# Safety Limits of Dive Computers

## Decompression Computers in SCUBA Diving

## a Workshop of the Swiss Foundation for Hyperbaric Medicine

**Chaired and edited by**
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# Preface

The workshop on safety limits of dive computers was sponsored by the Swiss Foundation for Hyperbaric Medicine. The reason was to bring international experts from Europe and Overseas to the country where from the beginning of dive computers use very many volunteer divers and diving instructors have participated in validation programs for our local decompression algorithm developed by the Diving Research Laboratory Zürich chaired by Prof. Bühlmann. As most of the symposia and workshops of the past were organized in the United States we felt that we had to offer to the Swiss scientists and diving instructors an opportunity to meet experts and to participate in the still ongoing discussion about the advantages and dangers of dive computer use by recreational divers.

Because of a limited budget we could not invite all the experts that would have been able to contribute to the subject, so we regret that we were not able to include several others of our international colleagues who would have made the workshop even better.

The workshop was organized with speakers that were invited to present their own contribution to the topics and with a general discussion of the presentations following the last speaker. We then arranged a round table discussion with a list of questions and proposals that had to be answered by all the participants. As most of the speakers would have known the position of the others the discussion following these questions was limited in time but as everyone had to give his position, the summary gives a good estimation of whether there was a general consensus or major disagreement about these particular questions. The rationale and calculations of the "no-bubbles" question in the roundtable discussion are published in the Appendix because the subject is of particular importance.

As the workshop was organized at the end of the Annual Scientific Congress of the European Underwater and Baromedical Society in Basel we invited a few speakers of the Congress to present their papers which can be considered as a contribution to the topics of the workshop in the Appendix of these proceedings.

We asked for manuscripts to be submitted and a majority of the speakers did this. The discussions were recorded by a tape-recorder and a transcript was prepared, however with many difficulties because the quality of registration was very bad. We apologize for the shortened text of the discussion and maybe some misunderstanding which may not have been corrected.

The publication of the workshop was accompanied by a lot of obstacles and finally the publishing of the proceedings could be realized with the help of the UHMS. We are very thankful for this obstetric assistance that we owe specially to Dr. Lee Greenbaum.

The production was done by Nicole Balstisberger and Michèle Spahr from Biel using winword 6.0 and we thank these two secretaries for the tremendous work and patience that lead to the finishing of the text. We also thank Bill Hamilton volunteering for lecturing the main part of the texts.

## Albert A. Bühlmann, 1923 - 1994

Professor A.A. Bühlmann died a little more than one year after the Round Table on Diving Computer we organized during the Joint Meeting: XVIIIth Annual Meeting of the European Undersea Baromedical Society (formerly European Undersea Biomedical Society - 3rd. Swiss Symposium on Hyperbaric Medicine).

It is our sad privilege to dedicate this book to his memory.

Prof. A.A. Bühlmann was personally known to us. We admire of course all of its work which will stay for many years an example for us, but furthermore, we remember the colleague, always ready to help and to give an advice when we called him to discuss the treatment of a diving accident.

We remember many long telephone debates on the advantage of using high pressure rather than low pressure in the treatment of diving accidents.

Farewell Prof. Bühlmann, we will miss you.

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# Introduction

The 19th century divers and caisson workers did not use decompression tables but rather empirical rules that promised a lesser percentage of caisson sickness during their industrial or naval activities. The basic concept that enabled divers to perform dives of different duration and depths with a reasonably low incidence of decompression sickness was the table of Haldane published in 1907. His approach was very scientific and the general principles are still valid for modern diving procedures. In the meantime many new tables were calculated by modified or completely differing algorithms which all tried to lower the incidence of decompression sickness under particular circumstances.

One of the main disadvantages of all these tables is that they are created for rectangular dives, as they are normally done by professional divers and navy divers. The sports diving popularity that arose in the fifties and is still growing in an exponential way led to the need of a real time calculation device that could be used to control and simulate untypical dives, that is irregular dive-profiles like multi-level diving, yoyo-diving, variable interval-diving and diving in variable altitudes. From 1983 on the Recreational Divers Community began to use the newly generated dive computers first in Europe a few years later as well in the United States and now ten years later the big majority of European divers use dive computers which seem to satisfy the needs of the recreational diving procedures much better than the formarly used tables.

The diving medical experts however are still quite critical, first because the development of the portable devices is going faster than any validation of the specific adapted tables, second because many are afraid of increasing incidence of decompression sickness. This latter fear is not mainly based on criticism towards the algorithm of the dive computers but rather based on the light-heartedness of its use and the newly arising diving habits of recreational divers. We believe that the workshop will help to clarify some of the misunderstandings and that it may help the dive computer industry to develop a new generation of dive computers which are better adapted to the known risk factors which would enhance a safer way of diving.

# Validation of the U.S. Navy Real-Time Probabilistic Air and N2-O2 Decompression Algorithm

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THALMANN E.D., SURVANSHI S.S., PARKER E.C. WEATHERSBY P.K. VALIDATION OF THE U.S. NAVY REAL TIME PROBABILISTIC AIR AND $N_2$ $O_2$ DECOMPRESSION ALGORITHM. DIVE COMPUTER WORKSHOP, BASEL 1992 (ED. WENDLING J./SCHMUTZ J.) P.9-14, ISBN 3-908229-06-5. - **The basis of all real-time decompression computers is an algorithm which monitors the depth/time profile and uses that information to compute a decompression schedule. The algorithm is a set of equations which is based on a decompression model. The decompression model in turn is a mathematical description of the events felt to be important in avoiding decompression sickness. There are many approaches which have been used in developing such models and a good review has been done by Wienke (1). No matter how well thought out, a decompression model must be validated in order to be useful. Validation is the process whereby some measure is made of how well a particular decompression model succeeds at computing "safe" decompression tables or schedules. The definition of "safe" varies depending on the type of decompression model being validated as will be discussed.**

**One of the unique features of the new USN probabilistic decompression model is the way in which it was validated. The validation process and the type of decompression model being evaluated are closely related and understanding this relationship first requires understanding the different types of decompression models.**

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## Deterministic vs Probabilistic Models

For purposes of this discussion decompression models will be placed in one of two categories, deterministic or probabilistic. Deterministic models compute decompression tables such that certain predefined criteria (so called ascent criteria) are never exceeded (i.e., the model is never violated). Deterministic models have no way of determining how "safe" or "unsafe" profiles which do not follow its ascent criteria are. Probabilistic decompression models, on the other hand, are capable of computing a probability (or risk) of decompression sickness for any profile. Using a probabilistic model one could not only compute a set of decompression tables to a specified level of risk but one could also compute the risk level incurred if one deviated from those tables. In contrast to the deterministic model, one can never "violate" a probabilistic model, one can only be exposed to different levels of risk.

In order to illustrate the difference between the probabilistic and deterministic approaches, one must first consider how decompression models are configured. All decompression models have two basic parts as shown in Fig. 1. The gas kinetics portion is a time dependent function which converts the depth/time profile into an accumulated decompression dose which is usually a dissolved gas tension in a theoretical tissue. In Fig. 1, this tissue gas tension is a function of depth, time and oxygen partial pressure but other independent variables such as inert gas species, water temperature, or exercise level could be included.

The simplest and most widely used gas kinetic function is a simple exponential equation, which for a step change in pressure has the form:

$$P_{Tiss} = P_A + (P_I - P_A)\, e^{-kt} \qquad (1)$$

where $P_{Tiss}$ is the tissue tension at any time $t$ after the step change, $P_I$ is the tissue tension before the step change and $P_A$ is the arterial gas tension after the step change. The parameter $k$ is the rate constant, which determines how fast the gas tension in the tissue changes in response to a change in $P_A$. The gas kinetic portion of a decompression model may be the same in both deterministic or probabilistic models. The difference between the two approaches lies in the so-called ascent criteria. In general, ascent criteria are the constraints placed on the values of variables determined by the gas kinetics portion of the model, which determine how the specific decompression stop times and depths must be distributed. For example, if equation (1) is used to compute inert gas tension, then one type of ascent criteria might constrain $P_{Tiss}$ to certain values during ascent. The name ascent criteria stems from the fact that DCS never occurs during descent but only as a result of ascent, that is, only during or after decreases in ambient pressure.

