithm than the first stop in a schedule prescribed for the same ascent by a different algorithm. Potential benefits of the different deep stop classes and types were then discussed in terms of the ways times spent at different depths during a decompression influence the instantaneous ascent depth (IAD)[1], and the corresponding safe ascent depth (SAD), the depth at which the IAD and depth become equal during an ascent at a finite rate, in hypothetical gas exchange compartments in the body.

The Class I, Type 1 deep stop is one or more stops added deeper than the initial algorithmically-prescribed SAD for a given ascent rate but shallower than the atmospheric saturation depth[2] of the controlling compartment at the start of ascent.

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[1] Safe decompressions can be scheduled by observing depth-dependent maximum permissible tissue tensions, M_i, that explicitly or implicitly limit gas bubble formation and growth during ascent in all of i modeled blood-tissue gas exchange compartments in the body. Specifically, decompressions are scheduled in such approaches to keep the compartmental total dissolved gas tensions, $p_{tot,i}$, less than or equal to the M_i:

$$p_{tot,i} \leq M_i = M_{i,0} + a_i D, \tag{1}$$

where $M_{i,0}$ is the maximum permissible $p_{tot,i}$ in the i^{th} compartment at surface, D is depth, and a_i is a slope parameter of value conventionally greater than or equal to 1. The shallowest depth to which ascent can be safely made at an infinite rate, or the instantaneous ascent depth (IAD), in each compartment at any point in a dive is given by the value of D that satisfies the equality on the left of Eq. (1) with the prevailing $p_{tot,i}$:

$$\text{IAD}_i = (p_{tot,i} - M_{i,0})/a_i. \tag{2}$$

With depth expressed in fsw, the condition for zero gas-supersaturation decompressions, $p_{tot,i} \leq P_{amb}$, is obtained from Eq. (1) with $M_{i,0} = 33$ fsw and $a_i = 1$ fsw·fsw^{-1} for all i compartments. The corresponding compartmental IADs at any point in a dive are then given by the prevailing $p_{tot,i}$ converted to units of fsw:

$$\text{IAD}_i = p_{tot,i} - 33. \tag{3}$$

Increasing values of $M_{i,0} > 33$ fsw correspond to increasing acceptable gas-supersaturations at all depths and to increasingly negative IADs in compartments at or near saturation at surface.

[2] The compartmental atmospheric saturation depth is the pressure equivalent depth of the prevailing inspired gas that would produce the prevailing compartmental total dissolved gas tension at equilibrium [2].

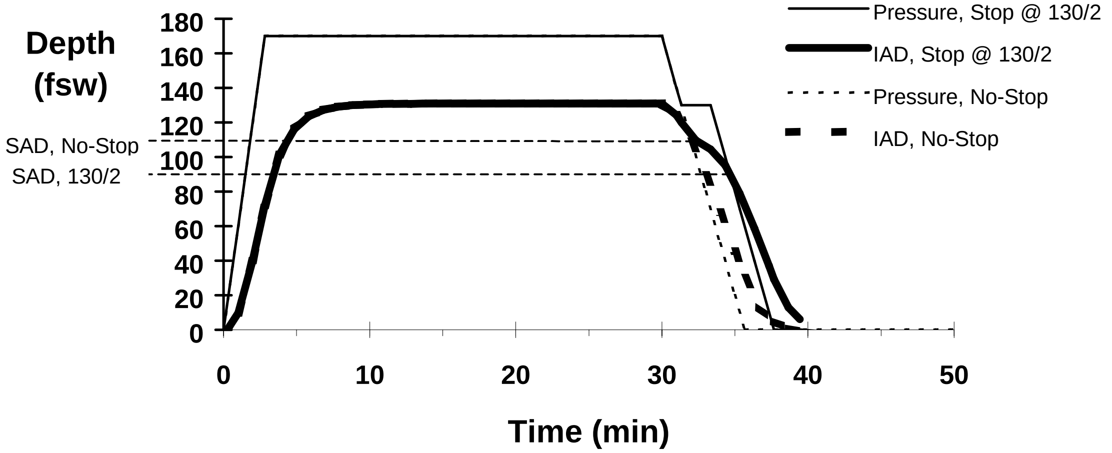

Figure 1 Variation of IAD and SAD in a "fast" compartment (T½ = 5 min) during decompression without and with an inserted 2-min stop at 130 fsw. The inserted stop decreases the SAD in this compartment and makes subsequent ascent to the initial SAD (and 1st stop) more conservative. (IAD = $p_{tot,i}$ - 33, see footnote 1.)

Such stops increase gas washout from the controlling compartment – and all faster compartments – before arrival at the original SAD and make the original stop more conservative (Figure 1). The same effect can also be obtained by reducing the rate of ascent to the original SAD [2]. Such stops or slowed ascent may consequently compensate for algorithmic insufficiencies that make the original SAD in fact unsafe. However, any benefit of the added stops or slowed ascent is limited to the controlling compartment on arrival at the original SAD and any faster compartments. The added stops or slowed ascent increase time at depths deeper than the atmospheric saturation depths of compartments slower than the controlling compartment, where such compartments continue to on-gas (Figure 2). As a result, subsequent decompression must be lengthened.

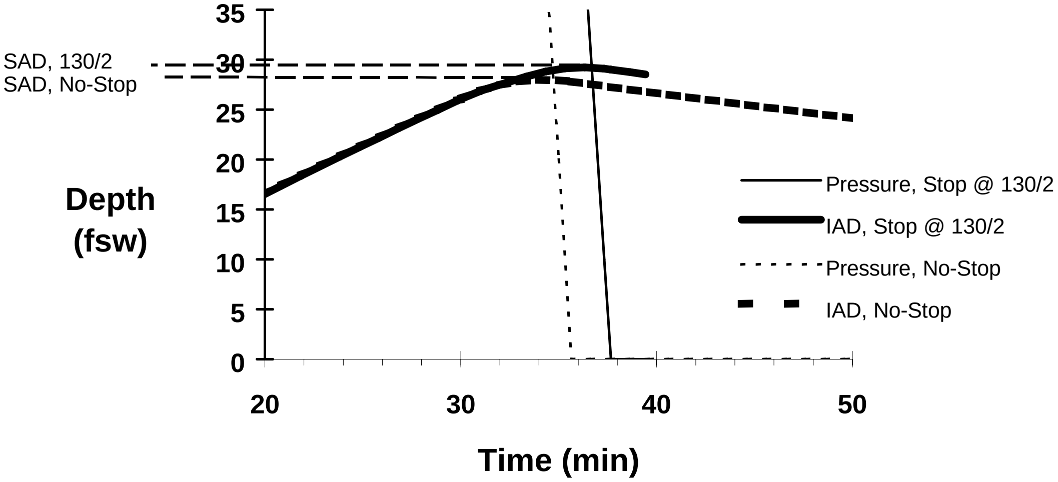

Figure 2. Variation of IAD and SAD in a "slow" compartment ($T½ = 80$ min) during a portion of the decompression illustrated in figure 7. The inserted 2-min stop at 130 fsw increases the SAD in this compartment and hence increases the required decompression time for subsequent ascent. (IAD = $p_{tot,i}$ - 33, see footnote 1.)

Excessive depth of the added stop, time at the added stop, or slowing of the ascent can even cause one of these slower compartments to become the controlling tissue and further deepen the SAD. In no case will insertion of this type of deep stop or slowing of ascent allow shortening of the subsequent decompression under the original safe ascent criteria – unless a switch to a breathing gas with increased oxygen partial pressure (PO_2) is made at the stop. The overall effects of inserted deep stops in a hypothetical air-only decompression from a 170 fsw/30 min air dive are shown in Figure 3.

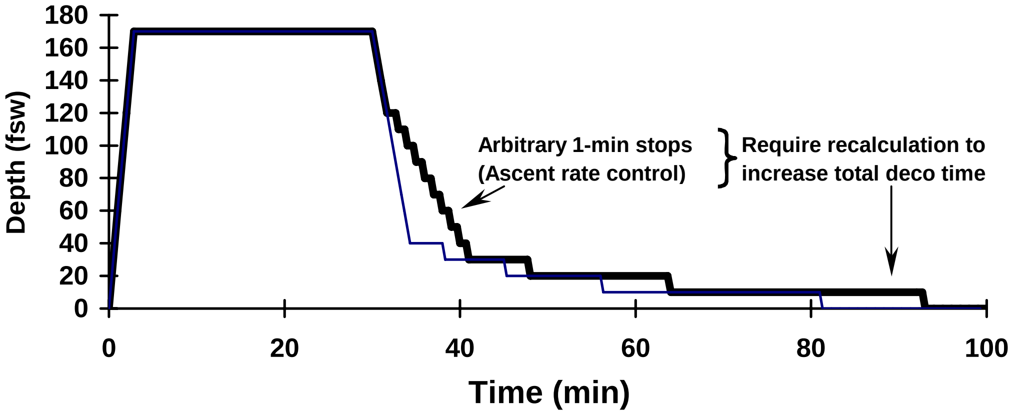

Figure 3. Overall effect of inserted Class I, Type 1 deep stops in a hypothetical decompression.

Class I, Type 1 Deep Stops in No-Stop Decompressions

A no-stop ascent is an ascent to surface that can be completed without any intervening decompression stops because the SAD is at surface or at a factitious negative depth. Large negative SADs often arise from the sometimes-considerable compartmental gas-supersaturations that must be allowed to obtain currently accepted no-stop limits. Nevertheless, expected effects of inserted stops in such ascents can be examined in the context of Class I, Type 1 deep stop behavior established above.

The variations of IAD and SAD in a 5-min half-time compartment during an 82 fsw/25 min air dive conducted with a no-stop ascent and with an inserted 2.5 min stop at 50 fsw are shown in Figure 4. Depths during ascent are projected to negative values to illustrate the locations of the SADs, but gas exchange after surfacing was appropriately computed at surface pressure. IADs were computed with a surfacing M-val (M_0, see footnote 1) of 120 fsw, approximately equal to the surfacing M-val for this compartment in the Thalmann Algorithm VVal-18 parameter set [3].

The inserted 50 fsw stop is at a depth shallower than the compartmental atmospheric saturation depth at start of the ascent, so that gas elimination during the stop reduces the SAD and makes the ascent more conservative than the ascent without the stop.

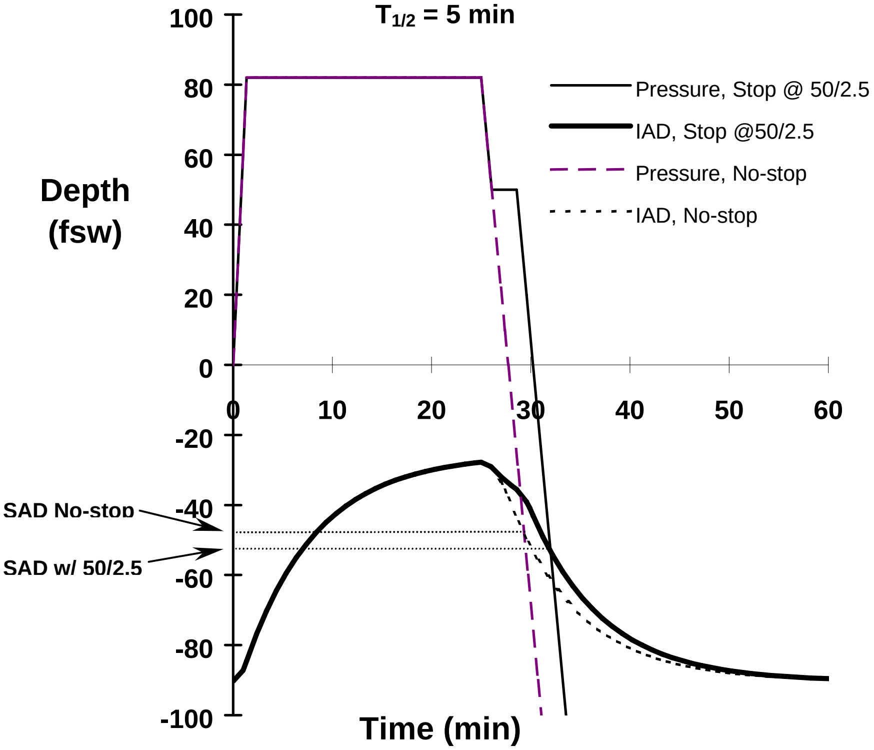

Figure 4. Variation of IAD and SAD in a "fast" compartment (T½ = 5 min) during a no-stop decompression from a 82 fsw/25 min air dive and during a similar decompression with an inserted 2.5-min stop at 50 fsw. (IAD = $p_{tot,i}$ - 120, see footnote 1.)

In contrast, the variations of IAD and SAD in an 80-min half-time compartment during the same dives are shown in Figure 5. Again, depths during ascent are projected to negative values to illustrate the locations of the SADs, but gas exchange after surfacing was appropriately computed at surface pressure. IADs were computed with a surfacing M-val (M_0) of 48.5 fsw, approximately equal to the surfacing M-val for this compartment in the Thalmann Algorithm VVal-18 parameter set [3].

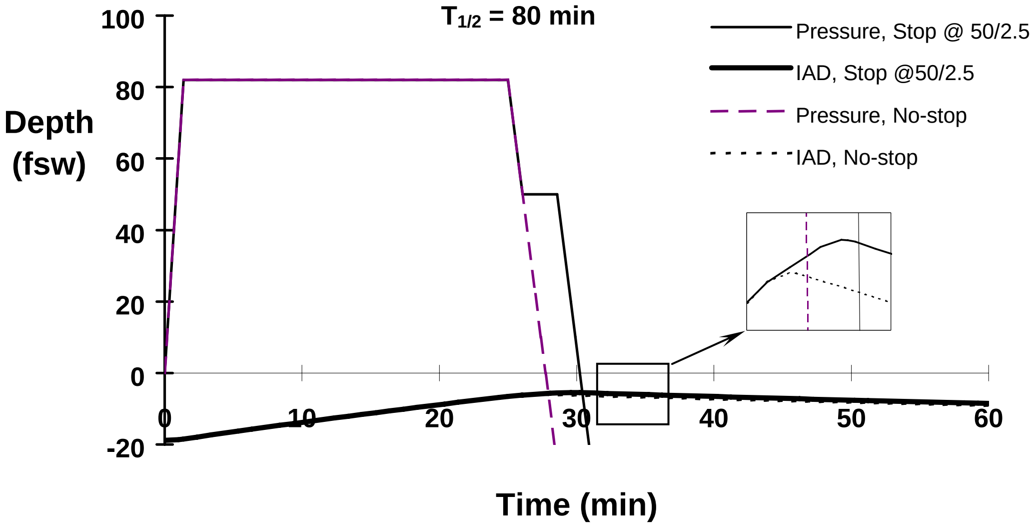

Figure 5. Variation of IAD and SAD in a "slow" compartment (T½ = 80 min) during a no-stop decompression from a 82 fsw/25 min air dive and during a similar decompression with an inserted 2.5-min stop at 50 fsw. (IAD = $p_{tot,i}$ – 48.5, see footnote 1.)

Although the ascent remains no-stop, continued gas uptake during the added stop increases the SAD and makes the ascent less conservative for this compartment. The adverse impact is small in this case, but excessive prolongation of the stop elevates the SAD to a value above surface, which must be accommodated by yet another decompression stop (Figure 6). Thus, even in no-stop dives, inserted stops or slowed ascents may compensate for algorithmic insufficiencies that make the no-stop ascents in fact unsafe, but such benefit is limited to the controlling compartment and any faster compartments. The added stops or slowed ascents increase gas uptake and decompression stress in slower compartments.

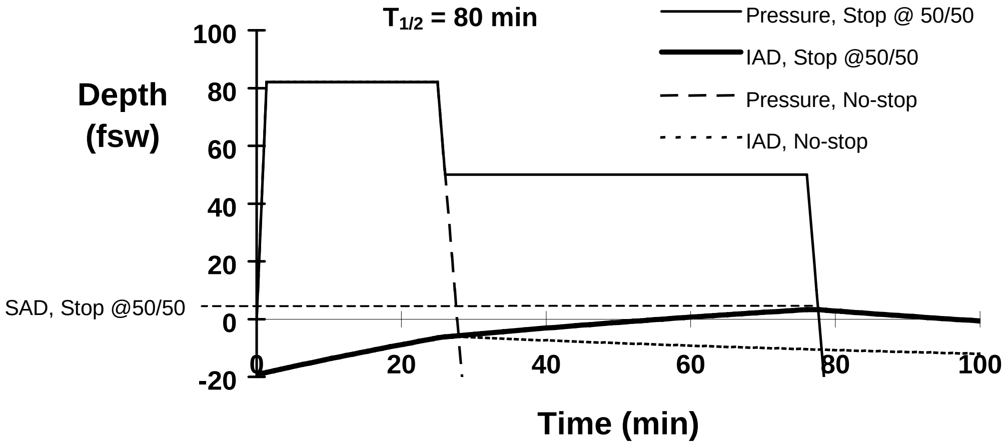

Figure 6. Variation of IAD and SAD in a "slow" compartment ($T½$ = 80 min) during a no-stop decompression from a 82 fsw/25 min air dive and during a similar decompression with an inserted 50-min stop at 50 fsw. (IAD = $p_{tot,i} - 48.5$, see footnote 1.)

Presuming that SADs for Doppler-detectable venous gas emboli (VGE) are systematically more conservative than those for DCS, recently reported incidences of central VGE grades after "no-stop" ascents with arbitrarily inserted stops [4] are in accord with Class I, Type 1 deep stop behavior. Relatively short stops inserted into ascents from 82 fsw/25 min air dives, which are widely accepted as no-stop dives, reportedly reduced the incidences of high central VGE grades after surfacing, while longer stops were without effect or increased the incidences of high post-surfacing central VGE grades.

Class I, Type 2 Deep Stop

The Class I, Type 2 deep stop is a deep stop added to a schedule to switch to a breathing gas with increased PO_2. Such a stop will usually have favorable effect, allowing shortening of the subsequent decompression or reduction of the overall DCS risk. This is NOT because of the "deepness" of the stop, but because the increased gradient for inert gas elimination caused by the gas switch hastens gas elimination after the switch - and hence the rate at which the SAD approaches surface - in *all* compartments. Most practical applications of this type of deep stop entail switches to decompression gas mixes with high O_2 fractions at inserted deep stops, as illustrated in Figure 7.

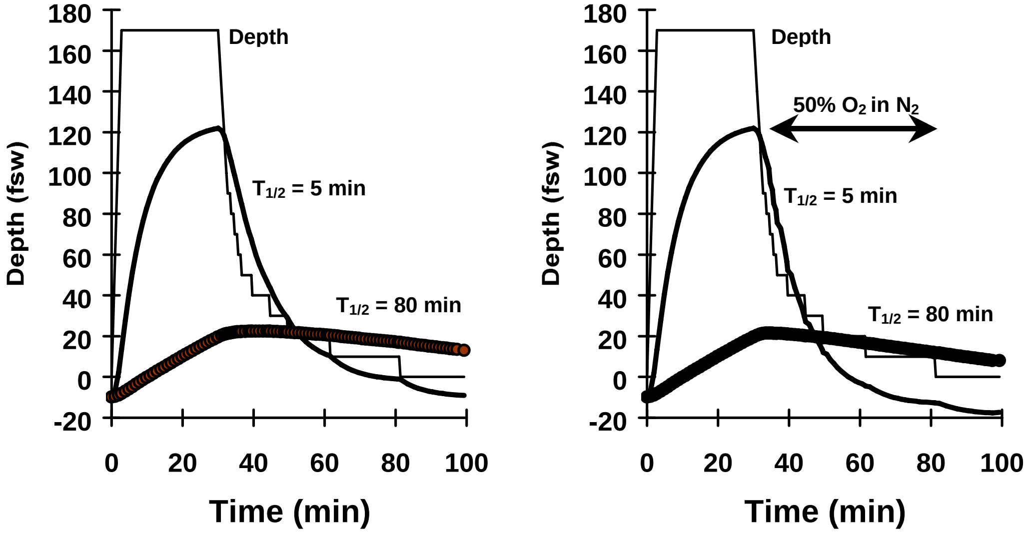

Figure 7. Depth and compartmental total dissolved gas tension profiles for a 170 fsw/30 min air dive with 1-min inserted deep stops at 10 fsw intervals starting at 90 fsw (left panel), and for the same dive with a breathing gas switch to higher FO_2 at the first of the inserted stops (right panel). The gas switch causes more rapid gas elimination in *all* compartments.

Class II Deep Stop

Class II deep stops are one or more first stops in an ascent computed with one algorithm that are at depths deeper than first stops in the same ascent computed with a different algorithm. This type of deep stop typically arises when two algorithms operate with different safe ascent criteria. Arguably the most interesting cases arise in schedules computed to limit the volumes and profusions of gas bubbles in the body compared with schedules computed to limit compartmental gas contents. Confusion on the internet over the essential features of these two analytic approaches, each of which can be implemented in either a classical deterministic or probabilistic context, motivates a brief review.

Approaches to limit compartmental gas contents during decompression are based on the schematic in Figure 8 with the classical deterministic implementation outlined in footnote 1.

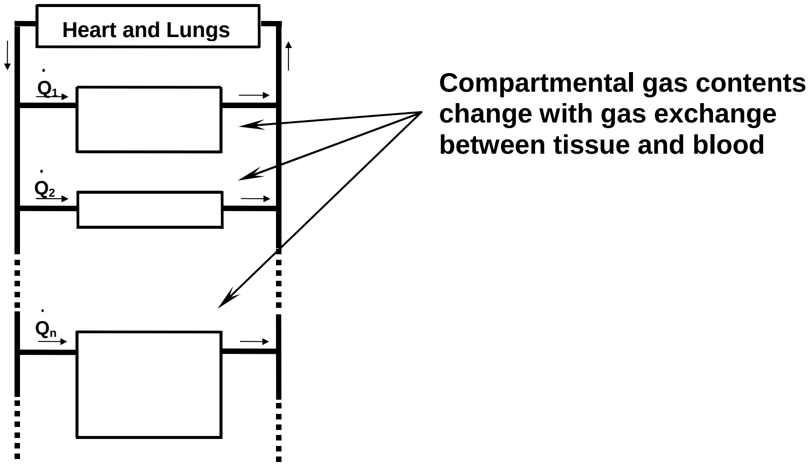

Figure 8. Schematic of gas content models for computing decompression schedules. Parallel perfused compartments represent tissue components involved in DCS.

A typical probabilistic implementation of the gas content approach is based on Eq. (4) [5]:

$$\text{instantaneous risk } \equiv h(t) = \sum_{i=1}^{n} G_i \left(P_{SS,i}(t) - Thr_i\right) / P_{amb}(t) \quad \text{when } P_{SS,i}(t) > Thr_i \qquad (4.a)$$

$$\equiv h(t) = 0 \quad \text{when } P_{SS,i}(t) \le Thr_i \qquad (4.b)$$

where

G_i = gain

$P_{SS,i}(t) = p_{tot,i}(t) - P_{amb}(t)$ = prevailing compartmental gas-supersaturation at time t

$p_{tot,i}(t)$ = prevailing compartmental gas content at time t

$P_{amb}(t)$ = prevailing ambient hydrostatic pressure at time t

Thr_i = compartmental gas-supersaturation risk threshold

The safe ascent criteria in the deterministic implementation and the DCS risk in the probabilistic implementation are functions principally of the prevailing total compartmental gas content, p_{tot}.

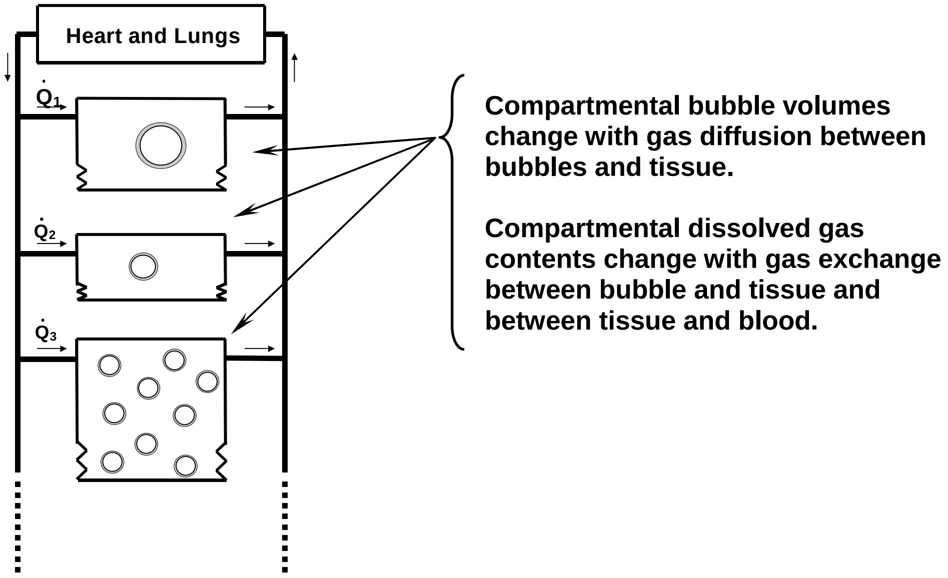

Figure 9. Schematic of gas bubble volume and profusion models for computing decompression schedules.

In comparison, approaches to limit gas bubble volumes and profusion during decompression are based on the schematic in Figure 9 with the probabilistic implementation in present work based on Eq. (5) [6,7]:

$$\text{instantaneous risk} \equiv h(t) = \sum_{i=1}^{n} \frac{G_i N_i(t)\left(V_{B,i}(t) - V_{B,i}^{o}\right)}{V_{t,i}} \qquad (5)$$

where

G_i = gain

$V_{B,i}(t)$ = prevailing compartmental bubble volume at time t

$V_{B,i}^{o}$ = bubble nuclear (or initial) volume

$N_i(t)$ = number of bubbles in compartment at time t

$V_{t,i}$ = compartmental volume

In order to complete the implementation, prevailing compartmental bubble volumes, $V_{B,i}(t)$, are computed as functions of time throughout a given dive with a gas and bubble dynamics model that includes provisions for perfusion-mediated gas exchange between tissue and atmosphere. DCS risk in this approach is consequently a function of only the portions of any prevailing compartmental gas-supersaturations that are relieved by bubble formation and growth and the numbers and volumes of those bubbles as they change during and after decompression.

The dynamics of bubble number and volume can differ markedly from the dynamics of gas content in any given compartment. Because of these different dynamics, schedules computed to limit the volumes and profusions of gas bubbles in the body tend to exhibit a skew of total decompression time for a given ascent to stops at deeper depths than stops in schedules computed to limit compartmental gas contents. The deeper stops prevent or delay bubble formation during decompression to provide two potential benefits.

The first is avoidance of the adverse effects of bubble formation on gas elimination kinetics. In the absence of bubbles, or formation of only relatively few bubbles in a large compartmental volume, modeled blood-tissue gas exchange follows the familiar semi-exponential function of time evident in the solid line curve of Figure 10.

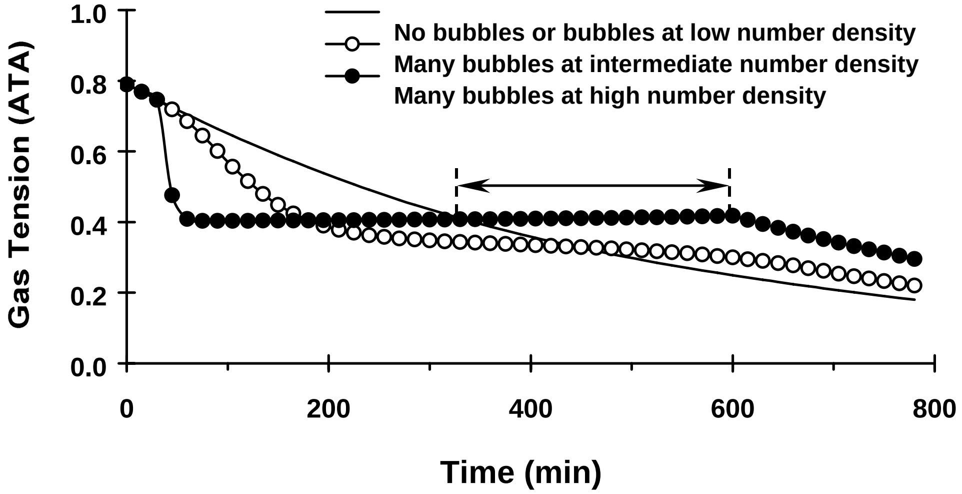

Figure 10. Impact of bubble formation and bubble-tissue mass balance on compartmental gas tension and gas elimination kinetics. (Adapted from Ref. 8)

The formation and growth of bubbles in increasing numbers, however, consumes increasing amounts of the compartmental dissolved gas, which reduces the compartmental dissolved gas tension and relieves the compartmental gas-supersaturation. In the limit as this relief is complete (curve with filled circles in Figure 10), the total compartmental gas tension is clamped to the total pressure of gases in the bubble, which for practical purposes is a function of ambient hydrostatic pressure only. In an isobaric stage, the tissue tension consequently remains constant and gas elimination from the tissue follows slower time-linear kinetics until the bubbles are completely resolved. Once the bubbles have dissolved, the rate of gas elimination resumes as a semi-exponential function of time along a curve practically parallel to that prevailing for no bubble formation, but displaced in time by the indicated delay. This slowing of bubble resolution and gas elimination from the tissue with increasing bubble number density is a central feature of the Exponential-Linear (EL) model described by Thalmann [9].

The second potential benefit of delaying or minimizing bubble formation during decompression arises from the attendant delay or minimization of DCS risk accumulation directly attributable to the bubbles per se. For example, schedule A1 in the top panel of Figure 11 is the schedule prescribed by the VVal-18 Thalmann Algorithm [3] for a 170 fsw/30 min air dive. Except for use of exponential-linear kinetics, the Thalmann Algorithm is a traditional deterministic gas content model in which decompressions are prescribed to limit compartmental dissolved gas contents in accord with a table of depth-dependent M-values or "maximum permissible tissue tensions." The accompanying compartmental bubble volume profiles are as estimated for the schedule with the BVM(3) probabilistic model of DCS incidence and time of occurrence [6,7] in which DCS risk is modeled as a time integral function of compartmental bubble volumes. BVM(3) has only three gas exchange compartments with respective half-times of 1.0, 21.4, and 317.3 min.

Schedule A2 in the bottom panel of Figure 11 is the schedule for decompression from the same 170 fsw/ 30-min dive that incurs minimum-attainable DCS risk under the BVM(3) model with the 174 min total stop time in schedule A1. Schedule A2 was obtained with an iterative "internal search" algorithm based on the algorithm described by Weathersby, et al. [10]. The deep skew of decompression stop time in the A2 schedule compared to the A1 schedule affords a reduced extent of bubble formation and growth that, under the BVM(3) model, reduces the estimated DCS risk from 6.2% to 3.7%.

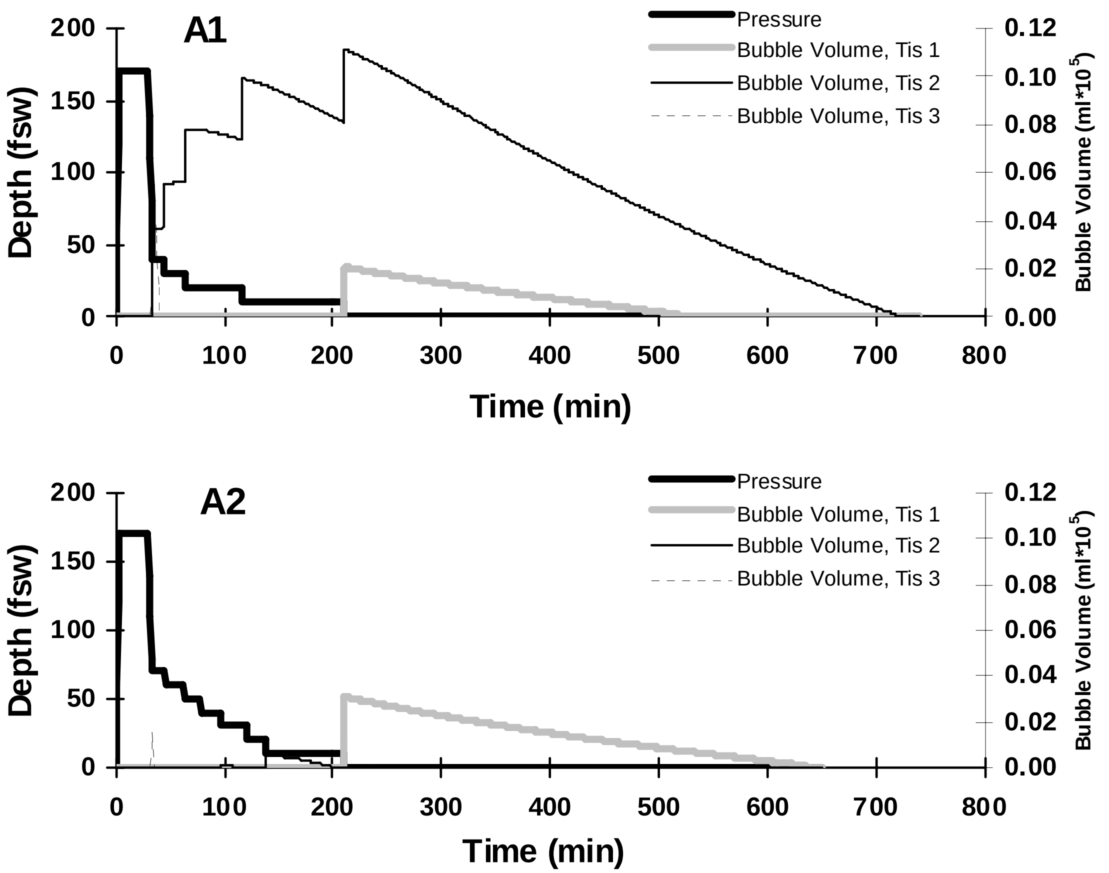

Figure 11. Hypothetical bubble-dependent DCS risk in two 170 fsw (52 msw)/ 30-min air dives identical except for the depth/time distributions of a 174-min total decompression stop time. Under the BVM(3) model, bubble formation in the A1 schedule causes the profile to incur an estimated DCS risk of 6.2%. Under the same model, the reduced extent of bubble formation afforded by the deep skew of decompression stop time in the A2 schedule causes the profile to incur an estimated DCS risk of 3.7%.

Compared to a schedule for a given dive computed to limit compartmental gas-supersaturations, a schedule with stops deep enough to prevent or limit compartmental bubble formation and growth can theoretically require less total decompression time for a given DCS risk or incur decreased DCS risk for a given total decompression time.

Navy Experimental Diving Unit (NEDU) Deeps Stops Man-trial

A man-dive trial was recently completed at NEDU under an NEDU Institutional Review Board-approved protocol [11] to test the efficacy of Class II deep stops in air decompression diving [12]. The methodological approach entailed comparison of DCS incidence following the two air decompression dives shown in Figure 11. The two dive profiles are overlaid for comparison in Figure 12.

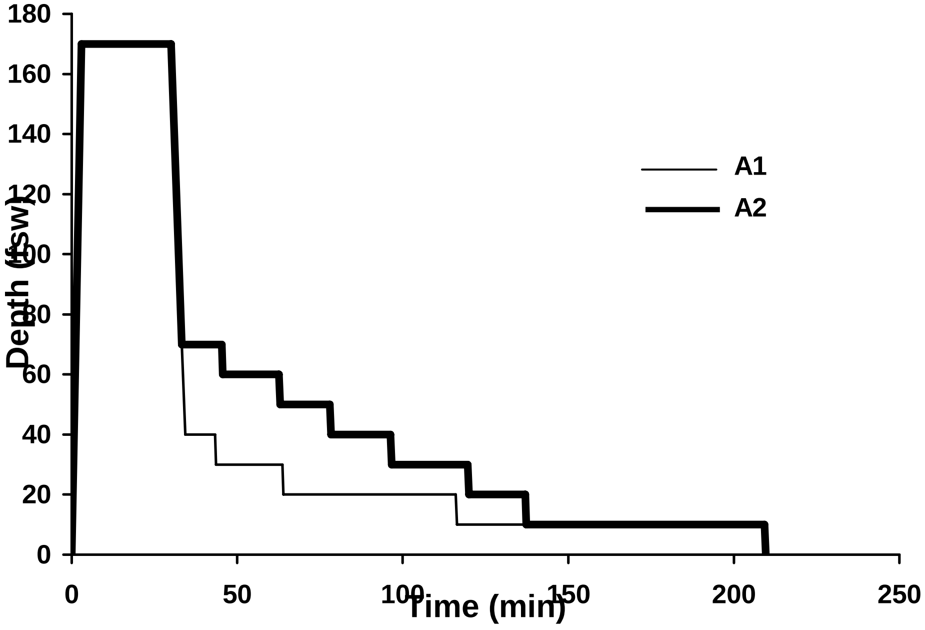

Figure 12. Overlay of the two 170 fsw/30 min air dive profiles man-tested at NEDU.

The profiles were man-dived under the following conditions:

- Descent rate = 60 fsw/min (18 msw/min).
- Ascent rate = 30 fsw/min (9 msw/min).
- Divers wore swimsuits and t-shirts, breathed surface-supplied air via full face masks (U.S. Navy MK 20 MOD 0 underwater breathing apparatus), and were immersed in 86 °F (30 °C) water in the NEDU Ocean Simulation Facility (OSF) wet pot throughout each dive.
    - Conditions were equivalent to 60 - 65 °C cold conditions for wet suited divers [13], but obviated introduction of any depth-dependent influence of suit compression on diver thermal exposure and DCS susceptibility [14].

- Divers performed 115 watt cycle ergometer work at 170 fsw until 1 minute before leaving bottom, then rested during subsequent decompression.
- Divers were monitored for venous gas emboli (VGE) with trans-thoracic cardiac 2-D echo imaging (Siemens Medical Solutions® Acuson Cypress Portable Colorflow Ultrasound System) at 30 minutes and 2 hours postdive.

Three hundred seventy five (375) man-dives on each schedule were planned with stopping rules to prevent unnecessary or excessively hazardous exposures. The trial was terminated after midpoint interim analysis when 81 divers had completed 390 man-dives and DCS incidence in Schedule A2 (deep stops, 11 DCS/198 dives) had emerged as significantly higher than in Schedule A1 (3/192, p=0.030, one-sided Fisher Exact). Figures 13 and 14 illustrate the trial outcome.

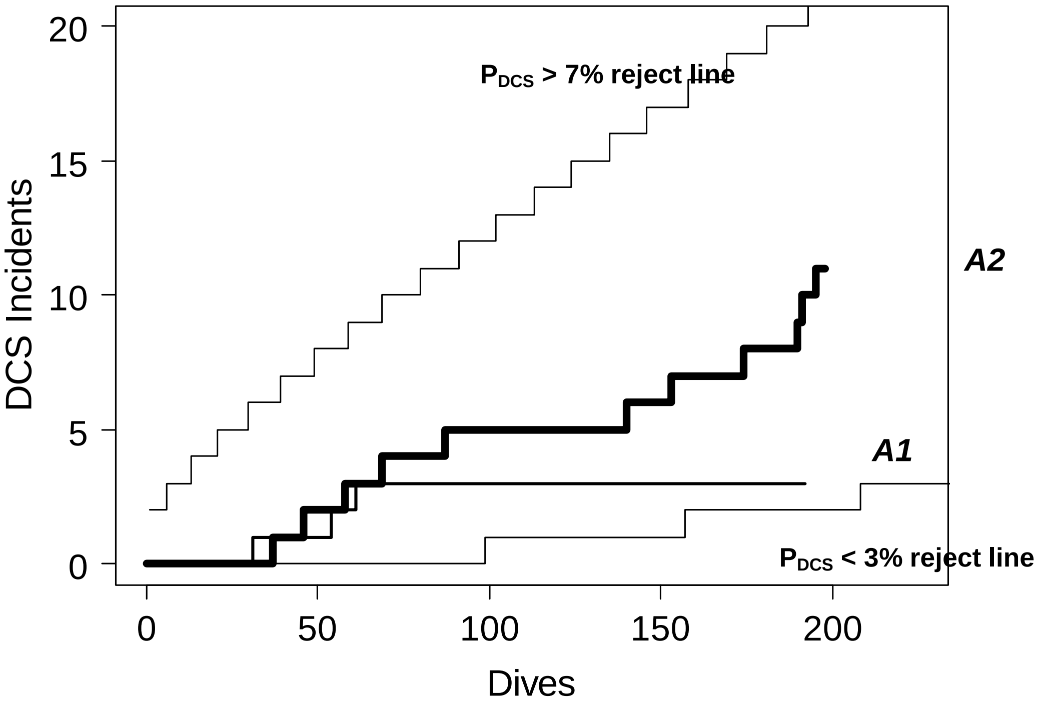

Figure 13. Sequential trial envelope (outer lines) and cumulative DCS incidents on the A1 Traditional (light line) and A2 Deep Stops (heavy line) schedules.

On review, one Schedule A2 DCS was excluded, but the result remained significant (p=0.047). Most DCS was mild, late onset (mean 9, SD 8 hours, n=11), Type I, but one case on each schedule involved progressing CNS manifestations.

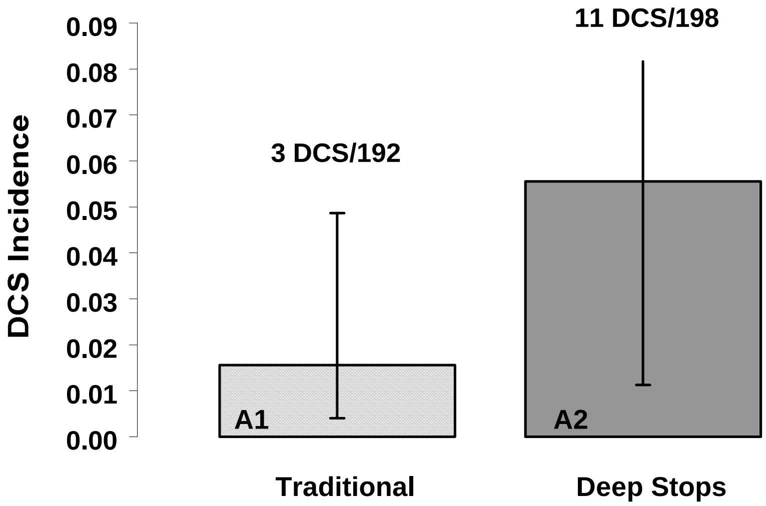

Figure 14. Observed DCS incidences (mean, 95% CI) for the two test dive profiles. (All 14 DCS cases are included.)

The association between DCS occurrence and maximum observed intravascular bubble grade is illustrated in the receiver-operator characteristic (ROC) curve [15,16] shown in Figure 15. High VGE grades were relatively insensitive and nonspecific indicators of DCS, with area under the ROC curve (AUC) only slightly greater than the no-discrimination value of 0.5.

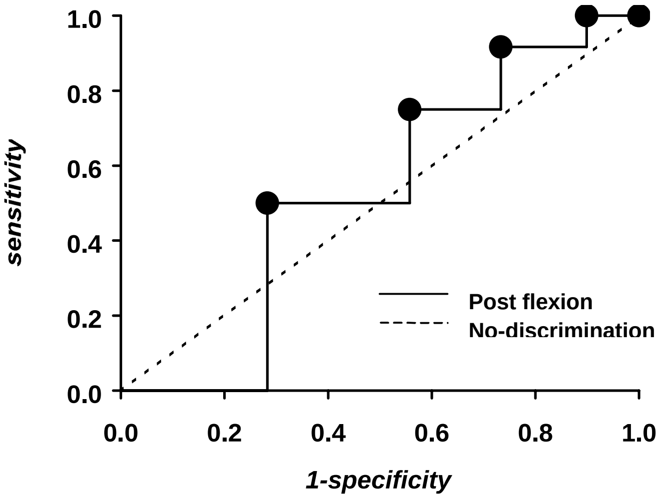

Figure 15. ROC curve for association of DCS occurrence with maximum observed VGE grades. Points graduate with increasing false positive rate (1-specificity) in order: VGE grades IV, III-IV, II-IV, I-IV, and 0-IV. AUC=0.68.

Despite the poor overall association between DCS and VGE, median VGE scores (maximum at rest and after limb flexion, Figure 16) were significantly higher after Schedule A2 than after Schedule A1 (Wilcoxon rank sum test, W=12967, p<0.0001). VGE scores at the 2-hour exam were increased over those at the 30-minute exam after Schedule A2 (Wilcoxon rank sum test, W=4418, p=0.0006) but not after Schedule A1 (Wilcoxon rank sum test, W=2578, p=0.734)

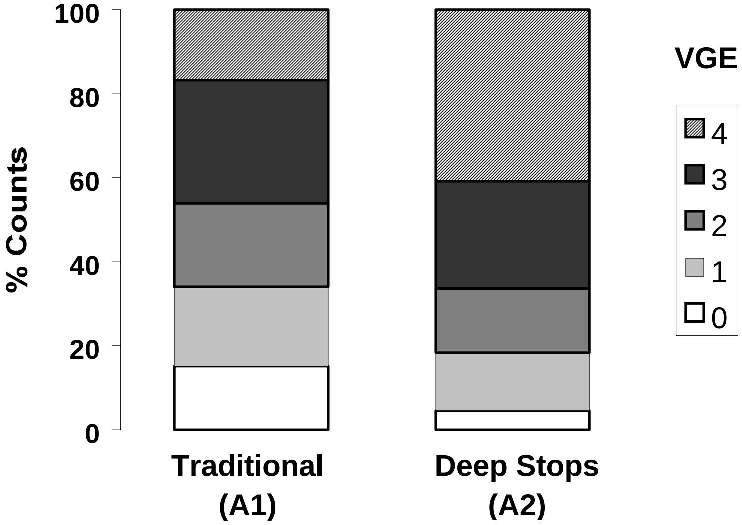

Figure 16. Maximum VGE Grade in all exams.

Discussion

Both DCS incidence and median VGE score were higher after the deep stops schedule than after the traditional schedule in the NEDU deep stops man-trial. Results failed to support any potential benefit of the deep stops schedule over the traditional schedule. It might be argued that the tested A2 deep stops schedule was not optimal and that alternative schedules produced by reallocating portions of the decompression time to either deeper or shallower stops would have yielded a lower DCS incidence. Reallocations of time to shallower stops produce schedules that approach the tested traditional schedule. Of greater interest are schedules that have longer or deeper initial stops than those in the A2 schedule. One such schedule with total stop time similar to that in the tested A2 schedule was proposed at this workshop [17] and is shown as schedule B5 with the tested schedules in Figure 17. Although the proposed schedule has not been tested, we use this schedule to illustrate that current results already indicate that schedules with deeper initial stops than in the A2 schedule and with the same total stop times cannot have intrinsically lower DCS risks than that of the A1 traditional schedule.

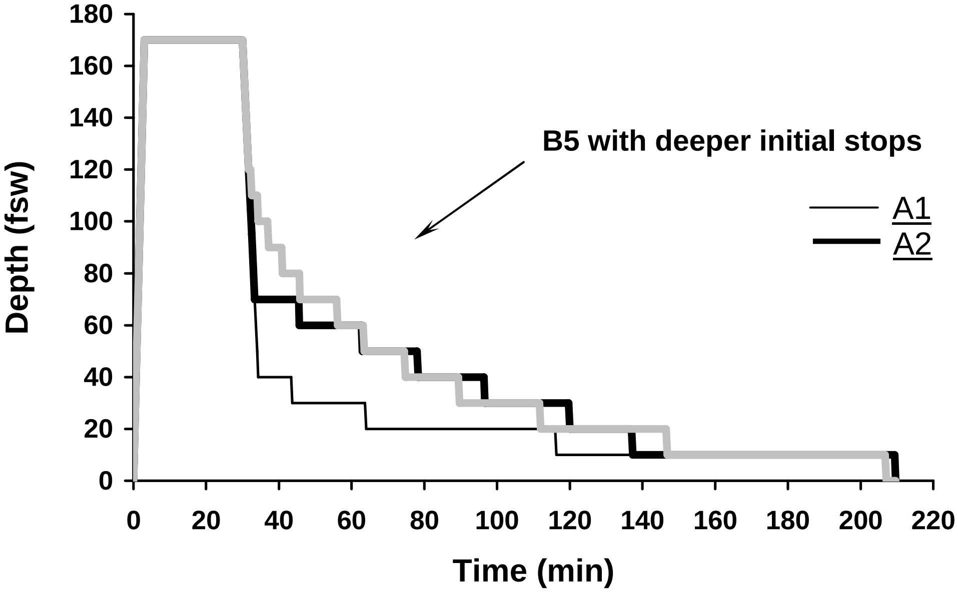

Figure 17. Alternative deep stops schedule (B5) compared with tested traditional (A1) and deep stops (A2) schedules.

Our argument need only be based on the compartmental gas-supersaturations that are produced during the different schedules. Gas-supersaturation ($P_{SS} > 0$) is a necessary condition for bubble formation and growth, which in turn is considered necessary for DCS [1,2]. While bubble formation and growth can considerably complicate the analytic landscape compared with that prevailing before such events, as illustrated in figure 10, such complications can arise only *after* the development of compartmental gas-supersaturations. The impacts of decompression stops at different depths on the initial development of these gas-superaturations, and the concordance of these impacts with observed DCS outcomes, provide unequivocal measures of decompression stop efficacy.