Deterministic ascent criteria usually consist of a set of maximum depth dependent limits on the values of some critical variables. In the model used to compute current U.S. Navy Tables the gas kinetics portion was similar to equation (1) and the critical variable was tissue tension, $P_{Tiss}$. Tables were computed such that at no time did any one of the several tissue tensions (each one having a different exponential rate constant) exceed its maximum depth dependent limit. Ascent was only allowed to the shallowest depth where no tissue tension exceeded its maximum value. Once this depth was achieved a decompression stop was required of sufficient length to allow all tissue tensions to decrease such that none was greater than the maximum value allowed at the next shallower stop. This process was repeated until the surface was reached.

Probabilistic ascent criteria place a constraint on the computed level of risk for any decompression schedule. That is, any decompression schedule which does not exceed a certain specified level of risk is acceptable. Since there are many decompression schedules which may meet this criteria, other constraints such as minimizing total decompression time may also be applied. The details of how this risk is computed in the U.S. Navy model will be discussed later but the important concept to remember at this point is that the probabilistic model will compute an actual probability, or risk of DCS occurring for any schedule, called *P(DCS)*. This ability to compute a *P(DCS)* not only influences the way in which the model is validated but can also provide a quantitative measure of how well the model succeeds in predicting *P(DCS)* for actual dive profiles.

## The Validation Process

In general validation can be done retrospectively, prospectively or using a combination of both. In one method of retrospective validation which has been used with deterministic models one devises a decompression model to "fit" a particular set of reference decompression tables. Once fitted then one might presume that dives done according to the model would be as safe as the reference tables. In order to establish how safe the algorithm might be information on the observed incidence of DCS for the reference tables in actual use would have to be available. One concern is that one may not be able to adjust the model parameters (e.g., rate constants, ascent criteria) so that all tables computed by the model are exactly the same as in the reference tables. For deterministic models there is no way of computing how unsafe the non-exact tables are. Another concern is that one could have no assurance that types of diving different from those in the reference tables would have equivalent safety. For example an algorithm fit to a set of "square dive" tables subsequently used for multi-level dives presents such a problem. While this validation method has been used, the problems cited above make it the least desirable method.

A better method of retrospective validation is to gather a data base of actual dive profiles along with information on whether or not DCS occurred in any particular diver. One source of this data would be actual dive profiles used in man testing an earlier set of decompression tables. If one has constructed a deterministic decompression model one would attempt to "fit" the model to the profiles in the data base in some way. However, unless there are large groups of identical profiles in the data base (so called replicated profiles) which can be used to estimate the actual risk of DCS independent of the model there is no way to objectively measure how safe the model is. In contrast there is a formal method of fitting a probabilistic model to a data base and obtaining an objective measure of how good the fit is (as will be discussed later) even in the absence of large numbers of replicated profiles.

Prospective validation consists of using the model to compute decompression profiles and seeing what the actual incidence of decompression sickness is when they are actually used. Deterministic models will require large numbers of replicated profiles in order to measure how well it performs while the performance of a probabilistic model can be measured even if there are no large groups of replicated profiles.

## Deterministic Decompression Models

As discussed earlier deterministic decompression models are either followed or are not followed. Profiles in a data base either do not violate the models ascent criteria (in which case they are safe) or do violate it (in which case they are unsafe). Once a model is developed the first step is usually to determine an initial set of parameter values by fitting it to either profiles from a data base of dives or to a set of proven reference decompression tables. These initial parameter values are then modified as necessary during prospective validation. The only way to measure the safety of a deterministic model is to independently determine the actual incidence of DCS profile by profile. Since deterministic models themselves have no way of computing risk, each dive profile must be treated as a independent event and information from one profile cannot be used to determine the risk of another.

Even though deterministic models can only distinguish between safe and unsafe profiles, validation must still take into account the fact that any dive profile has a finite risk or probability of DCS occurring. Any specific occurrence of symptoms will be random because of inter- and intra-individual variation. When a large group of divers is exposed to exactly the same profile DCS may develop in some but not all. Also if the same diver is exposed to the same profile many times DCS may occur on some but not all of the exposures. Predicting the occurrence of symptoms independent of a decompression model for a random process such as this which has a finite probability of producing symptoms is done using the binomial distribution which is found in all standard statistical texts. Simply put this distribution allows one to compute how many symptoms are likely to occur in a small number of dives (say 40) when the true incidence is a specified value. If a profile produces 500 cases of DCS in 10,000 exposures one can say with confidence that the true incidence is 5%. However, if this same profile with a true incidence of 5% is used on only 40 exposures, one could expect the observed number of symptoms to be anywhere between zero and 5 for 95% of the time. Conversely, if one dives a profile 40 times and 2 symptoms occur (a raw incidence of 5%), then the best one can do is say that the true incidence (95% of the time) is somewhere between the confidence bounds of 0.61% and 16.16%. In order to independently estimate the risk of DCS for a specific decompression profile to within a reasonable set of confidence limits, a large number of identical (or replicated) exposures are required. Keeping the raw incidence at 5%, five symptoms in 100 exposures narrows the confidence limits for the true incidence to between 1.6% and 11.3% and 50 out of 1000 narrows it to between 3.7% and 6.5%

Obtaining sufficient numbers of replicated dives to obtain a good statistical measure of the incidence of DCS (i.e., safety) using deterministic models is usually not possible because of time and money constraints. This has led to measures of safety being made based on judgement and past experience and although highly subjective this method has produced useful decompression tables (2-9). Some of the more modern efforts using deterministic models have made attempts at estimating the overall risk of decompression sickness (5-7,17) but still cannot quantitate changes in risk when computed profiles are not followed. This latter point means that data bases containing dives which were not computed by the model under consideration cannot be used to determine the safety of the model.

## Probabilistic Decompression Models

Since probabilistic decompression models compute a probability of DCS occurrence for any profile they are not constrained to the independent profile by profile validation approach of deterministic models. Formal methods have been described whereby the parameter values for a probabilistic model can be determined by 'calibrating' the model to a data base and once calibrated it can be determined just how accurately the model can predict the risk of DCS occurrence (10,11). The real advantage to probabilistic models is that the data base does not have to contain replicated profiles nor do the profiles have to be from the model under consideration. Profiles from any source can be used so long as they are known with sufficient accuracy and the outcome (DCS or no DCS) is known for each exposure. The U.S. Navy has been developing probabilistic models since 1980 (10-15) and is about to produce a real-time algorithm and a new set of nitrogen-oxygen mixed gas decompression tables using this approach.

The basis of the probabilistic approach to decompression modeling is the risk or hazard function. The risk function describes the instantaneous rate of symptom occurrence in survivors at a specific time. The derivation of these risk functions and their relationship to the probability of DCS occurring are well described in texts on Failure Time Analysis (18) and Survival Models (19). This risk function is related to the probability of a DCS symptom occurring [*P(DCS)*] in a specific time interval $T_1$, $T_2$ in those who have had no symptoms up to time $T_1$ by the equation:

$$P(DCS) = (1 - e^{-\int_{T1}^{T2} rdt}) \qquad (2)$$

where r is the risk function. Equation (2) describes what is called the conditional probability of symptom occurrence, that is, the probability of symptom occurrence during the time interval $T_1$, $T_2$ conditional upon having had no symptom before the beginning of the interval. The probability of a symptom not occurring in an earlier time interval $T_0$, $T_1$, is

$$P(No\ DCS) = e^{-\int_{T0}^{T1} rdt} \qquad (3)$$

and the probability of symptoms occurring only in the time interval $T_1$, $T_2$ in anyone (the interval probability) is the product of equations (2) and (3)

$$P(DCS\ T_1, T_2) = (e^{-\int_{T0}^{T1} rdt})(1 - e^{-\int_{T1}^{T2} rdt}) \qquad (4)$$

The risk function *r* will have several unknown parameters whose values must be determined. This is done by initially postulating parameter values and seeing how well the risk function describes the actual observed outcomes (i.e., DCS or no DCS) for each profile in a data set. Parameter values are systematically varied from these initial values until the set that best describes the observed outcomes is found.