Gas-supersaturations in a fast compartment ($T_{1/2}$ = 10 min) during the tested A1 and A2 schedules and the untested B5 schedule are shown in Figure 18. The B5 schedule produces smaller gas-supersaturations in fast compartments during the initial 45 minutes of decompression than those produced during the same period in either of the tested schedules. Subsequent gas-supersaturations in the B5 schedule are comparable to those in the tested deep stops schedule. The lower initial gas-supersaturations in the B5 schedule would certainly provide less driving force for bubble formation and growth than provided by the higher gas-supersaturations during this period in the tested schedules. If this were of benefit, however, VGE scores and DCS incidence would have been lower after the tested deep stops schedule than after the traditional schedule because the tested deep stops schedule also produces smaller initial gas-supersaturations in fast compartments than those produced in the traditional schedule. In fact, VGE scores and DCS incidence were higher after the tested deep stops schedule than after the traditional schedule. Results from the tested profiles indicate that reductions of initial gas-supersaturations in fast compartments during ascent do not manifest in reduced VGE scores or DCS incidence. On the contrary, results indicate that the large ascent to the first stop in the traditional schedule is not a flaw in that schedule that warrants “repair” by deeper initial stops.

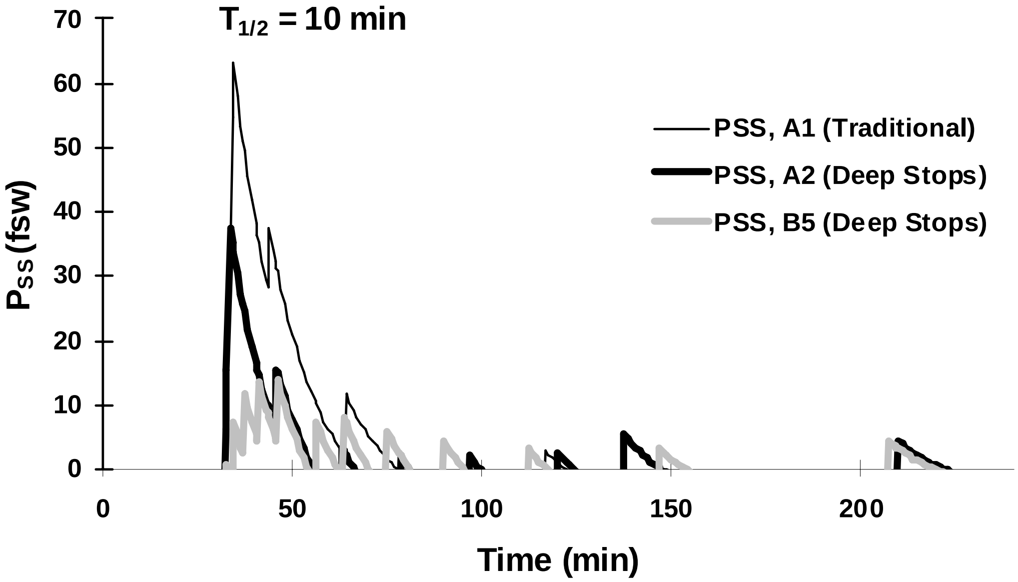

Figure 18. "Fast" compartment gas-supersaturations in the tested and B5 schedules. The B5 schedule produces smaller gas-supersaturations in fast compartments during the initial 45 minutes of the ascent than those produced in either of the tested schedules. Subsequent gas-supersaturations in the B5 schedule are comparable to those in the tested deep stops schedule.

Gas-supersaturations in slower gas exchange compartments are in accord with the observed decompression outcomes. Gas-supersaturations in a slow compartment ($T_{1/2}$ = 80 min) during the tested and B5 schedules are shown in Figure 19. The smallest and least persistent gas-supersaturations in this compartment occur during the tested traditional schedule, in accord with the observation that, amongst the two schedules tested, the lowest VGE scores and DCS incidence occurred on this schedule. On the other hand, gas-supersaturations in this compartment are higher and more persistent during the tested deep stops schedule, in accord with the higher observed VGE scores and DCS incidence on this schedule. Because the gas-supersaturations in this compartment during the B5 schedule are comparable to those during the tested deep stops schedule, results indicate that VGE scores and DCS incidence after the B5 schedule should more closely approximate the higher VGE scores and DCS incidence observed after the tested deep stops schedule than those observed after the traditional schedule.

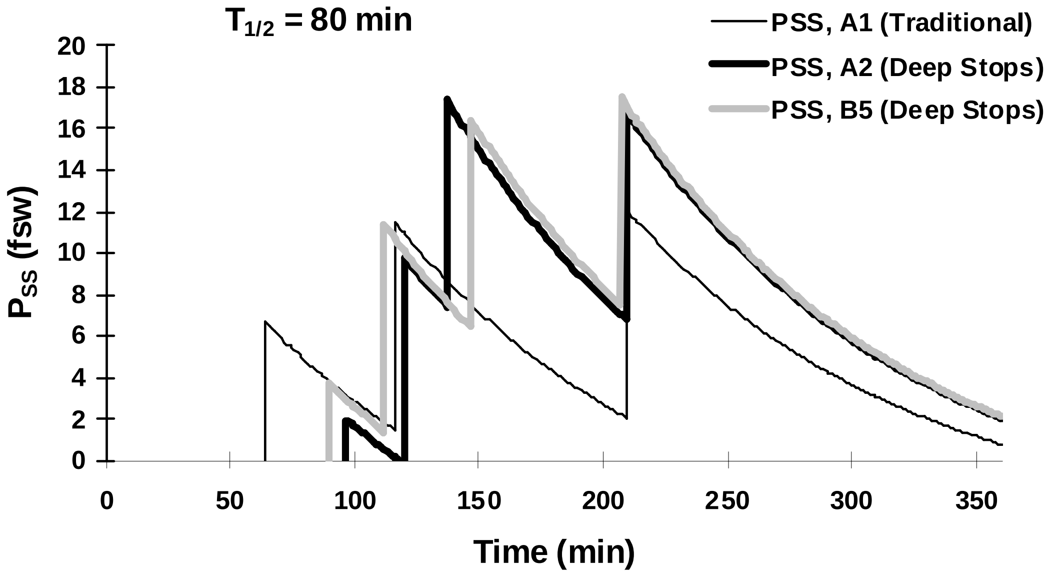

Figure 19. "Slow" compartment gas-supersaturations in the tested and B5 schedules. Larger and more persistent gas-supersaturations occur in both deep stop schedules than in the traditional schedule.

Conclusions

Two classes of deep stop can be identified. Deep stops of the first class are stops added deeper than the first prescribed by a given decompression algorithm. These may be beneficial under certain circumstances but serve to correct a deficient algorithm. They cannot allow shortening of the originally-prescribed schedule unless switch to a breathing gas with higher PO_2 is associated with the added stop or stops. Deep stops of the second class arise in comparison of schedules for a given ascent computed with different algorithms and types of safe ascent criteria. One serious attempt to empirically confirm the theoretical benefits of a deep stop air decompression schedule computed to control bubble formation compared with a traditional schedule computed to limit compartmental dissolved gas content was unsuccessful. Both DCS incidence and VGE scores were higher after the deep stops schedule than after the traditional schedule. Slower gas elimination or continued gas uptake offset benefits of reduced bubble formation and growth at deep stops in the tested deep stop schedule. Results indicate that deep stops air decompression schedules intended to accrue benefit of reduced bubble formation and growth during ascent instead pose increased risk of DCS compared to traditional schedules with the same respective decompression times.

Acknowledgements

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References

1. Tikuisis P, Gerth WA. Decompression Theory. In: Brubakk AO and Neuman TS, eds. Bennett and Elliott's Physiology and Medicine of Diving. 5th Edition. W.B. Saunders Co., London. 2003.
2. Gerth WA, Doolette DJ, Gault KA. Deep Stops and Their Efficacy in Decompression. DAN Technical Diving Conference, Durham, NC, January 18 – 19, 2008.
3. Gerth WA, Doolette DJ. VVal-18 and VVal-18M Thalmann Algorithm Air Decompression Tables and Procedures. NEDU TR 07-09, Navy Experimental Diving Unit, Panama City, FL, May 2007.
4. Bennett PB, Marroni A, Cronje FJ, Cali-Corleo R, Germonpre P, Pieri M, Bonuccelli C, Leonardi MG, Balestra C. Effect of varying deep stop times and shallow stop times on precordial bubbles after dives to 25 msw (82 fsw). Undersea Hyperb Med 2007;34(6): 399-406.
5. Thalmann ED, Parker EC, Survanshi SS, Weathersby PK. Improved probabilistic decompression model predictions using linear-exponential kinetics. Undersea Hyperb Med 1997;24(4): 255-274.
6. Gerth WA, Vann RD. Development of Iso-DCS Risk Air and Nitrox Decompression Tables Using Statistical Bubble Dynamics Models, Final Report, National Oceanic and Atmospheric Administration, Office of Undersea Research, Bethesda, MD, 1996.
7. Gerth WA, Vann RD. Probabilistic gas and bubble dynamics models of DCS occurrence in air and N_2O_2 diving. Undersea Hyperb Med 1997;24(4):275–292.
8. Srinivasan RS, Gerth WA, Powell MR. Mathematical models of diffusion-limited gas bubble dynamics in tissue. J Appl Physiol 1999;86(2): 732-741.
9. Thalmann ED. Computer Algorithms Used in Computing the MK 15/16 Constant 0.7 ATA Oxygen Partial Pressure Decompression Tables. NEDU TR 1-83, Navy Experimental Diving Unit, Panama City, FL, Jan 1983.
10. Weathersby PK, Hays JR, Survanshi SS, Homer LD Hart BL, Flynn ET and Bradley ME. Statistically Based Decompression Tables II: Equal Risk Air Diving Decompression Schedules. NMRI Technical Report 85-17, Bethesda, MD, 1985.
11. Gerth WA, Gault KA, Ruterbusch VL, Melton JL, Doolette DJ. Empirical evaluation of the efficacy of deep stops in air decompression diving. NEDU Protocol Number 05-23/32174, Navy Experimental Diving Unit, Panama City, FL, November 2005.
12. Gerth WA, Gault KA, Doolette DJ. Empirical evaluation of the efficacy of deep stops in air decompression dives. Undersea Hyperb Med 2007;34(4):231–2.
13. Doolette DJ, Gault KA, Gerth WA. Water temperatures for matched cold exposures in divers with or without wetsuits during air decompression dives. Undersea Hyperb Med 2007;34(4):251–2.
14. Gerth WA, Ruterbusch VL, Long, ET. The Influence of Thermal Exposure on Diver Susceptibility to Decompression Sickness. NEDU TR 06-07, Navy Experimental Diving Unit, Panama City, FL., November 2007.
15. Robertson EA, Zweig MH, Steirteghem AC. Evaluating the clinical efficacy of laboratory tests. Am J Clin Pathol 1983;79:78–86.
16. Zweig MH, Campbell G. Receiver-operator characteristic (ROC) plots: A fundamental evaluation tool in clinical medicine. Clin Chem 1993;39(4):561–577. [Erratum published in Clin Chem 1993;39:1589.]

17. Wienke BR, O'Leary TR. LANL Deep Stops Data Bank and Dual Phase Bubble Model for Profile Analysis and Risk. These Proceedings.

<u>DISCUSSION</u>: DEEP STOPS AND THEIR EFFICACY

DR. TOM NEUMAN: I'm absolutely fascinated by the fact that you had a 170-foot for 30-minute schedule, which was the exact schedule that we used for a 132-foot normoxic dive. I'm amazed that your incidence of decompression sickness was on the neighborhood of 3, 4, 5 percent because we had 1 in 14 divers who got decompression sickness on that schedule, and it was also pretty close. You had 174 minutes of decompression and we had 48. Can you explain that to me, please?

DR. WAYNE GERTH: Well, I have a lot more confidence in the absolute value of the risk associated with our observed incidence from our study than I would from yours. In other words, the binomial confidence.

DR. TOM NEUMAN: I agree, but how do we get away with one-quarter of the decompression table?

DR. WAYNE GERTH: We do know that it takes very large increases in decompression time to affect relatively small decreases in risk, so there's a trade-off there after a certain point. Initially, as you add, if you do a direct ascent from what should be a decompression dive, and it gives you an unacceptable risk, initially, as you add stop time and do steps, your risk will drop pretty fast, and then it levels off. The cost benefit, adding more time, and reduced DCS risk, starts getting pretty unfavorable after a while, so we had to work within that trial envelope. I can ask our guys to dive -- 6 percent risk. We think this might be as high as 6 percent, our guys will still do that. I can still go home at night and feel pretty safe with that, but when we start getting to higher incidences, like 8 and 12, that's when we start hurting guys. I don't feel good about it, even if our guys would do it, I wouldn't ask them to. So it was very important for us to conduct this trial within an envelope that we feel we could do both legs of and be complete. So we had to go to a longer time to get that top end of the risk below 6 percent. Does that help?

DR. TOM NEUMAN: 48 minutes versus 174, it boggles my mind.

DR. WAYNE GERTH: If I do that dive at 48 minutes that was right on our expected incidence, by the way. Neither model actually failed in the estimate there. We were within the confidence limits of either model. If we would have done the dive as prescribed in the manual, 48 minutes, that was a VVAL-18 algorithm there. I don't remember what the incidence was going to be, but I think it was going to be around 8 or 9 percent, so we increased the time up and this is why the algorithm we're using in the Navy today does cut risks on these deeper dives, or I wouldn't put a guy in on that original schedule you were giving.

DR. BRUCE WIENKE: Wayne, I appreciate your dissolve gas analysis, but what you're not taking into account, as far as I can tell from what you said and also taking a look through your papers, you're not considering the gas diffusion into the bubble. There's a time factor there and you're cuing on the bubble volume. You're cuing here on supersaturations and the slow and the fast compartments. Even though you may have it coupled to your version of a bubble model, you don't have the bubble dynamics the same as what we do.

DR. WAYNE GERTH: I'd like to see your bubble dynamics, Bruce. I really would.

DR. BRUCE WIENKE: Wayne, if you would ever answer your emails. If I could get through to you on emails, I would have mailed that to you years ago.

DR. WAYNE GERTH: Bottom line is we do have bubble dynamics. I showed you what they do. I showed you a plot of them. The thing I showed was something that occurs before a bubble can ever form; that is, supersaturation. All I was showing is how adding those stops affect when a bubble can form. I don't have to go to the point of them forming, so I don't have to start hand waving around bubble dynamics and do we have the right equations. I showed you that I don't need to control that supersaturation for bubbles to form there.

DR. BRUCE WIENKE: I would disagree with that. Let's agree to disagree. In our particular approach, the surface tensions of these lipid bubbles that we have, which are monomolecular layers, is very, very small. It doesn't take much difference between inside and outside gas pressures for it to start to grow.

DR. WAYNE GERTH: Will they grow when the liquid is undersaturated?

DR. BRUCE WIENKE: No.

DR. WAYNE GERTH: What I was showing is what is needed to affect supersaturation.

DR. BRUCE WIENKE: It doesn't take much to --

DR. WAYNE GERTH: We had a larger supersaturation, and that was the safer schedule.

DR. BRUCE WIENKE: Safer by what standard?

DR. WAYNE GERTH: Significantly. I have to go back to the slide. One was 5 percent and one was 1.7 percent.

DR. BRUCE WIENKE: Against what data do you make that prediction?

DR. WAYNE GERTH: One schedule tested against another. Yours isn't tested at all.

DR. BRUCE WIENKE: That's true.

DR. WAYNE GERTH: What I'm trying to make a point about is what those schedules that we tested tell us. They tell us a lot more than just about those two schedules. I assert that they tell us that your suggestion won't work either. They're sufficient to do that.

DR. BRUCE WIENKE: Your analysis of what happened in your experiment is based on your model. My analysis is based on my model. I would suggest that we don't --

DR. WAYNE GERTH: My analysis is based on the observation we made and a simple assertion about how gas exchange occurs before bubbles form, and I'll leave it at that.

DR. BRUCE WIENKE: The thing is, when you're trying to trigger on bubbles, you can't leave out bubble dynamics, and I don't see how you're getting that.

DR. WAYNE GERTH: I can if I have not reached the --

DR. PETER BENNETT: You have different opinions. There's no doubt about it, I think we'll hold it there for the moment. You can come back at the end of the session tomorrow if you want.

DR. BRUCE WIENKE: Just one last comment. Tom's observation about his decompression schedules and for how long and how deep and what he saw versus your 176 versus his 48, you know, to me, as a diver, I'm going, "Wow, what's going on there?" Now, I know you have to devise these things for the fleet, I understand that. You have certain safety standards. But I still maintain what I said this morning. Your gas buildup, the way it couples to real bubbles that we excite -- we have a distribution. Your profile excites too much in the shallow zone -- I mean, in the midzone and by the time you get to the shallow zone, it's built up, whether your supersaturation is exciting bubbles in your model or not. We would still maintain that you've got too much time in the midzone, where you're building up a lot of dissolved gas and building up a lot of bubbles.

DR. WAYNE GERTH: Okay.

DR. PETER BENNETT: Whatever. There are two different opinions based on the data and we have some data, the Navy data, which is very interesting, certainly would suggest that we don't know all that we think we do about the deep stop in those kinds of dives, either with your profile or yours. That neither, actually, is perhaps providing the truth.

DR. WAYNE GERTH: Let me challenge you to dive your profile. We thought about it a lot, too.

DR. BRUCE WIENKE: We have lots of guinea pig profiles. Maybe we will when we get some time. Nobody wants to go into deep air.

DR. WAYNE GERTH: You're off on another tangent. Deep stops and schedules you describe based on bubble models you expect to be different with air than they would be with helium?

DR. BRUCE WIENKE: There are differences definitely because there are differences in helium bubbles that are excited. There are differences in gas diffusion lengths across the bubble for helium and nitrogen. There are a host of little nuances that change the schedules dramatically. The other point is this: You know, I have to admit that we don't have many deep air schedules -- I mean, much deep air data. There's no question about that. So in some sense, what you've done helps us, because now we know how to avoid what you've done.

DR. WAYNE GERTH: Well, I'm glad.

DR. PETER BENNETT: We'll leave it at that for now. Dr. Vann.

DR. RICHARD VANN: In answer to Tom's question, and also, in part, to Bruce's, one of the things that's missing here is the effect of the dive conditions. The conditions can be much more important than the dive profile itself. I'll talk a little bit about this tomorrow. That's why there was such a big difference in there. It's just huge. If you don't recognize this, if we can't learn how to recognize this, we're going to be having this sort of argument from now until the end of time and I think we're getting there. The other point here is that probabilistic decompression models are the only way to come to grips with this, but you've got to calibrate them to observe data under certain conditions and you change the conditions, then you're going to get very different probabilities. So I'll talk about this a little bit more tomorrow.

DR. WAYNE GERTH: I've got to answer that. Dick and I are almost always in a hundred percent agreement, but I think he's a little bit misguided in his issue about dive conditions. Most people here will be very familiar with our work at NEDU on temperature effects during dives. We've published in technical reports and UHMS meetings over the past several years, a series of studies, again, hundreds of man dives, where we've shown that being cold on the bottom and warm during decompression is very favorable. The thermal conditions, that compared to being warm on the bottom and cold during decompression has an impact on dive, that's as important as depth and bottom time. Going from cold to warm and warm to cold has an impact on bottom time, and you can double your bottom time. So, yes, conditions are very important. But such things had no impact whatsoever on the difference between our A-1 and A-2. Maybe I should go back to the slide I showed with the divers on the cycle odometer horns showed we controlled the conditions that those divers were under in each of the two profiles very closely. The only things that were different between the A-1 schedules as we dove them and the A-2 schedules as we dove them were the distribution of the decompression time amongst the stops. Everything else was the same. Depth, temperature exposure, total decompression time.

DAVID DOOLETTE: I think what Dick was saying and addressing was that the 14 dives that Tom was talking about were dry, resting -- not resting. They were exercising, but warm, dry dives, and we had cold decompression. That could account at least for some of the discrepancy between the total decompression time.

DR. WAYNE GERTH: I stand corrected and apologize to Dick. I didn't know that you were addressing that. That wasn't the subject of what we were testing. That wasn't what we tested. In that case, I'm sorry, Dick, you're right.

DR. RICHARD VANN: So we agree still.

JOE DITURI: I wanted to ask you if you had considered any warm-up dives for these people, or did they basically just go from not doing any diving for a period of time, X, and then jumping right into the decompression series of dives?

DR. WAYNE GERTH: That's a very good question. There were almost 400 man dives before we ended up quitting. There were only 80 divers and obviously then we had divers doing multiple dives. The issue of each dive being independent of another, the assumption we usually make when looking at these numbers is one that is subject to some question and makes Joe's question a very good one. No, we did not work these divers up. If you'll remember, the track of the incidence during the time -- where I showed the trial envelope and the two curves going up within that and one finally going above the other until we rejected, there was a period of time essentially when both of those curves had a time when we had no hits whatsoever, and then they diverged. When we looked at whether or not that had to do with the fact that initially our divers weren't that worked up, and then later they were, we haven't been able to ascribe that not worked up, then were, to the outcome. But the thing you raise is a concern we have all the time. We think they're pretty close to independent.

DR. BRUCE WIENKE: Wayne, I have one last question for you. What is the population of your test divers, going back to what Dick had to say? Who are these folks you're testing at NEDU? Are Navy SEALS that you tested or are they just walk-ins off the street?

DR. WAYNE GERTH: These are all Navy divers. They're assigned to NEDU as divers. They have ancillary duties that they carry out in the course of their day-to-day activities there. We have people from EOD, Spec War. I don't think we have many salvage divers. Almost all of them are sat rated, the older guys, anyway. I can give you the subject characteristics of them, but they're all Navy divers, so they all have to pass the Navy physical standards and remain within standards.

DR. BRUCE WIENKE: Did you find one group more resistant than the other group when you did the experiments? For instance, were the spec war guys boilerplate, you couldn't bend them no matter what you did, and you had other results from other types of divers across the Navy spectrum?

DR. WAYNE GERTH: No, we don't have it broken down by groups like that. But we do find some divers that tend to be the ones that get bent or don't. So we have resistant individuals, but I haven't gone as far as trying to tag them to any particular group. I would guess, though, just off the top of my head, that there's going to be very little of that kind of association.

DR. ALF BRUBAKK: I just want to make a comment about the environmental conditions around when the dives are done. I think what is probably underestimated is the enormous difference between gas bubble formation when you do a dive in dry or you do it in water. We did a series of tests where we started with the divers dry. That was dives to 20 meters for 70 minutes, another to 54 meters for 20 minutes. We did it first in the dry, and then afterwards we did them in the water, exactly the same individuals the week after. I had never seen so many that had gas bubbles, but we had no decompression sickness so there's an enormous difference. Unless we take things like that into consideration, then we don't know what we're talking about and I think our data fits exactly with the difference that you have here between the dives. There actually is an increase in the decompression time, which is considerably longer. Another interesting aspect of that is, we've shown that actually if you do a dive with someone in the water, and take the individual out of the water and then test them after in the dry, you'll find that this has an influence on his cardiovascular system, his internal function, his heart function is reduced for up to two days of the exposure to water. So there's an enormous difference in what's happening here. It has to be considered.

DR. WAYNE GERTH: Alf, point well taken. And that bears directly on what Joe Dituri was asking about. We did tend to try to put two days in between each -- David, do you remember exactly what it was? It was 60-some hours, which ended up 72 hours between dives.

DAVID DOOLETTE: There's always a minimum of three days between dives. Even a Monday and Thursday, people occasionally did that.

DR. WAYNE GERTH: We were outside of your two-day envelope, Alf, but not outside the seven- to 12-day adaptation envelope that someone else raised earlier today. By the way, that seven- to 12-day envelope for multi-day diving and adaptation over the course thereof is something that has emerged from a couple of Navy studies, too. So we can kind of confirm the importance of that kind of period.

GENE MELTON: Hopefully, you can help me understand a few things. Your bubble model, your parameters that were involved in it, I'm familiar with BPM and RGBM, but I'm not familiar with yours. I don't know if the Navy is willing to share that model.

DR. WAYNE GERTH: It was published in 1997 in the UHMS BMR. It was published then. Called "the BVM-III," I can give you the reference.

GENE MELTON: The reason is that your parameters versus the other ones that we're using today had a much shallower deep stop than the other models. And I just wanted to know where to find it. Now I know, so thank you.

DR. WAYNE GERTH: That model is published. And the parameters that govern its performance were determined by fitting the equations and logic of the model to some 3,211 man dives that constitute what we call the Navy primary Collection data. That too has been published by NAMRC -- That database has also been published.

DR. BRUCE WIENKE: Isn't that data shallow stop? You fitted your bubble model to, was it VVAL-18 way back, or was it something else? I can't keep track of it. Most of that stuff in those days was mostly shallow stop. If you're fitting a bubble model to shallow stop data, you're going to see some shadows of shallow stop in there when you do your --

DR. WAYNE GERTH: I am? You'll have to show me that. The data or the models that were used to generate the profiles tested and the man dives that constitute the data for the primary data set were generated by a variety of different algorithms. Most of them were of the traditional type, the controlled gas content, but the bubble model that we fit to that data is the one that prescribed deeper stops.

DR. BRUCE WIENKE: That's right.

DR. WAYNE GERTH: I showed why it is you don't want to be too deep and you don't want to be too short.

DR. BRUCE WIENKE: If this is shallow stop data, depending on how you stage and how you compute within a model, you can get a biasing toward shallow stopping versus deeper stopping because that's just the nature of fitting a model to shallow stop data. We can fit our model to shallow stop data, too. As we get more and more deep stop data, we can merge the two, and then we can see what's going on. If you didn't have deep stop data when you were doing your parameter fits, I would suggest that possibly you may have a data bias when you do your fits. I don't know which parameters you fit, and I don't know which data you are talking about with respect to the '97 version of BVM-III. It's just an observation. I'm not accusing you of anything.

DEEP STOPS DURING DECOMPRESSION FROM 50 TO 100 MSW DIDN'T REDUCE BUBBLE FORMATION IN MAN

J.E. Blatteau, M. Hugon, B Gardette

ABSTRACT:

Background

The French Navy uses the MN90 decompression table for air dives as deep as 60 msw and the MN78 decompression table for trimix dives (60-80 msw). The resulting incidence of decompression sickness (DCS) for deep air dives (45-60msw) is one case per 3000 dives (with 89% of neurologic DCS). We hypothesized that introduction of deep stops could reduce fast tissue bubble formation and neurological DCS risk in deep air diving. We also expected that adding deep stops could reduce bubble formation and decompression stress for trimix diving (80-100msw).

Methods

We incorporated deep stops (DS) into a serie of 6 Experimental Ascent Profiles (EAPs) developed with decompression software built on a Haldanian model. Deep stops for air dives (EAP 1-4) were introduced at about ½ the absolute depth and about 1/3 for trimix dives (EAP 5 & 6). EAPs were tested in the wet compartment of a hyperbaric chamber. For EAPs 1-5, eight subjects dove to 50, 60 or 80 msw and ascended according to the french navy standard tables or an EAP. Precordial bubbles were monitored with pulsed Doppler at 30-min intervals after surfacing. The signal of bubbles was graded according to the Spencer scale before to be converted into Kissman Integrated Severity Score (KISS). EAP1: 60msw/20min, first DS at 27 msw, Decompression Times (DT) 59min versus 48min (MN90); EAP2: 60msw/20min, first DS at 27msw, (pure O_2 6-0msw) DT 42min vs 48min (MN90); EAP3: repetitive dive to 50msw/15min with a 3-h surface interval, first DS at 18 msw, DT 31min vs 46min (MN90); EAP4: 60msw/15min, only one DS of 2 min at 25 msw, DT 31min vs 29min (MN90); EAP5: 80msw/15 min with trimix $O_2$18%-He41%-$N_2$41% (80-12msw) and pure O_2 (12-0msw), first DS at 24msw, DT 74min vs 66min (MN78). For EAP6, 12 subjects dove to 100msw and ascended only according to the EAP, which was not compared to another table. EAP6: 100msw/15min with trimix $O_2$15%-He45%-$N_2$40% (100-30msw), nitrox 40% (30-6msw) and pure O_2 (6-0msw), first DS at 33msw, DT 121min.

Results

We found no significant differences in bubble scores KISS between standard tables (MN90 or MN78) and EAPs 1,2,4 or 5. Nevertheless EAP3 produced an increased level of prolonged bubbling for all 8 divers [mean KISS: 20 (EAP3) vs 8.6 (MN90), p=0.03], as well an important tiredness for 5 divers that improved with 1 h of normobaric O_2 breathing. One diver suffered joint pain DCS after EAP2 while exhibiting Spencer grade 3 bubbles at rest 60 min after surfacing. His symptoms improved with hyperbaric oxygen, but MRI showed a bone infarction of humeral diaphysis. EAP6 produced Spencer grade 4 bubbles 60 min after surfacing for 2 divers, without symptoms of DCS, fortunately bubbling was reduced after 30min of normobaric O_2 breathing.

Conclusion

The utility of deep stops in human decompression has yet to be demonstrated for deep air dives as deep as 60msw and trimix dives as deep as 100 msw with mixed-gas including $N_2 \geq 40\%$.

PAPER:

Background

The French Navy uses the *Marine Nationale 90* (MN90) decompression table for air dives as deep as 60 msw and the *Marine Nationale 78* (MN78) decompression table for trimix dives (60-80 msw). MN90 decompression procedure was developed using a "haldanian" model, including twelve compartments and has recently been studied (2). MN90 appears to be safe for a young population of trained military divers with a low risk of accident. The resulting incidence of decompression sickness (DCS) for all depths combined is one case per 30 000 dives. However the risk is not homogeneous and dives in the range of 45-60 msw have a ten-fold greater risk, with one case of DCS for every 3000 dives. 89% of divers suffering from DCS presented neurological symptoms. 100% of them respected the MN90 procedure and no additional risk factors (i.e. age, effort during diving, repetitive dives) were found. Since the French Navy requires the presence of a recompression chamber for dives in the range of 35-60 msw, the outcome is favourable for 97% of patients after an 8-hour hyperbaric recompression table from 30 msw.

These results suggested that the main risk factor was the depth and that supersaturation of "fast tissue compartments" (in the range of 5-30 min compartments), responsible for the neurologic forms of DCS, were involved.

To prevent this, we focused on decompression models using "deep stops". Paul Bert is the first to introduce the concept of deep stops. In his book, *la Pression barométrique* (1), Bert recommended a stop at halfway (for a quarter of an hour) to hard-hat divers coming from 30msw. Haldane (4) also observed that it was safe to come from 4 ATA to 2, or 6 ATA to 3, as from 2 to 1 ATA. In spite of these early observations, shallow stops close to the surface were adopted in the most of decompression schedules including Haldane's tables. Later, findings and theoretical work on excess gas phase models suggested an apparent advantage of using such deep stops (6, 11, 13). It is acknowledged that bubbles originate from pre-existing gas nuclei, and deep stops could be more efficient than shallow stops in reducing bubble growth from these micro-bubbles nuclei (3). Recently, Marroni et al. (7) suggested that introduction of a short deep stop during human decompression after a shallow repetitive dive reduces bubbles and fast-tissues gas tensions. Here, we hypothesized that introduction of deep stops could reduce fast tissue bubble formation and neurological DCS risk in deep air diving. We also expected that adding deep stops could reduce bubble formation and decompression stress for trimix diving (80-100msw).

MEHODS

Study population

Subjects were 12 trained, medically fit military divers, who gave their written consent to participate; experimental procedures were conformed to the declaration of Helsinki. The group's average age was 37.5± 2.7 years and 24.1 ± 2 $kg.m^{-2}$ for their body mass index. Each diver had approximately 10 years of experience; three of them had histories of previous pain-only DCS with recovery and return to dive. All divers were instructed to avoid physical exertion and diving during the 2 days that preceded each trial.

Experimental Ascent Profiles and diving procedures

We incorporated deep stops into a serie of 6 Experimental Ascent Profiles (EAPs) developed with decompression software built on a Haldanian model with 20 compartments.

Deep stops for air dives (EAP 1-4) were introduced at about ½ the absolute depth and about 1/3 for trimix dives (EAP 5 & 6).

All the dives were performed in the wet section of a hyperbaric chamber (CEPHISMER, Toulon, France) at a water temperature of 15°± 1°C. During bottom time, each diver carried out moderate fin swimming at a frequency that was reproduced across all dives. The order of the dives was randomly allocated.

Air diving

For EAPs 1-4, eight subjects (two for one dive) dove to 50 or 60msw and ascended according to the French navy standard table MN90 or an EAP. A first Deep Stop Decompression Schedule (DSDS 1) was used for EAP1, EAP2 and EAP3 and a second schedule (DSDS 2) was used for EAP4.

EAP1 involved 20min at 60msw, followed by ascent to a first deep stop at 27msw, decompression time was 59min versus 48min with MN90 procedure.

EAP2 involved 20min at 60msw, followed by ascent to a first deep stop at 27msw, but shallow stops at 6 and 3msw were carried out breathing pure O_2, decompression time was 42min vs 48min with MN90 procedure (Table 1).

Table 1

MN90, EAP 1 and 2 decompression procedures from the same diving profile at 60msw for 20min.

60msw/ 20 min	**MN 90**	**EAP1**	**EAP2**
Ascent to 1st stop	15 msw/min	12 msw/min	12 msw/min
Ascent after 1st stop	6msw/min	3msw/min	3msw/min
STOPS	min	min	min
27-24 msw		1	1
24		1	1
21		1	1
18		2	2
15		2	2
12		4	4
9	3	6	6
6	8	9	5 (O2 100%)
3	32	22	10 (O2 100%)
decompression times	48 min	59 min	42 min

EAP3 involved a repetitive dive to 50msw for 15min with a 3-h surface interval, the first deep stop was at 18msw, decompression time was 31min vs 46min with MN90 procedure (Table 2).

Table 2
MN90 and EAP 3 decompression procedures from the same diving profile (repetitive dive at 50msw for 15min).

Repetitive dive	**MN 90**		**EAP3**	
3-h suface interval	1st dive	2nd dive	1st dive	2nd dive
	50msw/15min	50msw/15min	50msw/15min	50msw/15min
Ascent to 1st stop	15 msw/min	15 msw/min	12 msw/min	12 msw/min
Ascent after 1st stop	6msw/min	6msw/min	3msw/min	3msw/min
STOPS	min	min	min	min
18-15 msw				1
15			1	1
12			1	1
9		1	2	2
6	2	8	3	5
3	9	32	7	13
decompression times		46 min		31 min

EAP4 involved 15min at 60msw, followed by ascent to only one DS of 2 min at 25msw, decompression time was 31min vs 29min with MN90 procedure (Table 3).

Table 3
MN90 and EAP 4 decompression procedures from the same diving profile (60msw for 15min).

60msw/15min	**MN 90**	**EAP4**
Ascent to 9msw stop	15 msw/min	15 msw/min
Ascent after 9 msw stop	6msw/min	6msw/min
STOPS	min	min
25 msw		2
9	1	1
6	4	4
3	19	19
decompression times	29	31

Trimix diving

Schedules DSDS 3 was used for EAP5 and DSDS 4 for EAP6.

For EAP5, eight subjects dove to 80msw and ascended according to the French navy standard table MN78 or EAP5.

EAP5 involved 15min at 80msw, followed by ascent to a first deep stop at 24msw. Trimix $O_2$18%-He41%-$N_2$41% was used from 80 to 12msw and pure O_2 from 12msw to the surface, decompression time was 74min vs 66min with MN78 procedure.

For EAP6, twelve subjects dove to 100msw and ascended only according to the EAP, which was not compared to another table. EAP6 involved 15min at 100msw with trimix $O_2$15%-He45%-$N_2$40% from 100 to 30msw, nitrox 40% from 30 to 6msw and pure O_2 from 6msw to the surface, first deep stop was at 33msw with a decompression time of 121min (Table 4).

Table 4

MN78 and EAP 5 trimix decompression procedures from the same diving profile (80msw for 15min), and EAP 6 trimix decompression procedure from 100msw for 15min.

Trimix dives	**MN78 80msw/15min**	**EAP5 80msw/15min**		**EAP6 100msw/15min**
Ascent to 1st stop	15 msw/min	12 msw/min	Ascent to 1st stop	12 msw/min
Ascent after 1st stop	6msw/min	3msw/min	Ascent after 1st stop	3msw/min
$O_2$18%-He41%-$N_2$41%	80-12 msw	80-12 msw	**$O_2$15%-He45%-$N_2$40%**	100-30msw
O2 100%	12-0 msw	12-0msw	nitrox 40%	30-6msw
STOPS	min	min	**STOPS**	min
			33-24 msw	3
24-21 msw		1	24	1
21		1	21	2
18		2	18	3
15	4	3	15	4
12 (O2 100%)	4	4	12	6
9 (O2 100%)	4	6	9	11
6 (O2 100%)	14	12	6 (O2 100%)	22
3 (O2 100%)	32	33	3 (O2 100%)	55
decompression times	66 min	74 min		121 min

Bubbles analysis

Circulating bubbles detection was performed by two different methods on the precordial area: continuous Doppler 5Mhz and pulsed Doppler 2 Mhz with independent and blinded operators. Precordial bubbles were monitored at 30-min intervals after surfacing during at least 2 hours and 5 hours after the repetitive dives. During bubble detection, divers were supine for 3 min at rest, then, in order to improve the detection, two successive lower limbs flexions were performed. The signal of bubbles was graded according to the Spencer scale (10) before to be converted into Kissman Integrated Severity Score (KISS). This score takes into account the kinetics of the bubbles at the different recording times and is assumed to be a meaningful linearised measure of post-decompression intravascular bubble activity status that may be treated statistically (8, 9).

Statistical analysis

Statistical tests were run on Sigmastat 3.0 software program (SPSS inc., Chicago, Illinois). Each subject has served as his own control. Data distribution was studied using a Kolmogorov-Smirnov test. For values obtained at 2 time points, a *t* test for paired data was used when the data were normally distributed. If not, the Wilcoxon's paired signed-ranks test was used. Differences between groups were considered significant at $p < 0.05$.

Results

Peak bubble scores were seen 60 minutes after surfacing in all dives. We found no significant differences in KISS bubble scores between standard tables (MN90 or MN78) and EAPs 1,2,4 or 5 (Figures 1,2,4,5). Nevertheless EAP3 produced an increased level of prolonged bubbling for all 8 divers [mean KISS: 20 (EAP3) vs 8.6 (MN90), p=0.03], as well an important tiredness for 5 divers that improved with 1 h of normobaric O_2 breathing (Figure 3). One diver suffered joint pain DCS after EAP2 while exhibiting Spencer grade 3 bubbles at rest 60 min after surfacing. His symptoms improved with hyperbaric oxygen, but MRI showed a bone infarction of humeral diaphysis. EAP6 produced Spencer grade 4 bubbles 60 min after surfacing for 2 divers, without symptoms of DCS, fortunately bubbling was reduced after 30min of normobaric O_2 breathing (Figure 6).

Figure 1

Bubble scores KISS for all the dives according to the different profiles and decompression procedures including standard tables (MN90, MN78) or EAP with deep stops.

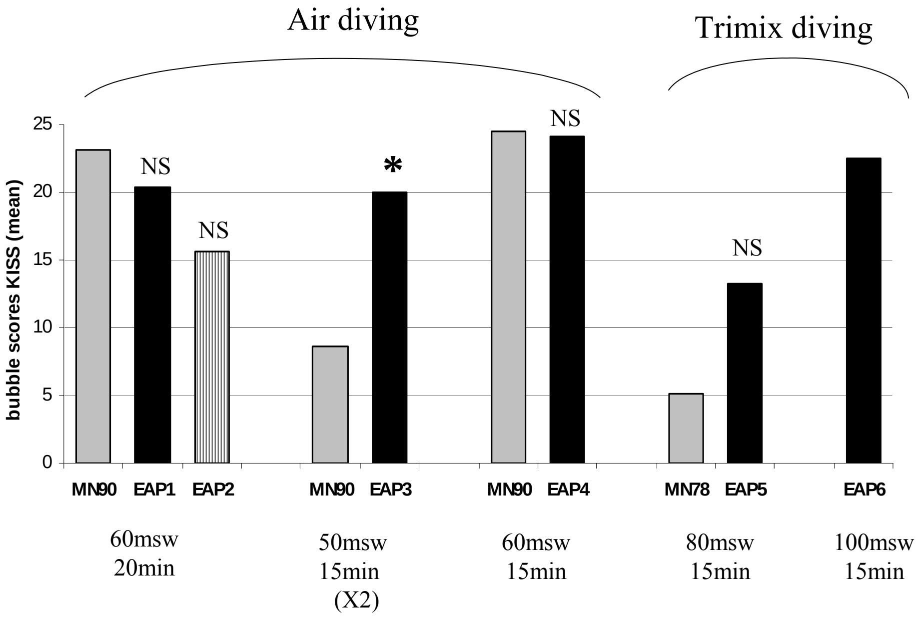


Figure 2
Profile of depth (msw) vs. elapsed time (min) for MN90 and EAP1. Grey colour represents the standard profile (MN90) and black colour the experimental ascent profile EAP1 with deep stops. The percentage of subjects with Spencer Grade 3 bubbles is given at specified times after surfacing from each profile.

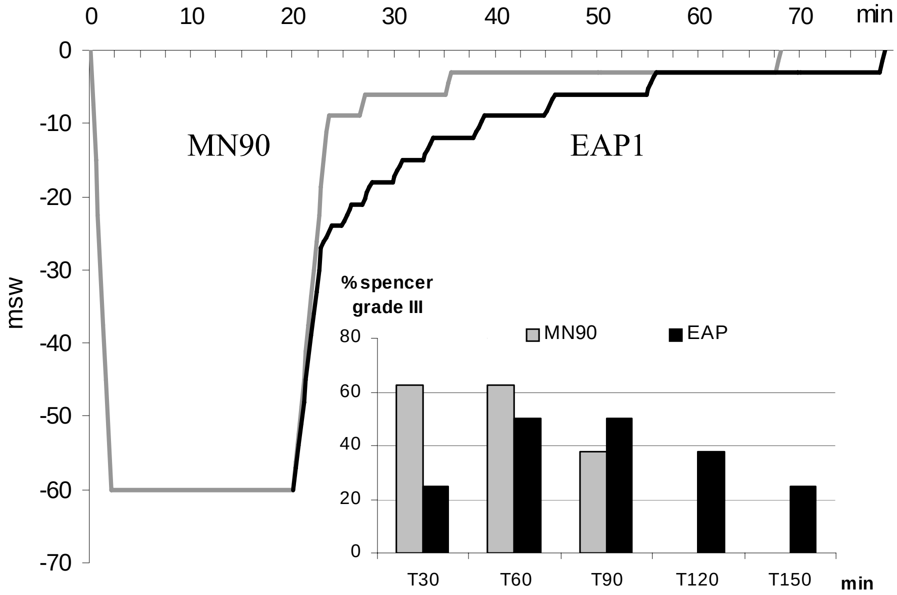


Figure 3
Profile of depth (msw) vs. elapsed time (min) for MN90 and EAP3. Grey colour represents the standard profile (MN90) and black colour the experimental ascent profile EAP3 with deep stops. The percentage of subjects with Spencer Grade 3 bubbles is given at specified times after surfacing from each profile.

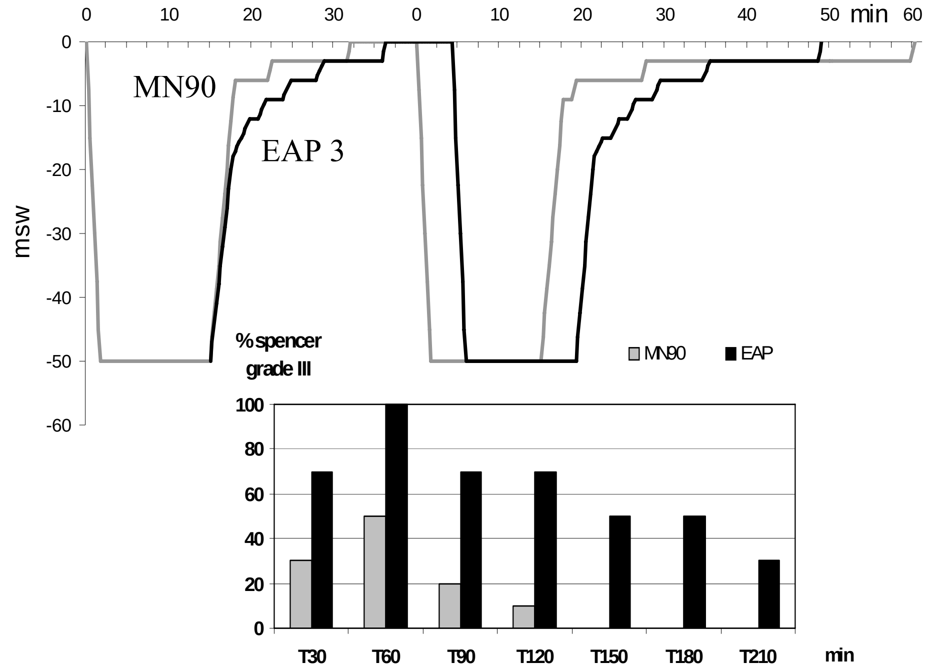


Figure 4
Profile of depth (msw) vs. elapsed time (min) for MN90 and EAP4. Grey colour represents the standard profile (MN90) and black colour the experimental ascent profile EAP4 with deep stops. The percentage of subjects with Spencer Grade 3 bubbles is given at specified times after surfacing from each profile.

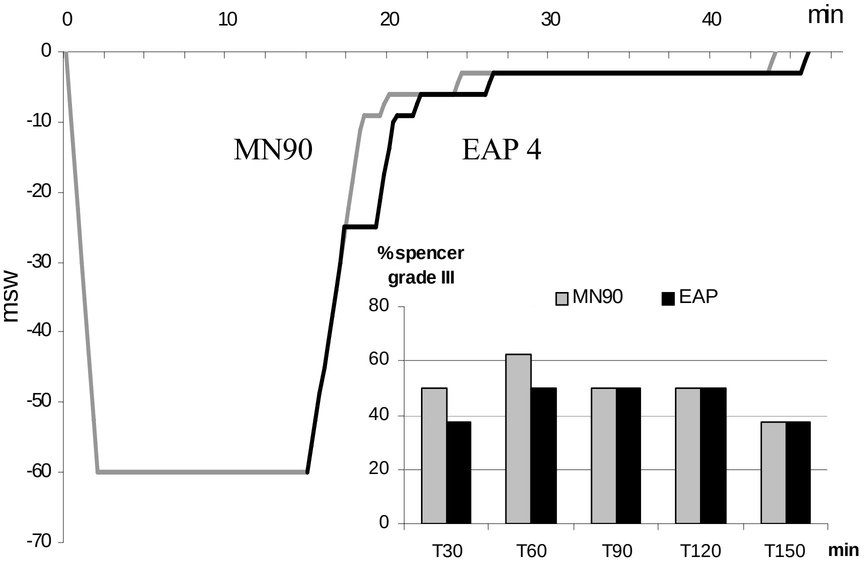


Figure 5
Profile of depth (msw) vs. elapsed time (min) for MN78 and EAP5. Grey colour represents the standard profile (MN90) and black colour the experimental ascent profile EAP5 with deep stops. Bubble scores KISS are given for each diver (n=8) and for each profile.

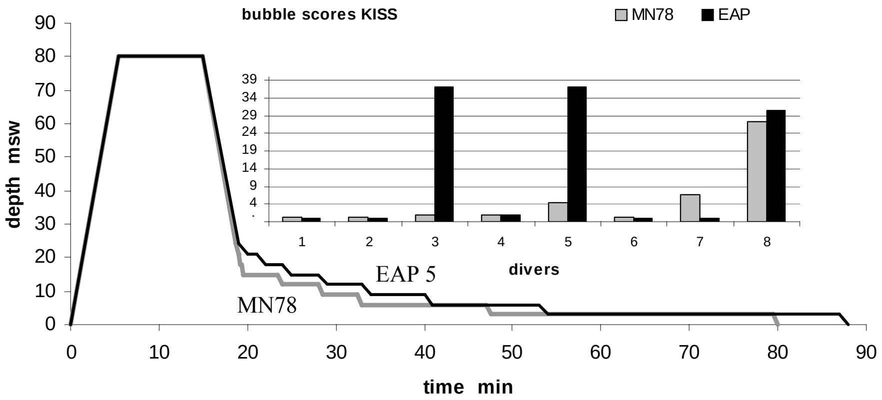
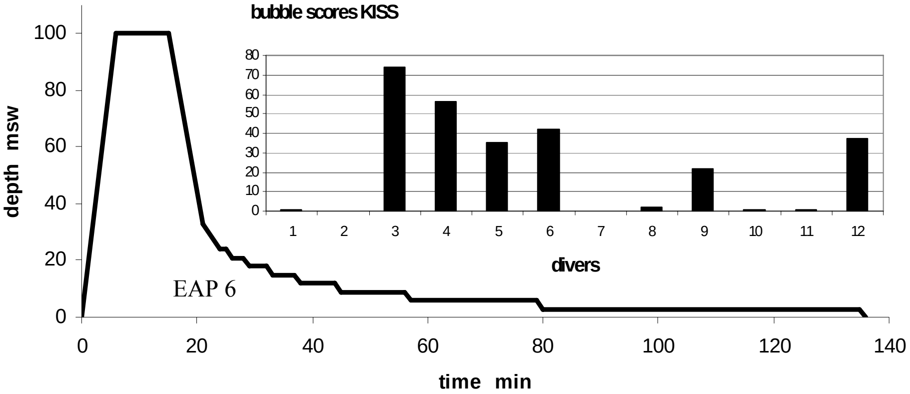


Figure 6
Profile of depth (msw) vs. elapsed time (min) for the experimental ascent profile EAP6 with deep stops. Bubble scores KISS are given for each diver (n= 12).