One determines how well the outcomes in a particular data set are described by a risk function using a specific set of parameter values using the method of maximum likelihood. If a particular profile did not produce a case of DCS the likelihood of that outcome, $l_i$, is set equal to *P(No DCS)* as given by equation (3). If a symptom did occur the likelihood for that profile is given by the probability of DCS occurring as calculated using equation (4). For each and every single exposure in the data base the risk function is used to compute the likelihood of the observed outcome using equations (3) or (4). The likelihood of all observed outcomes occurring is the product of the individual likelihood's:

$$L = l_1 . l_2 . l_3 .... l_N \qquad (5)$$

where *N* is the total number of individual exposures. Since $L_N$ is the product of many numbers less than 1.0 the value of the log likelihood (*LL*) is more convenient.

$$LL = \ln(L) \qquad (6)$$

The log likelihood value is always negative and in and of itself has no meaning. However, changes in the value of log likelihood can say something about the relative performance of a particular model when the parameter values change. Although we haven't yet explicitly defined the form of the risk function it will have several parameters which can take on any value. If one computes a value of log likelihood for two sets of parameter values then the set which produces the largest value (i.e., the smallest negative number) for *LL* is a better description of the data. In fact, once a risk function has been postulated, computer algorithms have been developed which allow one to systematically vary parameter values such that the set which produces the maximum likelihood is found. This then is declared as the parameter set which best describes the data set. Besides parameter values these techniques also compute the estimated precision for each parameter value.

So far we have just described a method for determining the optimal parameter values for a particular risk function without saying exactly what that risk function is. In fact the method of maximum likelihood is just a fitting procedure and will not produce a risk function. It will only optimize the parameters of a postulated risk function. There are no particular rules on defining a risk function as long as certain criteria are met:

- it must be a function of time
- it must always be $\geq 0$
- it must have a finite or zero integral value over all time intervals
- it must have a non-zero value over each time interval in which a symptom occurred (you can't have a failure if the risk is 0).

One may use an empirical function or a set of equations that describes some physical process (such as bubble growth) as a risk function. In developing the U.S. Navy algorithm described here, four types of risk functions were examined, based on two types of gas kinetics as shown in Fig. 2 (11). The EE kinetics use an exponential function similar to equation (1) to compute $P_{Tiss}$ during both uptake and elimination; this is symmetrical kinetics. The LE kinetics use an exponential function to describe gas uptake, but during off-gassing the rate of elimination becomes linear so long as a certain pressure above ambient [linear-exponential crossover point ($P_{XO}$)] is exceeded. That is:

$$P_{Tiss} = P_{tiss_0} + k(C - P_{O_2} - P_{XO}) \cdot t \qquad (7)$$

where $C$ is a fixed constant, $P_{O2}$ is the arterial oxygen partial pressure, $k$ the exponential rate constant used for tissue uptake and $P_{XO}$ the linear-exponential crossover pressure. These asymmetric kinetics are based on the decompression model used to compute the U.S. Navy constant 0.7 ATA $P_{O2}$ in $N_2$ tables (5,7).

The equations describing these two forms of gas kinetics allow a tissue tension ($P_{Tiss}$) to be computed at any time during a dive. The risk function was computed from $P_{Tiss}$ in two ways. The first was simply to relate the risk function to the supersaturation ratio:

$$r_i = \frac{P_{Tiss_i} - (P_{amb} + Thr_i)}{P_{amb}} \qquad (8)$$

where $P_{amb}$ is the ambient pressure, $Thr$ is a threshold pressure and the subscript $i$ denotes values specific to the $i$th compartment. The value of $r$ was never allowed to go negative by keeping it at zero until such time as $P_{Tiss} > (P_{amb} + Thr)$. In this implementation a single integration is all that is needed to compute the exponent when computing likelihood using equations (3) or (4), so this was called risk function 1. In the second implementation it was assumed that the supersaturation ratio described the rate of change of risk so the risk function was:

$$r_i = \int \frac{P_{Tiss_i} - (P_{amb} + Thr_i)}{P_{amb}} dt \qquad (9)$$

Since two integrations are involved in computing the exponents, this is risk function 2. Figure 3 shows what these two types of risk functions would look like for a step change in pressure. Risk function 1 is maximal at the step change and decreases monotonically. This type of risk function would best describe a symptom incidence distribution which reached a maximum very shortly after surfacing and which steadily decreased with time. Risk function 2 is zero just at the step change, rises to a maximum sometime later, then decreases. This would fit a symptom distribution which was initially low, rose to a peak then decreased. The two types of kinetics and risk functions result in 4 possible models (Fig. 4). Each model consisted of three compartments each with up to four parameters; a scaling factor, an exponential rate constant, a threshold, and a value for $P_{XO}$ (LE1 and LE2 models only). The risk for each compartment was computed according to equation (8) or equation (9). These individual compartment risks were used to compute the overall risk, $r$, used in equations (3) and (4) by the relationship:

$$r = A_1 \cdot r_1 + A_2 \cdot r_2 + A_3 \cdot r_3 \qquad (10)$$

Where $A_1$, $A_2$, and $A_3$ are the scaling factors, which determine how much each individual compartment risk contributes to the overall risk. The values for the 12 parameters were initially unspecified and were determined by fitting the risk function to a data set.

## Parameter Calibration and Model Selection

Having constructed these 4 risk functions it was now a matter of determining which one did the best job of describing real decompression data.

A data base consisting of well over 2300 well documented dives was assembled (Table 1). The details of the dives in this data base have been published (16). The decompression model was formulated to compute a value for the probability of DCS occurrence (*P(DCS)*) given the particulars of the profile as shown in Fig. 5. The method of maximum likelihood was used to compute the optimal parameter values for each of the 4 proposed models as described earlier (i.e., calibrate each model). The details of the models and of the parameter estimation are described in detail elsewhere (11).

The best fit parameters for the LE1 model produced the greatest maximum likelihood of the 4 models examined, thus establishing this as the best of the four models. Table 2 shows how well the LE1 model predicted the overall incidence for various types of dives. Single and repetitive air and saturation dives categories are self explanatory. The Non-air category consists of dives breathing an $N_2O_2$ mix.

In Table 3 the dives in the data base were categorized by risk level. While the observed cases of DCS do not agree exactly with the predicted number, they are all within the statistical confidence limits of the modeling procedure. Not all of the dives in the data base had time of DCS information but the fit of the model to those that did are shown in Table 4.

This parameter estimation can be considered a retrospective validation process. However, there were some types of diving where the model would be used which were not well covered in the data base. This meant further validation was required.

## Prospective Validation

A prospective study was done in order to verify the models ability to predict DCS occurrence (20) in areas not well represented in the data base. In order to do this the model was reformulated to compute a decompression profile from a given depth/time profile (Fig. 6) to a specified level of *P(DCS)*. This model was then run in real-time by constantly monitoring diver depth and displaying decompression information on a video terminal.

In actual fact, the real-time implementation used the specified target *P(DCS)* as the risk of DCS occurring at any time in the future after completing decompression. That is at approximately 5 second intervals, the model computed a decompression schedule such that when equation (2) was integrated from; $T_1$ = now to $T_2$ = 24 hours after surfacing, the value for *P(DCS)* was less than or equal to the target amount. What this means is that if the decompression profile is followed to the surface, the risk of DCS occurring from the time one reaches the surface until the time at which the risk function decays to a value of zero is equal to or less than the specified target value.

All dives were done in cold water with divers exercising at a moderate rate while at depth and resting during decompression. The results of this dive trial are shown in Table 5. Multilevel dives (multilevel Air, ML dives) were long dives (6-12 hrs) with most time spent 30 fsw or shallower and multiple short deeper excursion. The repetitive air dives were generally 2-4 dives with intervening surface intervals done during the same day. In general, the model did a good job of predicting both DCS occurrence and times of high and low risk.

Upon completion of the prospective study the model was finalized by incorporating all validation dives into the data base and recomputing the model parameters. The LE model with the finalized parameter values will be used to compute new air and $N_2O_2$ decompression tables which will allow repetitive diving with either gas, or switching gases on successive dives. Also, it will be programmed into a diver carried decompression computer for use in real-time.

## Advantages of the USN Approach

The new USN probabilistic decompression model differs fundamentally from other models in that the risk manager or end-user can determine the risk level of the decompression profiles. While the U.S. Navy will decide for itself what levels it wants to use for its divers, this in no way constrains others who wish to use the algorithm to use the same levels. If used by sport divers one may well want to use lower risk levels. However one chooses to use the algorithm its pedigree is clear. That is, the connection between the model and the data used to validate it is firm and one can apply it to any data set now or in the future to see how well it predicts observed outcome. Finally, when a sufficient amount of additional data becomes available, there is a clear and objective methodology for updating the model to take this new data into account.

Navy Disclaimer: The opinions and assertions contained here in are the private ones of the authors and are not to be construed as official or reflecting the views of the naval service at large.

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# Development of Decompression Computers and Tables at DCIEM

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**NISHI R.Y. DEVELOPMENT OF DECOMPRESSION COMPUTERS AND TABLES AT DCIEM. DIVE COMPUTER WORKSHOP, BASEL 1992 (ED. WENDLING J./SCHMUTZ J.) P. 15-18 ISBN 3-908229-06-5. - The DCIEM decompression research program had its origins in the pioneering work of Kidd and Stubbs in developing decompression computers for non-traditional types of diving. The extensive data base of dives done by Kidd and Stubbs and the considerable experience acquired at DCIEM with this model for experimental diving, has been instrumental in the development of new air diving tables and mixed gas helium-oxygen diving tables. Decompression computers and Doppler ultrasonic monitoring of decompression generated bubbles have been essential elements in the development of these new tables.**

## Introduction

The Defence and Civil Institute of Environmental Medicine (DCIEM) has been involved in decompression research for thirty years. In recent years, however, DCIEM has become better known for the development of new air diving tables, including a simplified version issued in 1987 as the DCIEM Sport Diving Tables (3). The full set of air diving tables that was completed in 1985 for the Canadian Forces has been recently issued in a commercially-available publication (1). DCIEM's decompression research effort has covered not only table development but also considerable decompression modelling and dive computer development (8, 11). The research effort can be divided roughly into three main thrusts: development of pneumatic analogue decompression computers; development of digital, microprocessor-based dive computers; and development of decompression tables using dive computers. To support the evaluation of dive computers and the development of dive tables, DCIEM has also carried out considerable research into the use of Doppler ultrasonic bubble detection for monitoring divers and validating dive profiles.

## Development of pneumatic analogue decompression computers (1962-73)

The DCIEM decompression research program was started in 1962 by a Royal Canadian Navy surgeon, D.J. Kidd, and a Royal Canadian Air Force scientist, R.A. Stubbs, who recognized that the future of deep diving and submarine techniques was limited by the difficulty in using traditional tabular methods of decompression with fixed depth and bottom times for complicated, random depth dive profiles, repetitive diving, and wide variations in gas mixtures (4, 5). Kidd and Stubbs set out to develop some form of analogue computer sensing the diver's actual depth-time history that would continuously provide the decompression status based on the actual exposure. After investigating various forms of analogue computers using pneumatic, hydraulic and electrical signals, they selected pneumatic analogues since they were small, simple, rugged and required no external energy source other than that provided by the inspired gas.

Initial models investigated were based on the traditional Haldanian concept using four parallel compartments. Some 21 different models and configurations were built and examined and over 16,000 man hours of diving were conducted. Single exposure dives and repetitive exposures were tested, involving random depth dives as well as dives to a fixed depth for a fixed bottom time. Multiple dives were carried out to investigate the validity of a "bends" threshold by ascending from each dive deliberately shallower than the "Safe Ascent Depth (SAD)" calculated by the computer to provoke decompression sickness (DCS).

The final model developed by Kidd and Stubbs contained four compartments in a series arrangement. By August 1967, approximately 4000 single and repetitive exposures had been completed on this final series model at depths from 9 metres of seawater (msw) to 75 msw and durations from 15 minutes to 4 hours with a bends incidence of only 0.6%, much lower than the other configurations tested. This version of the computer, available as a diver-carried portable computer and in a larger version with a chart recorder for surface-supported diving or for hyperbaric chamber monitoring, was used extensively for experimental diving, primarily physiological and psychological testing at depths as deep as 90 msw. In almost all cases, the decompression was conducted as a continuous ascent following as closely as possible the predicted SAD instead of using the traditional "staged-decompression" method. In 1971, the mathematical model governing the operation of the dive computer was modified by Stubbs to make diving in the 60-90 msw range safer.

Multi-compartment pneumatic mechanical analogue dive computers were complex and delicate instruments. Although they had an advantage in that no external source of power was required other than that provided by the inspired gas pressure, they had a major disadvantage because of the frequent maintenance and re-calibrations that were required. These were a result of the complex mechanical linkages required to monitor and select the greatest pressure in the compartments for calculating the SAD, and the need to ensure that the time constants of the pneumatic analogue compartments remained within specifications.

The small diver-portable version of the pneumatic analogue decompression computer was also licensed to a manufacturer for commercial production. However, only a few units were produced and sold because of high manufacturing costs and because the anticipated market demand did not materialize. Even within the Canadian Forces, the requirement had shifted to surface-supported diving and it was felt that there was no longer a requirement for a self-contained diver-carried unit. At DCIEM, the emphasis shifted to the larger units for surface-supplied diving or hyperbaric chamber operations. In the early 1970's, mechanical linkages and Bourdon tubes for measuring pressure were replaced with pressure transducers and electronic circuitry to produce a series of pneumatic-electronic hybrid computers.

## Development of digital microprocessor - controlled dive computers (1974-1986)

In the early 1970's, microprocessors became available and DCIEM scientists saw the potential for designing all-electronic, digital decompression computers to replace the pneumatic analogue computers. DCIEM embarked on a program of development with CTF Systems, Inc., a high-technology company experienced in electronic development.

The first computer was the XDC-1, completed in 1975. This was a desk-top dive calculator, programmed with the Kidd-Stubbs 1971 algorithm. It could be used for dive planning or dive analysis, with all information being entered from a keyboard. In addition, there was a real-time dive monitoring mode in which dive information could be entered from the keyboard or automatically from a pressure transducer.

A second model, the XDC-2 series, was completed in 1976, and was designed for real-time dive monitoring for hyperbaric chamber use or surface-supported diving. It had large digital displays showing elapsed time, actual depth, computed SAD, and rate of dive. It was designed to be "diver-proof". The only component requiring calibration was the pressure transducer to monitor the diver's depth or chamber pressure.

A third model, completed in 1978, was the XDC-3 diver-carried computer. The problem with this computer was that low power components were not available or if available, were too expensive. It was power hungry and four 9-volt batteries only lasted a few hours. Miniature pressure transducers were costly and not readily available. CTF Systems had to design its own transducers. The XDC-3 was taken only to the prototype stage.

The XDC-3 did have a commercial spin-off. Kybertec International was formed by two of the principals of CTF Systems to market a diver-carried computer. This computer, named the Cyberdiver, came on the market in 1978 and 1979. The first version was based on the US Navy Tables, consisting primarily of look-up tables which were entered from the maximum depth and bottom time. The second was a true real-time dive computer, programmed with the Kidd-Stubbs 1971 model and continuously calculating the diver's SAD based on the actual time-depth exposure. About 700 units were sold of both versions before production was terminated in the early 1980's. The company was ahead of its time; technology had not quite caught up to what they wanted to do at an affordable price. Although the computer had many innovative features, lack of adequate funding prevented the company from correcting problems such as water-leakage into the case and making further improvements to the product.

The XDC-2 replaced both the pneumatic analogue decompression computers and the hybrid pneumatic-electronic analogue computers for hyperbaric chamber monitoring at DCIEM. Because of its digital displays, it allowed the chamber operator to follow the SAD exactly as calculated by the decompression algorithm. It allowed, for the first time, a means of accurately following the Kidd-Stubbs model. A study, in 1979, using Doppler ultrasonic bubble detection, identified ranges where the risk of DCS was low, moderate, and high and thus defined the operational limits of the Kidd-Stubbs model (12). In 1982, the XDC-2 was used to determine how oxygen decompression could be used in the computer model and whether surface decompression dives could be carried out by following the computer.

In 1986, the XDC-2's were replaced with an IBM-compatible personal computer-based data acquisition system that was programmed with the decompression algorithm. This provided the equivalent of three XDC-2's in parallel for monitoring three divers or profiles independently. Unlike the XDC-2 in which the algorithm was coded in Read Only Memory, the PC provided much greater flexibility since higher level languages could be used and the decompression program could be reprogrammed easily, for example, to add a helium component to the algorithm.