Discussion

Air diving

The two decompression schedules including deep stops i.e. DSDS 1 for EAP 1-3 and DSDS 2 for EAP4 produced contrasting results: EAP 1-3 with their multiple deep stops and longer ascents magnified bubbling and DCS risk while EAP4 with a very short deep stop of 2 min had no effect.

We hypothesized that adding deep stops could prevent the gas bubble formation during the initial part of the ascent and reduce fast-tissue gas tension. Actually, decompression profiles where more time is spent deep do not always reduce decompression stress as might be expected. Probably, mid to slow compartments involving low supersaturation limits were significantly exposed. Our schedules didn't find the compromise between high gas elimination and low supersaturation to minimize bubble formation.

Trimix diving

Decompression schedules (i.e. DSDS 3 for EAP 5 and DSDS 4 for EAP 6) introduced deep stops at about 1/3 the absolute depth with mixed-gas including helium and nitrogen ≥ 40%.

Since helium is less soluble and exchanges more rapidly than nitrogen, helium dives might be expected to allow faster decompression than nitrogen dives. This is clearly true for saturation decompression, but differences for short, deep dives seem small. Actually previous studies reported the need for deep decompression stops to accommodate the initial "out-rush" of helium upon leaving the bottom (5)

Moreover Workman (12) have shown that for the deeper dives where helium was used as a breathing gas, a reduced gradient was required, producing deeper initial stops than those predicated in the standard air diving tables for an equivalent depth.

For dives with short bottom times with trimix of oxygen, helium and nitrogen to depths in the 60 to 100 msw range, one wants enough helium to eliminate significant narcosis, but with haldanian calculations, the more helium in the trimix the longer the decompression (5). Actually, our results suggest that breathing pure oxygen at shallow stops seem more efficient than adding deep stops breathing trimix or intermediate nitrox.

Problems encountered with deep mixed-gas dives may be as well related to the inadequacies of the base-compartment model to accurately describe multiple inert-gas kinetics and counter diffusion, as to the presence of deep stops.

Conclusions

The concept of deep stops in human decompression has yet to be demonstrated for short air dives as deep as 60msw and trimix dives as deep as 100 msw with inert gas including helium and nitrogen ≥ 40%.

Acknowledgements

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References

1. Bert P. La Pression barométrique. Recherches de physiologie expérimentale. Masson, Paris, 1878.
2. Blatteau JE, Guigues JM, Hugon M, et al. Plongée à l'air avec la table de décompression MN90. Bilan de 12 années d'utilisation par la Marine française. A propos de 61 accidents de désaturation de 1990 à 2002 *(Air diving with decompression table MN 90: 12 years of use by the French Navy: study about 61 cases of decompression sickness from 1990 to 2002).* Science & Sports ; 2005, 20 : 119-123.
3. Blatteau JE, Souraud JB, Gempp E and Bousssuges A. Gas nuclei, their origin, and their role in bubble formation. Aviat Space Environ Med ; 2006, 77: 1068-1076.
4. Boycott AE, Damant C and Haldane JS. The prevention of compressed air illness. J Hyg Cambridge 1908 ; 8 : 342-344.
5. Hamilton RW and Thalmann ED. Decompression practice. In: Bennett and Elliot's Physiology and Medicine of Diving, 5th edn, edited by Brubakk AO & Neuman TS. WB Saunders, London, 2003: 455-500.
6. Hills BA. The biophysical basis of prevention and treatment. Decompression sickness 1977 ; Vol 1. New York: John Wiley and Sons.
7. Marroni A, Bennett PB, Cronje FJ et al. A deep stop during decompression from 82 fsw (25 m) significantly reduces bubbles and fast tissue gas tensions. Undersea Hyperb Med; 2004, 31: 233-43.
8. Nishi RY, Brubakk AO and Eftedal OS. Bubble detection. In Bennett and Elliot's Physiology and Medicine of Diving, 5th edn, edited by Brubakk AO & Neuman TS. WB Saunders, London, 2003: 501-529.

9. Nishi RY, Kisman KE, Eatock BC, et al. Assessment of decompression profiles and divers by Doppler ultrasonic monitoring. In: Bachrach AJ, Matzen MM, eds. Undersea Medical Society, Bethesda MD: Underwater physiology VII. Proceedings of the seventh symposium on Underwater and Hyperbaric Physiology, 1981: 717-727.
10. Spencer MP. Decompression limits for compressed air determined by ultrasonically detected blood bubbles. J Appl Physiol; 1976, 40(2) : 229-235.
11. Wienke BR. Reduced gradient bubble model. Int J Biomed Comput; 1990, 26(4) : 237-256.
12. Workman RD. American decompression theory and practice. In: Bennett PB, Eliott DH, editors. The physiology and medicine of diving and compressed air work. London: Tindall & Cassell; 1969. Chapter 12.
13. Yount DE and Hoffman DC. On the use of a bubble formation model to calculate diving tables. Aviat Space Environ Med; 1986, 57: 149-156.

DISCUSSION: BUBBLE FORMATION IN MAN

DR. PETER BENNETT: I've got one comment that keeps coming to me, that one thing we need to do, I think, is to differentiate when we have decompression sickness, whether we're talking about neurological decompression sickness or pain only. I know that the NEDU dives, that most of the DCS they had was pain only, which means it's slow tissue. The fast tissue deep stop may be doing its job, but if you don't do the right decompression after you've made the deep stop -- and some of those look like they were very different from what I would have predicted we might use -- then you're going to build gas in the slow tissue and end up with perhaps pain-only decompression sickness. The only value of the deep stop, as I see it, is to stop neurologic DCS. In all the cases I've heard so far, I haven't heard a lot of neurological DCS being found. I found, in fact, there is much less of that, even though bubbles were present. So did you have more neurological DCS with the deep stop or less, if you had any?

DR. JOHN BLATTEAU: We don't know because divers using a deep stop in France use a deep stop only for trimix diving, but it's not very frequent--

DR. PETER BENNETT: No, but in your dives that you did, when you had decompression sickness, was it pain only or was it neurological?

DR. JOHN BLATTEAU: In this study, it was , only joint pain.

DR. PETER BENNETT: It's the slow tissue. This is the point. I think you are with slow tissues.

DR. CHRISTIAN GUTVIK: I think I'm misunderstanding your question. As far as I understood in the presentation, he used VGE as an end point so he didn't get any Type I or Type II DCS, so he couldn't compare with the question that you just asked because he used only VGE. He didn't observe any neurological or pain events.

DR. PETER BENNETT: I understand you, but that's the point. The point is that deep stop is designed to stop supersaturation in the fast tissues, which cause neurological DCS and spinal cord injury, because I'm getting ahead of my own paper, but the tissue half-time for the spinal cord is 12 minutes, something like that. So it's very fast. And that's why you get neurological decompression sickness. It forms in the spinal cord, at least that's what we believe. Now, in our own research, which you'll hear tomorrow, we're dealing with fast tissue. We remove that and supersaturation we believe we've stopped the neurological DCS in recreational diving. This is 70-plus percent neurological decompression sickness, not pain only. Spinal cord injury is another thing. If you can stop that with a deep stop, then you've made a good achievement. That's our philosophy anyway.

DR. SIMON MITCHELL: John, can I ask a quick question? It looks like to me that the study was underpowered to show a statistically significant difference. Do you think, had you done some more dives, that those results might have become statistically significant?

DR. JOHN BLATTEAU: It's very, very difficult. But we did give significant attention to good control data for each diver evaluation.

DR. WAYNE GERTH: Peter, you're going to speak to your results later in the meeting?

DR. PETER BENNETT: Yes.

DR. WAYNE GERTH: Then I'll be able to ask whether or not you had DCS in your findings and you were just working with VGE or not?

DR. PETER BENNETT: You know we had no DCS. That has to wait until the next symposium.

DR. WAYNE GERTH: You were speaking to what I was trying to show, that these deep stops will affect fast tissues potentially. You need to be messing with some neurological hits. If you don't have them, you can't make a statement about it’s better or worse. But, anyway, thank you.

DR. PETER BENNETT: I agree with you, you can't say it's better or worse. I'm saying the hypothesis we put out to test was if you put a deep stop in, you would lower gas saturation in the fast tissue to prevent DCS. We haven't done that with DCS yet. That's later. Any more questions?

AUDIENCE MEMBER: I just want to make a comment on the study. People talked about using Doppler for their studies and not finding bubbles or finding very low bubble scores. I think this paper was very important because it shows that you have to take a distribution, you have to consider distribution of bubbles over a period of time, at least over a two-hour period of time. And, you know, if you take a bubble reading too early or too late, you may not get any bubbles or very low bubble scores. So using a tool like the KISS index is very useful for comparing dives or for judging the safety of dives. Thank you.

DR. PETER BENNETT: Thank you.

DR. FRANK BUTLER: I wanted to go back to one of the presentations that we had earlier. There was a slide that was suggestive that some of the special operations forces were routinely using these deep stop tables. And just a couple of points of clarification. The special ops folks, to include the special missions units, are constrained to either use the Navy dive decompression computer, which EDU developed a few years back and did a great job with, or they used a Navy diving manual or they use a dive planner. They absolutely are not authorized to use anything other than those three things to calculate their decompression. So most of their decompression diving is done off the submarine base platforms, air and mixed gas. And they have been very well served by the decompression computer. They've used it for about eight years now, not had bends, and have greatly reduced their decompression time. And those are mostly shallow dives. So most of our decompression work is not done with very deep, short dives. It's mostly extremely long shallow dives. Just for clarification.

DR. PETER BENNETT: Thank you. I'll make another comment that a lot of those deep stops are only one minute long. And we found, again, sort of giving my paper beforehand, that we looked at the stop times, and we're talking only up to 100 foot, not 300 or whatever. We found that you would have to have at least two and a half minutes. Now, two and a half minutes was optimal. If you went more than two and a half, you had more bubbles. If you had less than two and a half minutes, you had more bubbles. And one minute was just insufficient. We had maximum bubbles at one minute deep stop, and we had to go to two and a half to reduce those bubbles to virtually almost zero. So time at that deep stop is also equally important, and it would have to be the right time at the right depth. And here's the crux of the whole problem. Because there's so much variability, how do you find out? We had to do the measurements of the dives to find out for that given depth. I fully believe at a different depth, at a deeper depth, that time may be different again. And it may be up to five minutes or longer. I don't think it will be shorter. I believe it will be longer. But I think that's what has to be done again in the future.

DR. JOHN BLATTEAU: But for the second schedule, we don't test one minutes. It was two minutes. Two minutes for 25 meters.

DR. BRUCE WIENKE: You may have to make other deep stops too after the first one. But you need a platform to compute that, a staging platform to do that.

DR. PETER BENNETT: Anything further? Any questions for the day?

BRUCE PARTRIDGE: I had a question for Wayne from earlier. There was a discussion of the different models that were tested and the bubble model you chose to test. I'm sure you've been asked this before. Why didn't you use one of the other commercial models to compare? Why did you use that specific bubble model that you chose to use?

DR. WAYNE GERTH: Well, first off, the objective of that study wasn't actually to test a particular bubble model. I used a particular model in order to calculate the schedule, but the test was to calculate what the effect is of that deeper stop versus the traditional distribution of stop time. Under a bubble model, I think if you pick any one, that because we were deeper should have minimized bubble growth or formation during the decompression. Now, whether or not it was the optimal schedule would be something that would follow from whether or not we chose the best bubble model to make the calculations. But overall, if deeper stops were better, we should have seen that that schedule was at least not worse. To show that would take me another hour lecture on showing you bubble profiles and stuff. But I guess, in short, we weren't aiming to test a particular model. And I used that one in order to calculate the schedule only because it's well documented and I developed it. That's the answer. And another thing, it is actually fit to data. So that model has been shown in the publication to actually provide a very good representation of data that we have for decompression air and nitrox dives.

BRUCE PARTRIDGE: I have a question for Bruce Wienke. I just went blank here. When you're looking at the different statistical representatives of different models, you used the traditional Buhlmann model and the RGBM. From what I see, a lot of people are using gradient factors these days. It seems to be a very common model. Have you done any risk analysis against grading factors decompression?

DR. BRUCE WIENKE: No, we haven't. But the problem with gradient factors is what they do is reduce M values. And you have to have some knowledge of how and why you're going to reduce the M values. And just like with certain recreational modified RGBM, you could do that. But what's easier to do is to use a model to come up with the structure of the decompression profile. So you could use gradient factors. According to your definition, it's been a safe dive. You can then look at traditional Buhlmann schedules or Workman schedules, or whatever, and then you can downgrade the M values with what are called gradient factors to come up with your schedule. But how you do that a priori is not easy. You have to have a model, you know, which gives you the full decompression profile, and then you could scale gradient factors to fit the model to go and superimpose it on the Haldanian supersaturation profiles. So the answer is, no, we don't do that. We don't do that for decompression diving. I don't know if that answers your question. Are you a diver that uses gradient factors?

BRUCE PARTRIDGE: I don't know if you can hear me. I can tell you from what I see in the logs, 50 to 5 is a real common gradient factor. And I think it's not a diver. It tends to be numbers that are arrived at over a longer period of time so that there are people -- there are some that are very standard.

DR. BRUCE WIENKE: They're standard because a lot of tech divers have twiddled with those M values to come up with those gradient factors, and then the word gets out, and people who are diving in that range start to use them. So it's a bootstrap kind of a thing. But on basic principles -- you know, on basic principles I don't know how to pull a gradient factor out for a 500 ft dive on a rebreather. But I could run it through somebody's model and I could come up with a decompression profile. And if I had to, I could come up with gradient factors. But why do that when I could just run the model straight.

DR. PETER BENNETT: One other comment about a statement made earlier that Haldane had used a deep stop originally and didn't use them later. That's true. In fact, I've got one or two original documents of the Haldane era. And the comment was made that they did not believe that you need to have stops deep, saying if you're coming from 100 foot, because the pressure was so great, it would compress the bubbles and, therefore, they only used the shallow stops. And that's in the documents in the books of 1933. Interesting statement.

DR. RICHARD VANN: That's not true. If you look at the original Haldane tables, they all have deep stops. They went away from those tables, particularly with the work that Hawkins Shilling and Hansen did. They found, when they were doing dry studies, that they could use much higher ratios for the fast tissues, so they knocked out the 2:1 ratio.

DR. PETER BENNETT: You'll see it in my slides too.

DR. RICHARD VANN: It's published in Bennett and Elliott.

DR. PETER BENNETT: It's on my slides too, Dick. Having said that, that was post Sir Leonard Hill.

DR. RICHARD VANN: Leonard Hill is not Haldane. The two of them hated each other.

DR. PETER BENNETT: I know that, too. Anyway, any more questions? No? Well, we'll close it down for now, and we'll be back here at seven o'clock for the dinner and film and talk. Thank you.

INTRODUCTION: WEDNESDAY, JUNE 25, 2008

DR. SIMON MITCHELL: It's my pleasure to introduce the first speaker for the morning, Dr. Neal Pollock. Neal is a research physiologist from Duke and DAN at Durham. He's well known to most of you. He's widely published in this area. He's going to be presenting on Doppler bubble scoring and Doppler monitoring in relation to decompression sickness. We heard some debate yesterday about appropriate outcome measures for deep stop research. I think his subject is highly relevant to that issue. I know that there's quite a number of high-end technical divers in this audience, and one of the issues that pops up from time to time on the Internet diving discussion forums is whether or not divers should be self-monitoring with Doppler and adjusting their decompression profiles in response to what they find. I think those of you who are in that group will find this talk enlightening, and it's perhaps another avenue of discussion after the presentation. Neal, thank you very much. Look forward to your presentation.

BUBBLE DETECTION AND DCS RELEVANCE

Neal Pollock

ABSTRACT:

Decompression studies traditionally rely upon symptoms of decompression sickness (DCS) as an endpoint. An observation made in the early 1960s that Doppler ultrasound could detect decompression-induced bubbles moving in the bloodstream expanded the possibilities for evaluation. The development of a series of semi-quantitative grading scales followed. The 0-IV Spencer scale remains the most popular (**0** = no bubble signals; **I** = occasional bubble signal; great majority of cardiac cycles signal-free; **II** = many but less than half of the cardiac cycles contain bubble signals; **III** = all cardiac cycles contain bubble signals, but not obscuring signals of cardiac motion; and **IV** = bubble signals sounding continuously throughout systole and diastole and obscuring normal cardiac signals). The Kisman-Masurel scale is more sophisticated, with signals separately scored on the frequency, percentage/duration and amplitude of bubble activity before these parameter scores are combined to produce a single 0-IV grade. Kisman-Masurel scores can easily be converted to Spencer grades, but the reverse conversion is not possible.

Ultrasonic monitoring can be used to provide a secondary measure of decompression stress if symptoms are to remain an endpoint. Alternatively, ultrasonic monitoring may be used as a primary endpoint measure of decompression stress if the endpoint of symptoms is not appropriate for ethical or practical reasons. For the latter case, in particular, it is important to consider the limitations of bubble data. Most critical is that the role that bubbles play in the development of symptomatic DCS is not clear. Part of the problem is that current technology makes it easy to study only intravascular bubbles. We know very little about the development of bubbles in extravascular tissues. Intravascular bubbles are associated with DCS, but DCS can develop in the absence of observed bubbles. Higher intravascular bubble grades (Spencer III or IV) are more strongly correlated with DCS than lower grades, but still at modest levels. A recent study of 1,726 air dives and 1,508 heliox dives showed extremely poor positive predictive value for Spencer grade III-IV intravascular bubbles. The greatest strength of the bubble data was in the negative predictive value − the absence of DCS symptoms − associated with Spencer grade 0-II bubble scores.

There are additional practical challenges in interpreting ultrasonic data. The marked variance in sampling protocols (inter-measure interval and total sampling duration) may affect the validity of the data. The presence of intravascular bubbles has been reported to peak at 60 minutes post-dive, but this can vary as a function of the dive profile and breathing gas. Differences in test procedures may also affect the comparability. This can include instrumentation, monitoring site selection, case sampling (rest or rest and various movement cases), and recording/review procedures. Variability in technician training and experience are also potentially problematic, more so when scoring sessions are not recorded and confirmed. Finally, self-selection within subject pools can be an issue, notably for more extreme exposures. It is possible that such groups will be disproportionately populated with bubble-resistant individuals, making it difficult to extrapolate the results from such groups to the wider population.

The above points are made not to discredit ultrasonic bubble monitoring but to remind the community that protocols should be carefully thought out and that the results of such monitoring must be critically and conservatively evaluated.

PAPER:

Introduction

Studies of decompression traditionally rely upon the development of symptoms of decompression sickness (DCS) as an endpoint. The options were expanded with the development of diagnostic ultrasound. Ultrasound devices use high-frequency sound waves to identify borders of changing density within three-dimensional objects. The reflected sound waves are captured to generate audible signals or multi-dimensional images of internal structures. The frequencies used for ultrasonic studies are typically in the 1-10 MHz range. The penetration depth is inversely related to frequency, making the lower frequencies a better choice to interrogate deeper structures.

Doppler

Ultrasonic flowmeters determine movement within the focal plane by measuring the Doppler shift between transmitted and reflected acoustical waves. The measurement of blood flow was described in 1957 (Baldes et al., 1957). The ability to identify intravascular bubbles (also known as gas emboli or gas phase) was reported in 1961 (Franklin et al., 1961). The fact that gas bubbles reflect acoustic energy more effectively than other components of blood made them easy to detect. The measurement of decompression-induced intravascular bubbles was first described in 1963 (Mackay, 1963).

Formalized techniques to study decompression-induced intravascular bubbles in sheep and pigs were described in 1968 (Spencer and Campbell, 1968; Gillis et al., 1968). The development of a series of semi-quantitative bubble grading schemes followed. Two five point scales (0-IV) rose to the level of general acceptance - Spencer (Spencer and Johanson, 1974) and Kisman-Masurel (Eatock and Nishi, 1986). The Spencer scale is the more straightforward in concept with signals scored in accordance with the definitions shown in Table 1.

Table 1. Spencer Scale - Doppler-Detected Bubbles (Spencer and Johanson, 1974)

Grade	Definition
0	no bubble signals
I	occasional bubble signal; great majority of cardiac cycles signal-free
II	many but less than half of the cardiac cycles contain bubble signals
III	all cardiac cycles contain bubble signals, but not obscuring signals of cardiac motion
IV	bubble signals sounding continuously throughout systole and diastole and obscuring normal cardiac signals

The Kisman-Masurel scale is a more complicated device. Signals are scored on 0-4 scales for three distinct parameters: frequency (the number of bubbles per cardiac period), percentage/duration (the number of cardiac periods with the specified peak bubble frequency [or duration of the bubble shower prompted by movement]), and amplitude (the intensity of bubble sounds in comparison to normal background cardiac valve sounds). The three parameter scores are then combined to yield a single grade with '+' and '-' modifiers on non-zero grades (note: there is no '+' modifier for grade IV). Kisman-Masurel scores can be converted to Spencer grades, typically to simplify analysis, but the reverse conversion is not possible.

Precordial monitoring, capturing the blood flowing through the pulmonary artery, is most compatible with the definitions used for the Spencer and Kisman-Masurel scales. Other sites, such as a carotid artery or subclavian vein, require some flexibility in interpretation given the loss of cardiac valve sounds. Precordial monitoring has the advantage of being a single site past which most blood flow will pass in fairly short order.

Two-Dimensional Echocardiography

Ultrasound was first used to generate two-dimensional images in the late 1970s. Two-dimensional techniques were employed to study decompression in the late 1980s (Ikeda et al., 1989). The most common approaches for two-dimensional study are transesophageal echocardiography (TEE) and transthoracic echocardiography (TTE). TEE is generally more sensitive (Siostrzonek et al., 1991) but positioning the transducer in the esophagus is more involved and favors restricted trial duration. TTE is conducted transcutaneously, which is more appropriate for the relatively long monitoring periods associated with typical decompression studies.

Two-dimensional imaging allows for monitoring both right and left sides of the heart. Right heart monitoring is generally expected to yield information similar to precordial Doppler which samples immediately downstream of the right heart in the pulmonary artery. Several scoring scales have been used or proposed to grade bubbles visible through two-dimensional cardiac imaging (Pollock, 2007). The most commonly used scale is described in Table 2 (Eftedal and Brubakk, 1997; Brubakk and Eftedal, 2001).

Table 2. Eftedal and Brubakk Scale - Two-Dimensional Echocardiographic Imaging (Eftedal and Brubakk, 1997; Brubakk and Eftedal, 2001)

Grade	Definition
0	no observable bubbles
1	occasional bubbles
2	at least one bubble every four cardiac cycles
3	at least one bubble every cardiac cycle
4	at least one bubble · cm^{-2} in every image
5	'white-out,' single bubbles cannot be discriminated

The lungs generally serve as an effective intravascular bubble filter (Butler and Hills, 1979; Diesel et al., 2002). Decompression-induced gas phase has been observed in invasive sheep studies to be slower to arise spontaneously in the aorta than in the inferior vena cava (Spencer and Campbell, 1968; Spencer et al., 1969). This is likely due to the relatively low inert gas content of blood leaving the lungs after gas exchange. Bubbles may reach the left heart, however, through intracardiac and/or intrapulmonary shunts. Left heart bubbles have been visualized post-dive in subjects who have not gone on to develop symptomatic DCS (Bakovic et al., 2008; Boussuges et al., 2008), but the risk of neurological DCS is believed to increase when bubbles are sent forward systemically from the left heart (Pilmanis et al., 1996). Left heart monitoring is used as a safety protocol by some facilities conducting altitude decompression studies. The observation of any bubbles in the left heart prompts immediate recompression of the subject to ground level (Pollock, 2003; Vann et al., 2007).

Bubbles and Decompression Sickness

Studies of altitude decompression have demonstrated that Spencer grades III and IV venous gas emboli (VGE) have a modest positive predictive value (0.39) for DCS. More powerful was the strong negative predictive value (0.98) for grade 0 VGE (Conkin et al., 1998). Other investigators have concluded that VGE were less useful in predicting neurological DCS than non-neurological DCS (Balldin et al., 2004).

Studies of decompression associated with diving present similar findings for VGE. Higher bubble grades are associated with an increased risk of DCS (Spencer and Johanson, 1974; Gardette, 1979; Eftedal et al., 2007), generally Spencer grades III and IV. Providing some contrast, the strength of the negative predictive value for grade 0 VGE is not as apparent in diving studies. While low bubble grades are more likely associated with an absence of symptoms, there are a number of reports describing symptoms developing in the absence of detected VGE (Gardette, 1979; Nishi et al., 2003; Vann et al., 2007).

Intravascular bubble grades are generally not correlated with the severity of DCS. Figure 1 depicts the relationship of DCS cases developing during decompression studies at one facility for which Doppler data were available (Pollock and Natoli, 2004; data published in abstract form only).

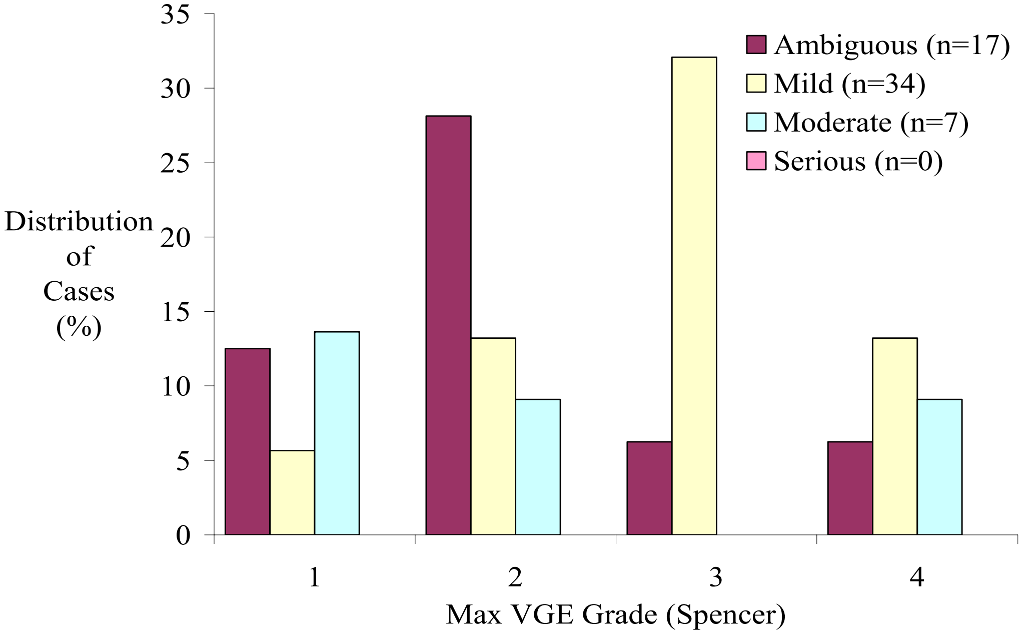


Figure 1. Distribution of non-zero DCS symptom ranks and non-zero VGE Spencer scores. VGE grades are not correlated with the severity of DCS outcome (Spearman's rho = 0.159; p=0.232) (Pollock and Natoli, 2004).

While intravascular bubbles are not directly comparable to DCS, they can provide a useful measure of decompression stress. This may be as a secondary measure if symptoms of DCS are used as a primary endpoint or as a primary endpoint if the endpoint of symptoms is not appropriate for ethical or practical reasons.

Limitations of Bubble Data

The most critical limitation of bubble data is the uncertainty regarding the role intravascular bubbles play in the development of DCS. The formation of bubbles is most strongly affected by the pressure profile but a host of individual factors may also play a role. Several studies have shown the formation of VGE to be positively correlated with age (Carturan et al., 1999; Carturan et al., 2002; Conkin et al., 2003). There are less clear and sometimes confounded influences of gender (Carturan et al., 1999; Webb et al., 2003; Cameron et al., 2007), aerobic fitness (Carturan et al., 1999; Carturan et al., 2002), fatness (Carturan et al., 1999; Carturan et al., 2002), exercise (pre-, during and post-dive) (Dervay et al., 2002; Dujic et al., 2004; Blatteau et al., 2005a; Dujic et al., 2006; Blatteau et al., 2007), state of hydration (Gempp et al., 2007), thermal stress (Dunford and Hayward, 1981; Mekjavic and Kakitsuba, 1989), and even postural changes (Dujic et al., 2006). Additional factors may well play a role in determining individual predisposition on the continuum of bubble proclivity. There may be significant self-selection in the communities involved in diving studies or extreme operational diving.

Monitoring schedules can also affect the validity of bubble data. Monitoring sessions completed significantly before symptom onset may not reflect the status at the time of insult. Monitoring is typically discontinued once symptoms develop and treatment is initiated.

Current technology makes it easy to study only intravascular bubbles. Little is known about the development of bubbles outside a limited number of commonly sampled vascular sites. It is possible that monitoring other vascular or extravascular sites could clarify the relationship between bubble and symptom development. This situation may be improved with the evolution of new technologies. Dual frequency ultrasound, for example, long appreciated in theory and demonstration studies (Nishi, 1975; Newhouse and Shankar, 1984), is moving towards providing a practical means of detecting and sizing bubbles in extravascular tissues (Buckey et al., 2005).

Optimizing Bubble Data

The utility of bubble data is increased through the use of well-trained technicians, standard monitoring and scoring protocols, and comprehensive reporting of results.

Training requirements vary as a function of the technology used and the expectations on the technicians. It is preferable for technicians to be able to independently grade signals in real time. This will generally result in higher quality scans and facilitate real-time decision-making as protocols might demand. While greater flexibility in training is possible if ultrasonic data are collected strictly for post-study analysis, lower quality signals will increase the challenges of proper review. The modest training period required to enable the basic capture of Doppler signals may not produce optimized recordings, making grading difficult and sometimes impossible. Preparing technicians to be able to reliably and accurately grade bubble signals demands good auditory discrimination and a commitment to develop and maintain the critical abilities (Sawatsky and Nishi, 1991). The level of skill required is higher for the Kisman-Masurel grading system than for the Spencer scale. There is currently little value in the use of other, non-standard Doppler scales given the established history and utility of these two options.

Training TTE technicians requires much more initial effort to ensure that images can be reliably captured, particularly when operating under time and other constraints associated with research protocols. Training to apply visual grading scales is relatively straightforward once signal capture skills are developed. The greatest challenge is simultaneous monitoring of both sides of the heart. High resolution images are required to make this manageable. Adequate resources are necessary to produce valid data. Groups with little experience in ultrasonic assessment should have their data reviewed by established groups for validation purposes. The results of the review and methods for handling disparities must be included when the data are published.

A range of protocols and variations are reported in the literature. The predominant monitoring site for Doppler ultrasound in precordial, but the subclavian is also used. The absence of cardiac valve sounds may make the subclavian site more sensitive for low grade assessment (Eckenhoff et al., 1990). However, the precordial site offers a single point capture of virtually the entire blood volume. Since the correlation between bubbles and DCS is stronger at higher VGE grades, the loss of sensitivity is probably less important than the ability to sample a much larger portion of the circulating blood volume.

Monitoring schedules vary dramatically, with repeated measures ranging from 10-60 minute intervals in most cases, and single measures reported by some. There is a common notion that bubble grades will peak at approximately one hour post-dive, but the actual evolution may be far more variable. VGE formation is most notably influenced by the pressure profile but it may also be influenced by other factors. Short intersample intervals are demanding operationally, but intervals that are too long or single measures may be unable to document the true course of bubble development and resolution. The shortest, practical interval should be maintained for a reasonable minimum duration. Best case monitoring might be a 20 minute intersample interval for a minimum of two hours. The intersample interval might practically be increased to 30 minutes to accommodate study demands, particularly if monitoring were to continue beyond two hours.

Monitoring protocols also vary between studies. Some rely upon measurements taken at rest only while others employ both rest and movement cases. Movement tends to increase detectable bubbles. While the transient nature of movement-induced bubble showers makes quantification more difficult, monitoring conducted following movement is likely more sensitive to decompression stress. Variations in movements employed increases the difficulty in cross-study comparison. Reported movement patterns include single limb, multiple sequential limb, and multiple simultaneous limb. Movement intensities also vary, for example, simultaneous leg flexion while resting in a supine position vs. standing deep knee bend. The traditional movement case was the standing deep knee bend. Challenges arise in needing the technician to match the movement of the subject to maintain a signal or to rapidly reacquire the signal in the critical period immediately following movement completion. The recent shift to movements initiated from a resting position make it easier to maintain the signal. Sequential limb movement may offer some utility in trying to localize regional bubble activity. Movement case data should be included when possible. The lack of standard movements and intensity remains a challenge.

Ultrasonic monitoring can generate significant amounts of data. Summarization schemes include reporting time to onset of any non-zero grade and maximum grade, grade collapsing, grade averaging, and grade integration to evaluate bubble loads over time. The most inappropriate of these techniques is grade averaging. While automated bubble counting capability may one day provide a reliable alternative, the current grade scales used in decompression studies are highly non-linear, ordinal constructs. It is not proper to average non-linear scores. The other summarization schemes offer varying utility and appeal. The best strategy for reporting ultrasound data is to include a sufficient accounting of the raw data to allow for recomputation using different typical techniques. This facilitates inter-study comparison. As a practical point, analysis should focus on the higher grades, Spencer and Kisman-Masurel III and IV, for example, that have the greatest correlation with DCS.

An important strategy to increase the value of bubble data rests with study design. Intravascular bubbles do not provide a reliable measure of absolute decompression stress. Independent of the exposure, bubble formation can be influenced by a host of factors. Confounding is minimized by employing repeated measures designs so subjects can serve as their own controls. VGE are most effective as an indicator of relative decompression stress. Repeated measures designs capitalize on this nature.

Ultrasound and Deep Stops Literature

The literature involving deep stops research can be considered in terms of the strength of the ultrasound data described. Four papers are discussed here; two reporting fewer bubbles after profiles with deep stops and two reporting fewer bubbles after profiles with deep stops. As will be obvious, methodological inconsistencies make it difficult to resolve the findings.

Marroni et al. (2004) reported fewer VGE after exposures with integrated deep stops. Doppler scores were used as the study endpoint. The monitoring protocol was fairly traditional: 30 seconds of standing rest and then 30 seconds following two deep knee bends. The intersample interval was ambitious with recordings taken at 15 minute intervals, but the post-dive monitoring duration was reasonably modest at 90 minutes. The design was repeated measures with a total of 181 dives completed. The study was unusual in introducing several new data management techniques. First was the use of "expanded Doppler" scoring; adding intermediate increments between each grade of the standard Spencer scale. This was apparently instituted in an attempt to linearize the data, but no evidence was provided to validate the approach. The scale remained non-linear. Additionally, grade II bubbles were included in the "high bubble grade" category of a two category collapse. Similar categorization has been used by other investigators (e.g., Dunford et al., 2002), but the correlation between VGE grades and DCS favors low and high categorization of grades 0-II and III-IV, respectively. Finally, the novel use of a "bubble score index" as another means to integrate Doppler scores over time was introduced. The advantage of this approach over the previously established Kisman integrated severity scale (KISS; Jankowski et al., 1997; Jankowski et al., 2004) computation was not provided. Problematically, sufficient raw data were not provided to allow reanalysis. Concerns over the methodology used in this paper were reported (Risberg and Brubakk, 2005). The ability to compare this paper with the existing literature was limited.

Blatteau et al. (2005b) reported similar or more VGE after exposures with integrated deep stops. Doppler scores, using the standard Spencer scale, were used as the study endpoint. The monitoring was modified from traditional - standing rest followed by two flexions of lower limbs while in a supine position. The intersample interval was not unusual with recordings taken at 30 minute intervals for a total post-dive monitoring duration of two hours. The design was repeated measures but with only a small sample size of 24 exposures being analyzed. The analysis was conservative with grades I and II VGE excluded from the tallies. The paper was weakened only by the small sample size.

Bennett et al. (2007) reported fewer VGE after exposures with integrated deep stops. The procedures employed in this study were identical to those described by Marroni et al. (2004) and the same weaknesses apply. The new concern regarding the Doppler analyses in this paper is an overstatement regarding the attempt to average Doppler scores. The bubble score index is described as a "... surrogate of continuous monitoring...." It is misleading to describe a protocol that involves monitoring for only one minute out of every 15 (6.7% capture) as a substitute for continuous monitoring. The ability to compare this paper beyond Marroni et al. (2004) was also limited.

Schellart et al. (2008) reported more VGE after exposures with integrated deep stops. Doppler scores, using the standard Kisman-Masurel scale, were used as the study endpoint. The monitoring protocol was fairly traditional - standing rest followed by observation periods after each of three deep knee bends. There were several significant limitations to the study, most of which were acknowledged by the authors. The design was not repeated measures, the Doppler sampling was infrequent (only at 40 and 100 minutes post-dive), the analyzed sample size was small (a total of 32 exposures), and most Doppler grades were very low (50 non-zero grades but only four achieving a maximum grade of III- [two in each exposure group]). The paper was well written but the value the data added to the literature was limited.

Conclusions

VGE are not a direct measure of decompression sickness but ultrasonic bubble monitoring can provide a useful measure of decompression stress. VGE are used most appropriately as a relative, not absolute, measure, particularly for studies in which they are the primary endpoint. Study designs should be selected to maximize the power of ultrasound data. This includes the use of repeated measures designs to control the impact of the myriad of potential individual differences. Intersample intervals should be short, preferably in the range of 20-30 minutes and continued for two hours post-exposure. Monitoring should include both rest and movement cases. Standard scoring should be employed and sufficient raw data provided for reanalysis where feasible. VGE data should be interpreted conservatively, with an analytical focus on the most meaningful Doppler grades - III or higher - on standard scales. The ability to directly compare results from different studies would be improved by an increasing attention to standardization.

References

1. Bakovic D, Glavas D, Palada I, Breskovic T, Fabijanic D, Obad A, Valic Z, Brubakk AO, Dujic Z. High-grade bubbles in left and right heart in an asymptomatic diver at rest after surfacing. Aviat Space Environ Med. 2008; 79(6): 626-8.
2. Baldes EJ, Farrall WR, Haugen MC, Herrick JF. A forum on an ultrasonic method for measuring the velocity of blood. In: Kelly E, ed. Ultrasound in Biology and Medicine. American Institute of Biological Sciences: Washington, DC, 1957; 3: 165-76.
3. Balldin UI, Pilmanis AA, Webb JT. Central nervous system decompression sickness and venous gas emboli in hypobaric conditions. Aviat Space Environ Med. 2004; 75(11): 969-72.
4. Bennett PB, Marroni A, Cronje FJ, Cali-Corleo R, Germonpre P, Pieri M, Bonuccelli C, Leonardi MG, Balestra C. Effect of varying deep stop times and shallow stop times on precordial bubbles after dives to 25 msw (82 fsw). Undersea Hyperb Med. 2007; 34(6): 399-406.
5. Blatteau JE, Boussuges A, Gempp E, Pontier JM, Castagna O, Robinet C, Galland FM, Bourdon L. Haemodynamic changes induced by submaximal exercise before a dive and its consequences on bubble formation. Br J Sports Med. 2007; 41: 375-9.
6. Blatteau J-E, Gempp E, Galland F-M, Pontier J-M, Sainty J-M, Robinet C. Aerobic exercise 2 hours before a dive to 30 msw decreases bubble formation after decompression. Aviat Space Environ Med. 2005a; 76(7): 666-9.
7. Blatteau JE, Hugon M, Gardette B, Sainty JM, Galland FM. Bubble incidence after staged decompression from 50 or 60 msw: effect of adding deep stops. Aviat Space Environ Med. 2005b; 76(5): 490-2.
8. Boussuges A, Blatteau JE, Pontier JM. Bubbles in the left cardiac cavities after diving. Heart. 2008; 94(4): 445.

9. Brubakk AO, Eftedal O. Comparison of three different ultrasonic methods for quantification of intravascular gas bubbles. Undersea Hyper Med. 2001; 28(3): 131-6.
10. Buckey JC, Knaus DA, Alvarenga DL, Kenton MA, Magari PJ. Dual-frequency ultrasound for detecting and sizing bubbles. Acta Astronaut. 2005; 56(9-12): 1041-7.
11. Butler BD, Hills BA. The lung as a filter for microbubbles. J Appl Physiol. 1979; 47(3): 537-43.
12. Butler BD, Morris WP. Transesophageal echocardiographic study of decompression-induced venous gas emboli. Undersea Hyperb Med. 1995; 22(2): 117-28.
13. Cameron BA, Olstad CS, Clark JM, Gelfand R, Ochroch EA, Eckenhoff RG. Risk factors for venous gas emboli after decompression from prolonged hyperbaric exposures. Aviat Space Environ Med. 2007; 78(5): 493-9.
14. Carturan D, Boussuges A, Burnet H, Fondarai J, Vanuxem P, Gardette B. Circulating venous bubbles in recreational diving: relationships with age, weight, maximal oxygen uptake and body fat percentage. Int J Sport Med. 1999; 20(6): 410-4.
15. Carturan D, Boussuges A, Vanuxem P, Bar-Hen A, Burnet H, Gardette B. Ascent rate, age, maximal oxygen uptake, adiposity, and circulating venous bubbles after diving. J Appl Physiol. 2002; 93(4): 1349-56.
16. Conkin J, Powell MR, Foster PP, Waligora JM. Information about venous gas emboli improves prediction of hypobaric decompression sickness. Aviat Space Environ Med. 1998; 69(1): 8-16.
17. Conkin J, Powell MR, Gernhardt ML. Age affects severity of venous gas emboli on decompression from 14.7 to 4.3 psia. Aviat Space Environ Med. 2003; 74(11): 1142-50.
18. Dervay JP, Powell MR, Butler B, Fife CE. The effect of exercise and rest duration on the generation of venous gas bubbles at altitude. Aviat Space Environ Med. 2002; 73(1): 22-7.
19. Diesel DA, Ryles MT, Pilmanis AA, Balldin UI . Non-invasive measurement of pulmonary artery pressure in humans with simulated altitude-induced venous gas emboli. Aviat Space Environ Med. 2002; 73(2): 128-33.
20. Dujic Z, Duplancic D, Marinovic-Terzic I, Bakovic D, Ivancev V, Valic Z, Eterovic D, Petri NM, Wisloff U, Brubakk AO. Aerobic exercise before diving reduces venous gas bubble formation in humans. J Physiol. 2004; 555(3): 637-42.
21. Dujic Z, Palada I, Obad A, Ivancev V, Valic Z. Venous bubble count declines during strenuous exercise after an open sea dive to 30 m. Aviat Space Environ Med. 2006; 77(6): 592-6.
22. Dunford R, Hayward J. Venous gas bubble production following cold stress during a no-decompression dive. Undersea Biomed Res. 1981; 8(1): 41-9.
23. Dunford RG, Vann RD, Gerth WA, Pieper CF, Huggins K, Wacholtz C, Bennett PB. The incidence of venous gas emboli in recreational diving. Undersea Hyperb Med. 2002; 29(4): 247-59.
24. Eatock BC, Nishi RY. Procedures for Doppler ultrasonic monitoring of divers for intravascular bubbles. Department of National Defence: Defence and Civil Institute of Environmental Medicine (DCIEM) Report No. 86-C-25, 1986; 28 pp.
25. Eckenhoff RG, Olstad CS, Carrod G. Human dose-response relationship for decompression and endogenous bubble formation. J Appl Physiol. 1990; 69(3): 914-8.

26. Eftedal O, Brubakk AO. Agreement between trained and untrained observers in grading intravascular bubble signals in ultrasonic images. Undersea Hyper Med. 1997; 24(4): 293-9.
27. Eftedal OS, Lydersen S, Brubakk AO. The relationship between venous gas bubbles and adverse effects of decompression after air dives. Undersea Hyperb Med. 2007; 34(2): 99-105.
28. Franklin DL, Schlegel W, Rushmer RF. Blood flow measured by Doppler frequency shift of back-scattered ultrasound. Science. 1961; 134(3478): 564-5.
29. Gardette B. Correlation between decompression sickness and circulating bubbles in 232 divers. Undersea Biomed Res. 1979; 6(1): 99-107.
30. Gempp E, Blatteau JE, Pontier JM, Balestra C, Louge P. Preventive effect of pre-dive hydration on bubble formation in divers. Br J Sports Med. 2008 [Epub ahead of print].
31. Gillis MF, Karagianes MT, Peterson PL. In vivo detection of circulating gas emboli associated with decompression sickness using the Doppler flowmeter. Nature (Lond). 1968; 217: 965-7.
32. Ikeda T, Suzuki S, Shimizu K, Okamoto Y, Llewellyn ME. M-mode ultrasonic detection of microbubbles following saturation diving: a case report and proposal for a new grading system. Aviat Space Environ Med. 1989; 60(2): 166-9.
33. Jankowski LW, Nishi RY, Eaton DJ, Griffin AP. Exercise during decompression reduces the amount of venous gas emboli. Undersea Hyperb Med. 1997; 24(2): 59-65.
34. Jankowski LW, Tikuisis P, Nishi RY. Exercise effects during diving and decompression on postdive venous gas emboli. Aviat Space Environ Med. 2004; 75(6): 489-95.
35. Mackay RS. Proceedings of the second symposium on underwater physiology. Washington, DC: Nat Acad Sci/Nat Res Council. 1963; 1181: 41.
36. Marroni A, Bennett PB, Cronje FJ, Cali-Corleo R, Germonpre P, Pieri M, Bonuccelli C, Balestra C. A deep stop during decompression from 82 fsw (25 m) significantly reduces bubbles and fast tissue gas tensions. Undersea Hyperb Med. 2004; 31(2): 233-43.
37. Mekjavic IB, Kakitsuba N. Effect of peripheral temperature on the formation of venous gas bubbles. Undersea Biomed Res. 1989; 16(5): 391-401.
38. Newhouse VL, Shankar PM. Bubble size measurements using non-linear mixing of two frequencies. J Acoust. Soc Am. 1984; 75: 1473-7.
39. Nishi RY. The scattering and absorption of sound waves by a gas bubble in a viscous liquid. Acustica 1975; 33: 65-74.
40. Nish RY, Brubakk AO, Eftedal OS. Bubble detection. In: Brubakk AO, Neuman TS, eds. Bennett and Elliott's Physiology and Medicine of Diving, 5th ed. London: Sanders, 2003: 501-29.
41. Pilmanis AA, Meissner FW, Olson RM. Left ventricular gas emboli in six cases of altitude-induced decompression sickness. Aviat Space Environ Med. 1996; 67(11): 1092-6.
42. Pollock NW. Transthoracic echocardiography (TTE) - a tool to monitor unsafe decompression stress. In: Norton S, ed. Diving for Science 2003, Proceedings of the 22nd Symposium. American Academy of Underwater Sciences: Nahant, MA. 2003: 65-71.
43. Pollock NW. Use of ultrasound in decompression research. Diving Hyperb Med. 2007; 37(2): 68-72.
44. Pollock NW, Natoli MJ. Venous gas emboli (VGE) grades are not correlated with severity of decompression sickness (DCS) symptoms. International Congress on Aviation and Space Medicine Scientific Programme. 2004; 17-8.

45. Risberg J, Brubakk AO. A deep stop during decompression from 82 fsw (25 m) significantly reduces bubbles and fast tissue gas tensions [letter]. Undersea Hyperb Med. 2005; 32 (2): 85-8.
46. Sawatzky KD, Nishi RY. Assessment of inter-rater agreement on the grading of intravascular bubble signals. Undersea Biomed Res. 1991; 18(5-6): 373-96.
47. Schellart NAM, Corstius JJB, Germonpre P, Sterk W. Bubble formation after a 20-m dive: deep-stop vs. shallow-stop decompression profiles. Aviat Space Environ Med. 2008; 79(5): 488-94.
48. Siostrzonek P, Zangeneh M, Gossinger H, Lang W, Rosenmayr G, Heinz G, Stumpflen A, Zeiler K, Schwarz M, Mosslacher H. Comparison of tranesophageal and transthoracic contrast echocardiography for detection of a patent foramen ovale. Am J Cardiol. 1991; 68(11): 1247-9.
49. Spencer MP, Campbell SD. Development of bubbles in venous and arterial blood during hyperbaric decompression. Bull Mason Clin. 1968; 22: 26-32.
50. Spencer MP, Campbell SD, Sealey JL, Henry FC, Lindberg J. Experiments on decompression bubbles in the circulation using ultrasonic and electromagnetic flowmeters. J Occup Med. 1969; 11(5): 238-44.
51. Spencer MP, Johanson DC. Investigation of new principles for human decompression schedules using the Doppler blood bubble detector. Office of Naval Research Tech Rep ONR Contract N00014-73-C-0094. Seattle, WA: Institute for Environmental Medicine and Physiology, 1974.
52. Vann RD, Pollock NW, Freiberger JJ, Natoli MJ, Denoble PJ, Pieper CF. Influence of bottom time on preflight surface intervals before flying after diving. Undersea Hyperbar Med. 2007; 34(3): 211-8.
53. Webb JT, Kannan N, Pilmanis AA. Gender not a factor for altitude decompression sickness risk. Aviat Space Environ Med. 2003;74(1): 2-10.