## Table design, development and validation (1983-1992)

The normal use of decompression computers is to allow divers to decompress safely on an optimum decompression profile based on the actual depth-time exposure rather than on a printed set of tables. Since decompression computers allow complicated dive profiles to be used, they can be used for example, during psychological or physiological testing of subjects at different depths or with different gases. When the subject is breathing one gas mixture and the researcher breathing another, both individuals can be monitored independently and safely decompressed by following the deepest

SAD. With the pneumatic analogue decompression computers, a large number of dives were done routinely to depths as great as 90 msw on air or helium-oxygen and in some cases, where subjects alternated between helium-oxygen and air. Dives using argon-oxygen as a breathing gas were also conducted successfully.

One of the main uses for decompression computers within the last ten years at DCIEM has been the investigation of decompression models and the development of new "traditional" decompression tables. In developing decompression tables, it is essential that the underlying decompression model or algorithm be validated. This can only be done by the use of a real-time on-line decompression computer programmed with the algorithm to monitor the actual time-depth profile and calculate continuously the decompression status of the dive subjects. Thus the computer will take into account any variation in depth or delays in achieving the bottom depth, for example, if divers have problems clearing their ears, and adjust the decompression accordingly. During decompression, the testing procedure would be to use the calculated SAD (Safe Ascent Depth) to dictate when ascent to the next shallower stop depth can take place. Trying to validate a decompression model by following a printed set of tables is impossible unless the dives can be done exactly as the ideal profiles that were used to generate the printed tables. With an on-line decompression computer, it is not necessary to discard or abort dive profiles because the ideal profiles were not attained. If the dives as done by computer are safe, then the printed tables generated from the model should also be safe. Tables are generally more conservative since stop times are generally rounded up to the next whole minute, thus resulting in slightly longer total decompression times than real-time computer-generated profiles. This will be particularly true with repetitive dives, since repetitive dive tables are designed for the worst case in each depth, bottom time and surface interval groupings.

In 1983, it was decided to develop a new set of air decompression tables for use in the Canadian Forces (CF). Previously, the CF had been using the US Navy Standard Air Tables. Because of the wealth of experience existing on the Kidd-Stubbs model (almost all dives done since 1964 at DCIEM are recorded with accurate time-depth information in a computer data bank), it was decided to improve on the safety of the Kidd-Stubbs model than to develop an entirely new model and tables. Thus it was possible to issue a well-tested set of tables in only two years (6).

Tables for standard air decompression, in-water oxygen decompression, and surface decompression with oxygen were developed and tested using the XDC-2 decompression monitors. For normal diving, these tables are restricted to 54 msw, and for exceptional exposures, to 72 msw. For most experimental dives during the validation testing, wet-working divers in 5-10 degrees C water and dry resting divers were used as subjects. Doppler ultrasonic monitoring for decompression-generated bubbles was conducted on each dive subject after the dives to determine the decompression stress of the dive profiles tested. Bubbles were classified according to the Kisman-Masurel Code developed by Kisman, a DCIEM scientist, and Masurel from the Centre d'Etude et de Recherches Techniques Sous-Marines in Toulon, France (9).

Repetitive diving tables were also designed and tested with all three modes of diving. Corrections for diving at altitude were computed but not tested. These tables were adopted by the Canadian Forces in 1986. The standard air decompression table and repetitive dive tables were also adapted for recreational diving and a plastic card version was released in 1987.

From 1986 to 1991, table testing continued with the development of mixed gas decompression tables using 84% helium/16% oxygen for diving to a maximum depth of 100 msw. Decompression was conducted on air from the first stop to a 9 msw oxygen stop. For these tables, the air decompression algorithm was modified to include a helium component in addition to the nitrogen component. An IBM-compatible PC-based data acquisition system with this algorithm was used to control the decompression. Tables developed included in-water oxygen decompression, surface decompression with oxygen, and emergency air decompression tables (2, 7, 10). These tables were adopted for use by the Canadian Forces in 1991.

Current research is concerned with adapting the helium-oxygen decompression algorithm to compute decompression using a constant partial pressure of oxygen rather than a constant fraction of oxygen. These tables are intended for use with a semi-closed circuit breathing apparatus for mine-countermeasures. Associated with this program is a parallel project to develop a probabilistic model for helium-oxygen diving based on the principle of maximum likelihood. This work is being carried out in a joint program with the US Navy.

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# Decompression-Computers in Scuba-Diving

A.A. Bühlmann[1]

The decompression-computer has changed scuba-diving to a great extent. On the one hand diving has become more comfortable and mistakes in reading decompression-tables are no longer possible. On the other hand the diver may become less attentive under water, relying only on his electronic guide.

Apart from the reliability of the hardware, it is the software which is mainly responsible for the quality of a decompression-computer. Aspects such as universality, the amount of information used or presented, safety margins and many more are defined by the software.

The model applied by the software of the decompression-computer should meet certain requirements. In the first place of course it must have successfully passed extensive test in adequate numbers and quality, both in chamber-dives and in the practice. Real dives at high altitude are among the most important tests. There, the divers sensitivity during decompression at a given depth is much higher than at sea-level.

In order to guarantee accurate functioning of the computer in any situation, the model must be as universal as possible. This concerns, in particular, its application to reduced atmospheric pressure as when diving in mountain-lakes or when flying after diving. An advanced decompression model must also be continuously altered in the light of new research data. The model must therefore be as transparent as possible, since only this allows for a quick and safe adaptation to new findings.

A basic model is a multi-tissue model using 16 half-value times for nitrogen from 5 up to 635 minutes (ZH-86). In our opinion, a range of at least 6 tissues is good enough to allow for sufficiently precise calculation for recreational divers (E. Völlm).

A decompression-computer makes use of a multi-level calculation procedure. Consequently, the decompression follows the pressure profiles very closely and the decompression-time of a multi-level dive will usually be reduced compared to the decompression-time as calculated by a table. The tissue-saturation calculated by the dive-computer follows very closely the actual course of the saturation, much more than a table can do. The safety-margin for the decompression is extended by adjusting the tissue-coefficients. This means that for a rectangular dive-profile, the safe ascent-depth is actually deeper, and therefore safer, compared with the table.

Statistics such as, for example, from the Diving Alert Network and the British Sub-Aqua Club confirm a higher risk of decompression-disease for repetitive dives. Micro-bubbles in the venous blood obstructing a part of the lung-capillaries produce a ventilation-perfusion trouble, a right-left shunt well known in the lung-physiology. The arterial nitrogen-pressure is for few hours distinctly higher than the nitrogen-pressure in the inspired air. Therefore the nitrogen-elimination by respiration is retarded. Today it is possible to introduce algorithms in the basic model for this slowed-down desaturation. For repetitive dives, particularly those with surface-intervals between 30 and 120 minutes, there is a prolongation of the decompression-time and a reduction of the no-decompression limit.

In the future, we should be able to simulate the effects of micro-bubble production during ascent even better. There are differences related to the profile of the previous dive, differences between a normal ascent and a fast ascent and Yo-Yo-dives. Diving in very cold water and diving with heavy work at bottom need a longer decompression-time than diving in warm water and performing light work. I anticipate the new generation of decompression-computers for scuba-divers in 1993.

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# Evaluating Decompression Procedures

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**BRUBAKK A.O. EVALUATING DECOMPRESSION PROCEDURES. DIVE COMPUTER WORKSHOP, BASEL 1992 (ED. WENDLING J./ SCHMUTZ J.) P. 20-21, ISBN 3-908229-06-5. -** **Decompression will lead to gas bubble formation in the cardiovascular system to a certain degree in all individuals. The degree of gas bubble formation as well as decompression sickness is not only dependent upon the degree of supersaturation, but on many physiological factors. Changes can occur in several organs, most notably in the central nervous system in the absence of clinical signs of decompression sickness. It is argued that the degree of vascular bubble formation should be used to evaluate decompression procedures.**

## Introduction

*"Decompression is not safe if the pressure of nitrogen inside the body become more than twice that of the atmospheric nitrogen"*, Boycott et al 1908 (1).