DISCUSSION: BUBBLE DETECTION AND DCS RELEVANCE

DR. SIMON MITCHELL: Thank you, Neal. A very nice summary. Don't go anywhere because I'm sure there will be some questions.

DR. FRANS CRONJE: Neal, an excellent overview of Doppler. Just two comments. The first is in terms of the use of the word "surrogate." There was no intent to suggest that it was a good surrogate. It was just a surrogate for continuous monitoring. So it was the best that could be achieved. But, clearly, it's not the same as doing continuous monitoring. So the qualifier is important to interpret in that particular sentence.

DR. NEAL POLLOCK: I do appreciate that, and there are a number of definitions. You definitely have wiggle room in there.

DR. FRANS CRONJE: We could have been more penitent, I agree. The second thing is that we realize that trying to wedge non-parametric data into a parametric sort of scale is heretical. But apart from the acrobatics that were related to that, one shouldn't lose the perspective that the high versus low versus zero bubble grades ultimately were the foundation of that particular study. So I don't think one should miss the wood for the trees. We did certainly try and reflect the Doppler scores and give an impression of the overall biological impact using these different calculations. But the fundamental premise was supported by using the high, low or zero bubble grades.

DR. NEAL POLLOCK: And I agree that the high and low concept is very reasonable. It's where you make that cut. I think we have enough evidence from a variety of studies that that cut should be between a II and a III, not between a I and a II. Alessandro, would you speak to that.

DR. ALESSANDRO MARRONI: Just a brief comment. It was *above* II. That is, we started high VGE from 2.5 in our scale and up. II belongs to the lower.

DR. NEAL POLLOCK: So that would make it the threshold for a “high” bubble grade, 2.5 on their standard scale. That's interesting. I'm glad to hear that, I thought I read that carefully. My understanding of what it said in the manuscript had it as under II. I appreciate that clarification. Thank you.

DR. JOHN MURRAY: Thank you for a great presentation. I'm just wondering if you've had any opportunity to work with any of the pulse echo Doppler units. There are a couple of companies that have got some prototypes out there. They're getting some limited exposure. I just wondered if you've seen any of those.

DR. NEAL POLLOCK: Yes, we've got some involvement with Creare now and with Dr. Jay Buckey's group. But it's largely the early stages. We are involved also with the Doppler suit, which is working on dual frequency ultrasound. So we're getting some of that, but we certainly haven't seen it at the point of being operational. But we're hoping in the next couple years we'll see a lot more because they really are trying to do some good things.

DR. SIMON MITCHELL: Can I make a comment about that, Neal? John, we're working with the Luna device in cardiopulmonary bypass circuits at the moment. It's a fabulous device. Its great advantage is that it actually counts the bubbles. Rather than leaving it to you to make a grade, it gives you a count, which is a far more objective method, and the counting system has been pretty well validated. We're very impressed with it. The limitation at the moment is they don't have a probe that's FDA approved for use on humans, but I don't think that's far away. So at the moment, it can only be used as extracorporeal circuits.

DR. PETAR DENOBLE: Neal, is there any difference in significance of bubbles at high altitude compression, or is this shallow air diving, continuous diving and the relationship between VGE in this type of exposure and DCS?

DR. NEAL POLLOCK: There are probably a lot of differences. To compare altitude and diving is difficult because your profiles are quite different, so I can't answer that. Certainly there have been a number of reports that have talked about helium-oxygen profiles generating different bubble patterns than air dives. But to try to quantify it, I certainly can't do it.

DR. ALF BRUBAKK: I just wanted to make a point about different equipment for measuring. It probably doesn't make any difference if you're using a pulse Doppler, if you're using a continuous Doppler, or if you're using ultrasonic scan. We actually tested that; we looked at the differences, and we found that it’s not possible to distinguish between them. You can use the grading system, I, II, III and IV, for all three of them, and you'll end up with approximately the same result. It's a very inaccurate measurement of how much gas is actually there. Because at grade III, for instance, or grade IV, there can be a lot of gas or there can be very little or relatively little. So it's a very inexact measurement system. But it doesn't matter what kind of system you're using. You can use the grading which we have shown. Doesn't matter.

DR. NEAL POLLOCK: I appreciate that. I'm familiar with the paper you've put out on that. I think that in the future, we may find that some systems make a difference. On some of the clear images, you do very well. But there are certainly some, to use TTE as an example, where you have some difficult subjects that may have more fat that you're penetrating through. You don't have quite the same resolution. I think for your lower grade, you can't get a mix. For Grade III and IV and higher, I have no problem with that. But it's for the low grades that I believe it's a consideration as we get an increasing array of devices out there.

DR. ALF BRUBAKK: That, of course, is an important point. We have shown, for instance, both in humans and in animal experiments, that when we do not detect any bubbles at all with any available system, even with megahertz ultrasound, that is the best resolution we can have, you have no gas detectable bubbles, and still we have changes in the endothelial function on the arterial side. So there must be something happening, even though you cannot see any gas bubbles. The importance of that clinically, I don’t know. Probably nothing. But it's interesting.

DR. BILL BATEMAN: Thanks for that excellent review, Neal. You've taken the pressure off of me because no matter how many times I go over this stuff, I keep forgetting what a Kisman score is and what's a Spencer, so I feel a little less stupid. My question or comment is about decompression sickness observed in subjects with zero Doppler scores. In some work that our lab has been doing, comparing the immune responses of naive and experienced subjects, I had an unexpected finding; namely, that in a profile that was expected to produce significant bubble scores right across the board, the naive subjects had almost zero, no bubbles. We can't really explain that. The question I had was surrounding your particular subjects in that, flying after diving. Could they be called naive themselves? And, second, how would you interpret that list that you gave of subject characteristics in terms of individual correlations or variations in that context?

DR. NEAL POLLOCK: To answer the first question, Bill, I can't quantify whether they're naive or not. We have a wide range. Most of them claim they are divers. We do take people who get a pressure test as well. But the majority are divers. As to how active they are, some definitely would be classified as naive, but we can't quantify that. We now do collect information on their diving activity, but on most of those cases, we don't have that. In terms of the list of inter-individual characteristics, I certainly think there are some that show up more strongly in our data than others. Some just don't. For example, fatness alone doesn't seem to be a big factor. Age and male gender are; certainly with altitude studies. I think the idea of proclivity to bubbling or bends is significant on an individual basis. But I think we need a lot more data to try to really tease out the relevant issues and to quantify them.

DR. BILL BATEMAN: I guess the message we took home from the zero Doppler studies is we don't know anything. No matter what we think we know, we're brought to our knees in studying decompression sickness. Subjects with no bubbles aren't supposed to get bent.

DR. DAVID SOUTHERLAND: With the Q-15 minute interval for Doppler monitoring, you're climbing up on the table and positioning yourself, doing the flexing and all that, is there a recommendation for exercise after diving?

DR. NEAL POLLOCK: Actually the NSMRL group is the only one around that I know of using a table. The reason for that table was because there was nothing else when those protocols were being developed. Most people don't make subjects climb up on a table. We have them sit on a very low cot. In some studies, they're actually resting in that cot and they're not moving between trials. But you're right. Certainly there are some individuals in whom rest and movement might be enough to introduce an impact on its own. So that certainly can be a consideration. Thanks.

DR. BRUCE WIENKE: Neal, have you had any observations or comments on Doppler on helium divers versus air divers?

DR. NEAL POLLOCK: No. I have no comments. There are certainly some relevant studies. Simple answer, I don't. We don't. And I don't have any data on the helium dives, so I have no great insights.

DR. SIMON MITCHELL: Neal, to get it on the record, a question about the ideal end point for deep stop research. Should we be doing studies along the lines of the “Gerth model” of picking a profile that produces a moderate amount of decompression sickness and measuring decompression sickness incidence, or should we be sticking with the ethically more comfortable Doppler outcome studies that we've been seeing most of?

DR. NEAL POLLOCK: That's an excellent question, and I think the answer is both. We need to have both the field trials, and we need to have the laboratory studies. Yesterday, I loved Wayne's presentation because when I see 200 cases where they have outcomes to the end point of decompression sickness or not, that's very powerful. We need that. At the same time, we can't pass up the opportunity to collect data when it wouldn't be ethically appropriate to try to strive for DCS as an end point. I think both are appropriate. I think if you use bubble only end point; you have to be much more conservative in how you talk about those outcomes. But I really believe both are valuable. But if there is more funding, I'd love to see more lab studies where you take people to the point of getting bent.

DR. PETER BENNETT: This is the crux of the whole thing. It's all very well to say, yes, we want to have trials where you can give DCS or bends to divers. But, for example, we were working with a group of volunteer Italian divers. We certainly don't want to go out and give them neurological DCS under water from those dives. Therefore, we have to use Doppler. We realize there are certain restrictions in the evaluation of that. When we are talking about decompression stress, we're not talking about decompression sickness. We understand the difference. That doesn't mean to say that the work that we're doing with these divers is invalid. It is a piece of the pie. And those who have the ability, such as Duke perhaps and the Navy, to put divers under the actual stress of decompression sickness, there are not many university groups will allow you to do this today, more strength to them. We need that data. But it's extremely difficult to do. I think we need to have a better grasp of what kind of Doppler data is good and perhaps how that correlates, for example, with spinal decompression sickness or neurological, which we are most concerned about. We think pain-only DCS is not a major problem. We should try to eliminate as much spinal DCS as we can and that, we think, is related to Grades III and IV more than anything else that we have at the present time. So it's a question of research and time and I think what I hear about this new Doppler, where you can actually record the number of bubbles, is ideal. We can get a better correlation if we have a standardized bubble measurement and I agree with Neal, that we do need standardization. We're all doing slightly different things, which is not very good if we're trying to find an answer to our problem.

DR. NEAL POLLOCK: I want to make sure it's clear, that all of my complaints on the limitations of Doppler or ultrasound shouldn't for a minute be interpreted as suggesting that I don't believe there's any value in Doppler. I really think we need both studies. And if I didn't have belief in Doppler, I wouldn't spend so much time thinking about how we can try to make it a little bit cleaner. So I'm definitely not trying to slam any studies that are using Doppler as an end point, as long as they're done as carefully as possible to get the best likelihood of a meaningful outcome and interpretation.

RON NISHI: I guess we have the largest collection of helium data since we've been doing dives for the Canadian forces since 1986 with the Doppler. What we found is that with helium dives, there's a tendency for more Grades III and IV bubbles and that the divers can tolerate the bubbles more than, say Grade III and Grade IV on air. And when we're raising air as part of decompression, we're getting more DCS than with straight helium and oxygen decompression. So there seems to be a difference between air and helium. And your criteria in IV or what your threshold should be for a safe dive I think would be different for air and helium.

DR. DAVID DOOLETTE: The point that you made, Peter, saying that Grade III and IV bubbles are associated with spinal decompression sickness; that's different than what you said, Neal, that there's no correlation between bubbles and neurological. So what am I missing there?

DR. NEAL POLLOCK: I didn't say there was no correlation. We have very few cases of neurological decompression sickness. In the last 15 years, we've had four cases or five cases. So we can't say that.

DR. DAVID DOOLETTE: What is the data that correlates to Grades III and IV with spinal?

DR. NEAL POLLOCK: I didn't make that correlation.

DR. DAVID DOOLETTE: I'm asking you or Peter to tell me that data.

DR. PETER BENNETT: There is no direct correlation at the moment that is true. That would have to be done with cases, and we don't have those cases. All we're saying is Grades III and IV bubbles dropped down to near zero with a deep stop. We're saying that in recreational diving, at the diving depths that we do, the predominant DCS is spinal decompression sickness, with over 70 percent. That's the only relationship.

DR. DAVID DOOLETTE: Right. You said the two were related, so you're now saying something different. Okay. Thank you.

DR. WAYNE GERTH: Just something to pick up from what David just mentioned. We're talking about Grades III and IV bubbles. The temporal pattern of Grades III and IV bubbles, when they occur, is also important. We've just completed two series of air dives. One of them I talked about yesterday and in another we were looking at lengthening the no-stop limits for deep dives. We didn't do Doppler on the no-stop limit dives, but I would like to put forth the notion that Grades III and IV bubbles occurring in, say, a long sat decompression, that are occurring long after you've started your decompression or even long after you've reached surface, where there's a latency between reaching surface and the occurrence of III and IV bubbles, that would be associated most likely with a much different kind of symptom than you would get with Grades III and IV bubbles occurring after a short period of time, immediately after a no-stop decompression, from, say, 190 feet air. So it's more than just the maximum grade. It's also the temporal pattern in which they occur that's going to govern the symptom you're going to get in association with this.

DR. NEAL POLLOCK: That is a good point. That does suggest that that's good support for the KISS analysis. There's no doubt that integration over time is important. The question is: How do you do it effectively? Thank you.

DR. ALF BRUBAKK: I think it's important to make the point that what ultrasound actually does, is tell you something about the stress of the dive. That means that you can use it to compare two different procedures. You have one procedure that produces a lot of bubbles, and you have another procedure that produces very few bubbles, and it means that the latter is a safer one, probably. The risk of serious complications is also much lower. And we know that if a diver has a right to left shunt that is related to neurological decompression sickness and, interesting enough, also related to skin symptoms, but not to musculoskeletal systems. So we know there is a relationship between the amount of gas that you actually produce and the risk of symptoms. So you can use it as an indicator. In air diving, we have reasonably good statistics because of the work that Nishi and his group have done. By using that prior knowledge and a statistical technique called Bayesian statistics, you can, with a limited number of dives, something in the order of 10 to 15 dives, discern between two different procedures. That is a useful tool. There's a lot we don't know about how bubbles produce symptoms. But we know that you can use that technique to tell that procedure “A” is more or less risky than procedure “B”.

DR. NEAL POLLOCK: Thank you. And I agree. That's why I think of it as a great relative measure, but not absolute measure. You definitely can do the pre and post and compare different trials and get great evidence of the decompression stress.

DR. SIMON MITCHELL: One last question, Neal. This is for the benefit of the technical divers in the audience, and slightly tangential. But given your comments on intra-individual variability, your thoughts on divers buying Doppler sets and using them to adjust their decompression profiles?

DR. NEAL POLLOCK: As Simon already said, there's that tech heavy need. And any bit of equipment that has technical content should be purchased by a technical diver. The more expensive, the better!! And now we get to a little bit of the reality. People who want to check themselves, absolutely. Go ahead. The biggest problem I see is the practical side. When do you check yourself? Somebody who gets a monitor, and they check themselves once, and it was immediately after they surface, well, so what? In most cases we don't see bubbles really starting to develop. Actually if you've got long decompression, deep dives, maybe you'll see them earlier. But on a lot of dives, it takes some period of time before they develop. So it would depend on what kind of monitoring those people want to conduct. And I have a feeling that most of those people wouldn't be that serious to do a lot of monitoring. At the same time, maybe after one or two extreme dives, they might want to check. So that's a good reason to get involved in a research study. But in terms of whether there's a high need, for some of the more extreme profiles, it certainly wouldn't hurt. You'd get some insight. But it's kind of like weighing yourself every day. As long as you're mentally healthy about the outcome, that's fine. But if you worry about it too much, it's probably not a good thing because some people -- we have a couple people in the lab who will bubble after almost every exposure, and they do not ever have problems. So there are people who will bubble Grade III, Grade IV all the time with no issues.

RICHARD DUNFORD: If you put a Doppler on somebody who is diving a recreational dive to 70 feet for 40 minutes, you're going to hear bubbles in a lot of people. If you put a Doppler on somebody who's done a high-level tech dive, you're probably going to hear high grades of bubbles every time. It's not going to tell you anything.

DR. NEAL POLLOCK: Actually, Richard, I'll disagree with one thing. I think Jarrod made this point yesterday. You can do subtle tweaks, and it may very well be that in that natural experiment you can make minor changes in your behavior and you might see a change in bubble grades. For the people like Jarrod and his team, they may very well change a modest number of things and see differences on a very similar, if not identical, profile. They have enough control in their activity that I believe they can run that as a personal natural experiment. So I don't know how much it's worth in all cases, but I think in some cases it may be useful.

DR. SIMON MITCHELL: I think we better call the discussion to a close. Neal, thank you very much. Fantastic presentation. Clear and concise as always. Thank you.

DR. SIMON MITCHELL: The next presenter is Dr. Richard Vann. Dick is well known to this audience. He's the Vice President of research at DAN America. His presentation to us today is entitled "The Optimal Path." Thank you very much Dick.

THE OPTIMAL PATH

Richard D. Vann, L.E. Howle, R.G. Dunford, Petar Denoble

ABSTRACT:

The optimal path is the decompression profile that has the lowest possible probability of decompression sickness (DCS) for a given depth, bottom time, and ascent time. The optimal path also applies to venous gas emboli (VGE). Understanding optimal paths for VGE will be important if arterialized VGE are proven responsible for cerebral DCS. Optimal paths were estimated using probabilistic decompression models calibrated to 841 nitrogen-oxygen dive trials that were conducted in 1985 at the U.S. Navy Experimental Diving Unit. Doppler VGE data were also available for these trials. To model VGE probabilistically, we defined a binary variable called 'High Bubble Grade (HBG)' with a value of 0 for Spencer Grades of 0-2 and a value of 1 for Grades 3-4. To validate the model predictions, we estimated the DCS and HBG probabilities for the deep stops trials conducted by the Navy for 30 min dives to 170 fsw. The DCS model predicted the observed DCS incidences relatively well, but the HBG model was unsatisfactory. The first decompression stop for the optimal DCS profile was deeper than for the U.S. Navy schedule used from 1957-2008.

PAPER:

The optimal path is the decompression profile that has the lowest possible probability of decompression sickness (DCS) for a given depth, bottom time, and ascent time. If the lowest probability is too high, a longer ascent time and different optimal path are required. The true optimal path is a hypothetical concept, but probabilistic decompression models can be used to determine model-specific optimal paths.

The optimal path also applies to venous gas emboli (VGE), but optimal paths for VGE and DCS are not necessarily the same. In theory, VGE may pass through or around the lungs, enter the arterial circulation, and cause cerebral DCS. Understanding the optimal path for VGE will be important if arterialized VGE are proven responsible for cerebral DCS. Should this be true, controlling the VGE incidence might reduce the risk of cerebral DCS.

Optimal paths have direct application for generating decompression procedures, investigating the relationship of VGE to DCS, and exploring the depth and duration of early decompression stops. This report describes our preliminary work with optimal paths.

Methods

We used the probabilistic exponential-linear (EL) model to investigate DCS risks and decompression profiles (Thalmann, Parker et al. 1997). The EL model has three parallel perfusion-limited ("well-mixed") tissue compartments with critical pressure ratios that determine the DCS probability associated with ascent to shallower depth. The EL model differs from conventional Haldane models in that when the critical ratios are exceeded, nitrogen exchange is treated as if bubbles have formed. In these circumstances, nitrogen elimination becomes linear rather than exponential which reduces the nitrogen washout rate. After the bubbles resolve, elimination becomes exponential again. This is the origin of the name 'exponential-linear.'

The EL model was implemented in the U.S. Navy dive computer for the SEAL Delivery Vehicle Teams (Butler and Southerland 2001) and was the basis for the new U.S. Navy Air Diving Tables issued in April 2008 (U.S. Navy Diving Manual 2008). Thus, the EL model was a reasonable starting point for our work with optimal paths.

The values of the tissue halftimes, critical pressure ratios, and other model parameters were found by calibration to actual dives having known DCS incidences. Calibration was accomplished by likelihood maximization which selected halftimes and critical ratios such that predicted DCS probabilities were as close as possible to known DCS incidences. Incidence-only maximization was used for both DCS and VGE (Gerth 2002).

The circumstances of a dive can affect the DCS incidence as much as the dive profile. Figure 1 shows a measure of estimated decompression stress on the x-axis and the observed DCS incidence on the y-axis for dives in different locations and under different environmental conditions (Vann, Denoble et al. 2005). Three groups of dives are illustrated: Caribbean recreational dives, Scapa Flow wreck dives, and Navy dive trials. Figure 1 suggests that the DCS risk for Scapa Flow dives (squares and dashed line) was 15 times greater than for equivalent stress dives in the Caribbean (diamonds and dotted line). The risk for Navy dive trials (circles and solid line) was estimated at twice the risk for equivalent stress Scapa Flow dives.

The Navy investigated the effect of thermal state on DCS incidence (Gerth, Ruterbusch et al. 2007). Divers who were cold while exercising at depth and warm during resting decompression (Cold-Warm triangle in Fig. 1) had a DCS risk estimated to be similar to equivalent stress Caribbean dives (dotted line). Divers who were warm at depth and during decompression (Warm-Warm triangle) had DCS incidences of about 15-times greater than the Cold-Warm divers. Divers who were cold at depth and during decompression (Cold-Cold triangle) had a 20-fold greater incidence than Cold-Warm divers. The most stressful conditions, however, were for divers who were warm at depth and cold during decompression (Warm-Cold triangle). These conditions could only be tested during short dives.

The previous discussion suggested that decompression probability might be managed by manipulation of the dive conditions. The work described below does not differentiate between dives having different conditions although we expect condition-dependent models will better estimate DCS and VGE probability.

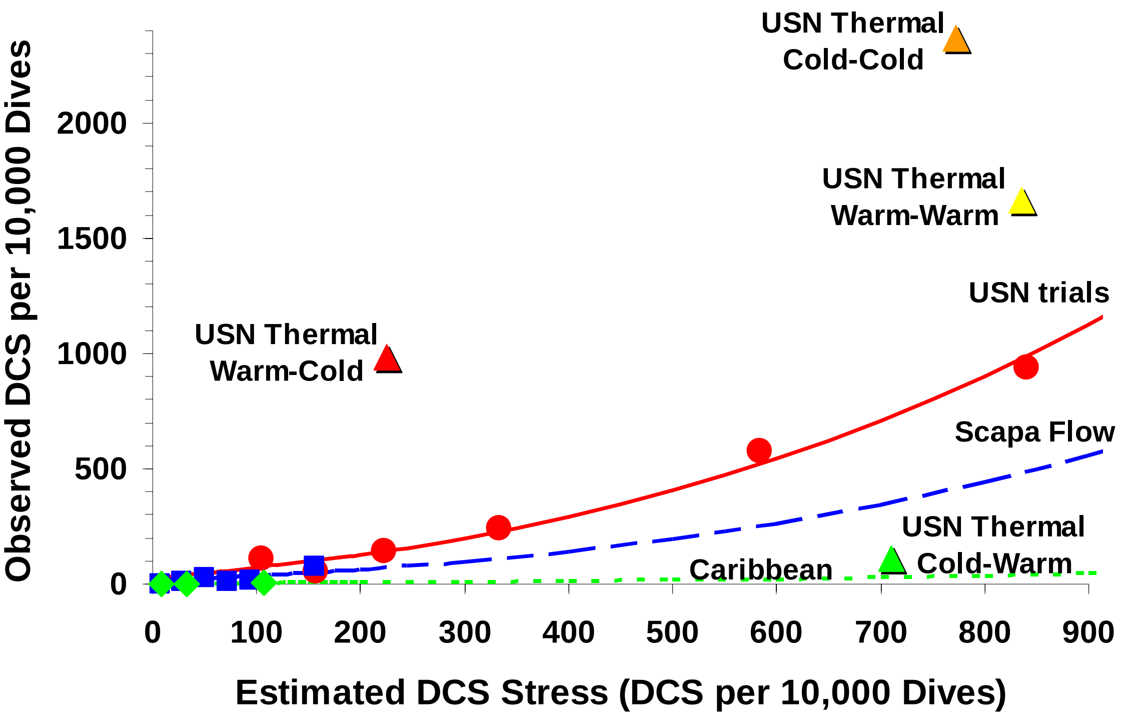


Figure 1. Estimated effects of dive conditions on DCS incidence.

Our model calibration data were from trials at the U.S. Navy Experimental Diving Unit (NEDU) in which the divers performed intermittent exercise at depth and rested during decompression while wearing wetsuits in 70°F water (Thalmann 1985). Most dives were with the Mk 15 or 16 Underwater Breathing Apparatus, a closed-circuit rebreather that maintained an oxygen setpoint of 0.7 atm with nitrogen as the diluent gas. The divers were monitored with Doppler ultrasound for VGE, but these data were only recently analyzed (Shannon, Vann et al. 2004).

The calibration data included 841 dives with a 5.8% DCS incidence and a 73% VGE incidence. About 10% were no-stop dives and 90% were decompression dives. The mean depth and bottom time for the no-stop dives were 93 fsw and 45 min, respectively. For the decompression dives, mean depth and bottom time were 112 fsw and 64 min, respectively, with an average dive time of 203 min. Most calibration dives were long, cold decompression exposures, unlike those in recreational diving, with DCS incidences higher than those of recreational diving.

For this report, we restricted the calibration data to the 841 dives for which both DCS outcome and VGE information were available, so we could investigate the relationship between DCS and VGE.

Weathersby and Gerth used multi-step search algorithms to find optimal dive profiles for probabilistic decompression models (Weathersby, Hayes et al. 1985a; Gerth and Vann 1996). We used a method similar to that for fitting model parameters to calibration data. The time at each decompression stop was treated as a parameter to be adjusted until the DCS or VGE probability was minimized with the sum of the stop times constrained through a Lagrange multiplier to a specified decompression time. The Lagrange multiplier was non-zero only when the constraint was active during optimization. We used an evolutionary search algorithm because the model behavior was non-linear and non-smooth (Ruszczynski 2006).

Results

After model calibration, the 841 dives were divided into eight groups of 106, and a chi-square goodness-of-fit test was applied to each group to evaluate the differences between observed and predicted DCS incidences. No significant differences were noted. A plot of predicted DCS against observed DCS in Fig. 2 gives a visual indication of fit.

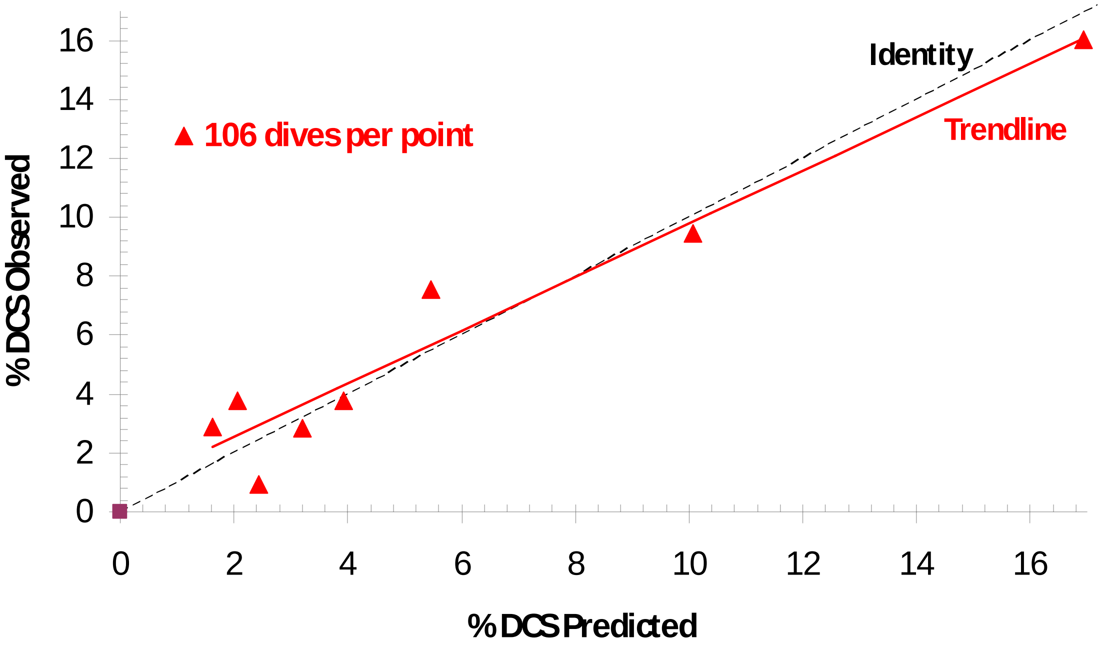


Figure 2. DCS probability predicted by the EL model versus the observed DCS incidence in calibration dives.

The Doppler data were scored according to the Kisman-Masurel (KM) code and converted to the five point Spencer scale (Nishi 1993). As the Spencer Bubble Grade increased from 0 to 4, the incidence of DCS rose from 4% to 21% (Table 1). To model VGE probabilistically, we defined a VGE variable called 'High Bubble Grade (HBG)' that had a value of 0 for Spencer Grades of 0-2 and a value of 1 for Grades 3-4. Three-fourths of the dives had HBG=0 with 4% DCS. One-fourth had HBG=1 with 11% DCS. Since HBG was a binary variable with values of 0 or 1, probabilistic models could be calibrated with the HBG data as for DCS.

Table 1. VGE and HBG calibration data (Shannon, Vann et al. 2004).

Spencer VGE Grade	% VGE	% DCS	High Bubble Grade	% HBG	% DCS
0	27	4	0	74	4
1	30	3			
2	17	7			
3	23	10	1	26	11
4	2	21			

The EL model did not fit the HBG data as well as an exponential-exponential (EE) model which Thalmann had also described (Thalmann, Parker et al. 1997). The only difference between the models was that the EE model did not assume bubble formation. We used the EE model for estimating HBG probability.

A chi-square goodness-of-fit test was applied to the eight groups of 106 dives to evaluate the differences between observed and predicted HBG incidences, and while no significant differences were noted, a visual comparison in Fig. 3 suggests that the correspondence of observed to predicted HBG was not as good as for DCS in Fig. 2.

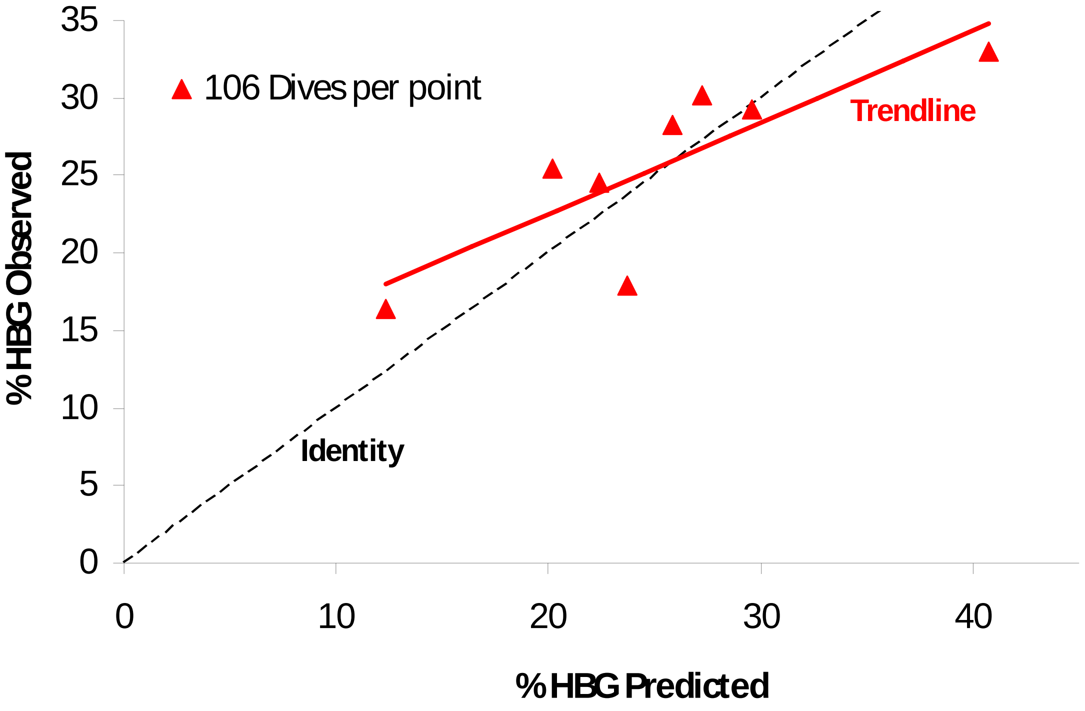


Figure 3. HBG probability predicted by the EE model versus the HBG incidence observed in the calibration dives.

When using probabilistic decompression models, the probabilities that might be considered acceptable must be addressed. For DCS, the Navy reckoned a 2% mild DCS risk and a 0.1% serious DCS risk to be reasonable (Van Liew and Flynn 2005). For this report, we do not differentiate between mild and serious DCS and apply the 2% limit to all cases.

For VGE, we reviewed the literature and canvassed investigators concerning acceptable HBG limits (Spencer Grades 3-4). From Spencer, we estimated an acceptable limit of about 5% HBG (Spencer 1976). Marroni suggested a limit of 5-10% (personal communication, Dr. A. Marroni). From Nishi, we estimated an acceptable limit of about 15% HBG (Nishi 1993). Neuman suggested 40-50% HBG over short durations (personal communication, Dr. T. Neuman).

Another method for selecting an acceptable HBG incidence was to graph the predicted HBG probability against the observed DCS incidence (Fig. 4). Figure 4 reveals that the observed DCS increased with the predicted HBG but with considerable scatter. There are two possible sources of error in this relationship: (a) inaccuracy of the HBG model; and (b) poor natural correlation of HBG to DCS. These sources of error cannot be untangled at present.

With these limitations in mind, an "acceptable" HBG incidence might be estimated from the trendline of Fig. 4. Because the models were calibrated with Navy data, we adopted the 2% Navy DCS limit. A 2% limit for observed DCS corresponds to a 15% limit for predicted HBG, within the range of community opinions for acceptable HBG incidence.

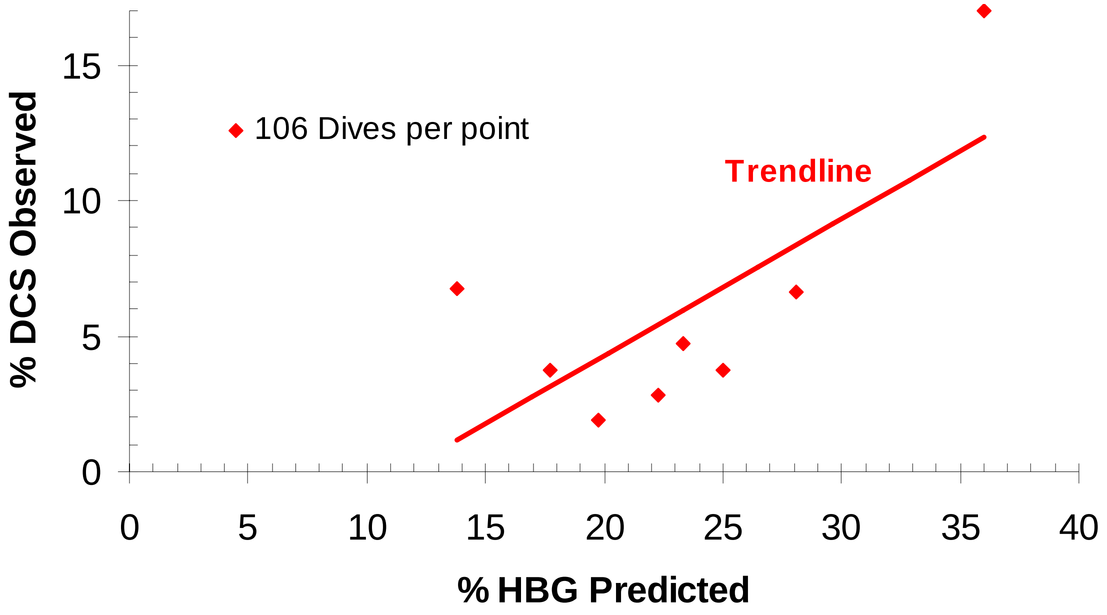


Figure 4. Estimating acceptable HBG probability from observed DCS incidence.

The Navy conducted trials of deep decompression stops with dives to 170 fsw for 30 min (Gerth, Gault et al. 2007). The divers were monitored by Doppler for VGE. Two profiles were tested with the same total decompression time but different distributions of stop time over depth. These are shown in Fig. 5 where the deeper profile, BVM, was tested in 198 trials, and the shallower profile, Vval-18, was tested in 192 trials. For comparison, USN57 is a traditional decompression schedule used by the Navy from 1957-2008 (U.S. Navy Diving Manual 1993). USN57 is shallower and shorter than Vval-18.

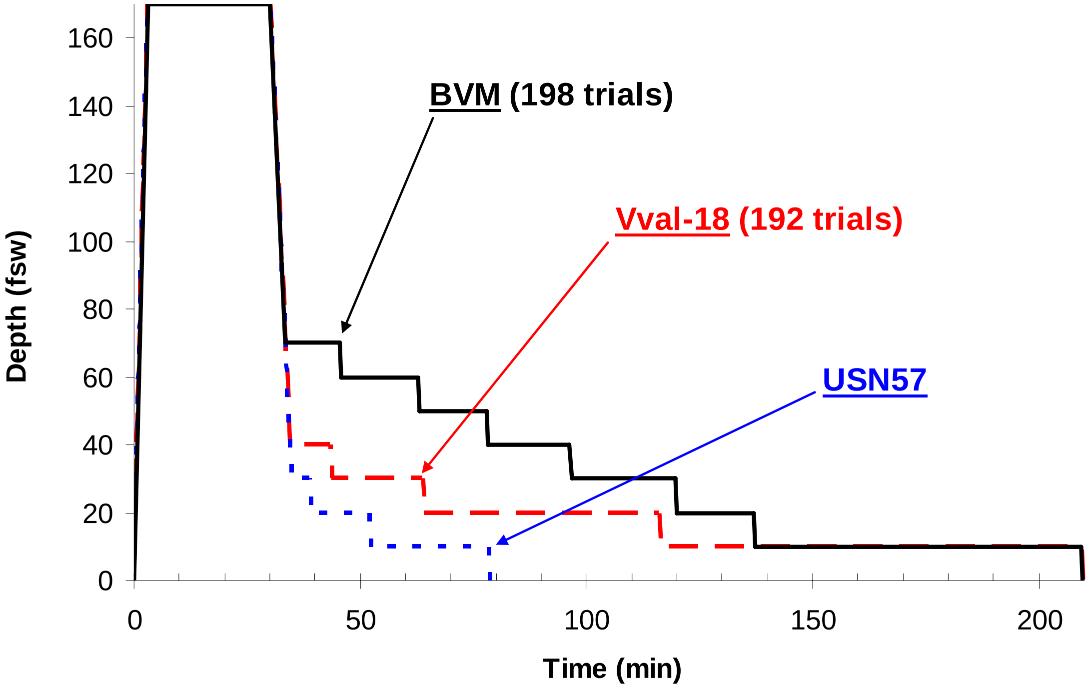


Figure 5. Dive profiles from NEDU deep stops trials (Gerth, Gault et al. 2007).

The deep stop trials were conducted under conditions similar to our calibration dives. To validate our model predictions, we estimated the DCS and HBG probabilities for the deep stop dives.

The BVM profile had an observed DCS incidence of 5.6% (Fig. 6) with a DCS probability predicted by the EL model of 8.4%. The Vval-18 profile had an observed DCS incidence of 1.6% with a predicted probability of 2.0%. The predicted DCS probabilities overestimated the observed incidences by a quarter to a half, but these differences were not significant by chi-square goodness-of-fit test. The observed DCS incidence for BVM of 5.6% exceeded the 2% incidence acceptable to the Navy while the 1.6% incidence for Vval-18 was within the desired limit.

The optimal path profile, also shown in Fig. 6, had an estimated DCS probability of 1.8%. Vval-18 and the optimal profile were similar, with the optimal profile having a little more time deep and less time shallow. This was not unexpected as Vval-18 and the optimal profile were computed with different versions of the EL model.

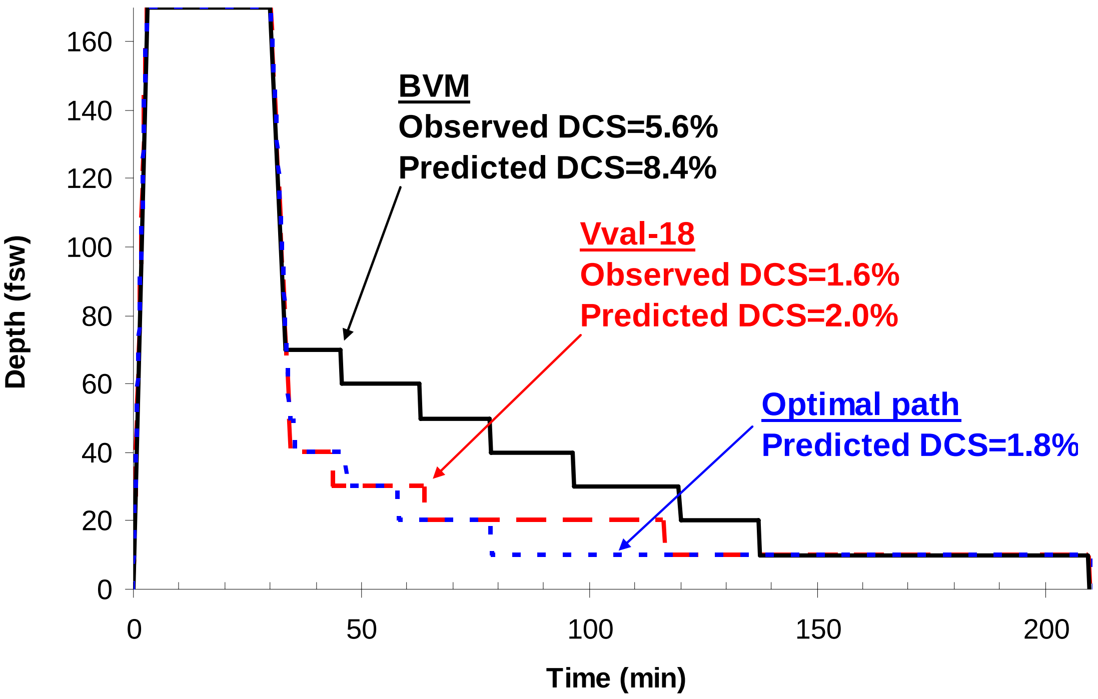


Figure 6. Predicted and observed DCS in the deep stops trials.

Figure 7 shows the observed and predicted HBG for the deep stops trials. The deeper BVM profile had an observed HBG incidence of 66% while the EE model predicted an HBG probability of only 24%. The observed HBG was 47% for the shallower Vval-18 profile with a predicted probability of 17%. The predicted probabilities underestimated the observed incidences by a factor of nearly three and were significantly different by chi-square goodness-of-fit test.

The optimal path profile predicted by the EE model (Fig. 7) had an HBG probability of 15%. The HBG optimal profile spent more time at the deeper stops than did the Vval-18 profile. The observed HBG incidences of 66 and 47% were well above the 5-15% incidences most people felt to be acceptable.

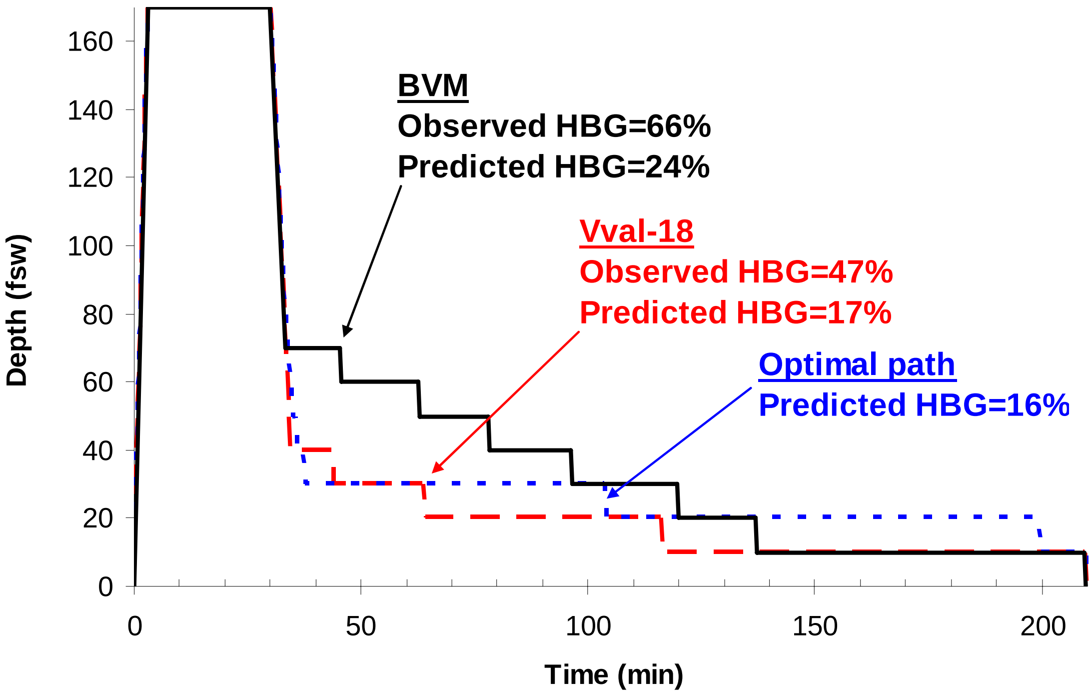


Figure 7. HBG observed and predicted in the deep stop trials.

Discussion

The EL model predicted the observed DCS incidences for the deep stops trials relatively well although with some overestimation, but neither the EL nor EE model predicted the HBG data satisfactorily, and the best model (EE) underestimated the observed HBG incidences by a factor of nearly three. Other HBG models require investigation. Having a good HBG model is important for investigating optimal paths that might reduce HBG probabilities. For example, it would be interesting to know how the HBG incidence of Vval-18 (Fig. 7) could be reduced from 47% to 15%.

The Vval-18, optimal path, and 2008 U.S. Navy decompression schedules (U.S. Navy Diving Manual 2008) were computed with different versions of the EL model and shared similarities, particularly at the deeper stops, although the 2008 schedule was shorter and surfaced from 20 fsw (Fig. 8). We estimated the DCS probabilities for these profiles as 2.0, 1.8, and 2.5%, respectively, with our version of the EL model. When an arbitrary 2 min stop was added to the optimal path profile at 80 fsw, the DCS probability increased from 1.77% to 1.82% according to our version of the EL model.

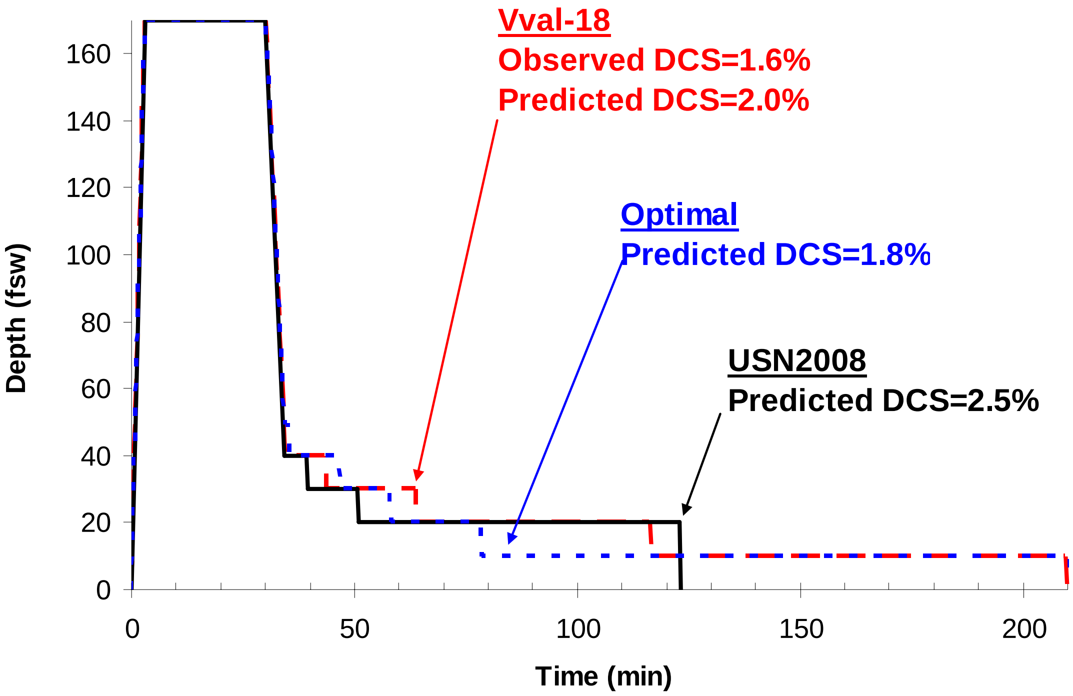


Figure 8. Decompression schedules for 170 fsw , 30 min air dives according to Vval-18, optimal path, and 2008 U.S. Navy air tables (2008).