The question about what constitutes a safe decompression is central to how decompression tables must be tested. The statement made above was based upon theoretical analysis of the problem and much experimental work and represented a milestone in decompression table development. There is, however, probably few who will argue today that a supersaturation of this magnitude is safe, in the sense that it will have no effect upon the body.

Most, if not all, practical decompressions will lead to some degree of gas bubble formation in the organism. The exact threshold for this bubble formation is not known, but it is probably in the range of 50 - 70 kPa in the tissue (2) and even lower in the vascular system. Eckenhoff et al (3) demonstrated that saturation at 3.7 msw on air was sufficient to produce bubbles and Norfleet et al (4) showed that 400 minutes at 6.1 msw produced bubbles in 25% of the individuals tested. The conclusion from these studies must be that gas bubbles will form in the vascular system at any supersaturation and that the concept of a minimum tolerable limit of supersaturation only relates to clinical symptoms and not to bubble formation.. Adding to this problem is the fact that it has been demonstrated repeatedly that a large inter-and intra-individual difference in bubble forming "ability" exist. Factors like sex, age, body build, circulation, temperature, blood composition and degree of exercise seem to play a role (5,6). Cavitation in joints, for example, have been demonstrated without any supersaturation following violent movements. Furthermore, there are data indicating that there is a large difference is susceptibility to decompression sickness not related to the amount of vascular gas bubbles observed (7)

## Use of decompression sickness as an endpoint

The use of decompression sickness as an endpoint for the safety of procedures is based on the assumption that procedures that give no symptoms of decompression sickness will have no effects upon the health of the individual. Furthermore it is assumed that if mild decompression sickness can be prevented, then more serious changes will not be found. There is no argument about the fact that procedures that have a considerable incidence of decompression sickness can represent a health hazard. However, modern decompression procedures have a low incidence of clinical decompression sickness, probably in the range of 0.3 to 1%. This makes these procedures very difficult to test as a very large number of dives will have to be performed in order to have meaningful statistics about the risk.

A large percentage of commercial divers have suffered decompression sickness in spite of careful use of accepted procedures. In a survey performed in a Norwegian diving company, we showed that 19 out of 40 divers (48%) who answered our questions (65% of the divers asked), had suffered Type I DCS (8). Todnem et al (9) have shown that changes in the central nervous system is positively correlated with clinical signs related to decompression and decompression sickness in saturation divers. In a recent survey of Norwegian air divers, we found that 3% of the sport divers and 15% of the commercial divers had been treated for DCS. However, 59% of the commercial divers had experienced clinical symptoms related to decompression that was not treated. Both treated DCS and untreated symptoms were positively correlated to symptoms from the central nervous system, and to reductions in lung function (Brubakk et al, Unpublished).

One of the more extensive studies of the relationship between diving and injury to the CNS was performed by Rozshahegyi on caisson workers (10). His data indicate that there is a positive relationship between the incidence of decompression sickness and the degree of abnormal neurological findings both clinically and in the EEG. This relationship seems to exist even for workers who only suffered from Type I DCS.

There are, however, other studies that show that even very unsafe diving does not lead to detectable changes in the central nervous system (11), indicating that the relationship between diving and possible effects is not simple. This is incidentally the same observation that can be made in patients with minimal head trauma, where it is not possible to establish a simple dose-response relationship (12).

There is often a lack of correlation between neuropathological findings and clinical signs. Clinical signs may vary over time and the disappearance of clinical signs does not mean that the pathology has disappeared. New connections, that is new neural circuits/pathways may develop over time, disappearance of perifocal edema, remodeling of the axon membrane, and eventually remyelination are some of the means and ways the CNS have to diminish and fight the effect of permanent brain tissue damage. In most testing schemes for decompression procedures, mild decompression sickness (muscle and joint pain only) is acceptable in a certain percentage of the cases (typically 1-5%), while serious (central nervous symptoms) are not acceptable. The acceptance of the procedure is thus dependent upon the diagnostic accuracy. Small areas of central nervous damage can for instance lead to very localized changes in skin sensitivity, easily missed even with careful investigations. This is perhaps most strikingly shown by the cases reported by Palmer et al (13), where a diver with considerable degeneration of his spinal cord following a decompression accident had only minute clinical signs and in fact were allowed to continue diving. Recent studies has shown that so-called "pain only DCS" is a rare event, happening only in 8 (14) to 13% (15) of all cases. Diving can often be very heavy work, with considerable use of muscles of the upper body. It is to be anticipated that joint and muscle pain caused by decompression sickness easily can be missed in this situation. Furthermore, many divers may be reluctant to report minor symptoms, as treatment of decompression sickness may have negative effect upon their further employment prospects.

There are indications that the tables evaluated using decompression sickness as an endpoint can be unsafe. This is demonstrated by the striking change in the occurrence of neurological decompression sickness in the last 10 years, from 20% of all treated cases in 1975 (16) to 80% in 1987 (17). The reason for this is not quite clear, but is probably related to the development of better equipment, enabling the divers to go to the limit of the tables. Many centers with extensive experience in treating decompression sickness claim that about 1/3 of all treated divers have dived inside accepted limits (Edmonds, personal communication 1993).

Another indication that the use of tested decompression tables will not prevent long term effects is documented by the fact that a large percentage of divers with no history of decompression sickness can have signs of changes in the retinal arteries compatible with gas embolism (18), other studies have demonstrated changes in diffusion capacity of the lung compatible with gas embolism (19)

All the above seems to indicate that decompression sickness is at best a very unreliable way of evaluating decompression procedures. This is perhaps even more serious when decompression computers are used, as they are designed to take advantage of the tables as written, trying to "optimize" the diving activity.

## Vascular gas bubbles as an endpoint

Using ultrasonic techniques, it has been possible to detect gas bubbles in the vascular system of individuals undergoing decompression. Several studies has demonstrated that there is no linear relationship between gas bubbles found in the right heart and clinical decompression sickness. (20,21). However, procedures that produce many intravascular gas bubbles have a high incidence of decompression sickness. Thus, the occurrence of a large number of gas bubbles in the vascular system will function as an early warning sign. This also shows that the clinical signs of decompression sickness and vascular gas bubbles are both based upon supersaturation by gas, but they are probably not directly related.

One of the assumptions made in using ultrasound to evaluate decompression tables, is that one table producing few gas bubbles will be safer than one producing many bubbles. This is probably not an unreasonable assumption, but as far as we know, no one has been able to document that. However, we have been able to show that it is possible to use gas bubble content in the venous system to distinguish between two different profiles (22), and that there is a relationship between the amount of gas and the "stress" of the dive. The advantage of this method is that even small dive series is sufficient to make this distinction.

Most studies using ultrasound has been performed in the right heart. It is generally assumed that the lung is a very good filter for gas bubbles down to a diameter of approximately 10 microns. We have, however, shown that procedures that was considered safe, will give rise to considerable gas bubble formation both on the venous and the arterial side of the circulation (23). Arterial gas bubbles were also detected in another study during routine decompression from saturation (24).

These studies seem to indicate that gas bubbles in the arterial system may be present without signs of decompression sickness. James and Hills (25) demonstrated that gas bubbles can lead to breakage of the blood-brain-barrier. Chryssanthou et al have in several studies demonstrated that decompression lead to disruption of the blood-brain barrier with leakage of fluid into the extra vascular space (26,27). In the white matter, this will lead to a separation of myelin lamellae, leading to changes in conduction velocity of the axon. Myelin changes seem to be central in experimental decompression sickness as demonstrated by Sykes and Yaffe who found changes in myelin sheaths in the spinal cord of animals (28).

## Methods for evaluating gas bubble content

Traditionally, the Doppler method has been used for this (29). The advantage of this is that the equipment is cheap and easy to use even in remote locations. The disadvantage is that the evaluation of the signals is very difficult and requires extensive training, in particular if few bubbles are present (30). We have developed a method based upon the use of ultrasonic imaging (31). Using this system, the bubbles are easy to identify and the classification is easy (32). Furthermore, the method has been extensively evaluated against bubble content measured by a computer system, demonstrating that the scoring system is approximately logarithmic (Eftedal and Brubakk, unpublished).