Have we found the optimal paths? Certainly not for HBG, and we can probably do better for DCS. The accuracy of optimal path estimates depends on model correctness and model calibration dives. The EL model seems to gain or shed DCS probability very slowly with changes in decompression time as suggested by the small differences in DCS probability between the optimal profile (1.77%) and the optimal profile with an arbitrary 2 min stop at 80 fsw (1.82%). Probabilistic models are statistically forced to fit their calibration dives, but as Goldman has demonstrated, parallel tissue models (Fig. 9a) extrapolate poorly to non-calibration dives while series, or interconnected, tissue models (Fig. 9b) extrapolate better and are more sensitive to changes in ascent rate and initial decompression stops (Goldman 2007). Pharmacokinetics, the theory of interconnected tissue compartments, simulates arteriovenous diffusion shunting and diffusion between adjacent tissues and is grounded in non-diving physiological experiments (Weathersby, Mendenhall et al. 1981; Novotny, Mayers et al. 1990; Novotny, Parker et al. 1993; Doolette, Upton et al. 1998; Doolette, Upton et al. 2001; Doolette, Upton et al. 2005; Doolette, Upton et al. 2005). In Goldman's pharmacokinetic model (Fig. 9b), only the central compartment accumulates DCS risk whereas all compartments are DCS-susceptible in Haldane models (Fig. 9a).

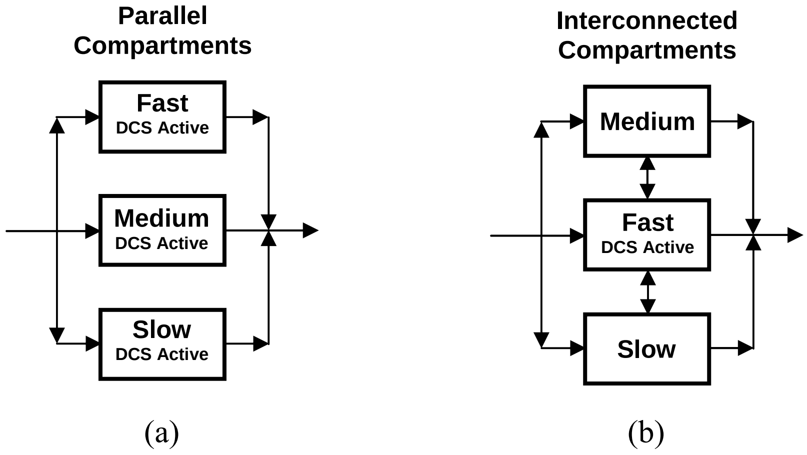
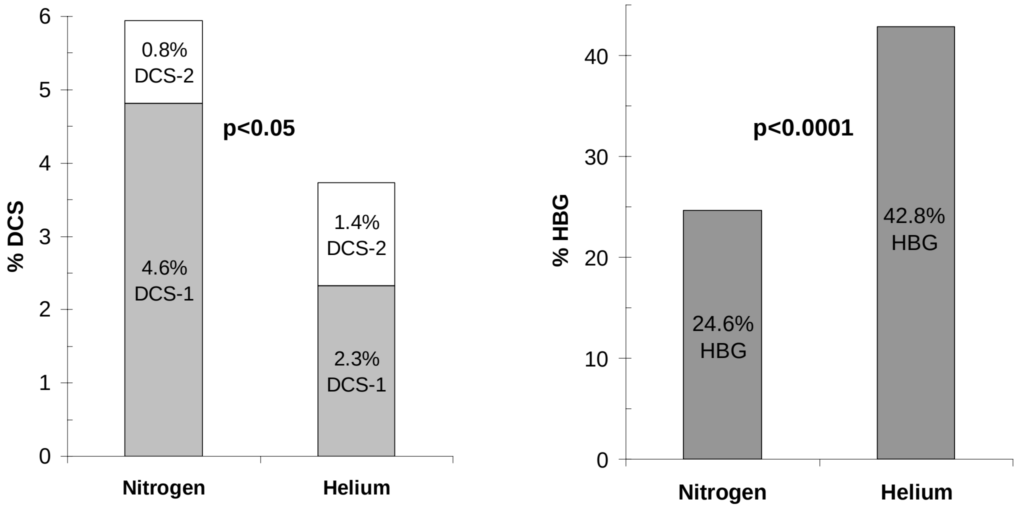


Figure 9. (a) Traditional parallel tissue compartments, as in Haldane decompression models, where each tissue is susceptible to DCS. (b) Pharmacokinetic, or interconnected tissue compartments, where only the central compartment is subject to DCS (Goldman 2007).

Our primary reason for investigating VGE probability was the potential involvement of VGE in serious neurological DCS as a result of arterialization. This possibility is consistent with data for nitrogen and helium diving illustrated in Fig. 10 (Thalmann 1985; Thalmann 1986; Shannon 2003). Figure 10a shows the incidences of Type 1 (“mild”) and Type 2 (“serious”) DCS. The overall DCS incidence was significantly higher for nitrogen than for helium, but there was significantly more Type 2 DCS with helium. Figure 10b shows the HBG incidences indicating that HBG occurred nearly twice as often with helium. Resolving the role of arterialized VGE in serious DCS remains an important issue in decompression safety, particularly for helium diving. While the question cannot be answered by probabilistic modeling, modeling does offer a quantitative tool for controlling potential risk.



(a) (b)

Figure 10. (a) The incidence of Type 1 DCS (DCS-1) and Type 2 DCS (DCS-2) in nitrogen and helium diving. (b) The HBG incidence in nitrogen and helium diving.

What, then, is a deep decompression stop? For air diving, Haldane's original stage decompression schedules, which introduced the decompression stop, might be a reasonable benchmark for comparisons (Boycott, Damant et al. 1908). For example, the first stops of the U.S. Navy Standard Air Decompression schedules used from 1957-2008 (U.S. Navy Diving Manual 1993) were shallow compared with the Haldane schedules (Vann 2004). But if there is a particular optimal path for each depth-time exposure and associated dive conditions, the concept of a deep stop is of little practical value.

At present, optimal paths determined by probabilistic decompression models are of not much more than theoretical utility because they are calibrated only for severe dive conditions. Planning for severe conditions is important, but milder conditions are more common in both military and civilian diving, and until model calibration is extended across a range of dive conditions, the full potential of probabilistic models will be illusive, and the best tools for solving the problems of decompression safety will be unavailable.

References

1. Boycott, A. E., G. C. C. Damant, et al. (1908). "The prevention of compressed air illness." J. Hyg., Camb. 8: 342-443.
2. Butler, F. K. and D. Southerland (2001). "The U.S. Navy decompression computer." Undersea Hyperb Med 28(4): 213-28.
3. Doolette, D. J., R. N. Upton, et al. (1998). "Diffusion-limited, but not perfusion-limited, compartmental models describe cerebral nitrous oxide kinetics at high and low cerebral blood flows." J Pharmacokinet Biopharm 26(6): 649-72.
4. Doolette, D. J., R. N. Upton, et al. (2005). "Countercurrent compartmental models describe hind limb skeletal muscle helium kinetics at resting and low blood flows in sheep." Acta Physiol Scand 185(2): 109-21.
5. Doolette, D. J., R. N. Upton, et al. (2005). "Perfusion-diffusion compartmental models describe cerebral helium kinetics at high and low cerebral blood flows in sheep." J Physiol 563(Pt 2): 529-39.
6. Doolette, D. J., R. N. Upton, et al. (2001). "Diffusion-limited tissue equilibration and arteriovenous diffusion shunt describe skeletal muscle nitrous oxide kinetics at high and low blood flows in sheep." Acta Physiol Scand 172(3): 167-77.
7. Gerth, W., Ed. (2002). Overview of Survival Analysis and Maximum Likelihood Techniques. Workshop on Survival Analysis and Maximum Likelihood Techniques as Applied to Physiological Modeling. Kensington, MD, Undersea and Hyperbaric Medical Society.
8. Gerth, W., K. Gault, et al. (2007). "Empirical evaluation of the efficacy of deep stops in air decompression dives." Undersea & Hyperbaric Med 34(4): 231-232.
9. Gerth, W., V. Ruterbusch, et al. (2007). The influence of thermal exposure on diver susceptibility to decompression sickness. Panama City, FL, Navy Experimental Diving Unit.
10. Gerth, W. and R. Vann (1996). Development of Iso-DCS Risk Air and Nitrox Decompression Tables Using Statistical Bubble Dynamics Models. Bethesda, MD, National Oceanic and Atmospheric Administration, Office of Undersea Research.
11. Goldman, S. (2007). "A new class of biophysical models for predicting the probability of decompression sickness in scuba diving." J Appl Physiol 103(2): 484-93.
12. Nishi, R. Y. (1993). Doppler and ultrasonic bubble detection. The physiology and medicine of diving. P. B. Bennett and D. H. Elliott. London, Saunders: 433-453.
13. Novotny, J. A., D. L. Mayers, et al. (1990). "Xenon kinetics in muscle are not explained by a model of parallel perfusion-limited compartments." J Appl Physiol 68(3): 876-90.
14. Novotny, J. A., E. C. Parker, et al. (1993). "Contribution of tissue lipid to long xenon residence times in muscle." J Appl Physiol 74(5): 2127-34.
15. Ruszczynski, A. (2006). Nonlinear_Optimization. Princeton, NJ, Princeton University Press.
16. Shannon, J. (2003). The relationship of inert gas and venous gas emboli to decompression sickness. Mechanical Engineering. Durham, NC, Duke University. Master of Science.
17. Shannon, J., R. Vann, et al. (2004). "Relationship between inert gas type, venous gas emboli (VGE), and decompression sickness (DCS)." Undersea and Hyperbaric Med 31: 336-337.
18. Spencer, M. P. (1976). "Decompression limits for compressed air determined by ultrasonically detected blood bubbles." J Appl Physiol 40(2): 229-35.
19. Thalmann, E. D. (1985). Air-N202 decompression computer algorithm development.

20. Thalmann, E. D. (1986). Development of a decompression algorithm for constant 0.7 ATA oxygen partial pressure in helium diving.
21. Thalmann, E. D., E. Parker, et al. (1997). "Improved probabilistic decompression model risk predictions using linear-exponential kinetics." Undersea Hyper. Med. 24(4): 255-274.
22. U.S. Navy Diving Manual. (1993). Wash., D.C., Naval Sea Systems Command. 0994-LP-001-9010/0927-LP-001-9011, Revision 3, February 1993.
23. U.S. Navy Diving Manual. (2008). Wash., D.C., Naval Sea Systems Command. SS521-AG-PRO-010, revision 6, Dated 15 April 2008.
24. Van Liew, H. and E. Flynn (2005). "Decompression tables and dive-outcome data: graphical analysis." Undersea Hyperb Med 32 (4): 187-198.
25. Vann, R., P. Denoble, et al. (2005). The risk of decompression sickness (DCS) is influenced by dive conditions. Diving for Science, AAUS.
26. Vann, R. D. (2004). Mechanisms and risks of decompression. Bove and Davis' Diving Medicine. A. A. Bove. Philadelphia, Saunders: 127-164.
27. Weathersby, P. K., J. R. Hayes, et al. (1985a). Statistically based decompression tables. II. Equal risk air diving decompression schedules.
28. Weathersby, P. K., K. G. Mendenhall, et al. (1981). "Distribution of xenon gas exchange rates in dogs." J. Appl. Physiol. 50(6): 1325-1336.

DISCUSSION: THE OPTIMAL PATH

DR. TOM NEUMAN: I feel I have to defend myself just minimally to the offhand remark that you made about my 40-50 percent high bubble grade because our conversation was a little bit longer than just the off-the-cuff thing, and there were some calculations involved in it. I would like to also point out that on the VVAL-18, 170 feet for 30-minute decompression profile that Wayne Gerth did, which had what I would suspect most people would say was an acceptable risk of decompression sickness, there was 40 to 50 percent high bubble grade scores. So what you actually have is a number that is really what you and I calculated when we came up with that or using the basis of our conversation to come up with that 40, 50 percent. I would also like to underscore that I think it is tremendously important what the dive profile is as to what is an acceptable high bubble grade score. As Wayne pointed out there are different temporal relationships with the bubble scores. On one dive, a high grade bubble score may be perfectly acceptable. And for another dive, the same bubble score is totally unacceptable.

DR. RICHARD VANN: I think that's absolutely right. Ron Nishi mentioned yesterday that with some of these dives being done today, Grade IV occurs all the time and without decompression sickness. So all that correlation that we had in the past doesn't seem to work anymore. So I think it's very, very profile dependent, absolutely right. And that's where this probabilistic modeling of VGE comes in, so then we'll be able to connect the profile. And we'll be able to tease out that relationship, at least statistically, between VGE and DCS. So that's the optimal path.

DR. FRANS CRONJE: If the Navy data suggested that the warm-warm profiles were so risky, why are the Caribbean dives so low in risk?

DR. RICHARD VANN: Remember, the Caribbean dives are no-D. The decompression dives start out with a much higher basic risk. Also, if you're exercising on the bottom, you're going to be taking up a lot more inert gas than if you're just kind of looking at fish and not working at all. Now, warm-warm was not nearly as bad as was warm-cold, because then when you're decompressing cold, perfusion goes down, you're getting cold.

DR. DAVID SOUTHERLAND: The technique you were describing, the shortest path and most optimal path, I thought Shalini did something like this. And I think Wayne used that when he actually designed his deep stop study. Could that be a reason why the deep stop data seemed to line up with the modeling that you did earlier?

DR. RICHARD VANN: Well, I think it's the same model, so it's not all that surprising that there are similarities. I remember Shalini's presentations, and I don't know if she did an optimization or just cut some kind of grid search. So it may be that we just redefined the wheel, and that may well be. But anyhow, we did it. At least Gordon came up with it on his own, so maybe he found the same thing.

DAVID DOOLETTE: I just wanted to address Frans' question a little bit more. You can't put too much weight to our warm-warm data. We think that when that study was done, there was a bit of heat stress in some of those DCS cases. So that warm-warm DCS risk is probably higher than it really is.

DR. RICHARD VANN: Also, I think there were fewer exposures than there was on the other ones.

DR. WAYNE GERTH: Just to follow-up on that one, we had to terminate those warm-warms because the DCS that we were seeing was confounded by hypothetical dehydration and heat stress. We had to terminate that. We hurt some guys. Inadvertently, bad design. My fault. But that doesn't bear on your use of the other parts of that data. I have a more general comment, though, regarding the "optimal path". We've spoken about this, but I have to point it out to everybody here. It's an extraordinarily model-dependent thing. The optimal path for a bubble model is the one that we tested for the 170 feet for 30 minutes air dive. The A2 BVM 3 schedule we tested was the optimal path. That was the path with the total stop time that the Vval-18 gave us for that dive recomputed using the BVM 3 model. That was the allocation of stop time that gave us the lowest risk. So that idea is not new. So your optimal path was matching closely the one that went with the VVAL-18 Thalmann algorithm because you were using the EL model fit to the same data that most of the VVAL-18 stuff was based on.

DR. RICHARD VANN: That's absolutely correct.

DR. WAYNE GERTH: So with the model commonality there, I'm not surprised you got a similar optimal path. I'm not faulting your conclusion, just you need to bear in mind the question we should ask, instead of do we have the optimal path, is do we have the optimal model? And that was the reason for our study; it was to try to choose between a bubble model or a gas content model. We have some insight into the possibility that the bubble model isn't the best one for air and nitrox. Still an open issue for heliox, but I think the focus ought to be redirected to model versus path.

DR. RICHARD VANN: That's correct.

DR. ALESSANDRO MARRONI: Dick, I couldn't agree more about what you said about conditions, conditions, conditions and I would like to stress also that individual conditions, not only external conditions, may influence the response to the same dive and the same amount of bubbles. We're actually now in the process of studying the influence of these variable individual conditions, such as hydration and other biological conditioning, let alone all the studies about endothelial response and so on, and that may condition the response to the same grade of decompression stress. So I would stress that conditions must be looked at even in this perspective. I have a comment about the acceptability of risk, because that is social.

DR. RICHARD VANN: Yes, it is.

DR. ALESSANDRO MARRONI: The amount of risk that a normal recreational diver, let's say the average recreational diver would accept today, whose average age is about 40 to 42, has a family, has a job to go back to, is zero. So acceptability of risk is something which is very social. I do believe that this is unachievable as a zero risk, but the data that you showed are quite nice. If we can keep it as low as that and if we can control that by, amongst other things, also curbing down the HBG levels and so on, so much the better. So that's a good interesting thing. And then I would also like to agree very much on what Alf has just said, that bubbles are biologically active and sometimes they are very much biologically active irrespective of their quantity. And they can release or provoke distance reactions, such as what is believed to be the skin manifestations in certain cases. Thank you.

DR. RICHARD VANN: We can keep the risk down to zero, too. The answer is trivial. Don't dive.

DR. ALESSANDRO MARRONI: Don't dive, of course. Don't even take a shower.

DR. JOHN MURRAY: Thanks, Dick, for a very interesting presentation. Just to comment on where we're going with the Navy. Rev 6 of the U.S. Navy diving manual is now in effect, and with the slight modification of the VVAL-18, the only point I want to make is that the Navy is implementing that, and has also implemented in-water oxygen decompression, as well as increased emphasis on Sur-D O2 (surface decompression on oxygen - eds). They are essentially telling the Navy diver, if you're going to do more than 15 minutes of in-water air decompression, that you really need to be, in fact, doing in-water oxygen decompression. We've provided the capability to our Navy divers to utilize oxygen in water, and obviously we'll see over time how that plays out. But it should improve for us the decompression risk below that 2.5% that you would predict with your model.

DR. TOM NEUMAN: I just realized that in the interchange with Dr. Marroni, we all said something in a kind of flippant fashion. And since it's being recorded and will be published requires a little bit of clarification. We said if you want to reduce the risk of decompression sickness to zero, don't dive. Well, that's not quite true. There are dives that really do have a zero incidence of decompression sickness, and I believe that to be a very important philosophical point. If there were really a finite risk of decompression sickness with every dive, we couldn't climb to the second story of the building and we couldn't take baths without a risk of decompression sickness. The fact is there are dives that have zero risk of decompression sickness, and that really has to be considered in our modeling, in the probabilistic approach to decompression sickness and in the definition of decompression sickness, which ultimately I'm convinced we will all come to agree on so that we're talking about the same thing when we go from study to study to study, whatever that definition may wind up being. We'll have entrance criteria into that, just like the Jones criteria requires an antecedent streptococcal infection. So I think that's an important philosophical point. We were sort of joking about it, and I think it has to e clarified for the record.

DR. RICHARD VANN: You're absolutely correct. The way they handle that in probabilistic models is with a threshold. You're right.

DR. WAYNE GERTH: Since this question came up, I wasn't rising to the microphone to address this, in particular, but the issue of a threshold must be taken very carefully. I think Tom is right, that there are exposures for which we would all argue that there's real risk, and I'm distinguishing the word "risk" from the next one I'll use, which is “incidence." The real risk may be zero. But we have to be very careful about what we infer from an observation of zero incidence in a given number of exposures. I've heard people assert that since we've seen no DCS in the order of 500 exposures, that the real risk is zero, and they've advocated setting a threshold in their models at zero. And I argue that if you put the binomial confidence limits on what we know from zero out of 500, you can't set a threshold there wisely. So instead of setting thresholds, we overestimate low risk. We overestimate the risk for low intrinsic risk dives kind of on purpose. And we accept that because we're not too confident on how to set a threshold. I just wanted to mention another thing. Dick, thank you for your acknowledgement of the thermal work. You mentioned Dick Ruterbusch and myself. Just for the record, and especially because he's here, Dr. Ed Long was involved.

DR. RICHARD VANN: Oh, I should have mentioned Ed Long.

DR. WAYNE GERTH: It was his idea to undertake that work in the first place.

DR. RICHARD VANN: Best study of the century.

DR. WAYNE GERTH: Dr. Long, thank you.

DR. SIMON MITCHELL: One question at a practical level, once again, on behalf of the technical divers in the room. Maybe it's a question for Wayne or David, but how do you do cold-warm? How do you do it at a practical level?

DR. RICHARD VANN: That's definitely tougher. I guess you use a scooter, for one thing, on the bottom. That will keep you cooler, and you won't exercise as much. If you exercise a little bit during decompression, that will help. If you can get a warm garden hose. Maybe you get some of those heat packs inside a dry suit. It's much harder for technical diving. The hot water suit is a practical solution for the Navy and commercial diving. But keep in mind, you want to avoid exercise while you're at depth. Stay a little cooler. I don't know what you do. You need to stay warmer during decompression.

DR. WAYNE GERTH: How do you do that? You're probably familiar with how we did it experimentally. I call them semi-nude divers, and we did a Chinese fire drill in different water baths. We also showed that we could effect the same outcome in divers wearing dry suits with hot water suits underneath. We could keep them cold by circulating cold water through the tube suits or keep them warm by circulating warm water. Now, for people who don't have that kind of capability from topside to circulate water at a controlled temperature through a suit, Dr. David Pendergast is developing a free-swimming suit which allows a diver to, at least in principle, control temperatures in a free-swimming situation. And then Dr. Lou Nuckols, in another context, is working on a new thermal protection technology that will allow active thermal control, which will enable us to cool and heat a diver in free swimming. So while we may not have free-swimming technology to effect this kind of thermal control to reduce DCS risk yet, it's on the horizon.

RON NISHI: Just want to go back to the relationship between bubble scores and DCS. On our dives we had 15 percent DCS for Grade IV bubbles. One thing I'd like to point out is that it's very difficult to get a good relationship between high bubble scores, especially Grade IV and DCS, in the experimental dive context, in Toronto anyway. When we do dives that are likely to produce DCS and the subject develops symptoms soon after surfacing, we lose the subject completely for Doppler monitoring because he's passed over to the physician, who has complete control after that. We can't delay treatment to get another bubble reading. So we may be underestimating the relationship between Grade IV bubbles and DCS.

DR. RICHARD VANN: That's happened to us as well. You're absolutely right.

GENE MELTON: The motorcycle industry has solved your problem for cold and warm. You can buy an electric jacket, 12 volts, and electric underwear. It's portable. Takes a small battery. Provides you heat. You leave it off during the dive so you're cold. You fire it up when you get back to decompression, and you stay warm. That's what Jarrod Jablonski is doing. The jacket, pants, control and everything, is less than 200 dollars. The other question was for Dr. Vann. In our models I think we should consider the equipment. Back to your conditions. A diver on a rebreather is breathing a different environment than a diver open circuit because of the nature of the warm, moist gas versus the cold, dry gas. And I think that that's really significant, in my mind as a technical diver, as to what is going to happen to my decompression profile.

DR. RICHARD VANN: That's a good point. I wonder if there have been any studies at core temperature or skin temperature between rebreather divers and open circuit divers? Wayne, do you know if the Navy has done any of that?

DR. WAYNE GERTH: I don't know.

DR. RICHARD VANN: That's an interesting point, yes.

DR. BRUCE WIENKE: Just an observation on cold-hot, hot-cold switches. In a bubble model, where you take account of material properties, you could account for temperature dependences during the dive. So you could change temperatures, and that would affect diffusion lengths, properties of the gas, and how the bubble excites. So you could, in principle, do such things. It's a lot of work, but just to let you know, that something like that can be done.

DR. SIMON MITCHELL: It's a great pleasure to introduce Alf Brubakk from Norway, and his colleague Christian Gutvik. They're going to be doing a joint presentation this morning. Alf and his team are well known as prolific authors in this area and over the last four or five years have produced a series of papers that I think it's fair to say have reshaped a lot of our thinking on decompression issues and decompression sickness physiology. So we're privileged to have them here this morning. The title of the presentation is "The Effect of Deeper Stops on Bubble Formation as Dependent on Length of Bottom Time." Alf, I'll leave it to you to kick off.

THE EFFECT OF DEEPER STOPS ON BUBBLE FORMATION IS DEPENDENT ON LENGTH OF BOTTOM TIME

Christian R. Gutvik, D. Glavas, A. Møllerløkken, Z. Dujic, Alf O. Brubakk

ABSTRACT:

Background

Deep decompression stops compared to more conventional shallower stops have recently been introduced. Most findings and theoretical work on excess gas phase / bubble models suggest an apparent advantage of using deeper stops. However, some reports indicate that the incidence or risk of decompression sickness may actually increase following such procedures.

Materials and Methods

As a part of the validation of the Copernicus decompression model, a series of experimental dives were performed on recreational divers in Split, Croatia. A total of 11 dive procedures with 7-8 divers in each group were tested in water. The protocol included two series of deep/short dives (54msw / 20min and 45msw / 16min) and two series of shallow/long dives (24msw / 70 min and 24msw / 40 min). The 4 dive protocols followed 2-3 different decompression procedures with both deep and shallow stop regimes. The dives were evaluated using ultrasonic bubble detection. At UHMS 2007 we presented a hypothesis based on animal experiments and a theoretical concept of stabilized bubble nuclei that the benefit of deep stops primarily applies for long bottom times. The present human data were analyzed to test this hypothesis.

Results

On the 24msw / 70min dive, the experimental deep stop procedure seems to produce less bubbles than the Bühlmann shallow stop procedure. On the 45msw / 16min dive, the VPM deep stop procedure gave more bubbles than the experimental shallow stop procedure. Simulation results from the Copernicus model with the implemented nuclei dynamics give the same results.

Conclusions

Although not statistically significant the results point in the same direction as the previously presented hypothesis and fit well with the Copernicus bubble model. Our suggestion is that deep stops are primarily recommended on longer dives, however more studies specifically designed to test this are advised.

PAPER:

Introduction

Deep decompression stops compared to more conventional shallower stops have recently been introduced in decompression. Theoretical work on excess gas phase models suggest an apparent advantage of using deeper stops, and several studies support this [1, 2]. However, some reports indicate that bubble formation and/or the risk of decompression sickness (DCS) may actually increase following such procedures [3, 4]. The motivation behind this paper was to investigate the mechanisms behind these diverging results.

Conventional supersaturation models like those developed by US Navy and Bühlmann are generally known for having relatively shallow decompressions. The concept of "deep stops" was introduced by Richard Pyle when he experienced a significant decrease of post dive fatique and malaise by adding deeper stops to the conventional procedures. The benefit of deep stops has later been supported by more advanced 2-phase models (bubble models), and deep stops have been embraced by deco algorithms like VPM [5] and RGBM [6]. However, in practice those two different theoretical approaches are not very different, as deep stops can just as well be a property added to a supersaturation algorithm as to a bubble-based algorithm. In bubble models deeper stops are justified inherently while in supersaturation models you get deeper stops by tuning the allowed supersaturation in the fastest tissues. In both approaches it is basically a comprehension of the fact that you need to compromise between efficient gas elimination and low bubble growth gradient. If a deco stop is considered a "deep stop" or a "conventional stop" is just a matter of depth definitions.

Experimental Setup

The impact of different decompression schedules was tested on pigs compressed in a dry chamber, and decompression was monitored using ultrasonic imaging [7]. A total of 26 pigs were divided into 4 groups of 6 and one group of 2 (aborted protocol). Two groups performed a shallow/long dive (30 msw / 70 min) where one group followed a Bühlmann decompression procedure while the other followed an experimental deep stop procedure (DS1). (Table 1) The three last groups did a deep/short dive (65 msw / 20 min) following a Bühlmann decompression procedure, an experimental deep stop procedure (DS2, n=2) and a revised shallow stop procedure (SS2) respectively. Dive depths were prolonged by 20% to provoke bubble formation in the pig model, so the Bühlmann controls followed a 24 msw and a 54 msw table.

Table 1: 30 msw / 70 min procedures

Stop-depth [msw]	**Stop-time [min]**	
	Bühlmann	**DS1**
9	-	14
6	22	21
3	47	25
Total deco	69	60

Table 2: 60 msw / 20 min procedures

Stop-depth [msw]	**Stop-time [min]**		
	Bühlmann	**DS1**	**SS2**
12	2	1	-
9	5	9	-
6	9	13	9
3	27	15	33
Total deco	43	38	42

Results

The long/shallow dive (Fig. 1) achieved a significant decrease of vascular bubbles following the experimental procedure with deeper initial stops (DS1, solid) compared to the controls (Bühlmann schedule, dashed) - despite having a shorter total decompression time.

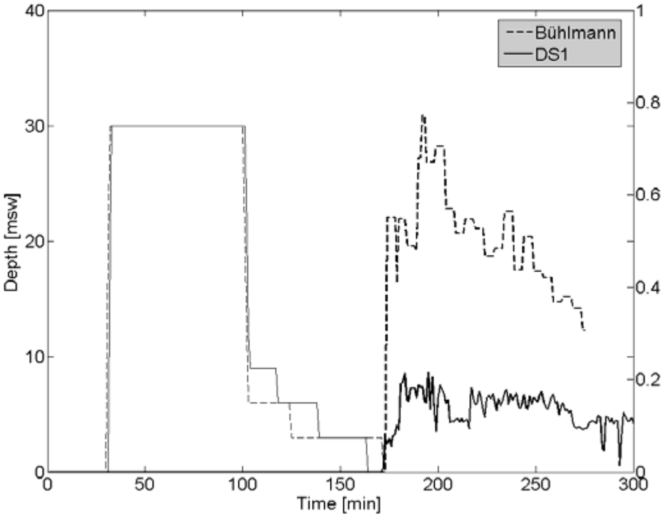


Figure 1: DS1 gave a significant reduction of vascular bubbles

However, on the deep/short dive (Fig. 2) the procedure with deeper stops (DS2, solid) gave a dramatic increase of bubble formation, resulting in the protocol to be aborted after two trials. A new revised experimental procedure with shallow stops (SS2, dotted), gave a significant decrease of vascular bubble formation.

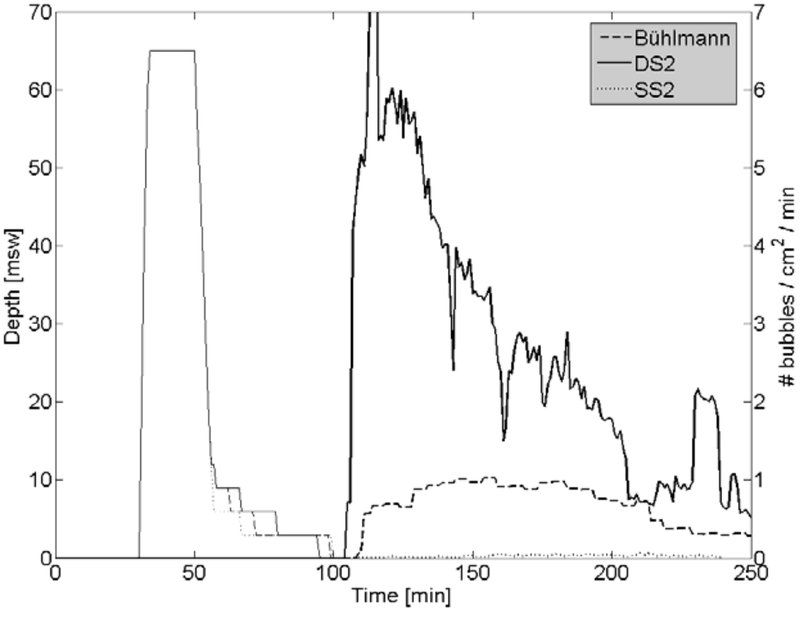


Figure 2: DS2 increased vascular bubbles while SS2 gave significantly less

Most 2-phase models consider an initial bubble size of a single bubble or a distribution. If such a model is fitted to show the benefit of deep stops, it can not predict our contradictory results. There must be an additional effect besides supersaturation and pressure drop that affect bubble growth differently in those two dives. It is an acknowledged fact that bubbles must grow from pre-existing nuclei [8] and variance in their initial size will greatly affect the degree of bubble growth.

Copernicus Implementation

Under normobaric, desaturated conditions, any bubbles in the body will shrink due to surface tension according to Laplace' law:

(1) $$P_b = P_{amb} + \frac{2\gamma}{r}$$

For any bubble nuclei to exist there has to be a stabilizing force, $\Gamma(r)$ opposing the surface tension:

(2) $$\Gamma(r) + P_b = P_{amb} + \frac{2\gamma}{r}$$

This stabilizing mechanism is suggested to be caused by crevices [9], stabilizing surfactants [10] and hydrophobic caveolas [11]. Regardless of origin, it is a fact that it will at some point work in the opposite direction of the surface tension and resist further shrinkage of the bubble. A bubble acting according to traditional theory will have a surface pressure diverging to infinite when the radius goes to zero *(Fig. 3, dashed line)*, eventually causing the bubble to collapse. Our candidates for a stabilizing function force the pressure-balance to equilibrium (here chosen to be 1μm). We want our function to follow the "traditional curve" for surface tension controlled dynamics while still being stabilized around initial nuclei size. A reasonable choice seems to be the 3rd power function

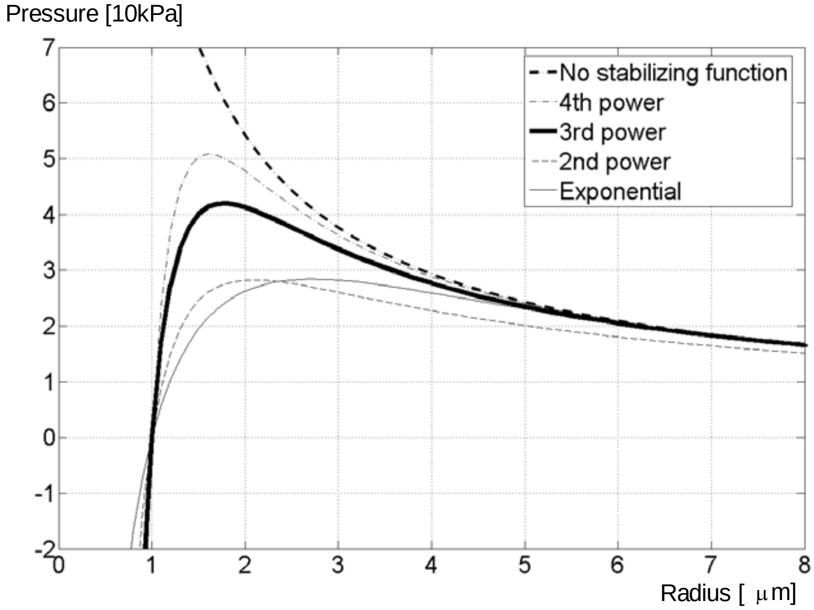


Figure 3: Pressure sum vs bubble radius. Equilibrium at 1 μm

Bubble Nuclei Regeneration

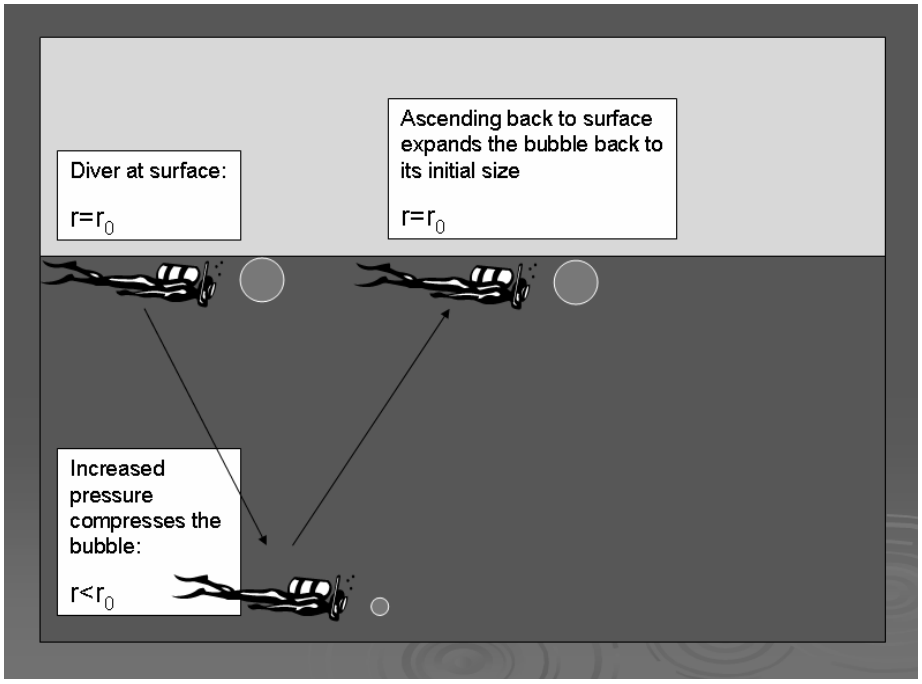


Figure 4: A short dive with no/low regeneration during bottom phase

(Fig. 4) Any bubble nuclei present in the body before the dive will immediately be compressed upon descending. If the dive is short enough, the bubble will return approximately back to its original size when the diver start to decompress. Assuming that this initial size is relatively small, the diver can tolerate large saturation gradients.

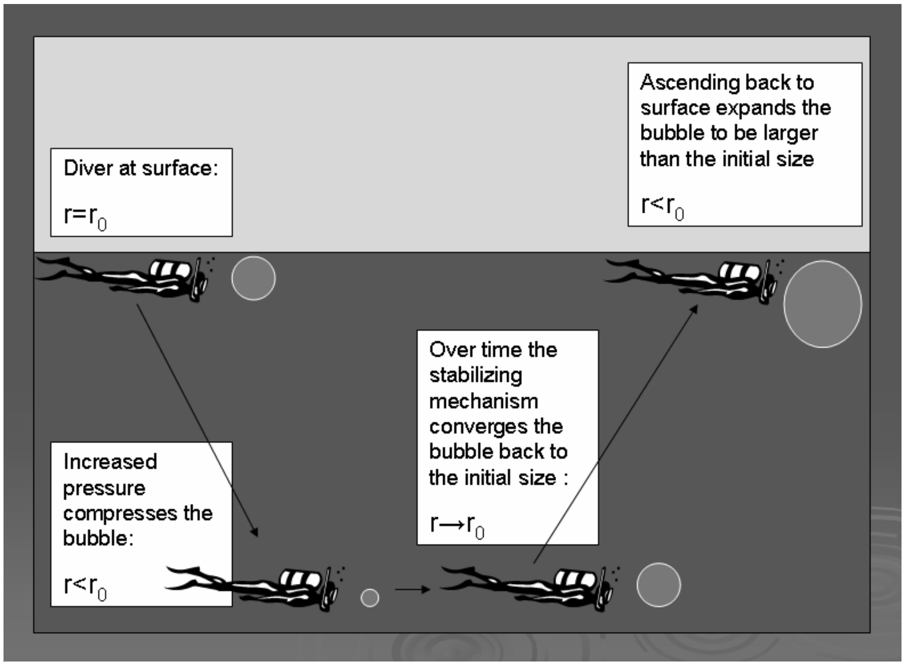


Figure 5: A long dive with higher regeneration during bottom phase

(Fig. 5) If the bottom time is longer it is reasonable to believe that the bubble will grow back to its initial size while the diver is at the bottom. The stabilizing mechanism excesses an expanding pressure causing gas diffusion into the bubble. After the diver has started his ascent, the bubble will be much bigger than the initial size when the decompression starts, and deeper stops would be beneficial to control the bubble growth. Higher blood perfusion and faster gas uptake may also contribute to faster nuclei regeneration during the bottom phase. So even though the supersaturation may be identical in those 2 different cases, the potential of bubble growth is greatly different.

Saturation dives are an extreme example where the nuclei most likely are 100% regenerated to their initial size. Desaturation procedures, which we know are very reliable, are doing an extremely slow ascent from the first feet, and establish no initial elimination gradient and can thus be considered as a deep stop procedure.

Simulation Examples

The Copernicus model is validated and statistically fitted with human data and can thus not simulate experimental results from the pig model. However, the experimental pig model can provide us information about fundamental mechanisms on decompression and thus be of qualitative value in modelling work. To demonstrate the impact of the suggested nuclei equation in combination with the bubble dynamics in Copernicus we selected four procedures for simulation. One deep/short dive and one shallow/long dive, each following a shallow stop procedure from Bühlmann ZHL8 algorithm [12] and a deep stop procedure from VPM algorithm [5]. The Bühlmann procedures were generated by an Uwatec Galileo Computer and the VPM procedure were generated by
V-Planner [13]. To get comparable results the conservatism setting in V-planner was tuned so total decompression time was equal for both procedures.

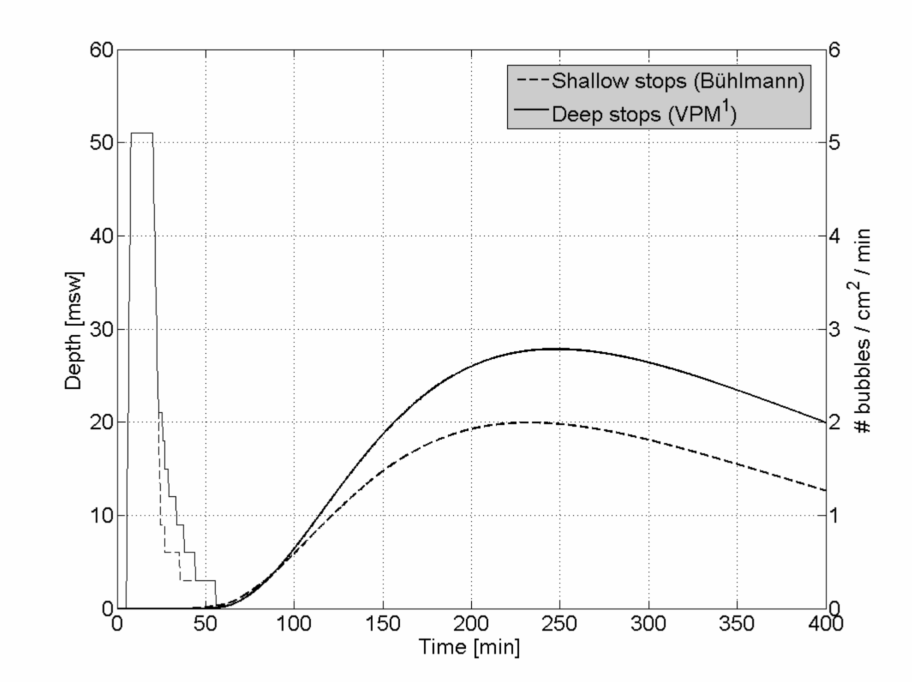


Figure 6: Copernicus simulation of 51 msw / 15 min

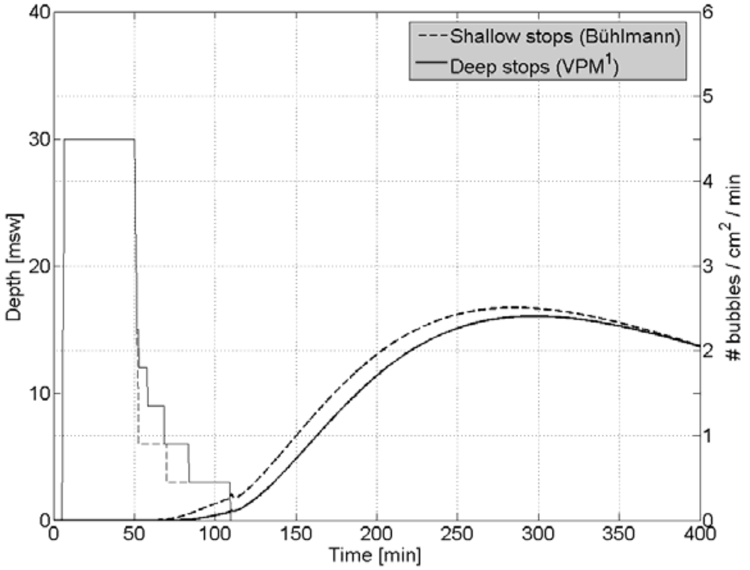


Figure 7: Copernicus simulation of 30 msw / 45 min

Fig. 6 shows a deep/short dive to 51 msw / 15 min where Copernicus predicts the deep stop procedure from VPM to produce more bubbles than the shallow stop procedure. Fig. 7 shows a shallow/long dive to 30 msw / 45 min where Copernicus predicts the deep stop procedure from VPM to produce slightly less than the shallow stop procedure. Note that we tuned the conservatism in V-Planner to achieve the same total decompression time, so we can't judge which algorithm that is best in terms of preventing bubble formation. We can only distinguish between deeper and shallower stops.

Conclusions

A stabilizing mechanism for bubble nuclei, which also expands the bubble actively during the bottom phase, is proposed to be included in the Copernicus model based on the experimental findings in the pig study. "Traditional bubble models" will in general suggest that adding deep stops is beneficial for decompression outcome, however this may not always be true. The current state of Copernicus which is fitted with human bubble data, predicts different benefit of deep stops depending on the length of bottom time. The present paper suggests that deep stops are not recommended on shorter dives but might be beneficial on longer dives. However, there might be adverse effects of decompression that is not related to vascular bubble formation. When Richard Pyle started the practice of deep stops it was not to prevent DCS but rather to get less post-dive fatigue and malaise. Such effects might not be covered by these simulations. Tech divers, who commonly use deep stops in their decompression practice, often perform longer, mixed-gas dives. Following the arguments from this paper, deep stops might be more beneficial in such dives opposed to the short / mid-range air-dives in the presented examples.

References

1. T. S. Neuman, D. A. Hall, and P. G. J. Linaweaver, "Gas Phase Separation During Decompression in Man: Ultrasound Monitoring," *Undersea Biomed Res,* vol. 3, pp. 121-30, 1976.
2. A. Marroni, P. B. Bennett, F. J. Cronje, R. Cali-Corleo, P. Germonpre, M. Pieri, C. Bonuccelli, and C. Balestra, "A Deep Stop During Decompression from 82 Fsw (25 M) Significantly Reduces Bubbles and Fast Tissue Gas Tensions," *Undersea Hyperb Med,* vol. 31, pp. 233-43, 2004.
3. J. E. Blatteau, M. Hugon, B. Gardette, J. M. Sainty, and F. M. Galland, "Bubble Incidence After Staged Decompression from 50 or 60 Msw: Effect of Adding Deep Stops," *Aviat Space Environ Med,* vol. 76, pp. 490-2, 2005.
4. W. A. Gerth, K. A. Gault, and D. J. Doolette, "Empirical Evaluation of the Efficacy of Deep Stops in Air Decompression Dives," in *Annual Meeting Abstracts*, 2007.
5. D. E. Yount and D. C. Hoffmann, "On the Use of a Bubble Formation Model to Calculate Diving Tables," *Aviat Space Environ Med,* vol. 57, pp. 149-156, 1986.
6. B. R. Wienke, "Reduced Gradient Bubble Model," *Int J Biomed Comput,* vol. 26, pp. 237-256, November 1990.
7. O. Eftedal and A. O. Brubakk, "A Method for Detecting Intravascular Gas Bubbles Using 2D Ultrasonic Scanning and Computer-Based Image Processing," *Proceedings of the XVII Annual Meeting EUBS,* pp. 311-16, 1991.
8. D. E. Yount, "Growth of Bubbles from Nuclei," in *Supersaturation and Bubble Formation in Fluids and Organisms*: Tapir, 1989, pp. 131-64.
9. N. M. Harvey, "Physical Factors in Bubble Formation," in *Decompression Sickness* Philadelphia: WB Saunders, 1951, pp. 90-114.
10. D. E. Yount, "Skins of Varying Permeability: A Stabilization Mechanism for Gas Cavitation Nuclei," *J Acoust Soc Am,* vol. 65, pp. 1429-1439, 1979.

11. A. O. Brubakk, "Endothelium and bubble injury: The role of endothelium in decompression illness," in *30th Annual Scientific Meeting of the European Underwater Baromedical Society*, Ajaccio, 2004, pp. 17-22.
12. A. A. Bühlmann, *Decompression-Decompression Sickness*. Berlin New York: Springer-Verlag, 1984.
13. R. Hemingway and E. C. Baker, "V-Planner," 2008.

<u>DISCUSSION</u>: EFFECT OF DEEPER STOPS ON BUBBLE FORMATION

DR. BRUCE WIENKE: Christian, what is the surface tension the 2 gamma term that you're using? What's the surface tension here when you did your simulations?

DR. CHRISTIAN GUTVIK: The exact numerical value? I don't remember, unfortunately.

DR. BRUCE WIENKE: Was it watery or was it fatty? Because it makes a big difference.

DR. CHRISTIAN GUTVIK: I used surface tension from blood because we assume bubbles grow at the endothelial layer. So we only considered vascular bubbles here. So that's the surface tension for both.

DR. BRUCE WIENKE: Can you give me a numerical value for that, roughly?

DR. CHRISTIAN GUTVIK: Not out of my head. But I can dig it up on my computer later.

DR. BRUCE WIENKE: You can send it to me. I just want to make an observation. When you do real bubbles the way you've been doing it, the surface tension comes into play very dramatically, and where you had deep stops, doesn't look so good. For shallow exposures for short times it depends. That particular picture depends crucially on the surface tension. In some of the materials we look at, that surface tension drops down to three or four. And when that happens for shallow dives, you don't get the kind of divergence that you showed on your graph. The surface tension in a real bubble model, not pseudo bubble models, but real ones like you're doing, there's a critical dependence on the staging on 2 gamma. And I think you've shown it very nicely.

DR. CHRISTIAN GUTVIK: Actually, I had done a parameter estimation of that as well. It's very true what you mention. The model gets sensitive to the surface tension. So that's probably the most sensitive parameter we have that will fit the model. Of course, it's quite disconcerting as well because that also means you're very wrong if you estimate it wrong. But that's how it is.