## Conclusion

The use of decompression sickness as an endpoint for the evaluation of decompression procedures was developed at a time when there were no equipment for the detection of gas bubbles. There is no doubt that this was a useful endpoint when developing procedures at a time when the procedures were generally unsafe and the incidence of decompression sickness was high. The present situation is however different. If the procedures are used properly, then the incidence of DCS will be quite low and our main concern will be the possible health effect of exposure to the decompression stress. The fact that changes can be seen in individuals who never have had clinical signs of decompression sickness, must lead to the conclusion that such changes may be unrelated to acute clinical signs. It is perhaps in connection with this interesting to note the statement by Behnke in 1940 (33)

"It may well be that bubbles form as soon as a state of supersaturation is initiated and that what appears to be a ratio of supersaturation tolerance is in reality an index of the degree of embolism that the body can tolerate".

We believe that changes observed in divers may be related to vascular gas bubbles and that gas bubble monitoring should be performed during decompression procedure testing to reduce the health hazards in each individual and to increase our understanding of the decompression process.

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# Decompression Computers

S. Daniels[1]

**DANIELS S. DECOMPRESSION COMPUTERS. DIVE COMPUTER WORKSHOP, BASEL 1992 (ED. WENDLING J./SCHMUTZ J.) P. 24-26 ISBN 3-908229-06-5. Decompression computers (dive computers) are becoming increasingly popular amongst recreational divers. They relieve the diver of the need to carry and use copies of the decompression tables and, perhaps more importantly, are perceived to allow more efficient use of the time available for a dive because they constantly record depth and elapsed time and compute the instantaneous body gas load. Knowledge of the gas load then permits an appropriate decompression strategy to be computed. However, I have two principal reservations with respect to the widespread and uninformed adoption of these devices. The first is in regard to the mathematical model used to compute the decompression solution. The second concerns the effects on diver training and safety. Finally, I will consider some specific questions on aspects of the design and use in practice of decompression computers.**

## The mathematical model

Decompression computers aim to calculate the quantity of gas dissolved in any part of the body, at any instant in time, throughout a procedure in which the pressure at which breathing gas is supplied to the diver is varied. To this end they use some mathematical model which describes inert gas transport processes in the body. Although historically there have been a number of gas transport models formulated based on concepts of inert gas supersaturation or phase equilibrium no completely satisfactory model has yet been devised ( for reviews see: Hills, 1977; Hennessy & Hempleman, 1977; Wienke, 1989; Homer et.al., 1989)

The most widely used model of inert gas transport, in a diving context, is that first formulated by Haldane (Boycott et.al., 1908) and later refined by Kety (1955). In this model, the body is represented as a series of parallel compartments in which the rate of uptake or elimination of gas is governed by the extent to which the compartment is perfused. There are two fundamental problems with this model. First, the calculated gas elimination rates do not agree with the experimental observations from gas washout studies and it would appear that merely adjusting the perfusion and local solubility parameters is not sufficient to provide good agreement (Homer et.al., 1989). Second, since the experiments of Hempleman it has been accepted that gas uptake and elimination are not symmetrical (Hempleman, 1969); yet the model suggests they should be.

The reason for the asymmetry, with gas elimination being slower than gas uptake, is the formation of a separated gas phase (Daniels, 1984). All conventional models of gas transport assume that the inert gas burden remains in solution. However, there is a wealth of experimental evidence to show that this is not the case, even for very mild decompressions typically used in recreational diving (Daniels et.al., 1981;1984). A separated gas phase cannot be simply accommodated by adjustment of the perfusion rates or solubilities. The separated gas phase acts (a) as a sink for dissolved gas, retaining it within the body, (b) to actively transport gas in the form of mobile, intravascular bubbles, (c) to retard the elimination of dissolved gas by blocking blood vessels and hence having a dramatic effect on the perfusion rate. Finally, the presence of a separated gas phase has serious implications for subsequent decompressions (Griffiths et.al., 1971; Gait et.al., 1975). One effect can be the sudden and unexpected appearance of serious decompression illness. The second is that a separated gas phase can act to 'seed' further bubble formation. Both these effects are cumulative over repeated decompressions, with the timing between exposures becoming of vital importance. These effects cannot at present be 'modelled'. Therefore a computer calculating the decompression profiles will, inevitably, become over optimistic when calculating repetitive exposure times.

Experiments have shown that the threshold decompression before bubble formation is approximately 0.7 bar (7 metres of sea water), irrespective of the absolute pressure (Daniels 1984;1986;1989). If then the ascent criteria is chosen such that at no time shall the effective partial pressure of inert gas in solution in blood or tissues be allowed to exceed 0.7 bar, then decompression schedules can be computed for which the inert gas exchange model should be valid; i.e., there will be no separated gas phase present. When this is done extremely long extensions to decompression times are required which would be unacceptable in practice.

Acceptably safe decompression procedures are arrived at by first calculating a schedule and then by an empirical process of testing and refining in the light of the observed outcome. Whilst I might express reservations about particular end points used in the experimental testing procedure (in particular an over reliance on the appearance of acute symptoms of decompression illness as the definitive endpoint) the process has the virtue of using a population response to a given procedure to combat the deficiencies in the original, theoretical model used to calculate the starting point for the tables.

Another reason for needing to base decompression tables on an expected population response is that individual responses to decompression vary widely (Weathersby et.al., 1984).

Even if an acceptable degree of understanding were brought to the formation, distribution and elimination of the bubbles, we have not begun to understand why the variation in response is, characteristically, so large; both between individual and for an individual at different times (Weathersby, 1989). Before being able to claim that a particular model could form the basis for an accurate calculation of the decompression required after any random pressure-time profile both these factors must be incorporated.

## In practice:

When conducted according to recognised procedures and after appropriate training diving, particularly recreational diving, has become very safe; with rates of decompression illness variously estimated at between 1 in 10,000 to 1 in 12,000 exposures (Marroni, 1993). This reflects the standards of training, the improvements to decompression procedures (largely through an accumulated experience rather than improvements in methods of constructing tables) and improvements to the equipment used. It is possible that over-reliance on decompression computers might undermine some of this gain by reducing the theoretical and practical knowledge of decompression tables acquired by the average diver in the course of his training. What then happens if a decompression computer goes 'wrong' or just gives a 'wrong' answer? Would the diver know the tables sufficiently well to complete his accent safely? Would the diver recognise when an answer was patently wrong? I do not know the answers to these questions but if we consider the analogy of children brought up using calculators for arithmetic then I am pessimistic. I have also observed an unfortunate tendency to believe any answer given by a machine even when it is patently wrong, and computers do go wrong.

These thoughts, then, constitute my reluctance to accept decompression computers with wholehearted enthusiasm. In an ideal world decompression computers would be used as a support tool by a well trained diving supervisor in a manner described so eloquently by Jean-Pierre Imbert (1993). However, recreational diving will not, and perhaps cannot, be organised in the same way as professional diving and in practice that means decompression computers are here to stay.

## Specific questions

(a) No artificial restrictions should be placed on the use of decompression computers as to the type of diving for which they are acceptable. Such restrictions would be unenforceable and might even lead to devices being introduced which would be designed to handle only the simplest type of dive but which would be used for other more complicated situations such as multilevel and repetitive diving. This potentially would be dangerous.

(b) The use of decompression computers to enable deeper stops (4-7 metres instead of 3 metres) to be made could be very useful, particularly in rough seas.

(c) Decompression computers must be designed to handle more than one dive in a 24 hour period. This is presumably one of the prime reasons why people buy them in the first place. However, divers should not have to add arbitrary safety margins to what the computer is advising as the solution. It is the responsibility of the manufacturer to design the device correctly in the first place.

(d) Evidence thus far does not indicate a patent foramen ovale to be a particularly important predisposing factor in the susceptibility to decompression illness (Cross et.al., 1993). If this remains the case then there would be no grounds for restricting the diving activities of anyone known to have a PFO nor should decompression computer manufacturers have to produce 'special case' software.

(e) I do not believe that computer manufacturers should produce software to allow oxygen diving. This is not a safe activity for recreational divers and I can see no necessity for it. It is possible that nitrox diving will spread amongst some sections of the recreational community and some provision for this by computer manufacturers might be made.

(f) The display of the dive computer should never be stopped, even if a catastrophic ascent had occurred as a result of accident or emergency. The data displayed may be vital to the emergency resuscitation team. In fact arguably the most important feature of a decompression computer is as a 'dive logger', providing a means of acquiring an accurate record of the depth-time profile.