DR. WAYNE GERTH: Thank you, Chris. That's very nice. This is interesting work. But I have a problem. I'm going to ask a question and get your answer, then I have another question. Am I correct in understanding that you're asserting that the probability of DCS is a function of the intravascular bubbles and their volumes? Yes?

DR. CHRISTIAN GUTVIK: Yes.

DR. WAYNE GERTH: Haven't we heard a whole lot of information that vascular bubbles, as we detect them, don't relate to DCS in an individual? So the assumption that vascular VGE caused DCS is unsupported by the evidence.

DR. CHRISTIAN GUTVIK: Yes. But that's also one of my points.

DR. WAYNE GERTH: So I have a problem with the foundation of the model that you're trying to build, and that would bear not necessarily on the final bubbles - bends modeling strategy you're taking, but it would bear a lot on the form of the equations for gas and bubble dynamics that you're going to use in this model.

DR. CHRISTIAN GUTVIK: I'm not sure if I understood that question. Sorry.

DR. WAYNE GERTH: Well, you had this complicated slide, and none of us would be able to understand it real quickly. You showed your bubble dynamics equation. It was on the right side of the slide. I guess my only point is: By virtue of this assumption that you're making, that equation should pertain to vascular bubbles, but yet if these bubbles aren't the ones we know to cause DCS, then you probably have the wrong equation there. That's all I'm trying to say. Once you get the right he equation there, then you're marching down the right path.

DR. CHRISTIAN GUTVIK: There is a correlation. You can't hide from that fact. Actually, I want to address this because we talked yesterday about sensitivity versus specificity. And your concern is that VGE is not very specific in terms of determining DCS. That is true. But let's think hypothetically that you can increase the range of this bubble grade and that you could possibly measure bubble Grade 10. That would result in 100 percent risk of DCS. Of course, that would give you a measure that has a high specificity. But you don't need that because DCS is a low-incidence phenomenon. And you would never, ever test a profile that is even remotely close to having 100 percent risk of DCS. The highest you can test is something in the order of 10 percent. So you have all the specificity that you need because if you test, for instance, a specific dive, 10 exposures, they all get bubble Grade IV, pretty strong data that shows that that's an acceptable risk.

DR. WAYNE GERTH: It all depends. The data you're using is Survanshi and Nishi's compilation of Doppler bubble scores and DCS incidence, which I agree is probably the gold standard for this sort of thing. But as you showed in one of your slides, the highest incidence of DCS I can predict from an observed bubble Grade IV is 12 percent. Now, following from what your last comment yes, normally we don't want to operate in the range of 12 percent DCS risk. But there are places in the diver risk realm that we would want to do so. For example, for a rescue of personnel from a disabled submarine, we would accept a higher risk, 20, 30 percent, as long as we're not killing them, because it's going to be a whole lot better to bend them and treat them than to watch them die in that submarine. So I would disagree that we have all the specificity and sensitivity we need.

DR. CHRISTIAN GUTVIK: Of course, on that particular application, probably this approach isn't suitable. But it is at least for the common recreational exposure.

DR. WAYNE GERTH: I'll just close my comment. Maybe it would still remain suitable if you had the right premise about what bubble dynamics equations you should be using. That's the crux of what I'm getting at.
Thank you. Very nice.

DR. ALF BRUBAKK: The reason why we decided to go to the vascular bubble route is simply that is the only place where there's data. The only data that we have is vascular bubbles. So we decided to concentrate on that and see where that can bring us. We're not saying that it is the final answer. And, of course, given the dual frequency transducer technology that was mentioned here by Neal, it's actually possible to track bubbles. It's not possible in tissue. We have people working on that particular problem in order to try to get more data. Regarding the incidence, it's quite true that in the data that we have we're talking about the maximum of 12 percent. However, the particular dive Christian showed, 54 meters for 20 minutes had an incidence calculated from the amount of gas that we saw of close to 30 percent, using the same type of argument that we were using before. So it's not limited to the 12 percent. It's just the data set. More data would give us more. So this is a principle that's been demonstrated.

DR. CHRISTIAN GUTVIK: Actually, I have a follow-up comment on that. If someone can give me a better marker, I would be ready to just throw VGE overboard and replace my model with a more accurate marker. Unfortunately, we don't have that yet. So I'm just using what we have. So that's where I stand now.

KARL HUGGINS: I'm going to take it from the other direction, from Wayne, which is that I agree that since you're developing this basically for recreational divers, to get zerobubbles is a good goal. But at the same time, if the attitude is if zero bubbles means you're not going to have decompression sickness, then you may have people developing decompression sickness that don't accept that it is because they've got this device that's supposedly producing zero bubbles and, therefore, no decompression sickness.

DR. CHRISTIAN GUTVIK: Yes. Of course, the model itself is not limited to predict zero bubbles. Like any model, there are some fundamentals behind it. You have some data points and you extrapolate them. Of course, at some point, the extrapolation would probably diverge from the real world. But we have data here that's very close to Grade IV. Not many but a few. But hypothetically, you could extrapolate your model so it would be valid, if that answers your question.

KARL HUGGINS: Yeah. It's just that I've seen people that say they shouldn't have decompression sickness because their little graph on their download has no little micro bubbles showing on it, and things like that.

DR. BILL BATEMAN: I'd like to just comment that this dances around an issue which I think is often lost, both in the research community and in the operational community. And I think when we all think about it, we realize this, but it's something that is easy to forget about. And that is that, on one hand, we talk about the risk of bubble formation. On the other, we talk about the risk of decompression sickness. And they're not the same thing. And I think most of us will all sit down and say, of course, of course. But we sometimes confuse ourselves and say, hey, there's bubbles forming; therefore, there must be DCS happening. We have to remember that bubble formation, in our current understanding, is probably just a necessary first step. All the other stuff that we're talking about, conditions, conditioning, immune responses are difficult to study. But we all accept that those things are very real and apply. And we sometimes forget in our models, when we are trying to address the significance of these things, that there's no way, until we start looking at those subsequent steps that we're going to get closer to predicting DCS.

DR. CHRISTIAN GUTVIK: Actually, what you're saying there is one of the strongest motivations to use an objective stress marker. Because all the individual response to the stress is just noise to your model. And you can't control for this when you calculate your procedures. So it just lowers the quality of your data sets. That's individual response that you're talking about. So, of course, like I said previously, VGE is not a perfect marker, but it's at least an objective one and it also removes some noise.

DR. BILL BATEMAN: And this is critically important and why it's worthwhile studying. But as our colleague has also pointed out, the danger is, unless we're absolutely up front about it, we will lose track of the fact that it isn't a perfect marker. Furthermore, the operational benefit later on is to say, look, we will be able sometime to predict other factors that will associate even “zero bubble scores” with unacceptable risk of DCS. And the other way around, “terrible bubble scores”, can be tolerated under certain circumstances because the other factors, once we're able to nail those down, will be less important. Bubble formation will just become one other factor in the development of what we're really interested in; namely, DCS risk.

DR. CHRISTIAN GUTVIK: Actually, I have a small comment on that as well. Let's assume that we found the perfect marker. Even if we had that available, you would still get noise if you look at clinical symptoms because of this individual variability.

DR. DAVID DOOLETTE: Thanks for that, Christian. Nice talk. I particularly liked your suggestion that we drop the "deep stops" terminology. I think it's something we should consider strongly. But I have a technical question. You assumed a regeneration of the nuclei at depth to explain your difference between the short and the long dives, and that's pretty similar to Yount’s idea, assuming a shorter regeneration time than he did. Did you look at any other possible mechanisms that could account for it, like different halftime compartments contributing in a long dive, or have you just looked at that one mechanism so far to explain your data?

DR. CHRISTIAN GUTVIK: How should I answer that? The thing is that I saw a need to add this stabilizing mechanism. Because if you look at, for instance, Gilman, for those who are familiar with his work, they just stop the simulation at, for instance, 1 micron, which is the initial size. I realized there must be something wrong here, so I just added this kind of arbitrary stabilizing function, and it's turned out to explain this difference in the benefit of deep stops.

DR. DAVID DOOLETTE: I was just wondering if you looked at any other potential mechanisms.

DR. CHRISTIAN GUTVIK: But, of course. This is also dependent on the tissue gas upload and the elimination. So if the tissue is fast, they also regenerate faster because there has to be gas present in the tissue for gas to diffuse even at the bottom. There are other things than just time that influence this effect. So hypothetically, if you even imagine that, for instance, exercise workload underwater would also change this effect.

DR. DAVE SOUTHERLAND: It's more of a general question. You've got a vascular model. You're going to a tissue-based model. That seems to be what I'm hearing. For these avascular bubble models that people are going to be developing, are you going to end up testing those with an outcome of DCS or Doppler. One of the reasons why we've had to go to Doppler is we're not allowed to use DCS as an outcome measure. Have you got a new technology, or are you just going to end up checking that against your Doppler bubble scores for your vascular? Is your outcome measures to compare which one is better, or does this mean you're going to make a step back and take people to decompression sickness to see if it's a more useful test than the Doppler scores? That was a little bit unclear. Translate for me, please.

DR. ALF BRUBAKK: I think one very important point is that we know, because of the work that we've been doing, we now have at our disposal methods that very easily can prevent formation of vascular bubbles more or less totally. We've shown it in the experimental animal species. We've shown it in man. The question is, does that make a safe profile? And we're able to test that. We can look for changes in various biochemical factors. We can look at x-ray. We can look at MRI. Things like that. But the trick here is that by using the Doppler system and the methods, that we have, we're actually able to test the hypothesis that preventing vascular bubble formation can that make a dive safe. So that’s the most important thing -- consequence of this, I think.

DR. SIMON MITCHELL: All right. Thank you very much, Christian. Very good presentation. Good discussion. Thank you, everybody. It's time to move on to the next presentation.

DR. SIMON MITCHELL: This gentleman requires no introduction really, Peter Bennett. A long history in this field, probably longer than all of us in this room. Currently, the executive director of the UHMS and prior to that, as everyone knows, the president and CEO of DAN over a period of some 20 years. A very widely published gentleman in this field, and he's going to present today on I-DAN deep stop research for recreational divers. Thank you very much, Peter.

INTERNATIONAL DAN DEEP STOP RESEARCH FOR RECREATIONAL DIVING

Peter B. Bennett

ABSTRACT:

The predominant signs and symptoms of decompression sickness (DCS) in recreational divers are pain (23.9%), numbness (22.0%) and weakness (7.2%) and are of a neurological nature indicative of spinal cord involvement rather than joint pain. The incidence of DCS has changed little over the past decades (0.04-0.07%). Review of the history of ascent profiles shows that the 1906 Haldane 2:1 staged ascent was far superior to the Hill linear ascent. Yet today we are still making linear ascents, plus only a shallow stop at 3-5 m for 3-5 mins. Since the UK and US Navy divers experienced mostly joint pain DCS, they considered the problem was in the joints with their poor blood supply which saturated or took up gas very slowly. Haldane's (1906) model of the body had 5 compartments (or exponentials) representing very full blood supply as in the brain and spinal cord at 5 min, 10 min, 20 min, with 40 min, 80 min and 120 min (representing poorer blood supply like the joints). But the recreational diver's problem is in the fast tissue spinal cord with 12.5 min half time, not the slow joint 120 min. It is proposed, therefore, that we now ascend far too rapidly and cause bubbles to form deep. Working with Italian divers in the Mediterranean and an IDAN team of physicians and scientists, we hypothesized that introduction of a deep stop at half the depth would reduce the deep bubble formation and decompression risk in the spinal cord. A total of 181 dives were made to 25 m (82 fsw) by 22 volunteers with 8 different ascent protocols. Ascents of 3, 10, or 18 m/min (10, 33 or 60 fsw/min) were combined with no stops, or a shallow stop at 6 m (20 fsw) or a deep stop at 15 m (50 fsw) and shallow stop at 6 m (20 fsw). Bubbles were detected by Doppler over the heart after reaching the surface. These experiments indeed showed the highest gas loads were in the fast compartments (5 and 10 min), not the slow. More importantly, the lowest bubble scores were with an ascent rate of 10 m/min (33 fsw/min), not 3 m/min (10 fsw/min). Stops were best for 5 min at 15 m (50 fsw) and 6 m (20 fsw). More recent additional research has shown, in fact, that the best stop time for the deep stop is 2 ½ mins at half the depth. The one minute stop recommended by some training agencies is too short. We, therefore, recommend a deep stop at half the depth of 2 ½ mins followed by the customary 6 m (20 fsw) for 3 to 5 mins. While the direct correlation with signs and symptoms of DCS has not yet been made, this still does constitute a definite decrease in decompression stress.

PAPER:

The deep stop research to be described is related to recreational SCUBA diving to depths of 130 fsw by a team of International DAN physicians, researchers and divers over the last seven years (1-3). It was started because in spite of numerous different theories and algorithms and many different dive tables, the incidence of decompression sickness (DCS) has remained surprisingly constant in this dive population between 0.04-0.07%.

This is considered as possibly due to the present decompressions not permitting sufficient time to eliminate enough accumulated nitrogen during certain deep phases of the ascent. As a result, supersaturation occurs with the growth of bubbles in the spinal cord leading to neurological DCS.

Many of the decompression methods used today are based on the 100 year old hypotheses of Haldane (4) which related to gas uptake and elimination to different exponentials. Haldane proposed that there was a set of 5 exponentials for 5 "tissue half times" or compartments of the body. These were 5 mins, 10 min, 20 mins, 40 min and 75 mins. The 'fast' compartments of 5, 10 and 20 mins may be associated with well perfused tissues like the brain and spinal cord. Conversely the 'slow' compartments, 40 and 75 mins, would be associated with poorly perfused tissues like the joints and bone.

In the years prior to 1960 most diving was carried out by the world's navies. The US Navy reported DCS occurred while diving. However, it presented as 90% with pain only symptoms in the joints (DCS I) and neurological symptoms only 10% (DCS II).

Therefore prevention was directed to the slower compartments or tissue half times as responsible and these were modified with even slower tissue half times added in attempts to prevent supersaturation and DCS. For example, the Buehlmann decompression tables (5) had as many as 16 compartments, the longest with a half time of 635 mins.

The 'fast' compartments, on the other hand, were mostly ignored as it was believed it is possible to come safely to the surface at 60 fsw/min from a 100 fsw dive for 25 mins with little risk of DCS.

However, in recreational divers today, DCS is mostly neurological in nature (DCS II) not just pain (DCS I) in the joints. This points to the 'fast' tissues as the probable site (6), such as the spinal cord with a tissue half time of only 12.5 mins.

This is due to the very different kind of diving profiles made by recreational divers compared to the early navy divers. Today, recreational dives are often short deep square dives compared to the long shallow dives of the navies involving harbor clearance, painting ship bottoms, etc.

If we consider a dive to 100 fsw for 25 mins, the 'fast' 5 min compartment is 97% saturated in that time (Table 1).

Table 1. It will take 6 cycles to fully saturate this compartment. In 30 mins the 5 min tissue is 99% saturated.

Tissue Halftime 5 min (fast)

1. 5 mins	50% full
2. 10 mins	75% full
3. 15 mins	87.5% full
4. 20 mins	93.8% full
5. 25 mins	97% full
6. 30 mins	99% full

NEED SAME OR LONGER TO FULL DESATURATION!

However, if we now consider a slow 60 min compartment (Table 2), it is only 50% saturated even after 60 mins exposure.

Table 2. Compared to Table 1, the slow 60 min compartment is only 50% saturated even in 60 mins.

Tissue Halftime 60 mins (slow)

1. 60 mins	50% full
2. 120 mins	75% full
3. 180 mins	87.5% full
4. 240 mins	93.8% full
5. 300 mins	97% full
6. 360 mins	99% full

Therefore, in a rapid ascent from a dive, the ‘fast’ fully saturated tissue is more likely to produce bubbles than the slow and more decompression time deep may be required for a safe ascent. Indeed, the original Haldane decompression table (4) for such a dive included stops at 30, 20 and 10 fsw for a total time of 19 mins.

Yet today, typical ascents from such a dive are 30 fsw/min with a ‘safety stop’ only at 15 fsw for 3-5 mins. In fact, the diver is back on the surface in only 6 mins. Uptake of gas into the body therefore took 25 mins plus descent time compared to only 6 mins for elimination. Yet it is widely accepted that elimination of gas during ascent requires more time than uptake during the dive. But, at what depths should the stops be made and how long should be the stop?

A further observation in Haldane’s research in 1908 (4) was that a pressure reduction could be made safely from an absolute pressure P_1 to a lower pressure P_2 by a ratio of 2:1. Therefore, a diver could come from 4 to 2 ata or 6 to 3 ata, for example, without much risk of supersaturation, bubbles and DCS. This, in fact, was not utilized in his decompression tables because he believed that the very high pressures deep would prevent bubble formation and so he kept his stops shallow.

On the other hand, Sir Leonard Hill (7), who also was interested in the early 1900’s in trying to develop safe decompression schedules for the Royal Navy, believed that the safest method was a slow linear ascent to the surface with no stops at all. This is very much like recreational SCUBA divers during the past decades, except for more recently the added shallow “safety stop” for 3-5 mins at 10-20 fsw. But in a comparison in 1907 between the Haldane stop methods and Sr. Leonard Hill’s linear ascent, the goats that were used favored Haldane as linear ascent produced much DCS.

The UK and U.S. Navy in 1956 empirically settled on a safe linear ascent rate of 60 fsw/min. More recently this was reduced to a linear 30 fsw/min. When this still resulted in DCS, a single brief shallow “safety stop” was introduced for 3 to 5 mins at 15-20 fsw, based on reduction of bubbles detected by a precordial Doppler.

However, DCS still occurs in recreational divers at levels of 0.04-0.07% and, as discussed earlier, is primarily neurological or DCS II rather than pain only.

Pearl divers historically and more recently technical divers introduced a deep stop into their decompression procedures to stop or reduce DCS with apparent success (8). Further, Marroni, et al. (1) used ‘black box’ depth-time recorders to predict tissue gas tensions with the diver unable to see the data being collected. The occurrence of precordial bubbles was measured post-dive by Doppler. In 1418 SCUBA dives, 85 of them produced bubbles and 67% were high bubble grades (i.e. Spencer 3 or 4).

Using Buehlmann algorithms (5) the peak nitrogen tensions were determined for the various tissue compartments. It was found that the presence of bubbles was directly related to the critical supersaturation in the faster (5-20 min) tissues rather than the slower compartments which predicted the need for a deep stop.

Accordingly, a matrix (Table 3) was developed of experimental ocean SCUBA dives to 82 fsw (25 m). The matrix involved three rates of decompression, i.e. 10, 33, or 60 fsw (3, 10, 18 m/min) with either no stops, only one at 20 fsw (6 m) or stops at both 20 fsw and 50 fsw (6 and 15 m), thus incorporating a Haldanian deep stop at half the absolute depth (Table 3).

As previously, blacked out UWATEC depth-time recorders were used to predict tissue gas tensions and precordial doppler was used to determine the presence of bubbles on return to the surface.

Table 3. Matrix of Experimental Dive Profiles

Profile (Code no. for dives)	Depth (m)	Time (m)	Ascent Speed m/min	Stop @ 15 m	Stop @ 5 m	Total Ascent Time (min)
1 (13)	25	25	10	0	0	2.5
1R (11)	25	20	10	0	0	2.5
2 (13)	25	25	3	0	0	8
2R (12)	25	20	3	0	0	8
3 (15)	25	25	18	0	5	6.5
3R (12)	25	20	18	0	5	6.5
4 (16)	25	25	10	0	5	7.5
4R (10)	25	20	10	0	5	7.5
5 (13)	25	25	3	0	5	13
5R (13)	25	20	3	0	5	13
6 (13)	25	25	10	5	5	12.5
6R (12)	25	20	10	5	5	12.5
7 (7)	25	25	18	5	5	11.5
7R (7)	25	20	18	5	5	11.5
8 (7)	25	25	3	5	5	18
8R (7)	25	20	3	5	5	18

From Marroni, Bennett, Cronje, et al. Undersea Hyper Med 2004

The hypothesis to be tested was that by combining a deep and shallow stop, and avoiding supersaturation in the "fast" tissues, a significant reduction in Doppler recorded bubbles would occur with a reduction in decompression stress and possibly also the neurological DCS seen in recreational diving.

A total of 181 dives were made to 82 fsw (25 m) by 22 volunteer divers using the matrix in Table 1 with 1086 doppler recordings. The doppler data obtained is shown in **Figures 1a** and **b (2)**.

Figure 1a: Doppler Grade Variation (ESS) after each dive profile

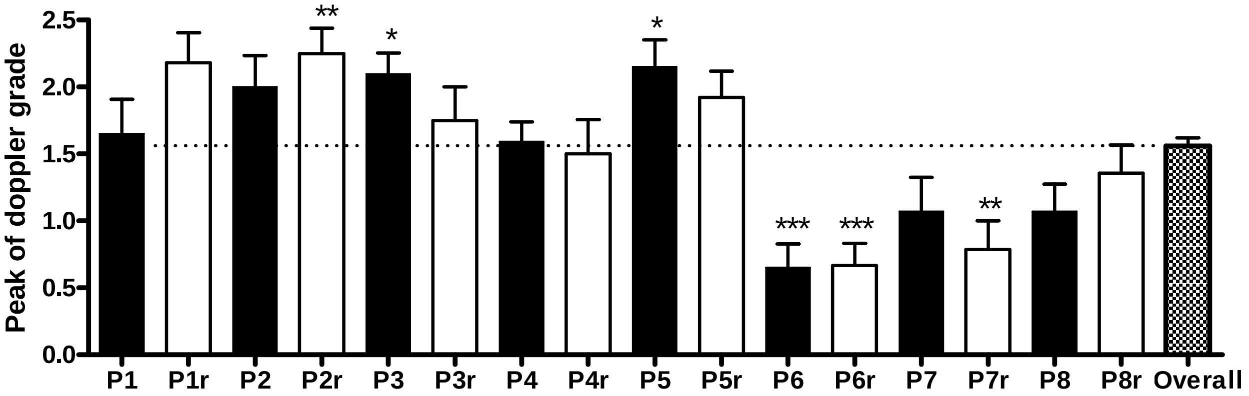
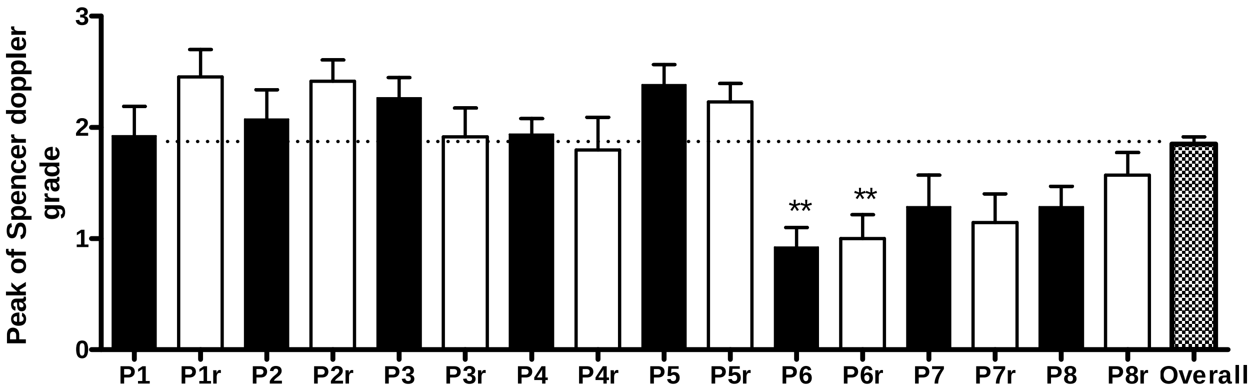


Figure 1b: Doppler Grade Variations (SS) after each dive profile



The comparison of means has been done computing the peak Doppler scores for each individual after each dive profile according to the Expanded Spencer Scale (ESS) and Spencer Scale (SS). The means have been compared using parametric tests when possible after KS normality testing (ANOVA with Neuman-Keuls post tests) and Kruskal-Wallis and Dunn's post test when the normality testing does not allow parametric evaluation. By accepting a ESS score of 1.5 and an SS score of 2 as "safe", it can be seen that the deep stop appears "safer" using both ESS and SS scales, while repetitive profiles 1,2,3 and 5 are "unsafe".

From Marroni, Bennett, Cronje, et al. (2004)

In Figure 1a it can be seen that the highest bubble score is in profile 2/2R using a slow linear ascent of 3 m/min (10 fsw/min). On the other hand profile 6/6R with a deep stop of 5 min at 15 m (50 fsw) and a shallow stop of 5 min at 6 m (20 fsw) at an ascent rate of 10 m/min (30 fsw/min) had the lowest bubble scores.

The average surfacing saturation percentage for the fast 5 and 10 compartments compared to their Doppler bubble score index (BSI) is shown in Table 4.

Table 4. Fast Tissue Saturation and Bubble Scores after the Different Dive Profiles

Ascent Rate	Stops	Average surfacing saturation (%): 5 min Tissue	Average surfacing saturation (%): 10 min Tissue	BSI (ESS/SS)	Total Time to Surface minutes
3 m/min (Profile 2)	No Stop	48	75	8.78 / 9.97	8
3 m/min (Profile 5)	6 m/5 min	30	60	8.10 / 10.04	13
3 m/min (Profile 8)	15 + 6 m/5 min	22	49	3.50 / 4.53	18
10 m/min (Profile 1)	No Stop	61	82	7.51 / 8.46	2.5
10 m/min (Profile 4)	6 m/5 min	43	65	5.39 / 7.07	7.5
10m/min (Profile 6)	15 + 6 m/5 min	25	52	1.79 / 2.50	12.5
18 m/min (Profile 3)	6 m/5 min	42	60	7.41 / 8.78	6.5
18 m/min (Profile 7)	15 + 6 m/5 min	28	55	3.25 / 4.64	11.5

From Marroni, Bennett, Cronje, et al. (2004)

This shows that this lowest bubble score in Profile 6 is not due to the longer total time to surface of 12.5 mins, but it is among the lowest for surfacing saturation in the 5 and 10 min tissues with the lowest BSI of 1.79/2.50. This compares with profile 5 with a total linear ascent time of 13 mins and only a shallow stop but a BSI of 8.10/10.04 and high surfacing saturation percentages. It would seem that the deep stop has been very effective in reducing “fast” tissue tension bubbles.

This is endorsed by Table 5 which gives the incidence of Doppler detected bubbles in four grades: 0 (none), Low Grade, High Grade, and Very High Grade compared to the BSI. It is pertinent that in the presence of the deep stop in profiles 6, 7 and 8, with a deep stop, the percentage of High or Very High Grade bubbles is zero or very low compared to the other profiles. The highest bubble grade is seen in profile 2 which used a linear ascent of 3 m/min (10 fsw/min) with no stops. Research elsewhere (9, 10) indicates that high grades of bubbles do correlate with an increased risk of DCS. Further, this reaffirms the failure of the Sir Leonard Hill 1908 linear ascent studies with goats to prevent DCS compared to the success of Haldane.

Table 5. Incidence of Doppler Detected Bubbles for the Different Dive Profiles

Dive Profile	***BSI*** **(ESS / SS)**	**Grade 0 %**	**Low Grade %**	**High Grade %**	**Very High Grade %**
1 – 1R	7.51 / 8.46	9.7	63.9	17.4	9.0
2 – 2R (worst)	**8.78 / 9.97**	**10.0**	**50.6**	**19.4**	**20.0**
3 – 3R	7.41 / 8.78	16.0	56.2	19.8	8.0
4 – 4R	5.39 / 7.07	18.6	62.8	10.9	5.7
5 – 5R	8.10 / 10.04	5.1	65.4	19.2	10.9
6 – 6R (best)	**1.79 / 2.50**	**64.7**	**33.3**	**2.0**	**0.0**
7–7R (2nd best)	*3.25 / 4.64*	***34.5***	***64.3***	***1.2***	***0.0***
8 – 8R ***(3rd best)***	*3.50 / 4.53*	***33.3***	***63.1***	***3.6***	***0.0***

Nevertheless further research is required before a direct correlation can be made of a reduction in the incidence of DCS as a result of these low bubble scores resulting from the use of a deep stop.

The times utilized in this research for the deep stop and shallow stop were 5 mins each. Some training agencies suggested instead a 1 min deep stop and 2 min shallow stop. As a result, additional research has been carried out to determine the optimal times for each stop to reduce bubbles.

The same methods were used as with the previous matrix. In this next research 209 dives were made to 25 m (82 fsw) for 25 min breathing air by 14 Italian divers (3) with varying times for the deep and shallow stops. There were three groups of profiles. Profiles 1-5 had deep stop times from 0 to 2 mins. Profiles 6-10 were all 2.5 min deep stops with the shallow stop gradually decreasing from 5 min to 1 min. Profiles 11-15 had deep stops ranging from 3 to 10 mins.

Table 6 shows the results on the BSI of various deep and shallow stop times with the total ascent time.

Table 6. Bubble Score Index for various deep (15 msw/50 fsw) and shallow (6 msw/20 fsw) stops on ascent from 25 msw (82 fsw) at 10 msw/min (33 fsw/min)

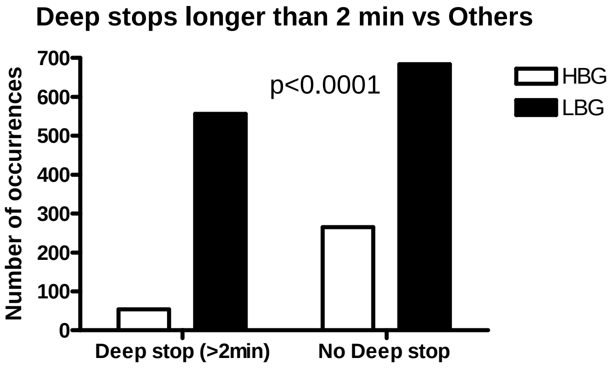
Profile No.	Dives	Depth (m)	15 m Deep Stop (mins)	6 m Shallow Stop (mins)	T Time	BSI
1	24	25	0	0	2.5	7.98
2	26	25	0	5	7.5	6.23
3	21	25	0	10	12.5	5.48
4	16	25	1	3	6.5	8.04
5	18	25	2	3	7.5	3.98
6	24	25	2.5	5	10	2.23
7	7	25	2.5	4	9	2.71
8	6	25	2.5	3	8	3.58
9	6	25	2.5	2	7	2.58
10	7	25	2.5	1	6	3.36
11	8	25	3	2	7.5	4.94
12	8	25	3	1	6.5	5.63
13	25	25	5	5	12.5	2.14
14	4	25	5	2.5	10	5.5
15	9	25	10	0	12.5	2.89

From Bennett, Marroni, Cronje, et al. 2007

The profiles with the lowest BSI were with a 2.5 min or more deep stop at 15 m (50 fsw), i.e. profiles 6-15. Shorter stops (0-2 min) as in protocols 1-5 had higher bubbles scores. Longer times as in profiles 11-15 gave no further advantage

That this data is statistically significant is shown in Figure 2. Comparison of the number of High and Very High grade bubbles for profiles with a deep stop greater than 2 min compared to no deep stop is at $p < 0.004$ by the Fischer exact test (12).

Figure 2. shows the statistical significance comparing a deep stop longer than 2 minutes versus no deep stop ($p < 0.0001$). However, if the comparison is done for deep stops overall (even less than 2 minutes) the difference is still at $p < 0.004$ by Fisher exact test (12).



The tissue compartment gas saturation percentages for the 5, 10, 20 and 40 tissues calculated from the blacked out computers worn by the divers is shown in Table 7.

Table 7. The calculated tissue compartment gas saturations for the various stop times are shown from data recorded by the UWATEC computers worn by the divers during the dives.

Profile	Stops (Mins) Deep	Stops (mins) Shallow	Tissue Compartment Gradients (1/2 T mins)				BSI
			5	10	20	40	
1	0	0	61	82	81	64	7.98
4	1	3	44	62	70	71	7.38
12	3	1	51	69	76	77	5.63
14	5	2.5	40	61	72	76	5.50
2	0	5	43	65	69	58	5.39
11	3	2	46	65	73	74	4.94
3	0	10	30	49	62	68	4.93
5	2	3	40	56	67	71	3.72
8	2.5	3	42	62	72	77	3.58
10	2.5	1	49	68	75	78	3.36
15	10	0	46	66	78	84	2.89
7	2.5	4	39	64	76	81	2.71
9	2.5	2	41	61	72	78	2.58
6	2.5	5	35	51	64	70	2.23
13	5	5	29	57	70	63	2.14

Profile 13 with 5 min deep and shallow stops has the lowest BSI of 2.14 and lowest 5 min tissue saturation at 29 percent. A 2.5 min deep stop and 5 min shallow (profile 6) also showed a low saturation of 25 percent and BSI of 2.23. However, lengthening the shallow stop to 10 mins with no deep stop had a saturation of only 30 but a BSI of 4.93. So lengthening the shallow stop alone was ineffective in reducing bubbles.

Conclusions

On the basis of this data, it was concluded that the optimal deep stop time following a 25 m (82 fsw) dive for 20 to 25 min to prevent precordial Doppler bubbles is 2.5 mins at 15 m (50 fsw). Shorter or longer times were less effective. The shallow stop at 6 m (20 fsw) for 3-5 mins presently used by divers does not seem so vital if a deep stop is taken, but is still recommended. However, longer times in the shallow stop do not seem to afford additional benefit.

The present data does not support the NAUI recommendation (13) that divers should take a 1 min stop at half the depth and a 2 min stop at 20 fsw (6 m) as shown by Profile 4. This profile has a high BSI of 7.38 which is virtually the same as Profile 1 with no stops at 7.98.

There have been many different algorithms and decompression models developed towards safer diving ascents after diving. For recreational SCUBA diving, we appear to have been relying on too brief linear ascents which had been proved ineffective as long ago as 1906. While the shallow safety stop is effective in reducing bubbles already formed, it would seem better to stop bubbles before they form deep and growing bigger according to Boyles Law during the rest of the ascent. Thus, a deep stop at half the absolute depth for 2 ½ mins plus a shallow stop for 3-5 mins at 6 m (20 fsw) appears effective in stopping or significantly reducing bubbles and thereby possibly reducing the risk of DCS in recreational SCUBA diving.

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References

1. Marroni A, Cali Corleo R, Balestra C, Longobardi P, Voellm E, Pieri M, Pepoli R. The use of a Proportional M Value Reduction Concept (PMRC) Changing the Ascent Profile with the Introduction of Extra Deep Stops Reduces the Production of Circulating Venous Gas Emboli After Compressed Air Diving. Proceedings European Undersea Biomedical Society Annual Scientific Meeting, U Van Laak, ed, p 69-73. September 12-16, 2001, Hamburg.
2. Marroni A, Bennett PB, Cronje FJ, Cali Corleo R Germonpre P, Pieri M., Bonuccelli C, Balestra C. A deep stop during decompression from 82 fsw (25 m) significantly reduces bubbles and fast gas tissue tensions. Undersea Hyperb Med 2004; 31(2):233-243.
3. Bennett PB, Marroni A, Cronje FJ, Cali Corleo R, Germonpre P, Pieri M. Bonuccelli C, Balestra C. Effect of varying deep stop times and shallow stop times on precordial bubbles after dives to 25 msw (82 fsw). Undersea Hyperb Med 2007; 34(6):399-406.
4. Boycott AE, Damant GCC, Haldane JS. The prevention of compressed air illness. J Hyg Comb 1908; 8:342-443.
5. Buehlmann AA. Decompression theory: Swiss Practice. In Bennett PB and Elliott DH, eds. The Physiology and Medicine of Diving. 4th edition, London, Saunders. 1993; 342-375.

6. Edmonds C, Lowry C, Pennefather J. Historical and physiological concepts of decompression. In Diving and SubAquatic Medicine. Butterworth-Heinemann, 1992; 140-158.
7. Hill L. Caisson Sickness and the Physiology of Work in Compressed Air. London: Arnold, 1912.
8. Wong RM. Empirical diving techniques. In Bennett and Elliott's Physiology and Medicine of Diving 5th Edition. Brubakk, AO and Neuman TO, eds. Sanders, London, 2003; 64-76.
9. Nashimoto I, Gotoh Y. Relationship Between Precordial Doppler Ultrasound Records and Decompression Sickness. In CW Shilling, MW Beckett, eds. Undersea Physiology VI. Undersea Medical Society, Bethesda, 1978; 497-501.
10. Nishi RY, Brubakk AO, Eftedal OS. Bubble detection. In Bennett and Elliott's Physiology and Medicine of Diving. 5th Edition. Brubakk, AO and Neuman TO, eds. Sanders, London, 2003; 501-529.
11. Bennett PB, Marroni A, Cronje FJ, Cali Corleo R, Germonpre P, Pieri M, Bonuccelli C., Leonardi MG, Balestra C. Effect of varying deep stop times and shallow stop times on precordial bubbles after dives to 25 msw (82 fsw). Undersea Hyperb Med 2007;34:399-406
12. Agresti A. A survey of exact inference for contingency tables. Statistical Science 1992; 7(1):131-177.
13. Gentrup G. A tenet of diving fine tuned. Two safety stops now urged for divers exceeding 40 feet. Dive Training. June 2003; 16-17.

DISCUSSION: IDAN DEEP STOP RESEARCH FOR RECREATIONAL DIVERS

DR. PETER BENNETT: I would just add that it's unfortunate that we have lunch between us because Dr. Marroni's presentation is almost a follow-on to mine, and I would have ideally had him talk immediately after me, and then we would have the discussion. But it's not going to be that way.

DR. SIMON MITCHELL: So questions for Dr. Bennett.

DR. DAVID DOOLETTE: It's a shame you're not going to put them together to discuss this because I've got a question about the manuscript, about your paper, about how you treated repetitive dives. In the paper that describes the second study that you just described, it says that some of the dives were actually repetitive dives. It says that they're indicated in the manuscript with asterisks, but the printer seems to have left those out. I was a referee of the paper, and I have my review copy which has those in. So you obviously put them in originally, and they got lost. It looks like a lot of your high bubble grades were associated with the dives that were repetitive. I was wondering how you dealt with that.

DR. ALESSANDRO MARRONI: Yes, some of the dives were repetitive, and actually we have the split data for either the first or the rep. The fact is, the data we had from both the single dive and the repetitive dives didn't differ that much. So we just grouped the data together, and a dive and a rep was considered a normal dive that a recreational diver would do. So this is how we did it. But if you are interested in the source, I can give them to you.

DR. DAVID DOOLETTE: So you had similar bubble scores.

DR. ALESSANDRO MARRONI: Yes, very similar. I will present later on this afternoon. I will present data which will show a difference in the first dive and rep dive, but they do not belong to this set of dives.

DR. DREW RICHARDSON: Peter, I would just qualify saying “what doesn't work”. If you're going to get up and speak on the recreational window, since 1988, we've instituted the S.A.F.E dive (slowly ascend from every dive - eds) campaign. There's 12 million people trained on it. They are slowing their ascents and they are taking a safety stop. As you'll recall, it cured the world of venous gas embolism and other things we were worried about at the time. With the advent of the AEES workshop and the computer launch in the dives in the no-stop recreational envelope, generally people have slowed down and we've reduced the incidence of DCS, I think, remarkably. A denominator is always a problem, but even if you just take what occurs in the training scheme annually, just the PADI experience, which last year just for entry level resulted in 564,000 times four required dives, there's 2,200,000 right there. The incidence seems reasonable for this end user. When we start talking about other risks with other modalities of diving, different story. But I don't think the outcomes are particularly unacceptable. I think, generally, things have gone in the right direction. Now, whether, for the average punter, two and a half minutes, somewhere halfway between maximum depth and the surface is pragmatic is another whole argument. I know some computer algorithms are already accounting for that, and maybe that's the solution. But what's occurring now is quite intentional, and I think we should celebrate a little bit. We always want it to get to zero. It will never be zero, but we've made a contribution in the last 20 years. Things have gone in a better direction for this particular community. So it's cost benefit to whether or not somebody can actually work this out. Maybe computers will help divers do this if this is the direction it goes. And then I'm not sure on your recommendation here, what your ascent rate recommendations are.

DR. PETER BENNETT: Thirty foot a minute.

DR. DREW RICHARDSON: Right now the range is 10 to 18 meters a minute. It seems to be working reasonably well. I just want to make that observation that we're dancing on the head of a pin a little bit, too.

DR. PETER BENNETT: I take your point, Drew. And I think that's true. We have certainly become much safer in our diving. I don't want to suggest that from a recreational diving point of view, we have a lot of decompression sickness. We don't. But DAN records 1,000 cases a year, and if you happen to be that case that has a spinal DCS hit, it's unfortunate. Our motive was just to see if we could reduce that to a somewhat lower level by reducing bubbles by putting in a deep stop. Our data suggests you can reduce bubbles significantly by making that simple move in the recreational mode. Now, we know that as we go deeper as, you'll hear later on from Dr. Marroni, as you go deeper, it doesn't seem to hold. Whether that's because the duration of that deep stop or what, we don't know yet. That would be further work. So it's only within a simple framework. You'll also hear as you go shallower, it doesn't work. I'm not surprised at that because as you go shallow, you're moving into the longer times of dives where you're getting the pain only becoming more prevalent.

DR. ALF BRUBAKK: I'm a little disturbed about the fact that you're actually giving such precise advice on what the divers should do. You seem not to take into account that the data are variable. I mean, some get a benefit from deep stops, some do not get a benefit. When we first got into this, we thought, as you did, that the deep stop would be beneficial until we actually tested it and saw that different types of dives had vastly different results. Not only different results, but sometimes deep stops turned a dive that produced very little bubbles into a dive that produced a lot of bubbles. So that's why we came up with the suggestion that the duration of the bottom time seems to be a critical factor. So in respect of giving general advice like this and saying that this is what divers should do; it's based on your experimental data, but there are other data around that would say that this is a bit too exact. It's not as exact as you seem to indicate here.

DR. PETER BENNETT: For the deeper and the longer duration dives, that may be so. But for the average kind of diving that people do within the NDL limit, we think it's acceptable. We're not saying all things to all people, no.

DR. NEAL POLLOCK: A few comments, one to Drew's. Training dives were mentioned yesterday. There may be two million of them, but odds are those profiles have the potential to be a lot less extreme than what the recreational diver might do once he or she is off on their own diving. So I think we have to be careful with those data. My question to Dr Bennett. You spoke a lot in the presentation about the reduction in pressure by half. But now you're talking about the reduction in absolute depth, which is not the same.

DR. PETER BENNETT: Yes, I understand that.

DR. NEAL POLLOCK: So this is a very different animal. When you're talking about a 100-foot dive, you're half the depth, 50 feet, of course, but half the pressure is a lot less. So I'm wondering why this logic.

DR. FRANS CRONJE: The decision of half the depth was really to give a practical approach. It's inherently an observational study. So the original profiles that this particular presentation represents were all 25-meter dives. And at that stage, it was simpler to just have a half-the-depth approach. And then when we started asking additional questions and going to deeper depths, we still needed to concentrate on what would be a practical thing for people to keep in mind. Again, it was observational, so it was an empirical choice, and we're just employing what we saw. How we ultimately apply these recommendations really will be a combination of political and scientific debate. All that is saying is that's what we did and that's what we saw.

DR. NEAL POLLOCK: I think this just echoes Alf's comment that this is a very limited number of data to make the general recommendation. And that could potentially be problematic.

DR. FRANS CRONJE: I would agree, we are not extrapolating beyond the observation related to this particular dive. I think it's unfortunate that we're having this discussion before seeing the additional elements of the profiles that were examined. But I would certainly support the fact that we cannot extrapolate beyond the parameters that were tested. All we saw was that within this particular dive profile and series of dive combinations and stop combinations, it seemed that this configuration was optimal as determined by precordial Doppler measurements.

DR. RICHARD VANN: I want to address the issue of 70 or 80 percent Type II DCS. First of all, that's rather old, and we don't see that much right now. Secondly, Type II DCS is a mixed bag. A lot of that is very trivial stuff. Any kind of mild neurological symptoms get thrown into that category. There's no evidence that this is spinal. This was one of the issues addressed in the remote DCS workshop. That if you have mild neurological symptoms, no problem at all. I think you have to dissect out the serious symptoms from the mild ones. If you look at the more recent DAN data, we've made an attempt to do that. And there's not all that much serious decompression sickness out there. It's all fairly fluffy.

DR. PETER BENNETT: Nevertheless, you show 70 percent DCS II, and 30% DCS I in your DAN data.

DR. RICHARD VANN: Life is different nowadays, I guess.

DR. PETER BENNETT: I don't think that's the case.

AUDIENCE MEMBER: You're giving a practical recommendation for recreational divers, and you've seen that changes in depth and time can give you different results. "Practical" means that people will apply it without thinking too much about it. How many people actually do square profiles to 25 meters? Probably very few. If you have a maximum depth of 25 meters, and then you do a different profile, and then you start stopping at 15, based on what you have shown, it could actually be not so beneficial. How do you actually implement this recommendation in a way that works for the general public?

DR. PETER BENNETT: I'm not implementing it. All we did was a research study that we found the data we have at 25 meters. Bruce has done an analysis with his model, which shows that, in fact, this does work under his model, and they want to use it. That's up to them to do. I'm not professing anybody should use it necessarily without doing the further analysis that Bruce has done, which enabled NAUI to make their decisions. Other organizations must do that in the same way.

AUDIENCE MEMBER: Because this is published material, and people might read it and get the impression that it works.

DR. PETER BENNETT: The data is what it says.

TIM O'LEARY: I just want to clarify we're not *trying* to do it; we have done it. The board has approved it. It was a one-minute stop, and we implemented that since about, 2002 when the NAUI recreational large tables first came out. Now we've implemented it at two and half minutes. We're recommending these for hard tables. This is not computer based. If the diver is coming up slow enough along the reef, we don't recommend a two-and-a-half minute stop. I think the computers take care of that. However, for the hard tables, we are recommending the two-and-a-half-minute stop at half pressure.

DR. ALESSANDRO MARRONI: We are not recommending divers to do anything. We're just reporting. And we have been very careful in not only our scientific papers, but also communications to the diving community, to specify that this was a result limited to what we were saying. And this is not yet a recommendation because the research is going on. With respect to the comment made by Angelini, there are very few ways to study multi-level dives other than having millions of dives to study, and this is what we are doing with Project Dive Exploration. But when you are doing something different, you have to define certain saturation of tissue and other parameters. So the square dive profile is a good tool to start with. I would also like to remind you that most of the recreational dives today in the Caribbean or in the Maldives are actually multi-level, almost square to deep stop to shallow stop safety stop profiles. So this is what we are really seeing. The dives that are dived in the Caribbean and Mexico and the Maldives are very, very much like this kind of profile. Actually most of the dive leaders accompany divers down to 30 meters. The average dive in these environments is about 40 to 45 meters, air, no D. The bottom time is 10 to 15 minutes. They come up at a plateau around 15 meters. They spend some time there and then they are brought to the safety stop, and they spend another five to six minutes there. So what we are doing is very much similar to what millions of divers do every day nowadays. So this is one of the reasons behind why we chose this empirical model.

DR. PETAR DENOBLE: I'm not going to dispute the academic value of this research. I would just like to invite you to set some criteria. What are we trying to improve? I would remind you of Blatteau, who presented here, that in dives less than 40 meters, the incidence of DCS was one case out of 30,000 dives. And in dives deeper than 40 meters, it was one out of 3,000 dives. We have seen something similar in the recreational diving. I don't have a completely clear view before we finish analysis. But the collection of DCS cases that we have with the Project Dive Exploration documented dive profiles show that a lot of these recreational diving cases would be what Ed Thalmann used to call "population noise." So although DAN records 1,000 cases among recreational divers annually, I would still say we still have very low incidence, and it's not clear whether improving the decompression procedures in these shallow dives would impact dive safety. Also, when we say we would want to improve dive safety, then we should look at clinical trials, where we say, if we will make 30 percent difference in outcomes, then it's meaningful improvement. It's hard to choose the same criteria for recreational diving, because when we base everything on bubbles, having 30 percent less bubbles didn't mean that the outcome is 30 percent better. So although it's all nice and good to know whether the deep stop affects something, I think it's meaningful in deep dives and in technical diving. But in recreational diving, it may not be really a big impact.

DR. BRUCE WIENKE: Just an observation. Apart from the bubble analysis that we've done that supports a minimum somewhere in the two to three minute range for recreational diving, out to the US Navy no decompression time limits, from a practical point of view back to my old days when I was an instructor, there's still the question of controlling ascent rates and whether you do deep stops on recreational diving for a minute or three minutes. The fact is that by making that deep stop at something like one-half the depth or one-half the pressure, for recreational training purposes, it's really a good thing because it teaches buoyancy control and it makes the diver aware of the fact that he's got to come up slowly, and that's a double plus.

DR. PETER BENNETT: If you'll take your seats, we'll start. This is the last talk of the workshop. I'm pleased to introduce good friend and colleague, Dr. Alessandro Marroni. He has a big research program which he has pulled together with DAN Europe. I always admire him pulling all the Europeans together, all the languages and all the politics, and he manages to work it very, very well. He's something of a Renaissance man. He grows olive oil, and he makes wine and he sails a big sailboat and does all these other things aside from decompression. So, Alessandro.

THE USE OF DEEP STOPS IN RECREATIONAL DIVING DAN EUROPE AND IDAN – OVERVIEW OF EARLIER STUDIES AND RECENT OBSERVATIONS

Alessandro Marroni, Frans J. Cronjé

ABSTRACT:

Decompression illness (DCI) affects some 1500 divers every year. Although DCI is relatively rare, two thirds of these divers develop neurological manifestations. To study the factors associated with DCI, and to make diving even safer for recreational divers DAN Europe, in collaboration with International DAN, performed a series of experiments since 1995. This presentation summarizes the highlights of these investigations.

Between 1995 and 1999, DAN Europe conducted an observational study and collected and analyzed 2105 fully monitored, unrestricted recreational dives. The dives ranged from 5 to 65 meters sea water (MSW) and involved 575 volunteer Research Divers. The largest number of dives – 33.15% -- were made in the 20 to 30 meters depth range. All the divers were Doppler monitored at fixed intervals post-dive. The presence of venous gas emboli (VGE) was graded as LBG (Low Bubble Grades – occasional bubbles), HBG (High Bubble Grades – frequent to continuous bubbles); and HBG+ (Very High Bubble Grades – continuous bubble showers). VGE were detected in 37.4% of the monitored dives; LBG were observed in 25.4%; HBG in 12%; and HBG+ in 2.4% of the dives. Only 15% of the repetitive dives were bubble-free; LBG were detected in 18% of the repetitive dives and HBG/HBG+ were recorded in 67% of the repetitive dives. Careful analysis of these dives suggested that post-dive High Bubble Grades were directly related to three key factors (TKF): gas loading of Fast to Medium Half Time (HT) tissue compartments (TC) as per Buehlman ZH-L8 ADT model; computed Venous Partial Pressure of nitrogen ($PvenN_2$) in excess of 1100 mbar; and Leading TC Nitrogen Partial Pressures ($PltN_2$) exceeding 80% of the allowed M-Value.

Based on these results, a project was started to confirm the validity of the TKF's in controlling bubble grades. Three experimental square dive profiles were selected: (1) a single dive to 20 m for 60 min; (2) a single dive to 40 m for 10 min: and (3) a series of three repetitive dives to 30 m for 16 min with 75 min Surface Intervals. The dives were made according to the original ZH-L8 ADT model and repeated with a modified algorithm designed to stay within the TKF limits. This implied a gradual reduction of the Leading TC M-Value, inversely proportional to the TC HT (Proportional M-Value Reduction Concept – PMRC), extended to include the 80 min HT TC and reaching correction factor 1 for the 160 min HT TC (i.e., no change). To achieve these partial pressures and gradients, extra deep stops had to be introduced during the ascent. These drastically reduced Post-dive Precordial Doppler Detected Venous Gas Emboli (PPDDVGE) in a sample of 14 volunteer divers performing 210 dives and serving as their own controls. The study showed that the pressure gradient (i.e., Delta-P) imposed on the leading TC, irrespective of the rate of ascent, appeared to be the critical factor for bubble production in this series of experimental dives.

Given the experience with the extra deep stops, and in order to establish practical recommendations relevant to typical recreational divers, the next phase of the study considered the effect of adding deep stops of varying durations at half-the-depth of the dive – Half Depth Deep Stops (HDDS). These were evaluated during experimental repetitive diving to 25 MSW. The results are presented elsewhere at this workshop.

The final part of the experiment examined the effect of HDDS, in addition to the standard "Safety Stop", during single and repetitive recreational dives, from 18 to 40 MSW. Eight volunteer divers performed 24 different No-Decompression dives between 18 and 40 MSW, with or without HDDS. Six of the profiles involved repetitive dives, designed according to the current USN Diving Tables, with 3hr 30 min Surface Intervals. The depth patterns were chosen to reflect the normal habits of most recreational divers (18+18, 21+21, 25+25, 27+21, 30+2, 40+24 MSW respectively).

The introduction of a HDDS generally reduced PPDDVGE, with an overall decrease of High Bubble Grades compared to the same dives without HDDS. The data suggest that the inclusion of a HDDS on dives between 25 and 30 MSW, with Bottom Times of 25 minutes or less (i.e., the typical dive profiles performed by recreational divers) reduces decompression stress as measured by PPDDVGE. The value of HDDS in reducing PPDDVGE was not as evident for shallower (18 – 21 MSW) and deeper dives (40 MSW), when brought to the limit of the respective No-D bottom time according to USN Dive Tables, and showed conflicting results. Further investigation is now being planned to unravel the apparent ambiguity of HDDS at these depths.

PAPER:

PART I

Introduction

Research on recreational diving differs from military or commercial diving in several ways: For a start, recreational diving is difficult to simulate in a laboratory due to the wide range of depth-time combinations; variable depths attained during the dives; varying number of repetitive dives; varying absolute number of dives; and the variable sequencing of dive depths. Dives may range from the relatively shallow, repetitive dives carried out in the Caribbean to the single deep daily dives usually practised in the Mediterranean. Secondly, fitness standards in recreational diving are far less stringent than those of professional diving; gender ratios and age ranges are also different: Recreational diving includes both males and females and starts from pre-teenage with no defined upper limit. Professional diving is male dominated and usually restricted to persons from young adult to early middle age. This enormous variability together with a low incidence of DCI creates great difficulties when designing a research protocol to evaluate the level of risk associated with recreational diving. Statistically significant results are hard to obtain.

The DAN Europe project SAFE DIVE, subsequently renamed Diving Safety Laboratory (DSL), has addressed the above mentioned problems by monitoring a large and varied sample of completely unrestricted European Research Divers (RD) while diving at home and during holidays abroad. Post-dive precordial Doppler measurements were carried out by appropriately trained diving instructors. The first Research Field Operator (RFO) course and the Pilot research trip were held in Malta between 24 February and 4 March 1995. Fifty instructors and divers attended. Various administrative, operational, technical and logistic modifications were made subsequently, leading to the definitive research protocol that has been in use ever since.

MATERIALS AND METHODS

The data required for the study were: (1) the electronic dive profiles; (2) demographic details of the diver; (3) pre- and post-dive fitness and health information with a 48 hour post-dive report; (4) any dive medical complications and treatment if required; and (5) precordial Doppler recordings.

Forms and questionnaires.

A six-page form was developed on which the RFO and RD were to record the age, sex, height, weight and diving experience of the diver; the dive details, including purpose of dive, type of equipment used, the gas/gases breathed, method of decompression planning and subjective dive data; health and fitness details including pre-existing health problems, liquid intake, alcohol and tobacco consumption, fitness and readiness to dive; a self evaluation form for recording any health problems post-dive; and a 48 hour post dive / altitude change report.

Dive Profile Recording: the DAN Diver's Black Box, the DAN Europe Research Kit[3].

Objective dive details were recorded using specially adapted dive computers known as "Black Boxes". These modified Aladin dive computers, allowed monitoring and recording of detailed time-depth profiles of the dive, water temperature, calculated inert gas uptake and ascent/decompression calculations. The modifications also included eliminating the in-water display and all alarms in diving mode. This prevented the diver from planning their dives using the computer, or modifying their diving behaviour due to alarms or prompting by the "Black Box" computer, thereby assuring objective recording of completely unrestricted diving.

The elimination of the error mode also assured objective recording and function in the presence of major mistakes by the diver. Usually egregious errors block computer function for a minimum of 24-hours.

Circulating Gas Bubble Doppler Recording.

The original plan was to Doppler monitor all divers using both precordial and subclavian areas with readings taken immediately post dive and 40 minutes later. However, monitoring the subclavian vein proved impractical, unreliable and time consuming. Doppler monitoring immediately post dive was also impractical as divers usually surfaced in buddy-pairs and they wanted to shed essential gear and dry themselves before submitting to examination; this caused delays up to 25 minutes post dive.

Based on the available literature, a decision was made to perform only a single assessment during basic surveillance work, 20 - 40 minutes post dive, thus permitting an RFO monitoring 4

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[3] The standard DAN Europe Research Kit that is sent to RFO's applying for a SAFE DIVE- DSL Research Trip according to a pre-defined calendar, consists of 3-4 Black Boxes, 1 Doppler Recorder, 1 Black Box Downloading Interface with dedicated software, the necessary forms, instructions and manuals, plus spare parts, consumables and promotional materials for the research project. The Kit is contained in a rugged, rigid and watertight case and is to be returned by the RFO to DAN Europe at the end of the research trip, together with the collected data. The recent implementation of an original, dedicated software, called "Immersioni", allowed for the full electronic recording of the data and their immediate transmission to the DAN Europe Central Data Base via internet, to include Doppler Recordings, without any more need for paper forms and a more rapid, virtually "real-time" data collection.

divers to spend at least 5 minutes on each diver even if they surfaced simultaneously [4]. Greater precision was adopted for specific studies of risk factors. Here Doppler recordings were made at 15 minute intervals from surfacing for a period of 90 minutes (i.e., 6 recordings per diver).

The DAN Europe Data Acquisition Software – "Immersioni" (DAN-E-DAS / Immersioni)

All the data collected by the RFOs were entered into a proprietary software database prepared for the project by the DAN Research Division. This software included a database server and client program at DAN Headquarters, as well as field versions, including the dive profile and decompression illness log. The DAN-E-DAS / Immersioni software allowed the RFO to enter data in a standardised format and permitted the transfer of this data in electronic format to the central DAN database.

The main functions of the DAN-E-DAS / Immersioni software were:
- Data entry from forms filled by the RDs
- Import of dive profile data as downloaded from the dive computers
- Dive outcome data reported by the RFO after each dive and dive trip
- 48 hour outcome report including altitude exposure reports
- Entry of Doppler data
- Description of any symptoms present during or post dive
- Description of treatment for DCI (oxygen, medication, recompression)
- Transfer of data to DAN database

The electronic transfer was done via floppy or CD or via the internet.

FIRST RESULTS

Between the start of the project, in February 1995, and the year 2000, data from 2105 fully monitored, unrestricted recreational dives were collected. The mathematical analysis of the dive profiles and the associated Doppler recordings showed that post-dive High Bubble Grades were directly related to saturation of the Fast to Medium Half Time (HT) Tissue Compartments (TC). Specifically, Computed Nitrogen Venous Partial Pressure ($PvenN_2$) higher than 1100 mbar and Leading Tissue Nitrogen Partial Pressure ($PltN_2$) higher than 80% of the allowed M-Value, according to the Buehlmann ZH-L8 algorithm, were associated with high and very high bubble grades.

EXPERIMENTAL DIVE PROFILES

A specific research project was then started to identifying bubble-safe dive profiles based on the above findings. Three square dive profiles were selected: a single dive to 20 m for 60 min, a

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[4] The RFO is to monitor and record 30 seconds of precordial signal with the diver at rest and a further 30 seconds after the diver has carried out a standard effort of 2 deep knee bends. The RFO is trained only to identify and record the correct Doppler signal by its "musical quality" and good signal-to-noise ratio and not to recognise or grade any bubbles present. They are trained how to locate the 3rd left intercostal space just lateral to the sternum and, starting from there, adjust the probe position until the correct sound is heard. The original Doppler Recorder Units were Huntley Healthcare Mini Dopplex with a 5 MHz probe connected to a Sanyo mini tape recorder using external cabling and jacks. This arrangement gave good quality signals in trained hands but unfortunately was prone to disturbances due to poor connections and movement. A simpler and more rugged unit was developed using a Sonicaid 2 MHz integrated Doppler, factory moulded into a water resistant case. This was attached to a mini tape recorder by a single cable. The recording quality was improved by using electronic filtering to clean up the Doppler signal and reduce tape noise. This type II Doppler recorder was inexpensive, reasonably rugged, water resistant and small enough to be packed in a standard waterproof protective box. The cassette recorder was subsequently exchanged for an MP3 Recorder. This produced much better recordings and allowed for real-time storage of Doppler files into the same electronic file of the related dive and made electronic transmission of the complete dataset simple and reliable.

single dive to 40 m for 10 min, a series of three repetitive dives to 30 m for 16 min with 75 min Surface Interval.

Table 1 – SUMMARY OF TEST DIVES			
Dive 1a 20 m 60 min TAT: 17' 50''	**Dive 1b** 20 m 60 min TAT: 30' 25''	**Dive 1c** 20 m 60 min TAT: 28' 25"	**Dive 1d** 20 m 60 min TAT: 35' 25"
Dive 2a 40 m 10 min TAT: 4'	**Dive 2b** 40 m 10 min TAT: 18'55''	**Dive 2c** 40 m 10 min TAT: 12'24"	**Dive 2d** 40 m 10 min TAT: 17'15"
Dive 3.1a 30 m 16 min TAT: 3'25'' SI: 75'	**Dive 3.1b** 30 m 16 min TAT: 18'55'' SI: 75'	**Dive 3.1c** 30 m 16 min TAT: 12'08" SI: 75'	**Dive 3.1d** 30 m 16 min TAT: 17'20"
Dive 3.2a 30 m 16 min TAT: 6'25'' SI: 75'	**Dive 3.2b** 30 m 16 min TAT: 18'55'' SI: 75'	**Dive 3.2c** 30 m 16 min TAT: 12'03" SI: 75'	**Dive 3.2d** 30 m 16 min TAT: 17'20"
Dive 3.3a 30 m 16 min TAT: 11'20'' SI: 75'	**Dive 3.3b** 30 m 16 min TAT: 18'55'' SI: 75'	**Dive 3.3c** 30 m 16 min TAT: 12'07" SI: 75'	**Dive 3.3d** 30 m 16 min TAT: 17'20"

(TAT – Total Ascent Time; SI – Surface Interval)

For this study, Doppler Recordings were performed every 15 minutes post dive for 90 minutes (six recordings per diver). Grading was according to a variant of the Spencer method: Low Bubble Grade (L) – occasional bubble detection; and High Bubble Grade (H) – frequent to continuous bubble detection.

All dives were made according to the original ZH-L8 model (Dive Series A) and then repeated with a new algorithm, modified to keep the $PltN_2$ within the above indicated limits (Dive Series B). A total of 184 Doppler Recordings were made after 10 test chamber dives (90 man-dives) on 9 volunteers.

Precordial Doppler Results

After Dive Series A, 5 of the 9 divers presented with High Bubble Grades for an extended time and 1 Diver suffered *cutis marmorata*. Because of the small sample, the absolute risk could not be determined. However the objective was to develop dive profiles that would be safe for al divers, even for "high bubble risk" individuals. After Dive Series B, only occasional Low Bubble Grades were registered. However, the ascent profiles for the modified algorithm were impractical for field use. As a result, a third profile (Dive Series C) was calculated, based on a different concept: introducing a gradual reduction of the Leading TC M-Value, inversely proportional to the TC HT (Proportional M-Value Reduction – PMR). M-Values were reduced by a value of 0,3 for the faster TC's compartments whereas the 80 minutes HT TC was left unchanged according to the original Buehlmann algorithm.

The set of experimental dives was repeated with the same group of 9 volunteers, plus an additional 3 new divers, known as "bubblers" from previously monitored dives (Dive Series C).

A total of 96 Doppler Recordings were made during 5 test dives (60 man-dives) on 12 volunteers.

After Dive Series C, eight of the 12 divers produced only occasional Low Bubble Grade signals. The 20 meter dive produced constant LBG readings (and 1 HBG reading in one diver) in all the divers, over the entire 90 minutes post-dive monitoring period. This was considered an indication that the slow compartments M-Values were still too high. The PMR Concept was then extended to include the 80 minutes HT TC leaving the 160 minutes HT TC unchanged.
All the ascent profiles were re-calculated and were tested during a fourth series of chamber dives (Dive Series D) with 10 of the volunteers from the previous dives plus two female divers who had shown HBG Doppler readings during previous field exposures to "normal" dive profiles and had suffered multiple episodes of skin DCS.
A total of 108 Doppler Recordings were made during these last 5 test dives on 12 volunteers (60 man-dives). Six of the 12 divers produced only minimal LBG Doppler readings, which were intermittent rather than continuous.

The Rate of Ascent variable

Rapid ascent is universally considered a risk factor for developing DCI. However, to delineate the effect of the maximum "speed"/ rate of ascent (i.e., the "instant" ascent rate), rather than the average rate of ascent, we determined the maximum ascent rate (delta P) for each dive using measurements from the DSL "Black Boxes". The ascent rates were sampled every 20 seconds during ascent and the peak and average ascent rates were determined and compared to the PPDDVGE findings.

In this study, Doppler Recordings were performed every 15 minutes post dive for 90 minutes (6 recordings). Grading was according to a variant of the Spencer method: Zero: no bubbles detected. Low Bubble Grade (L) – occasional bubble detection; High Bubble Grade (H) – frequent to continuous bubble detection.

Rate of ascent based Results

Table 2 shows the PPDDVGE grades after each experimental dive and the different values of peak "instant" rate of ascent and the average rate of ascent (note: safety stop times were excluded from average ascent rate calculations).

Table 2 – DOPPLER BUBBLE GRADE, PEAK AND AVERAGE RATE OF ASCENT IN METERS / MINUTE RECORDED DURING THE 20 EXPERIMENTAL DIVES (ZERO: NO BUBBLES; LBG: LOW BUBBLE GRADES; HBG: HIGH BUBBLE GRADES)

Dive 1a 20 MSW 60’ ***HBG*** **Peak 9.41** **Average 5.06**	**Dive 1b** 20 MSW 60’ ***Zero / LBG*** **Peak 11,21** **Average 3,22**	**Dive 1c** 20 MSW 60’ ***LBG*** **Peak 10.29** **Average 4.33**	**Dive 1d** 20 MSW 60’ ***Zero / LBG*** **Peak 13.33** **Average 4.09**
Dive 2a 40 MSW 10’ **HBG+ (Skin Bend**) **Peak 13.94** **Average 7,96**	**Dive 2b** 40 MSW 10’ ***Zero / LBG*** **Peak 22.94** **Average 6.67**	**Dive 2c** 40 MSW 10’ ***Zero / LBG*** **Peak 24.55** **Average 7.56**	**Dive 2d** 40 MSW 10’ ***Zero / LBG*** **Peak 10.3** **Average 4.56**
Dive 3.1a 30 MSW 16’ ***HBG*** **Peak 15.15** **Average 6.21**	**Dive 3.1b** 30 MSW 16’ ***Zero / LBG*** **Peak 16.18** **Average 5.14**	**Dive 3.1c** 30 MSW 16’ ***Zero / LBG*** **Peak 17,27** **Average 6.02**	**Dive 3.1d** 30 MSW 16’ ***Zero / LBG*** **Peak 13.03** **Average 5.45**
Dive 3.2a 30 MSW 16’ ***HBG*** **Peak 14.55** **Average 6.36**	**Dive 3.2b** 30 MSW 16’ ***Zero / LBG*** **Peak 14.55** **Average 5.12**	**Dive 3.2c** 30 MSW 16’ ***Zero / LBG*** **Peak 18.18** **Average 5.72**	**Dive 3.2d** 30 MSW 16’ ***Zero / LBG*** **Peak 21.82** **Average 5.99**

Tables 3 and 4 show the actual Doppler readings for the two 40 MSW dives where the difference between peak and average ascent rates were the most obvious. Rate of Ascent

TABLE 3: DOPPLER READINGS, DIVE 2A – 40 METERS 10 MIN.

Ascent Time 4min. Peak instant speed 13,94 m/min, Average ascent rate 7.56 m/min

RD	Bubbling Tendency	Doppler Time / Grade	Doppler Time / Grade	Doppler Time / Grade	Doppler Time / Grade	Doppler Time / Grade	Doppler Time / Grade
RS34	High	+5 / L	+18 / H	+33 /H+L	+48 / H+	+63 / H	+79 / H
RS35	Low	+7 / 0	+20 / 0	+35 / L	+50 / L	+65 / L	+81 / L

TABLE 4: DOPPLER READINGS, DIVE 2C – 40 METERS 10 MIN.

Ascent Time 12.24 min. Peak instant ascent rate 24.55 m/min, Average ascent rate 7.96 m/min

RD	Bubbling tendency	Doppler Time / Grade	Doppler Time / Grade	Doppler Time / Grade	Doppler Time / Grade	Doppler Time / Grade	Doppler Time / Grade
RS34	High	+5 / 0	+18 / L	+33 / L	+48 / L	+63 / L	+79 / 0
RS35	Low	+7 / 0	+20 / 0	+35 / 0	+50 / 0	+65 / 0	+81 / 0
RS124	High	+9 / 0	+22 / 0	+37 / 0	+52 / 0	+67 / 0	+83 / 0
RS125	High	+11 / L	+27 / 0	+39 / 0	+55 / 0	+69 / 0	+85 / 0

All the other dives showed similar patterns. The experimental dives, conducted with the corrected algorithms to reduce M-Values, with the addition of extra deep stops, actually showed frequent bouts of higher “instant” ascent rates when compared to the “normal” dives. The average rate of ascent did not differ significantly between the “normal” and modified dive profiles.

Tables 5 and 6 show the charts of the two 40 meter dives with the actual figures listing the variations of the rate of ascent during decompression. This clearly shows the “peaks” of the instant ascent rate and its variability over the ascent, illustrating the variegated nature of recreational diving. The two charts shown in table 7 above refer to an open water dive to 30 MSW for 21 minutes, followed by a seemingly unremarkable ascent, a 2 minute safety stop at 4 meters followed by uninterrupted ascent to the surface. The ZH8-LDT algorithms signaled M-Values of the fast and medium compartments reaching 100%. The diver reported neurosensory symptoms of DCI 30 minutes after the dive and was successfully treated. Peak “instant” rate of ascent was never faster than 5 m/min, with an average ascent rate (excluding stops) of 2.9 m/min.

Three other cases of DCI were observed following DAN DSL monitored dives. None showed any correlation between fast “instant” ascent rates and the appearance of symptoms. Only the computed M-Values in the leading TC’s suggested an increased risk according to the ZH8-LDT algorithm.

Conclusions after the first set of experimental dive profiles

No direct correlation could be found between “instant” ascent rates and PPDDVGE in this series of dives. In fact, in several dry dives, the “instant” ascent rates increased up to 24.55 m/min on the modified algorithm and yet showed no increase in PPDDVGE. Conversely, high PPDDVGE were observed following the standard ZH-L8 ADT algorithm, even though the “instant” ascent rates never exceeded 13 m/min.

In summary

Significant Post-dive Precordial Doppler Detectable Venous Gas Emboli (PPDDVGE) could be eliminated in a sample of 14 volunteers performing 20 dry test dives and 210 monitored in-water dives by (1) the introduction of Proportional M-Value Reduction (PMR) to the ZH8-LDT algorithm, and (2) by the addition of extra deep stops, without altering the original rate of ascent to, or between, any stops as determined by 388 Post-dive Precordial Doppler assessments performed every 15 minutes for 90 minutes (6 measurements). These preliminary observations suggest that only the Delta-P imposed on the leading TC, irrespective of the "instant" rate of ascent, correlates with PPDDVGE in this series of experimental dives, and – possibly – with the development of DCI. These findings suggested that extra deep stops may be of greater value in reducing PPDDVGE (and possibly DCI) than mere modifications in ascent rate. A natural extension of this research has been the quest for optimal combinations of stops and ascent rate to improve gas exchange and reduce PPDDVGE in recreational dive profiles. This has now been called the "economy of decompression" by the authors and is presented in the next section.

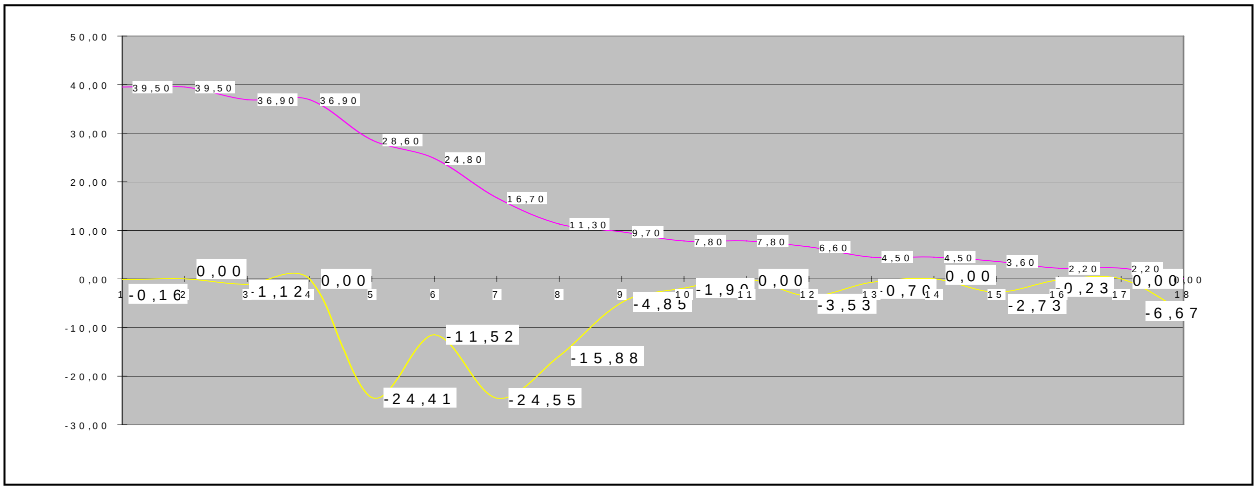
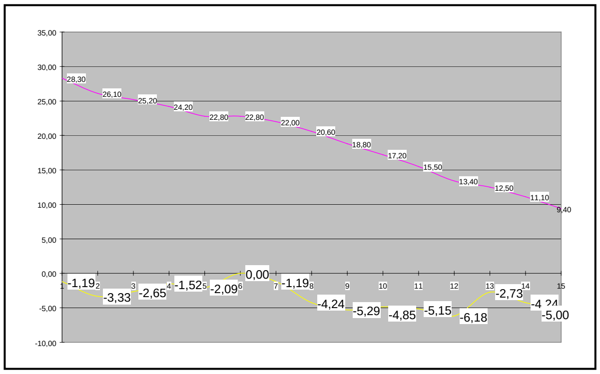
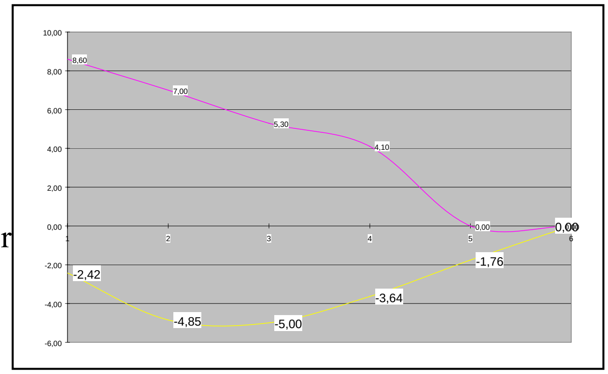


Fig. 2. Dive to 40 meters 2. Average rates of ascent: 7.56 m /min; Peak speed: 24.55 m/min



meter



PART II

The "Economy of Decompression" Study – Phase I

Given the experience so far described, and in order to establish practical recommendations relevant to typical recreational divers, the next phase of the study considered the effect of adding deep stops of varying durations at an empirical choice of half-the-depth of the dive. These were evaluated during experimental repetitive dives to 25 MSW.

This first study examined the effect of different ascent rates and decompression stops on the Doppler Bubble Score Indexes (BSI) of 22 volunteer divers. Two, consecutive, 25 m dives were performed for 25 and 20 minutes respectively. The dives were separated by a 3h30 surface interval and each dive series was separated by at least 7 days. Following these dives, the divers ascended according to 8 different protocols: Ascent rates of 3, 10 and 18 m/min were combined with no stops, only shallow stops, or deep and shallow stops.

The introduction of a 15m deep stop appeared to significantly decrease the degree of PPDDVGE and calculated gas tension loading in the 5 and 10 minute tissues, after these series of dives; the best results were obtained with the ascent rate of 10 MSW/min.

Since the publication of these results, several recreational diving agencies have recommended empirical stop times that were shorter than the 5 min stops used in the research: Stops of only 1 min (deep) and 2 min (shallow) have been recommended. Therefore, as a second part of the study, the optimal time for stops was determined using PPDDVGE as the outcome measure. Several combinations of deep and shallow stops were introduced after both single and repetitive open-water dives to 25 MSW for 25 mins and 20 minutes respectively. Ascent rates were maintained at 10 MSW/min. The results have confirmed that a deep stop of 1 min is too short.
Various shallow stop times, while keeping a fixed time of 2.5 min for the deep stop, were also evaluated. With the deep stop fixed at 2.5 min, increasing the shallow stop time incrementally from 2.5 to 10 min did not reduce PPDDVGE appreciably. The results of this work are being presented by the other member of our group at this workshop.

The "Economy of Decompression" Study – Phase II

The final part of the experiment examined the effect of a Half-the-Depth Deep Stops (HDDS) plus a standard "Safety Stop", during single and repetitive recreational dives, within the 18 to 40 MSW range.

Eight volunteer divers performed 24 different No-Decompression dives between 18 and 40 MSW, with or without HDDS. Six of the profiles involved repetitive dives, designed according to the current USN Diving Tables, with 3hr 30 min Surface Intervals.

The depth patterns were chosen to reflect the normal habits of most recreational divers (18+18, 21+21, 25+25, 27+21, 30+2, 40+24 MSW respectively). The results are shown in Table 5
The introduction of a HDDS generally reduced PPDDVGE, as measured according to our previously published grading system, with an overall increase of Zero Bubble Grades and Low Bubble Grades compared to the same dives without HDDS.

The data suggest that the use of HDDS for dives between 25 and 30 MSW, and Bottom Times of 25 minutes or less (i.e., the typical dive profiles performed by recreational divers) can reduce decompression stress as measured by significantly reduced levels of High Bubble Grades compared to the same dives without HDDS.

The value of HDDS in reducing High Bubble Grades was not as evident for shallower (18 – 21 MSW) and deeper dives (40 MSW), when brought to the limit of the respective No-D bottom time according to USN Dive Tables, and showed conflicting results. However the use of a HDDS consistently increased the number of bubble-free recordings as compared to the dives without a DS.

Further investigation is being planned to unravel the apparent ambiguity of HDDS at these depths.

TABLE 5 – PRECORDIAL DOPPLER BUBBLE GRADES OBSERVED AFTER A SERIES OF 24 RECREATIONAL DIVES ON 8 VOLUNTEER DIVERS

Dive #	Depth	Time	HDDS	SS	BSI	ZBG %	LBG %	HBG %
1	**18**	60	0	5	5.1	17	70	13
2	**18**	60	1	5	6.3	32	46	22
3	**18**	50	2.5	3	5.2	39.6	41.7	18.7
4	**18 (Rep)**	33	2.5	3	6.1	33.3	50	16.7
5	**20**	40	2.5	3	4.5	44	42	14
6	**21**	40	2.5	3	7	30	43.3	26.7
7	**21 (Rep)**	25	2.5	3	3.9	33.3	63.4	3.3
8	**25**	25	0	5	5.7	18.7	64.6	16.7
9	**25 (Rep)**	20	0	5	4.7	23.3	61.7	15
10	**25**	25	2.5	5	2.75	51.4	47.2	1.4
11	**25 (Rep)**	20	2.5	5	1.5	66.7	31.9	1.4
12	**27**	25	2.5	3	3.22	60	51	9
13	**21 (Rep)**	25	2.5	3	1.79	39	48	3
14	**30**	25	0	5	8.38	17	46	37
15	**30**	25	1	5	7.39	26	41	33
16	**30**	20	2.5	3	3.54	50	41	9
17	**30**	20	2.5	3	7.1	22.2	44.4	33.4
18	**24 (Rep)**	17	2.5	3	2.83	66.7	30.5	2.8
19	**40**	9	0	5	3.31	40	54	6
20	**40**	9	1 *	5	7.36	21	46	33
21	**40**	9	1+1 **	5	3.5	56	33	11
22	**40**	10	2.5+3 **	3	3.33	58	28	11
23	**39**	5	2.5+2.5**	3	2.9	50	47	3
24	**24 (Rep)**	26	2.5	3	5.5	33	47	20

Legend: HDDS: Half Depth Deep Stop; SS: Safety Stop; BSI: Bubble Score Index.
ZBG: Zero Bubble Grade; LBG: Low Bubble Grade; HBG: High Bubble Grade.
40 and 39 MSW dives: * Deep Stop at 20 MSW ; ** Deep Stop at 20 and 10 MSW

Conclusions

The current limits of no decompression diving have evolved from theoretical mathematical models. Some of these have been tested with exposures designed to produce an incidence of decompression illness between 1 to 8%. The limits have been modified gradually by respective users, training organizations and computer algorithm developers to further reduce the probability of DCI. The most common approach has been to empirically reduce bottom time and to slow the ascent rate.

In more recent years, an arbitrary "safety stop" at 3-5 meters was added to further reduce DCI and avoid pulmonary barotrauma. The impact of this intervention has not been evaluated formally. In fact, very little is known about the risk of so-called "safe dives". Testing the extreme limits of dive tables to a clinical endpoint of DCS is relatively simple, although ethically troublesome, and does not require many exposures. Assessing the risks related to "safe diving" is far more difficult.

Precordial Doppler has evolved as a useful non-invasive technique that allows for a somewhat objective determination of decompression stress. High bubble grades are associated with a higher incidence of DCI, and there are also the additional concerns about PFO and pulmonary shunting in the presence of such bubbles.

On the other hand, it is also known that significant bubbling may follow slow ascents from saturation dives as well as altitude exposure where neurological injuries are uncommon. Therefore, the exact association between the presence of PPDDVGE and the incidence of DCI is unclear and the key lies in unraveling the association between PPDDVGE and DCI. Nevertheless, high bubble grades do potentially introduce biological injury such as damage to endothelium and the release of cytokines. Therefore, even in the absence of DCI, low bubble grades are preferable to high bubble grades. As such, PPDDVGE determination is a reasonable and practical risk assessment tool for DCI in the absence of clinical symptoms.

Table 6. Dopple Bubble Detection (Precordial) & DCI Incidence (Modified from Brubakk)

Author	**Number & Incidence**	*Bubble grade*	
		0	**I-IV**
Spencer& Johanson 1974	**N**	**110**	**64**
	DCI inc.(%)	**1.0**	**22**
Nashimoto& Gotho 1978	**N**	**64**	**88**
	DCI inc.(%)	**0**	**19**
Marroni 1981	**N**	**64**	**33**
	DCI inc.(%)	**0**	**9**
Nishi 1993	**N**	**1265**	**331**
	DCI inc.(%)	**0.6**	**8**
Brubakk 1993	**N**	**68**	**40**
	DCI inc.(%)	**1.5**	**7.5**

Our previous studies have shown an association between PPDDVGE and computed nitrogen pressures above 80% of the M-Value or above 1100 mbar as predicted by the Buehlmann ZH-8 or ZH-16 Models[5]. Work emanating from Tokyo Medical University and St Thomas Hospital,

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[5] Note that the pressure values computed by the Buehlmann model are absolute values.

London, are supporting our conclusions[6]. Also, an internet publication by Richard Heads, PhD; Cardiology Dept.; The Rayne Institute; Saint Thomas Hospital, London – www.oceanwreckdivers.com/images/the_**trouble**_with_**bubbles**.pdf called "The Trouble with Bubbles", presents a variety of observations, reports and personal opinions, with an interesting graph, in which the amount of circulating gas bubbles is graphically compared to the level of inert gas supersaturation in TC's and the amount and volume of bubbles growing gradually when approaching and passing the M-Value line. While the Authors presumptively call bubbles beyond the M-value line "symptomatic", the graphical representation of the concept is consistent with the objective of reducing the volume and number of circulating bubbles, by changing the ascent profile so as to prevent the pilot TC supersaturation from exceeding the M-Value line. Although not a novel approach, the correlation between the high bubble grades and tissue saturations approaching the M-value, in tandem with the results of the HDDS study, draw the theoretical approach much closer to a biological reality.

Some of the remaining immediate challenges are to determine the most economic decompression for 18 and 40 meter profiles as determined by PPDDVGE and to see how this expands our understanding of the empirical deep stop within this range of diving. Ultimately we hope to refine the appropriate biological surveillance of decompression stress beyond current PPDDVGE methodology to better titrate all depth-time combinations of compressed gas breathing activities without the need for clinical DCI as an outcome measure. Endothelial damage monitoring and body impedance measurements are moving us closer to this reality.

While the HDDS may not work for all depths, as it obviously could not, it appears to address the essential diving safety needs of recreational divers within the 20 to 30 meter diving range. Importantly, managing fast and intermediate tissue M-value supersaturations appear to be critical, although this does not explain why ultra-slow ascents sometime fail to prevent high bubble grades and DCI. Ultimately, achieving a practical, high, Delta-P without violating M-values, may prove to be the best economy of decompression.

References

1. Bennett PB, Marroni A, Balestra C, Cali-Corleo R, Germonpre P, Pieri M, Bonuccelli C. What ascent profile for the prevention of decompression sickness? I – Recent Research on the Hill/Haldane ascent controversy. Paper presented at the 28th Annual Meeting of the EUBS, Bruges, 5-8 September 2002.
2. Bennett PB, Marroni A, Cronjè FJ, Cali-Corleo R, Germonpre P, Pieri M, Bonuccelli C, Leonardi MG, Balestra C. Effect of varying deep stop times and shallow stop times on precordial bubbles after dives to 25 msw (82 fsw). Undersea Hyperb. Med 2007; 34(6) :399-406
3. Marroni A, Bianchi P, Rilevazione di bolle gassose circolanti dopo immersione in aria compressa. Med.Sub.Ip.1980; 6:27

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[6] Recent unpublished observations by Yoshihiro Mano, of the Tokyo Medical University, on a number of Japanese Compressed Air Divers show a relationship between precordially detected bubbles, with DCI symptoms, and tissue supersaturation level close or slightly above the M Value of the pilot tissue for that dive.

4. Marroni A, Zannini D, Effetti della variazione della velocita di risalita sulla produzione di bolle gassose circolanti dopo immersione ad aria compressa. Med.Sub.Ip.(Min.:Med.) 1981; 1:83
5. Marroni A. "Prevenzione e Diagnosi Precoce della Malattia da Decompressione. Ricerca di Bolle Gassose Circolanti mediante Analisi Ultrasonora ad effetto Doppler" Tesi di Specializzazione in Medicina del Nuoto e delle Attivita Subacquee, Universita di Chieti, Italy 1984
6. Marroni A., Cali Corleo R. et Al. Project Safe Dive - a preliminary report. In: S.A. Sipinen, M. Leiniö (Eds) Proceedings of the XXI Annual Meeting of the EUBS; 1995:216-221. ISBN 952-90-6626-0
7. Marroni A, Cali-Corleo R, Denoble P. Understanding the safety of recreational diving. DAN Europe's Project SAFE DIVE Phase I: Fine tuning of the field research engine and methods Proceedings of the International Joint Meeting on Hyperbaric and Underwater Medicine, EUBS, ECHM, ICHM, DAN., p. 279-284:1996 September 4-8 Milano, Italy
8. Marroni A, Cali Corleo R, Balestra C., Longobardi P, Voellm E, Pieri M, Pepoli R. Effects of the variation of Ascent Speed and Profile on the production of Circulating Venous Gas Emboli and the Incidence of DCI in Compressed Air Diving. Phase 1. Introduction of extra deep stops in the ascent profile without changing the original ascent rates. DSL Special Project 01/2000. EUBS 2000 Proceedings. Diving and Hyperbaric Medicine, Proceedings of the XXVI Annual Scientific Meeting of the European Underwater and Baromedical Society, R. Cali Corleo Ed., 2000: p 1-8: 2000, September 14-17 Malta
9. Marroni A, Cali Corleo R, Balestra C, Voellm E, Pieri M. Incidence of Asymptomatic Circulating Venous Gas Emboli in unrestricted, uneventful Recreational Diving. DAN Europe's Project SAFE DIVE first results. EUBS 2000 Proceedings. Diving and Hyperbaric Medicine, Proceedings of the XXVI Annual Scientific Meeting of the European Underwater and Baromedical Society, R. Cali Corleo Ed., p 9-15:2000, September 14-17 Malta
10. Marroni A, Cali Corleo R, Balestra C., Longobardi P, Voellm E, Pieri M, Pepoli R. The use of a "Proportional M-Value Reduction Concept" (PMRC) Changing the Ascent Profile with the introduction of extra deep stops reduces the production of Circulating Venous Gas Emboli after Compressed Air Diving. DSL Special Project 01/2001. EUBS 2001 Proceedings of the 27th Annual Meeting. U van Laak Ed.,: p 69-73: 2001, September 12-16, Hamburg, Germany
11. Marroni A, Cali Corleo R, Balestra C, Longobardi P, Voellm E, Pieri M, Pepoli R. The use of a "Proportional M-Value Reduction Concept" (PMRC) The Speed of Ascent Dilemma: "Instant Speed of Ascent" or "Time to Surface" – which one really matters? Instant speed of ascent vs Delta-P in the leading tissue and post dive Doppler Bubble production.. DSL Special Project 02/2001. EUBS 2001 Proceedings of the 27th Annual Meeting. U van Laak Ed.: p 74-78: 2001, September 12-16, Hamburg, Germany
12. Marroni A, Bennett PB, Balestra C, Cali-Corleo R, Germonpre P, Pieri M, Bonucelli C. What ascent profile for the prevention of decompression sickness? II – A field model comparing Hill and Haldane ascent modalities, with an eye to the development of a bubble-safe decompression algorithm. Proceedings of the 28th Annual Scientific Meeting of the European Underwater and Biomedical Society, pp 44-48:2002. September 4-8. Brugge, Belgium.

13. Marroni A, Bennett PB, Cronje FJ, Cali-Corleo R, Germonpre P, Pieri M, Bonucceli C, Balestra C. A deep stop during decompression from 82 fsw (25 msw) significantly reduces bubbles and fast tissue compartment gas tensions. Undersea Hyperb Med 2004 31(2):233-243.

<u>DISCUSSION</u>: THE USE OF DEEP STOPS IN RECREATIONAL DIVING

DR. ALF BRUBAKK: I understand that the high bubble grade that you used in this paper is the same that Neal alluded to this morning. But high bubble grade is anything from two and upwards; is that correct?

DR. ALESSANDRO MARRONI: Two is still low.

DR. ALF BRUBAKK: So the high area is two and higher.

DR. ALESSANDRO MARRONI: If we use the classical Spencer scale, high would be three, yes. If we use ours, then 2.5 and above is high.

DR. ALF BRUBAKK: Then the first comment I'd like to make is I think it is very unlucky that we're using different nomenclature. As I said to you before, I don't quite understand the "half"; it is not a system that's accurate actually. You can say high bubble grades or low bubble grade. It would be just as meaningful. But the other comment I'm going to make is the curious results here; that the short dives in the region of 20 meters plus show benefit from the deep stops. Our work showed totally different results. Our results suggested that the short dives are actually the ones where we should get out as fast as possible and the deep stop is not beneficial; on the contrary, it produces many more bubbles. That needs much more work. It is very, very curious that the results are so vastly different and the conclusions are vastly different from what we talked about this morning.

DR. ALESSANDRO MARRONI: What do you define a short; where is the borderline between short and long?

DR. ALF BRUBAKK: We don't know what "short" is. But we tested 24 meters for 20 minutes. That was short. And we tested 24 meters for 70 minutes, and that was long dive. They benefitted significantly from having deep stops and the short dives with 20 minutes bottom time produced significantly more gas. So the only comment I'm making is that the curious thing is that it's totally opposite observations. Our conclusions are totally different from your conclusion. Ours might be wrong, I don't know.

DR. ALESSANDRO MARRONI: Or ours might be wrong or we are starting to explore a very varied universe. And maybe other conditions may have differed there, such as hydration, divers' condition or whatever. Other things that should probably be considered as well as this data.

DR. NEAL POLLOCK: Just to clarify, we've had this bubble grade thing. My comments were based on what appears in the two published documents by Bennett, et al., and the Marroni, et al. And both of them do indicate low bubble grade, occasional bubble signals, Doppler bubble grades lower than two in the Spencer scale. I understand from Alessandro that this is an error in the manuscript. So I think that it's going to be corrected. But that's where the confusion is coming from. It's what's in the manuscript.

DR. ALESSANDRO MARRONI: Yes. In fact, we are going to write a letter to clarify this. It depends on the difference between the Spencer scale and our scale. I agree with you, Alf, that we should get to a common modality so that we hopefully are going to get there.

DR. BRUCE WIENKE: Just to comment on M-value reductions. You've correlated your M-value reductions with Doppler. There are other, ways of reducing M-values for repetitive dives and reverse profiles, things like that. And you will find that kind of an approach in a bunch of commercially marketed meters. And so it's pretty interesting. If you have something like a bubble model, and you want to convert that to a fast calculational tool within the framework of mathematics and electronics that the present generation meter vendors use, this M-value reduction scheme, coupled to whatever you want to reduce it by, is very fast and very efficient scheme on dive computers.

DR. DAVID DOOLETTE: I know you haven't finished this study yet, but would you say that since the half-dive stop depth only seems to work for one depth, that that's not a good model? You may find that some other depth or some other function, like Bruce suggested, you could do it with a computer would work, but really the half-dive depth is probably not a good way forward. It only seems to work for a narrow depth.

DR. ALESSANDRO MARRONI: Frankly, David, I don't think that any of us can say which is which at the moment. We think that in the range of 25 to 30 meters, which represents probably 90 percent of what is being dived in recreational dive resorts and so on, this may be a good idea. The practical experience that I get from analyzing all these data, working with the DAN alarm centers, and with many dive centers, is that the average dive that is done in the Maldives, which is where the majority of our European divers go, is between 25 and 30 meters. They stay down about 20 minutes. They come up slowly to about 15 meters. They stay there for about five to ten minutes, and they complete the dive with a safety stop of at least five minutes at 15 meters. And in the Maldives, there is a surprisingly no incidence of accidents with respect to the over 10 million dives dived every year there. On the contrary, in the Mediterranean, the kind of dive done is much more aggressive than this. I can tell you something out of the data that we are now merging and collecting. It's much more of a square profile type. In the Sinai, in Egypt, it's also like that, and we have a different incidence of DCS. This is not science. This is just anecdotal reporting. So to be honest, I don't know yet. I think we have to keep on studying and analyzing the data. I don't feel I'm recommending anything at this stage.

DR. SIMON MITCHELL: All right. Well, Alessandro, I thank you very much for a very good presentation.

CONSENSUS SESSION

DR. SIMON MITCHELL: We set aside this period at the end of the day for discussion. We will try to direct that discussion with some slides we've created here. We would like to go away from the workshop with a few messages that we can actually deliver to the diving community. Based on the discussion and debate that's taken place, we've tried to generate a definition of deep stops. We've tried to generate a couple of points that summarize what we know and don't know about their efficacy, and the message we can deliver on that basis to the community. And we'd also like to discuss briefly where we go from here in terms of future research. Our plan is to put these slides up and allow discussion on them. If we can reach any kind of consensus, that would be wonderful. Having been involved in a few consensus workshops before, I realize that the best laid plans in that regard often go awry, and its extraordinary how differently people feel about things and how many debates can arise out of seemingly feeling innocuous statements. This is the definition of deep stops we've generated. We're suggesting that there are two types of deep stops. One of them is **empirical deep stops**. That means “one or more voluntary or empirically derived decompression stops that are deeper than any prescribed by the algorithm utilized”. And that embraces Pyle stops. It embraces Bennett- Marroni stops. It embraces deep stops imposed by algorithm users manipulating gradient factors. So any manipulation that the user imposes to generate a stop that is deeper than the algorithm would otherwise give you, that's an empirical deep stop. Then **model-derived deep stops** are straight forward. They're deep stops prescribed by bubble model algorithms that are deeper than determined by gas content models for equivalent time/depth profiles. Anyway, those are the definitions. Does anyone want to discuss those definitions? Object to them? Add to them? Challenge them?

KARL HUGGINS: On the empirically determined ones, basically that defines any multi-level dive.

DR. SIMON MITCHELL: Does it? I'm not sure that it does, Karl. If you dive a multi-level dive according to a dive-planning algorithm, then that's a multi-level dive prescribed by that dive-planning algorithm. That's not an empirically added deep stop.

KARL HUGGINS: So if you're doing a no-decompression dive, there's no decompression stops that are defined by whatever (algorithm) you're using. And if you're coming up shallower, you're making stops on the way up. And decompression stops aren't defined by any timeframe there, so it sort of seems in my mind to fit into the definition of a multi-level dive.

DR. SIMON MITCHELL: I suppose it's a matter of intent, isn't it? You could see it that way. To be honest, I think it's a red herring. I think the intent is pretty clear. When you're multi-level diving, to make your way up a cliff face and enjoy the scenery, that's a bit different than what we're talking about here.

DR. RICHARD VANN: On your second model-derived definition, you don't really need to have bubble algorithms there. You can just take the tissue ratios and by jiggling them, you could get your stops deeper. It doesn't pertain to whether it's a bubble model or not, I don't think. In other words, in the comparison I did between the Navy tables this morning and the original Haldane tables, Haldane had the 2-to-1, 1.57-to-1 ratio. And when the Navy bumped it up to 4.3, the depth of the first stop came down in the five-minute tissue. So I don't think you need to invoke a bubble model as opposed to a content model.

DR. SIMON MITCHELL: So you're saying that if someone was using that content model that you described, but still decided to put some extra empirical deep stops…

DR. RICHARD VANN: No, it's not empirical. It's driven by the assumed supersaturation ratios.

DR. SIMON MITCHELL: I can live with that. Can you live with that, Peter? I'd be happy to take bubble models out of there.

AUDIENCE MEMBER: Just as an example, PDIS, what we call profile-dependent intermediate stop, we only suggest a stop depth which is the depth at which the leading tissue switches. So it's Haldanian based, but it's in the algorithm.

DR. SIMON MITCHELL: Yes. But that's an example of what Dick is saying.

DR. DAVID DOOLETTE: I don't disagree with Dick. I guess he was talking about what's commonly called a tech dive gradient factor. That's a different model. So it doesn't necessarily have to be bubble versus gas content. But if you change, it's different models. Maybe we're agreeing, then. Sorry.

DR. SIMON MITCHELL: I think that the consensus appears to be that we just take bubble model out of there and put whatever the algorithm is.

DR. DAVID DOOLETTE: And then I know this point is a little bit supercilious, but with the empirical ones at the top, would that cover safety stops if your algorithm doesn't call for decompression at all, and you do a traditional safety stop? Is that now a deep stop? Are we changing that? Or should we clarify that's not what we mean, that it has to be a decompression dive already under an algorithm.

DR. SIMON MITCHELL: A safety stop is not a decompression stop. But it is a decompression stop, but it's not a decompression stop!!

DR. DAVID DOOLETTE: You walked into that.

DR. SIMON MITCHELL: I walked out of it, though.

DR. DAVID DOOLETTE: So one of these empirical inserted stops, then. You could say they're not decompression stops.

DR. SIMON MITCHELL: Actually, to be honest with you, David, I don't care. If you want to call your safety stop a deep stop. I don't think anyone would do that, but, yes, you could fit safety stops in there. The trouble is to exclude safety stops, then you're going to have to include more verbiage in there that just makes it all more cumbersome. But,you know what we're talking about, and I think most people reading the definition would understand the inherent difference.

DR. DAVID DOOLETTE: I'm not sure with the stuff that Peter and Alessandro are talking about. Are they really just "deep safety stops" that they were doing in their dives. They were safety stops that happened to be at 15 meters instead of 5.

DR. SIMON MITCHELL: Would it help you if we put a depth in there that they have to be deeper than?

DAVID DOOLETTE: No, it wouldn't.

DR. TOM NEUMAN: I see tremendous confusion. I mean, not that a definition isn't mportant, but if you take bubble model algorithms out, then what you're saying is decompression stops prescribed by basically any algorithm, that are deeper than those determined by gas content algorithm. But you can make a gas content algorithm have a deeper stop by merely fiddling with the M-values. Or, even worse, you can do the equivalent by just changing the ascent rate. So I'm afraid that the definitions are still not clear. Unfortunately, I don't have a better idea. It's always so much easier just to be critical without having any idea of what to do about it. But the problem is by taking out bubble model algorithms, you're, in essence, increasing the confusion.

DR. WAYNE GERTH: Picking up from where Tom left off, up and where David was, what we're trying to do in this particular slide is we're trying to make a definition that is useful within the context of current thinking. So people have a given model in mind, and they insert a stop and that becomes a deep stop in the context of that model, and that's meaningful to everybody. And in the other case, we're talking about one model against another, as I said before, where the models have different ascent criteria and they have different schedules, one which is inevitably going to have a deeper first stop than another and that's a deep stop. Even in that context, you get into the argument that Bruce and I got into; my stop is deeper than yours, but we've still got a bubble model. In the end that's useful. That somehow fills in some verbiage that acknowledges that we're stuck with the conundrums and provocations that are inevitable in those words because in either case, we're talking about not having the right model. Once we had the right model, then that distinction disappears. So I don't know if that helps. This is very similar to what we ran into in the repetitive dive workshop. What's a repetitive dive?

DR. SIMON MITCHELL: One of the footnotes to this definition refers to the comment made earlier by Christian. Thus, while the term "deep stops" is presently useful for describing the applicable variations in approach to decompression it is expected that the eventual elucidation and proof of optimal decompression technique may see the term abandoned. In ten years' time, we might not talk about deep stops. We might just talk about decompression because we've figured out how to do it, which is what you're getting at.

DR. WAYNE GERTH: Right, the elucidation of the right model for doing and optimal decompression.

DR. SIMON MITCHELL: I totally agree and that's why we've put that footnote there. But at this stage we're still using the term "deep stop" and I think we need to try to define it. So I'll go back to that original slide.

DR. WAYNE GERTH: Just one other comment going back to that original slide because I think it's useful to be there, maybe we can help Karl with his problem by going back to what we all said in our first slide. First off, define a deep stop. It's not a decompression stop. It's not necessarily one prescribed by an algorithm. It's an interruption of ascent. We're always decompressing. A deep stop is an interruption of that ascent in order to effect a safe wash out of gas. I haven't seen anything about whether an algorithm prescribed it or not. And that gets us outside of the multi-level dive thing. Because now I'm interrupting my ascent to effect some sort of safer gas elimination, not to stop and look at a piece of coral on a wall or something.

DR. SIMON MITCHELL: I think we need to have this distinction between empirical and model derived, though, don't we? Certainly it wouldn't mean much to the technical diving community if we didn't have that. Many of the people using Buhlmann- derived algorithms are putting in empirical deep stops that wouldn't otherwise be there, the whole Pyle stop thing for example. If we don't embrace that in our definition, then we're going to leave a lot of these guys behind. We first need to describe whether the “model derived” definition is going to include the term “bubble model algorithms” or not. There appears to be a division on that.

DR. BRUCE WIENKE: I kind of like what you've got written up there already. I think what we would hope to do is be short and sweet and talk in common parlance. Today, whether it's a bubble model algorithm or a modified algorithm, they associate deep stop with bubble models.

DR. SIMON MITCHELL: Correct.

DR. BRUCE WIENKE: So gas content, well, those are supersaturations. Those are classical models. Not that you can't tweak them up to do something like a bubble model. So, I mean, I kind of like it because it relates to me, Joe average diver, when I pick up a decompression course manual or a set of tables, I make a nice, easy association with this terminology. Now, we can nitpick about whether we call it this or that, but I don't know that that's a useful thing for this workshop. I'd like to see it kept short and sweet and used in common, everyday terms with common word associations. Whether it's entirely correct or not, you know, you could argue that behind the scenes.

DR. SIMON MITCHELL: Let me put this to you. Dick, would it work for you if we put some kind of footnote acknowledgement there to the effect that classical decompression models can be manipulated or certain iterations of them -- manipulations of these models can give rise to stops that are deeper than the raw algorithm or something along those lines, but the intent of this is to refer to the bubble models, because that's the common association in the diving community? And likewise, with David, would it work for you if we just said, look, this doesn't include safety stops?

DR. WAYNE GERTH: Alessandro just showed us how we can take a classical model, not a bubble model and get deep stop out of it. So that's one algorithm against another with different ascent criteria.

DR. DAVID DOOLETTE: You can put gas content and bubble models out in a footnote and say in a lot of cases, this is a difference between bubble models and gas content. As everyone is agreeing, you can make it deep stop, you can get deep stop out of supersaturation gas content. That's one suggestion. And the safety stop thing is maybe another footnote, saying we don't mean the classic safety stop at 5 meters. If, in fact, we do mean that.

DR. SIMON MITCHELL: Yes, we do mean that.

DR. RICHARD VANN: I think the kind of model is irrelevant.

DR. SIMON MITCHELL: Thank you, Dick. I think what I'll do is what we've done in the past in these kind of situations, where we get into these sort of circular arguments. We seem to have a rough agreement that we're somewhere along the right lines. Some kind of clarifying statement will probably help keep Dick happy and will exclude safety stops for David. I'll write it.

DR. PETER BENNETT: And we'll take that as God's gospel.

DR. SIMON MITCHELL: I'll write it and show it to Dick and the people that have been discussing it in some depth. I'll show it to Wayne and to Dick, and I'll show the statement about safety stops to David, and hopefully they'll be happy with that.

DR. PETER LINDHOLM: Did I miss something? The thing that's been presented here has been discussion and data presented to say whether the models we use today are inadequate. Do we need to stop earlier on the ascent? And there hasn't been any data produced or shown that actually convinced me, at least, that the models we have are wrong. And as I understand it, deep stops, we don't need that word at all. If we can show scientifically that the models we use today are wrong, we need new models and they will produce stops, decompression stops or whatever at different depths. But before we have that data, why include this in scientific terminology?

DR. SIMON MITCHELL: Well, we include it because that term is in widespread use outside of this room. The diving community understands what we mean by "deep stop." They're asking for direction on that issue. I think for us to suddenly abandon the term and come out with some other iteration of advice couched in terms that they don't understand would be the wrong thing to do. We are going to come to a statement about what we think about the data in just a moment. So if we'll accept that the term "deep stop" is out there, we're going to make it clear what we mean by it. Then shortly, we'll consider a statement about what we think the data shows at the moment. And that is pretty much what you just said. Come back to us if you're not happy when we get to that slide.

DR. DREW RICHARDSON: Is it a fair assumption to say that the diving community understands this, and who are the diving community? Because I think we're here really addressing a very specialized segment of the diving community in a generic sense.

DR. SIMON MITCHELL: Yes, that's probably true. It's the technical diving community mainly.

DR. DREW RICHARDSON: The recreational diving community doesn't really have a clue about this, and that's the whole safety stop concern coming back in. They know what that is.

Maybe it will titrate down there eventually, as we saw. But at the moment, let's not assume that the diving community, the millions, have a clue.

DR. SIMON MITCHELL: Common use of the term. I agree.

DR. DREW RICHARDSON: I just think it needs to be defined maybe here, safety stops are a recreational procedure. The evolutions of this, Pyle and WKPP, et al., are technical in nature. And maybe they'll evolve, but at the moment, that's the community.

DR. SIMON MITCHELL: I think most recreational divers realize it doesn't apply to them straight up. We're talking about decompression here.

DR. DREW RICHARDSON: I think they trip on empirical.

DR. ALF BRUBAKK: Isn't the point here that most recreational divers are diving quite happily, and they're following a procedure that tells them that you have to have a reasonably slow ascent rate and then you should have a safety stop at the shallow depth. That is what people do. Now, someone had come up with the idea to say that deep stops are a good thing. And there is conflicting data. We do not know. We cannot tell anybody that deep stop make sense. So the advice to do something about this is really we don't have the data to say that. So I suggest that we drop the whole deep stop thing totally. I agree with that. We don't win anything by trying to define it and we can't even define it ourselves.

DR. SIMON MITCHELL: We can't do that Alf. The term is out there. I don't think any of us in here disagree with that, and we've got a burgeoning technical diving community that wants direction on this. By just burying our heads in the sand and pretending they don't exist, will not achieve anything.

DR. ALF BRUBAKK: The point is, there is no data that's reported.

DR. SIMON MITCHELL: We're going to say that. We're coming to that.

KARL HUGGINS: On the empirical, just a recommendation. Where it says, “deeper than the first required decompression stop prescribed by the algorithm utilized”; so there you're talking about a stop added into a deep decompression dive that has required decompression stops.

DR. SIMON MITCHELL: Not necessarily a decompression dive, just whatever diving. I'msorry. I didn't quite get the point of your message, Karl.

KARL HUGGINS: The point was that it was deeper than the first required stop. Because you're deeper than prescribed. Prescribed may be surface.

DR. SIMON MITCHELL: Than any prescribed or recommended stop; that would get around the safety stop issue, wouldn't it? I like that. Any prescribed or recommended stop. Yep. That would work. That's good. Thank you, Karl.

DR. ALESSANDRO MARRONI: Drew, I'd like to address what you just said because I disagree with the fact that the deep stop is something that belongs to technical diving and does not belong to what you referred as "the recreational diving community." There are many organizations, national, regional, local or international, that are now recommending or speaking about deep stop in recreational diving. There are many dive computers that speak about these level stop, deep stop, whatever it is, the other acronym. So there is a need for direction. So I think we need to define this. Even if we end up saying there is no evidence so far, research is going on, but I think we have to address the point.

DR. SIMON MITCHELL: We're going to come to the absence of data. No one is recommending deep stops on this slide. We'll get a chance to discuss that.

DR. TOM NEUMAN: Not talking about the recommendation, but back to the definition. The notion that this only applies to the technical community, please remember that Peter's work and Alessandro's work, these deep stops that we're talking about in their work are really safety stops. Because we're talking about 82-foot dives for 25 minutes. Those are, in common parlance, no decompression dives. Certainly they're no-stop dives. So to think that the data that are being presented are pertinent only to the technical community is, I think, incorrect. It's going to filter down to Drew's community, unless we're very careful about what we're saying here.

DR. SIMON MITCHELL: I think it's mainly technical diving. I think that's okay with these definitions.

DR. NEAL POLLOCK: I think Karl had a good idea right now. You have recommended by the algorithm. In a lot of cases, the recommendation is coming outside of the algorithm.

DR. SIMON MITCHELL: Recommended by. Prescribed by the algorithm or recommended.

DR. NEAL POLLOCK: Or recommended. Because it is a separate. It's separate.

DR. SIMON MITCHELL: By the algorithm or recommended. Okay.

DR. BRUCE WIENKE: I just wanted to comment about the idea about whether there is any need for this to be done at all. Deep stops are very much a part of the technical diving community. Deep stops are implemented on computers, on tables. They are being done now. If nobody has any data on it, maybe somebody should tell people that.

DR. SIMON MITCHELL: We're coming to that, Bruce. Can we please stop talking about whether we’re going to recommend deep stops. We're coming to that in a minute.

DR. DAVID SOUTHERLAND: The way that it's written right now, does that mean like safety stops, what wouldn't count as an empirical deep stop?

DR. SIMON MITCHELL: Correct.

DR. DAVID SOUTHERLAND: But the recommendation that's come out about stopping at half the absolute depth for two and a half minutes, does that count as a safety stop?

DR. SIMON MITCHELL: It's a deep stop. By that definition, that would be a deep stop.

DR. TOM NEUMAN: How? It is a voluntary or empirically derived decompression stop that is deeper than any stop prescribed by the algorithm or recommended. You're making an unnecessary stop by the algorithm. It's empirically put in. It's a deep stop.

DR. SIMON MITCHELL: That's what I just said.

DR. SIMON MITCHELL: The safety stop is recommended by the people who issued the table. We're talking about deep stops. PADI doesn't recommend the Marroni stop, does it. They recommend a safety stop. So that's what makes the Marroni stop different. You choose to put a Marroni stop in, you're putting in an empirical deep stop. Look, the problem with these things is you can always find some kind of minor exception. Have we got the spirit of this right? I think we have. I think we have. So there are two qualifying footnotes. One of them is this, which I don't think there needs to be any debate about. It's just the fact that these practices are occurring in recreational, technical and commercial and military diving, which kind of gets to your point, Tom, about not excluding the recreational divers. And then there's the other point that we made to take into account Christian's concern and David's concern about the fact that this whole concept of deep stops is in some way flawed because at some point in time we'll derive what is appropriate decompression, and this whole “deep stop” thing will just go away. We're acknowledging that that could happen. That's just there to say that. So this is the point that you've all wanted to debate. What can we recommend to the diving community now, based on the discussions that have taken place here this weekend? And this is open to debate. So let's go through it all first, and then we'll debate it. There are two statements: First: “Single deep stops may be of value in reducing decompression stress related to no-decompression dives between 18 and 40 meters of seawater as determined by reduction in Doppler bubble scores”. Second: “In technical, deep military and occupational diving, there is no evidence that empirical or bubble model-derived deep stops are superior to decompression regimens prescribed by gas content models. I imagine there will be even more debate about this.

DR. NEAL POLLOCK: I think that by saying single deep stops may be of value, you're introducing a bias in favor of deep stops. I think it would be more appropriate to say that there is insufficient data to conclude whether or not deep stops may be a value. I think that's a significant distinction.

DR. SIMON MITCHELL: We won't make a decision on that right here. We'll take that on advisement; hear what other people have got to say.

DR. ALF BRUBAKK: I certainly agree with Neal. I mean, the data seem to say we do not know. There are some data seem to show it works, other data show it doesn't work. And I don't quite understand the difference between the first paragraph and the second paragraph. Are you sort of implying that on the top, we're talking about recreational dives. It might be a benefit to them, but not with someone that's occupational dives. They're diving in the same water.

DR. SIMON MITCHELL: I think the original intent of this, correct me if I'm wrong, Frans, Frans sort of put this together and I modified it. But I think the issue is that it was a weight of evidence thing. That the weight of evidence is slightly more in favor of making a more positive statement in relation to the work that they did. Whereas, the weight of evidence in relation to the sort of work that's been done on these technical or military deep dives for example, the Gerth study and the Blatteau paper is more towards the negative side of things. So that's been kept very much a neutral statement. The first is a slightly more positive statement based on weight of evidence. But that's up for debate.

DR. ALF BRUBAKK: I certainly will object for the record. If you're going to insist on having that first statement there, at least I want to object and say that I don't quite understand why you want to do that. I feel shanghaied here.

DR. SIMON MITCHELL: Alf, this is why this is a democracy. You're getting your chance to speak. Neal and Alf don't like that first statement. Sounds like other people don't like it as well. It's not “my” statement. It's just up there for discussion. We'll change it if necessary.

DR. FRANS CRONJE: The first sentence relates to what we define as the empirical stop and the second, the model-derived stop. I will just want to make sure that that message is transferred in this discussion.

DR. SIMON MITCHELL: No, I'm not sure that's true, Frans. The second could include Pyle stops or similar. This could include Pyle stops, or that sort of thing. I think the distinction was made on the basis of the weight of evidence, but we can change the whole thing to a single statement if it's the feeling of the meeting. I've got no axe to grind here. That's why I'm chairing this part of the session.

DR. BRUCE WIENKE: I'm sort of caught in the middle on this. I've got a perjorative statement to make when I look at the second statement. What is your definition of "evidence"? I hate to get into this. But is your evidence test results in a chamber or is it a data bank or is it something else? I would say that from our perspectives at the laboratory, the data we've collected suggests and the analysis we've done suggests that we have evidence that bubble model deep stops are superior to decompression regimens for gas content models. So that's a data statement. That's not a wet or dry lab test statement. How about competing evidence or something that there's evidence on both sides, depending on how you look at it.

DR. SIMON MITCHELL: It's a fairly neutral statement, and it reflects the issue of evidence on both sides. My personal view, and I think I probably speak for quite a few people here, and I've said this at this meeting already, is that a lot of the so-called data bank evidence is weak because of the way it's been collected. I don't think it's particularly reliable. Against that, we have some highly objective studies which have shown that there was no difference or even that deep stops were disadvantageous. You'll note that we haven't said deep stops are worse. We've just made it a neutral statement. Is this a time for a show of hands on that one?

DR. WAYNE GERTH: You've been very brave in making that statement, and I'm standing back here saying, maybe it is time for a show of hands.

DR. SIMON MITCHELL: If we just leave the first part of it out, how many people would agree with the second statement as it is now? What's the matter, Tom?

DR. TOM NEUMAN: I don't understand what we're agreeing with and not agreeing with.

DR. SIMON MITCHELL: Do you agree with that second statement or do you think it should say there is evidence that supports deep stops?

DR. BRUCE WIENKE: Competing, conflicting.

DR. SIMON MITCHELL: What it says now is there is no evidence that empirical or bubble model-derived deep stops are superior to decompression regimens prescribed by gas content models. Would you rather have that, or would you rather have a statement saying there is conflicting evidence?

DR. NEAL POLLOCK: Can you say insufficient evidence? I think "insufficient" will resolve it.

DR. SIMON MITCHELL: Some people might consider that too positive but I'm happy to change it to insufficient.

DR. PETER LINDHOLM: This is not a democracy. You can't suggest that my vote would count as much as the people here who have been doing decompression research for 30, 40 years. I object to a vote by democracy in this. We should have scientific data and make conclusions from scientific data.

DR. SIMON MITCHELL: I understand that, Peter, you're absolutely right. But, in fact, I think that, the way it's worded now, is the best summation of the scientific data that we've had. I think it is. The problem with these workshops is that we want to have a statement at the end that reflects a consensus of the workshop, and I don't know a better way of doing that than a show of hands. I know that not everyone in here is an expert decompression modeler, but people have been sitting here, forming their opinions. Okay. We'll hold off on the vote for a moment and hear a few more. There are lots of people who want to speak to this.

DR. RICHARD VANN: I would agree that that second one is reasonable. There's no evidence or insufficient evidence. The first one might be updated a little bit just by a couple of words and made, I think, a little clearer. Single deep stops may or may not be of value in reducing decompression stress, et cetera.

DR. PETER BENNETT: May or may not.

DR. DAVID DOOLETTE: I think the first point should just go. It's completely wrong. For a start, there was a little bit of evidence, for between 25 and 30 meters, not 18 to 40, across that range. The Marroni stuff showed there was no value at those ends of the range. And, yeah, you could say maybe there was some evidence. But it doesn't also incorporate the fact that it was time dependent. Also seems to be it's depth dependent. I think it's just wrong as it is and shouldn't be in there at all. As to the second statement, I like the second statement.

GENE MELTON: The only thing I would have to say is where you say no evidence, "no" means absence or lack thereof. Absolutely nothing. What we have heard today in the last two days have been evidence by one group that says that the deep stop bubble models don't work, and we've heard stuff from the other side that said they do work. We have conflicting opinions, so to speak, on what it is. And if anything should go out of this workshop would be that that's what we would say, they are conflicting opinions as to whether the deep stop works or doesn't work. I don't think we can say there's no evidence because both of these guys are going to tell us they have evidence.

DR. ALF BRUBAKK: I certainly agree. I mean, the point is that there is conflicting evidence. And as someone who is interested in the decompression, I would love the bubble models to be vastly superior. And I think they are in some way describing the reality better than the supersaturation models. On the other hand, I have data to show that in some cases, actually the supersaturation models work better than the bubble models. That is some of the data I have. So the opinion is we simply do not know. And I think we should say that quite clearly, and I can't quite understand why someone wants to say something that most of us probably know can't be quite correct, that is there are people thinking it has value. I'd love it to have. But it's not as simple as that. So I think it simply is the conflicting evidence. I think it's a very, very good statement. I think we should leave it with that. I also think that we should drop this discussion and discuss a little about the future of science, what can we do.

DR. BRUCE WIENKE: Just to give you my perspective on this, as a technical diver, not as a scientist. I can tell you that if you even say there's conflicting evidence now, this will cause a storm in the technical diving community because since Pyle stops, the vast majority of people have taken this as fact for years now. This is going to be a big eye opener.

DR. SIMON MITCHELL: He's exactly right. Thanks, Bruce. Obviously, that's what we want to do.

DR. PETER BENNETT: I've been listening to this with some concern. I said when we started, we had different platforms in which we were discussing deep stops. Some were recreational. Some were military, with a different form of deep stop entirely. Some were technical, again, with a totally different type of deep stop. And we're now talking about deep stops, again, as sort of one animal. I don't like the idea that we're making recommendations like this. I think we have obviously conflicting views on various aspects in all categories. And it's probably best not to put anything down in writing at the point now and just let the workshop speak for itself and the discussion you had with the various topics under their titles and let that carry as it is now. I don't think, with the evidence we have to date and the polarization of those groups, and I mean that. They're very polarized. People are very aggressive in attacks on different aspects. They shouldn't be that way. We're all trying to work for the same person and trying to help the diver. My vote is to not do this. I originally thought it was a good idea. I'm against it in principle now because I don't think the evidence we have as a total group is sound enough to put things down which people are going to take a gospel and use in the industry or anywhere else.

DR. SIMON MITCHELL: Peter, if we take the first statement out of there entirely, what is the matter with the second, “in technical deep military and occupational diving that there's conflicting evidence?”

DR. PETER BENNETT: I don't think we need to make that statement. Let people make their own judgment on the data that's in the actual document. I don't have consensus from everybody. People are polarized. You are making statements there which you can't back.

DR. SIMON MITCHELL: There's no consensus reflected in this. It's conflict. But out there at the moment, the technical divers think that it's a God-given thing that deep stops work.

DR. PETER BENNETT: What works, works.

DR. SIMON MITCHELL: I'm sorry. No. I think that Bruce has got a very good point. I don't think that there's anything wrong with this statement as it now stands. It's not saying either side is right. It is pointing out that there is conflicting evidence. And for an authoritative body to actually come out and say that, at least it alerts the diver to the fact that everything they read about this on the Internet might not necessarily be true. I think this is worth saying. Your concern is more about the first statement I suspect. We can get rid of that entirely and just work with the second.

DR. BENNETT: I'll go with that, but that's as far as I'll go.

DR. SIMON MITCHELL: Fair enough. How do other people feel about that?

DR. SIMON MITCHELL: All right. Let's do it. Deleted. (the first statement).

DR. CHARLES PERDRIZET: Instead of saying conflicting, you can call it equivocal. I think we can all agree that there's equivocal evidence here and that we don't know what it is. But to say we don't know makes those that look at the leadership, well, that's not a good thing, they're fighting. But just say it's equivocal.

DR. SIMON MITCHELL: "Equivocal" sounds like weak positive to me, whereas "conflicting" sounds like a bit of both.

DR. DAVID DOOLETTE: It's not equivocal. It's conflicting. Look at Brubakk; they had stuff going both ways. It's conflicting.

DR. SIMON MITCHELL: Peter just suggested insufficient. I feel insufficient is a weak positive. I think.

DR. WAYNE GERTH: We're a body trying to make a statement about what we feel we've heard here. I think what accurately reflects what we feel as a body is that we cannot assert that one or the other is superior. We cannot assert.

DR. SIMON MITCHELL: I'm happy with that.

DR. DREW RICHARDSON: We haven't even got recreational divers in here now. Gene, we've made your change. It says conflicting now.

DR. WAYNE GERTH: Now that we've just pulled out the no-D problem, remember I showed and Peter showed that there are ways that this added stop in an already acceptable no-D dive can help. So it's like Alf said, these technical military and occupational divers, do they dive in different water, do they breathe different gas? No. Those are decompression dives. In decompression dives, we cannot assert that one type of schedule is superior to another.

DR. SIMON MITCHELL: We'll take the "technical, deep military and occupational out". I'm fine with that.

DR. DREW RICHARDSON: We don't envy your job, Simon.

GENE MELTON: The only thing I'd like to point out is that we've sort of gotten away from the fact that the evidence produced by Wayne is for deep air dives. The evidence on the bubble model is mostly substantiated by trimix. And we have different animals, and we're trying to say that they're equivalent, and I don't think we should try to blend this as to one. In our agreement to disagree, we have to agree that they're different.

DR. SIMON MITCHELL: I don't think we do actually, Gene. Wayne, do you want to speak to that? Gene's concern is that your work pertained to deep air, whereas most of the evidence favoring deep stops applies to mixed gases. Should we be making that distinction here?

DR. WAYNE GERTH: I would agree that we did not show anything having to do with a helium decompression. I can imagine ways that we might get a different outcome when we test that. I will, however, stand here and say that I don't expect the evidence we've seen for the helium dives constitutes evidence of superiority of one type of schedule over another. What works, works is fine, but we haven't been shown that what works is better than something else or worse than something else.

DR. SIMON MITCHELL: Gene, honestly, I think that's a reasonable stance based on strength of evidence. Thank you for the discussion there. That was very good. Okay. Should we move on to the future, because I think there was some concern about that. In fact, we've got a blank slide for this one. So what research needs to be done? Peter, do you want to do that bit now? Peter has just got three slides to show you.

DR. PETER BENNETT: I just want to show something. We are very much aware that the deep stop, as we use it in recreational diving, does not necessarily have a relationship to decompression sickness. So what we've been trying to do is to come up with a large animal study since we cannot use humans. We put together a proposal to use sheep, which is supposed to be done as a Haldane model. The project will be done, I hope, at the University School of Medicine (Madison) where they have big experience in working with sheep. They have a model which shows that in these type of square dives that we do, with a short deep dive, that they have neurological type hits, and in the shallow, long dives, they have pain only. The dive which will produce 50 percent incidence is 145 foot for 30 minutes. We plan to observe the DCS signs and symptoms, do MRI Diffusion imaging, to pick up any kind of inflammation or damage from the dives. Five weeks post dive, animals will be re-scanned and then six weeks post dive they'll kill the animals and do a necropsy for pathological evaluation, to see if there is any ischemia or blood type of injury. Then they'll do an MRI again. This is an attempt to try to find a relationship between the deep stop Doppler bubble grades and spinal cord DCI injury in a large animal model. It's one example of a problem which obviously is right in front of us and a way perhaps to get at it. It may be able to stimulate you to think of others that you might be able to do somewhere as well. We can't do large animal studies, in very many places either. I'd like to have done it at Duke, but we just can't do it there. We can do it in Madison. Thank you.

DR. SIMON MITCHELL: Okay. So these were just a couple of things we jotted down. Wayne's original challenge to perform objective comparison of RGBM or VPM with a gas content model algorithm in a trial, not unlike the one they did at NEDU, that would be fantastic. Maybe with a different outcome measure, such as using decompression stress versus decompression sickness. We realize the difficulty with the latter. The other ideas we had were accurate profile versus outcome data along the lines of project dive exploration, and animal studies. It's a blank slide. Ideas, just things we can put in the proceedings that the discussants came up with. So the floor is open.

DR. WAYNE GERTH: Well, two comments. I mean, I don't enjoy the prerogative of the chair of the meeting. I wish I was told that we were supposed to submit research proposals to have reviewed here by the people, the meeting.

DR. SIMON MITCHELL: It's not quite at that level, Wayne.

DR. WAYNE GERTH: When we talk about RGBM or VPM, I'd like to know exactly which it is we're speaking about. Because I understand the VPM. I also understand RGBM is a brand that has at least three distinct versions out there, and there's all sorts of ambiguity about which one we're talking about at any given time.

DR. BRUCE WIENKE: No. There's only one.

DR. WAYNE GERTH: And only two of the three I mentioned are described in any intelligible way in the literature.

DR. BRUCE WIENKE: I'm sorry you find them unintelligible, Wayne. As far as RGBM goes, there's only one. And then for dive computer usage, that one model is folded over M-values. Okay. The one that's folded over M-values is for recreational diving, nitrox, light decompression. The full up model that Wayne doesn't understand is the one that you would want to test for decompression.

DR. WAYNE GERTH: Okay. You did mention two. There's a third, and that's the one that was in the set of equations that you showed on your slide there that has appeared in your most recent publications that has a bubble volume-like $\delta R/\delta T$ equation in it. That is the other one. That's the one I don't understand. So if I'm going to be charged with trying to compare one of these things against another, I'd like to know which one it is, and I'd like to have it presented in such a way that I could reproduce it. Because, otherwise, I can't test it.

DR. BRUCE WIENKE: Let's see, what did you say? I mean, there's only one. Okay. And the manifestations of things that are included in it have to change a little bit. But the basic idea remains unchanged. I will provide you with all the information to read between the lines that you presently don't understand. And I'll take blame for that because I haven't got time to write 25 pages of stuff for a proceedings. Okay. And I'm sorry if some of it doesn't come through. I'm glad to discuss it with you. But I'll give you whatever you want, and I'll explain it to you in complete detail. That's number one. Number two, I will give you a profile to test in the event that you continue not to understand what's going on. And I'm not saying that in a nasty way. I'm just saying it in general.

DR. DAVID DOOLETTE: I don't like that first point at all. Why pick out RGBM and VPM? Why don't we test Copernicus? Why don't we test the tissue growth model or any of the other models out there? I don't want to see this meeting hijacked by one particular style or model, I guess. I think some people, Wayne, for example, might be suggesting that we test it. But maybe it should say we challenge people who have these models to do objective comparative testing. But I certainly don't think we should be singling out any particular models for testing in that statement, given that that's just one of many different bubble models that are out there, and there are different ways of doing deep stops as well.

DR. SIMON MITCHELL: The reason these are singled out, David, is that these are the two models that the recreational technical community is focused on the most and that are in the most widespread use. And Wayne challenged Bruce to do it; that's why I put it in there.

DR. DAVID DOOLETTE: Your second point is we should challenge the modellers to actually test them, but I don't agree with your first point. I agree it's true that they are the ones that technical divers understand or have access to, but I don't think that we should be focusing on them for that reason. There are a whole range of other bubble models.

DR. SIMON MITCHELL: Well, that's true. But how do you choose. Surely it would be most sensible to start with the one that most people are using.

DR. DAVID DOOLETTE: I don't think that should be the recommendation of this society at all. Because there's other decompression models out there that you could be using. I think it should be a generic statement. That's my opinion.

DR. ALF BRUBAKK: I certainly agree with that. I think it should be a generic statement. And I think if you change the first or the sentences to say that we have to use objective methods to determine which procedure is actually better or which model describes the reality better than the other. So I think the first sentence changed to the fact that we're going to look at objective comparison of the different procedures and that we should be encouraged to actually do that. I think we should state that.

DR. SIMON MITCHELL: I'm happy to make it a more generic statement.

DR. ALF BRUBAKK: When it comes to looking at the actual outcomes, its part of the thing, that you're saying in the first part, we should look as carefully as we can at objective criteria. For instance, if you use ultrasound, you should compare the ultrasound with the outcome. When it comes to the animal studies, I don't quite understand why we're suddenly presented with a sheep study, because it's obvious. This protocol is very, very similar to the protocol that we are implementing at the moment in different animal species. I think, again, we should encourage researchers to use animal studies, to look at one thing that I think is very important; namely, to see the comparison between what we can measure, namely, the gas bubbles, and the actual outcome in the animals. And we can do that. We have the methods today that are much, much better than it was a long time ago, that we can actually look at what happens when you have more or less gas bubbles, and we can study that in animals and we should be encouraged to do that. I think a third thing that should be very important to study is simply to look at the effect of environmental and other factors on the outcome of decompression. We know nearly nothing about that. We know there is some data saying this might be very, very important. I just want to remind you that the work we've done ourselves showing that a bit of exercise changes the whole situation. It's vital to have the same amount of gas supersaturation. In one case, you kill the animal with bubbles. In the other, nothing happens at all. I think we can study that sort of thing very easily.. We have the methodology. We have the equipment to do it. We have the ideas to do that, and we should encourage that instead of trying to go directly to some model that might be good. The model's still there.

DR. SIMON MITCHELL: Thanks, Alf. I agree with all of that. I'm a big proponent of this whole issue of studying the pathophysiology of disease and the related factors of that influence outcome, other than focusing entirely on decompression models. I think that's probably where the real money is, in fact. And there's plenty of evidence emerging that that side, such as the temperature work, your exercise work; all of that is pointing in the direction you suggest.

DR. RICHARD VANN: I bet if the Navy was asked nicely, they might make available some of their data to anybody who wanted to try to model it. Because a lot of this stuff does not require and should not start with human trials if there are good, solid data available. And you could test your models against that data. Now, the Navy is one possibility. As I say, you might have to ask them nicely. You probably don't even have to ask DAN nicely. We've already offered some 70 dive profiles that resulted in decompression sickness for anybody to use, and nobody was interested. The point is that a lot of this can be done with probabilistic modeling. And it’s probabilistic modeling, you're going to have to resort to in the end anyhow. So the community has to step up to the plate and start learning how to do this. But if we can have a database that was available for people who wanted to do it, if we could have more people, maybe a workshop to train people how to do probabilistic modeling, maybe making some tools available that people could use, then -- you know, there are a lot of good ideas, and those good ideas might be able to be tested by more people. But if there's data available that can be used, why not start there, and use that to pare down your choices for decompression models, rather than jump into a very expensive, possibly hazardous program.

DR. SIMON MITCHELL: Thank you.

RICHARD DUNFORD: I have a suggestion that perhaps we might want to have another section. And I say this because this document apparently is not going to be distributed only to the scientific community, but it's also going to wind up in the diving community and, in particular, the technical diving community, and there are certain understandings the scientific side has and certain understandings the technical community has, especially in regards to the kinds of research and the strength that the research brings back to the information you're trying to convey. Dr. Wayne Gerth does detailed comparative studies that are extensive, long-term and difficult. Other people have been training, have not seen decompression sickness from the types of profiles they're keeping. They don't see any decompression sickness, and they are wondering why the people in the scientific community don't get it. And the people in the scientific community are saying, well, we don't get it because we don't think it's good research. So perhaps what we could do is describe levels of scientific inquiry and their value to the information and the problems they create so that the people who read this document will understand, when we say that there is conflicting evidence, what the conflict is about.

DR. SIMON MITCHELL: In other words, what you're really saying is we should try and educate the diving community about levels of scientific evidence.. .

GENE MELTON: How many divers are there in the fleet, just a rough guess? 3,000? How many technical divers would you guess? 10,000?

DR. SIMON MITCHELL: Way more than that.

GENE MELTON: So the Navy has a mission. We all recognize that. And it's an incredibly important mission. The technical diving community is folks out trying to have fun, mostly. And they're basically a living laboratory. We've already said that and established it. So we have 3,000 versus 10-, 15-, maybe 20,000 people out there. We have a large number of folks that are exposing themselves potentially to harm. We all recognize that. We all do it. When I walk out of here, will I change my diving style based on what I've heard here today? No. I'm going to do the same. And I expect that other people will do so too. But there are computer programs, dive programs that potentially might be of use to you. I say "potentially." I don't know that they will be. But they're potentially there. And there have not been the detail studies that you performed, but they have been done by folks, and they're walking and talking and still doing well. Now, something must be working for that to happen. And maybe it will be beneficial to you, maybe not. But I do know that there are a large number of people that are exposing themselves, that look to this group for support as to what they do, that they're hopefully not going to be hurting themselves. Because not one of them is charging into the face of a cannon. Not one of them.

DR. SIMON MITCHELL: Thank you, Gene. Those are good comments, and that's exactly what we're trying to do. The workshop is giving the best answer that it possibly can based on what we've heard over the weekend. What we’ve heard is that the evidence is conflicting. It's a scientifically accurate, if somewhat general appraisal. I don't think we can do better than that. I think your comment about the large amount of diving that goes on out there amongst technical divers is a good one, and somehow we need to tap into that more for projects like Dick Vann's project dive exploration. We need to get more technical divers contributing data. That would be very useful.

DR. KEITH GAULT: I wanted to address Gene. I'm a technical diver. I go diving. I stay warm. Our guys (*in the NEDU experiments – eds*) are in the equivalent of 63 degree waters, they were cold. They were miserable by the end of these dives. That's going to make a world of difference. When you give us data, if all we've got is the profile and we don't know how the guy felt, water temperature doesn't help. They're going to try to make themselves comfortable. We can't match that up with the military side. It's that part of it. And that's why, if you're doing it, you can get rid of your decompression sickness cases. We know how our divers are going to dive, so we can set it up that way, and that's how we define the trial. It's trying to match up the data that's different.

DR. SIMON MITCHELL: We'll have one last comment. The cascade of ideas seems to be slowing down.

KARL HUGGINS: Wayne reminded me of the paper I put together for the deep dive workshop for the Smithsonian. Looking at the dive computers that are out there and the software, in terms of going and asking the manufacturers what their database was and what their models are, the database for verification of that model isn't there, just like most of the dive computers. And that's one of the things that needs to be out there. If people are pushing these ideas, pushing these models, pushing these computers, they have to make some attempt on their side to get the data to support it and not just the anecdotal reporting back in.

DR. SIMON MITCHELL: Thank you for your comments. Everybody's comments are on the record. Your concerns, your comments, your issues, they're all on the record. So no one has been ignored. I'd just like to thank you for your discussion. I think it's been lively and productive. And I think that the few conclusions or definitions that we've drawn are good ones. I just want to ask Peter Bennett to make a few closing remarks. Thank you, Peter.

DR. PETER BENNETT: Thank you. I'm glad we had this workshop. I think it showed where there are divisions and where there is some altercation in trying to defend various grounds on different areas. That needed to be done because before this meeting, we didn't have that information, and it wasn't clear, as I said earlier, these various divisions with the different kind of deep stops we have. I'm very grateful for all of you coming, some of you long distances, and contributing your papers. I would also like to give thanks to Stacy Rupert and Cindi Easterling in the back there for all the work they've done to help. We also have a very kind hard-working court reporter here, Kim Farkas, who is taking all your words. We need to give her a hand, please.

CONSENSUS STATEMENTS

DECOMPRESSION AND THE DEEP STOP WORKSHOP.

SALT LAKE CITY

JUNE 25, 2008

DEFINITION OF DEEP STOPS

Deep stops may be:

Empirical
One or more "voluntary" or empirically derived decompression stop(s) that are deeper than any stop prescribed by the algorithm utilized.[2]

Model-derived
Decompression stops prescribed by bubble model algorithms or manipulated gas content model algorithms that are deeper than determined by "un-manipulated" gas content models for equivalent time / depth profiles.[3]

Footnotes
1. There were difficulties (see discussion) in defining "deep stops" in this era of evolving decompression practice. Many commentators felt it was a meaningless term whose use should be discouraged or discontinued. Nevertheless, we have attempted to produce a definition that is both objective and relevant to current usage in the diving community. The term "deep stops" remains useful in describing different approaches to decompression at the present time, but it is acknowledged that as research steers decompression practice toward an optimal "final common pathway", the term will become increasingly less meaningful and may eventually be abandoned.

2. It is not the intent of the "empirical" definition to embrace multi-level diving or shallow (≤ 5m) "safety stops" recommended by some training agencies in no decompression diving. However, this definition would include deeper stops in no decompression dives.

3. The definition of "model-derived" deep stops specifically compares bubble model algorithms to "bare" or "un-manipulated" gas content model algorithms because this has historical relevance, and is consistent with the contemporary understanding of deep stops among divers (technical divers in particular). However, as was pointed out by several expert discussants, the m-values and surfacing rules for gas content models can be (and are) manipulated in a way that also produces deeper stops. It follows that these must also be considered as "model derived deep stops" and are included in the definition.

4. Both empirical and model derived deep stops may be applied in recreational, technical, and commercial / military diving. While there are subtle differences in application in these different diving scenarios, these definitions of deep stops remain valid in each context.

STATEMENT REGARDING THE EFFICACY OF "DEEP STOPS" APPROPRIATE FOR RELEASE TO THE DIVING COMMUNITY:

Only one could be agreed on as follows:

"In respect of decompression diving there is conflicting evidence regarding the relative efficacy of decompression regimens that include empirical or model-derived deep stops (as defined) and decompression regimens prescribed by gas content models."

DIRECTIONS FOR FUTURE RESEARCH

There were no firm conclusions, but there was general agreement that the following strategies would be likely to contribute positively to the debate on ideal decompression:

1. Formal objective dive and outcome comparisons between those contemporary bubble models used in the technical diving community and gas content model algorithms. The NEDU has demonstrated that such studies are possible, but outcome measures other than clinical DCS may be necessary if others are to replicate such work.

2. Continue accumulating a database of electronically recorded dive profiles coupled with formally recorded dive outcomes. This has already been started by DAN (Project Dive Exploration) and the workshop endorsed the need to encourage technical divers to contribute to this database.

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Peter	Bennett	Durham	NC	United States
Ed	Betts	Durham	NC	United States
Nicholas	Bird	St. George	UT	United States
Jean-Eric	Blatteau	Durham	NC	United States
Brian	Bourgeois	Gretna		United States
Alf	Brubakk	Trondheim		Norway
Frank	Butler	Pensacola	FL	United States
James	Canty	Gainesville	FL	United States
Kevin	Chan	Singapore		Singapore
Robert	Cook	Severna Park		United States
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John	Duncan	Auckland		New Zealand
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Richard	Hodgson	Grand Rapids	MI	United States
Laurens	Howle	Box 90300	NC	United States
Karl	Huggins	Two Harbors	CA	United States
Robert	Hulst	Schagen		Netherlands
Jarrod	Jablonski	Durham	NC	United States
WeeLee	Kang	Singapore		Singapore

Christopher	Kareores	Haverhill	MA	United States
Edmond	Kay	Seattle	WA	United States
Dawn	Kernagis	Morrisville	NC	United States
Michael	Lang	Washington	DC	United States
Gary	Latson	Panama City	FL	United States
Toni	Leskela	Vantaa		Finland
Peter	Lindholm	Stockholm		Sweden
Edwin	Long	Poulsbo	WA	United States
Tommy	Love	Layton	UT	United States
Richard	Mahon	Rockville	MD	United States
Kari	Makiniemi	Vantaa		Finland
Alessandro	Marroni	Roseto Abruzzi		Italy
Gene	Melton	St. Augustine	FL	United States
Robert	Michaelson	San Antonio	TX	United States
Samuel	Miller	San Deigo	CA	United States
Simon	Mitchell	Auckland		New Zealand
John	Murray	Fairfax Station	VA	United States
Suriya	Na Nagara	Bangkok		Thailand
Tom	Neuman	Del Mar	CA	United States
Gerard	Newman	Kailua-Kona	HI	United States
Victoria	Newman	Kailua-Kona	HI	United States
Ronald	Nishi	Toronto	ON	Canada
Tim	O'Leary	South Padre Island	TX	United States
Hiromichi	Oiwa	Tokyo		Japan
Dan	Orr	Durham	NC	United States
Bruce	Partridge	Vancouver	BC	Canada
Lynn	Partridge	Vancouver	BC	Canada
John	Peacock	Panama City	FL	United States
George	Perdrizet	Hartford	CT	United States
Neal	Pollock	Durham	NC	United States
Drew	Richardson	Rancho Santa Margarita	CA	United States
Karen	Richardson	North Balgowlah		Australia
Karl	Shreeves	Rancho Santa Margarita	CA	United States
Jeffrey	Sipsey	Glendale	CA	United States
Ben	Slade	Vacaville	CA	United States
Aleksey	Sobakin	Madison	WI	United States
David	Southerland	Groton	CT	United States
Bret	Stolp	Durham	NC	United States
Tabby	Stone	Playa Del Rey	CA	United States
Linda	Takvorian	Playa Del Rey	CA	United States
Anthony	Turner	Buderim Qld		Australia
Gunalp	Uzun	Istanbul		Turkey
Richard	Vann	Durham	NC	United States

Donald	Verschoor	Amsterdam		Netherlands
John	Wan	Singapore		Singapore
Dan	Warkander	Panama City	FL	United States
Kevin	Watts	Portland	OR	United States
Lindell	Weaver	Salt Lake City	UT	United States
Bruce	Wienke	Los Alamos	NM	United States
Robert	Wong	Fremantle, WA		Australia
Margaret	Yap	Singapore		Singapore
David	Youngblood	Haleiwa	HI	United States

APPENDIX C: WORKSHOP SCHEDULE

UHMS PRE-COURSE:
"DECOMPRESSION AND THE DEEP STOP"
JUNE 24-25, 2008
SALT LAKE CITY, UTAH

TUESDAY, JUNE 24		
0700	Registration/Continental Breakfast	
0820	Introduction to the program	*P. Bennett*
0830	Early Observations on the Effect of "Deep" Decompression Upon Doppler Ultrasonic Bubble Signals Following 210/50 and 170/30 Dives	*T. Neuman*
0900	LANL Deep Stop Data Bank and Dual Phase Bubble Model for Prfile Analysis and Risk	*B. Wienke*
0930	Discussion	
1000	Technical Diving Overview	*S. Mitchell*
1030	**Coffee Break**	
1045-1245: TECHNICAL DIVING USE OF THE DEEP STOP		
1045	NAUI- A Decade of Deep Stop Training with the Reduced Gradient Bubble Model	*T. O'Leary*
1100	IANTD- A Practical Look at Decompression Survival on Dives Deeper than 100 Meter and use of Intuitive Decompressions (Presented by J. Dituri)	*T. Mount*
1115	GUE- World Record Cave Dive	*J. Jablonski*
1130	ANDI- The Application of "Deep Stops" in ANDI's Technical Diver Training and Expeditions	*E. Betts*
1145	PADI Deep Stop: Awareness and Current Practive in the Technical Diving Community	*D. Richardson*
1200	Discussion	
1245-1345	**Lunch**	
1345-1645: NAVAL USE OF THE DEEP STOP		
1345	Could the U.S. Navy Benefit from Technical Diving Techniques?	*J. Dituri*
1400	Empirical Evaluation of the Efficacy of Deep Stops in Air Decompression Dives	*W. Gerth*
1430	Discussion	
1500	Coffee Break	
1515	Deep Stops During Decompression from 50 to 100 msw Didn't Reduce Bubble Formation in Man	*J. Blatteau*
1545	Discussion	
1645	Close Session	
1900	**Symposium Dinner: Film Presentation/Speaker** **"WKPP Deep Diving and Exploration"**	*J. Jablonski*
WEDNESDAY, JUNE 25		
0700	Registration/Continental Breakfast	
0800	Bubble Detection and DCS Relevance	*N. Pollock*
0830	Discussion	
0900	The Optimal Path	*R. Vann*
0930	Discussion	
1000	Coffee Break	
1015	The Effect of Deeper Stops on Bubble Formation is Dependent on Length of Bottom Time	*A. Brubakk/ C. Gutvik*
1045	Discussion	
1115	IDAN Deep Stop Research for Recreational Divers	*P. Bennett*
1145	Discussion	
1215	Lunch	
1315	The Use of Deep Stops in Recreational Diving	*A. Marroni*
1345	Discussion	
1415	General Discussion, Future Research	*Faculty*
1515	Close Session	