(g) Some index of 'decompression stress' would be useful, perhaps the calculated cumulative gas load. However, if this became widespread divers would have to be educated in the meaning and interpretation of the data.

(h) I would not have thought that any special changes were necessary for manufacturer to validate their machines. After all, if a person suffers decompression illness following the advice provided by a machine and it can be established that that advice was substantially at variance with what would have been the case if some recognised table had been followed, then the person would appear to have a case for suing the manufacturer on the grounds of that the device was not suitable for the purposes advertised and should be able to claim compensation for any injury.

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# French Data and Risk of Dive Computer Use

J.-L. Meliet[1]

For this workshop data of 4 French treatment centres are put together. They list cases of decompression illness during 1992, in Ajaccio for the year 1991. The results are showed in Table 1.

From 107 cases of decompression illness, only 47 (44%) occurred in divers using a decompression computer. Only 23% of the cases of computer users were due to a clear mistake in diving procedures, while 68% of the accidents were in divers respecting the dive computer display features. Of these unexplained accident cases only 1/5 are divers without any clear risk factor, while the other 4/5 all have at least one risk factor for decompression illness.

Table 2 shows the comparison between decompression illness cases of computer users and French Navy divers using the old GERS 65 tables. We see about the same percentage of decompression illness in divers who followed the tables as in divers who followed the computer's display

| | | | Toulon Hop. Ste-Anne | Toulon Hop. Font-Pré | Ajaccio Hosp. (91) | Marseille Hop. Salvator | Total | Rates | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Total number of D.I. | | | 29 | 11 | 42 | 25 | 107 | | | 100% |
| D.I. using D.C. | Total | | 9 | 7 | 13 | 18 | 47 | 100% | | 44% |
| | Mistakes | | 3 | 4 | - | 4 | 11 | 23% | | |
| | Respect of D.C. Display Features | Without favouring factor | 1 | - | 1 | 5 | 7 | 15% | 100% | 22% |
| | | With favouring factor | 4 | 2 | 12 | 7 | 25 | 53% | | 78% |
| | Unknown cause | | 1 | 1 | - | 2 | 4 | 9% | | |

*Table 1: Some statistics about decompression illnesses (D.I.) and use of dive computers (D.C.)*

| | D.I. with Dive Computers | | | French Navy study* | | |
|---|---|---|---|---|---|---|
| **Total number of D.I.** | 47 | 100% | | 50 | 100% | |
| **D.I. due to mistakes** | 11 | 23% | | 17 | 34% | |
| **D.I. with respect of tables/computers** | 32 | 68% | 100% | 33 | 66% | 100% |
| **Without favouring factors** | 7 | | 22% | 7 | | 21% |
| **With favouring factors** | 25 | | 78% | 26 | | 79% |

*Table 2: Comparison between D.I. with computers and D.I. in the French Navy (1)*

indications. The same relationship is observed for the cases with risk factors and without risk factors.

The main risk factors favoring decompression illness are successive dives, tiredness before diving, efforts before, during or after diving, bad physical condition or unfitness to dive, antecedents of decompression illness, yo-yo-dives. No square dive profiles however are not considered as risk factors. The comparative result of the French Navy and decompression computer studies are very parallel.

| | F. N. Study | D.I. with D.C. |
|---|---|---|
| Successive Dives | 16 | 11 |
| Tiredness before Diving | 9 | 11 |
| Efforts before, during or after Diving | 16 | 7 |
| Bad Physical Condition or Unfitness to dive | - | 4 |
| Antecedents of Decompression Illness | - | 3 |
| Yo-Yo Dives | - | 1 |

*Table 3: Favoring factors found in decompression illnesses with respect of dive computers features*

## Conclusion

Although no data are available, about 1/2 of the divers in France may use diving computers (44% of diving casualties with diving computers in our study, about 50% divers using computers in an estimation of the "Fédération Française d'Etude et de Sports Sousmarins" FFESM).

There is no significant difference between the etiology and incidence of decompression illness in divers using computers or using the French (1965) Navy tables.

About 80% of decompression illness cases occur associated with favoring factors as successive dives, tiredness and efforts, physical unfitness.

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# Development of Computer Use and Decompression Illness Incidents by Italian Divers

A. Marroni[1]

I try to present a snap-shot of what is happening in Italy during the last few years. With more than 3000 members in Italy DAN Europe, former IDA (International Divers Assistance) is in the position to give a comparative analyse of representative data.

We refer to the data published by DAN (Divers Alert Network of USA) 1988. This study tried to compare the use of decompression computers and the incidence of decompression illness in a sample of 220 cases, 40 of which were using a dive computer. There was no way to extract more details from these dates besides the percentage of 18,1% of computer users in the group of treated divers. What came out of the risk analyses was that multidays repetitive diving is a clear risk factor and that divers using computer were relatively safer than table users if the dives were performed within the first 30m of sea water and relatively unsafe if diving deeper than that.

As showed by Table 1, the percentage of computer users in the decompression illness cases in Italy was gradually increasing during the last years with an actual percentage of about 40%. This reflects of course the increasing popularity of diving computers. To know more about this specific safety or risk factor given by the use of the computer we performed a study by sending out some 20'000 questionnaires in the diving magazine "Il Subacqueo". 7'238 divers responded. Besides other questions investigating the diving habits of the Italian divers population 85,4% reported the regular use ot the computer for diving. From the analyses of DAN, the Italian studies of IDA and DAN Europe we see an increasing degree of computer using divers while the total rate of decompression illness incidence in divers using any kind of decompression indicator does not vary significantly.

**COMPUTER USE PREVALENCE ON DAN DCI CASES**

| | - 1987 / 1992 - | |
|---|---|---|
| **1987 - USA** | **40/220 CASES** | **18.1 %** |
| **1989 - ITALY** | **14/47 CASES** | **29.7 %** |
| **1990 - ITALY** | **5/19 CASES** | **26.3 %** |
| **1991 - ITALY** | **15/43 CASES** | **34.9 %** |
| **1992 - ITALY** | **14/36 CASES** | **38.8 %** |
| | **(preliminary)** | |

*Table 1*

**1991 DAN DIVING HABITS QUESTIONNAIRE**

**7238 RESPONDERS**

**85,4% DECLARED USE OF DIVE-COMPUTER**

*Table 2*

To conclude, we may even rise a question which is somehow speculative: if the rate of computer users in the actual diving population is about 85% and the percentage of computer users of the decompression illness casesis only about 40% it appears that the use of computers in decompression illness cases occurs at a lower percentage as opposed to the use of tables. So we could ask the question "can the decompression sickness risk be considered higher among table users than among computer users?".

**DIVE COMPUTER USE: HIGHER % VS. TABLES**

**COMPUTER USE IN DCI CASES: LOWER % VS. TABLES**

| | |
|---|---|
| **? DCI INCIDENCE:** | **HIGHER IN MINORITY TABLE GROUP VS. COMPUTER GROUP MAJORITY?** |
| **? DCI RISK:** | **HIGHER WITH "TABLES" DIVING VS. "COMPUTER" DIVING?** |

*Table 3*

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# Dive Computers - Today and Tomorrow

M.H. Hahn[1]

**HAHN M.H. DIVE COMPUTERS - TODAY AND TOMORROW. DIVE COMPUTER WORKSHOP, BASEL 1992 (ED. WENDLING J./ SCHMUTZ J.) P. 30-35 ISBN 3-908229-06-5. - By no question, dive computers are here to stay. It is still remarkable, that pneumatic analog decompression computers, of which well over 300,000 units were sold, did not by far stir up so many discussions as did their digital successors. This cannot be because they were not taken serious, the first divers to buy them were those who had to make several descents per day - instructors! Contrasting to today's instruments, these pneumatic devices displayed only one "vital" information: a pointer marked the actual "ceiling", i. e. the shallowest depth presently allowed. And - also contrasting to today's situation - these instruments were rarely worn by beginners. Modern dive computers, crammed with features, suggest a feeling of omnipotence to their mostly novice users: Depths are displayed to fractions of feet, almost ten times more accurate than mechanical gauges. Time spent submerged is not only shown permanently, but - together with maximum depth - correctly stored in the logbook-memory. Why should the decompression data displayed not have the same level of credibility?**

For decompression computation, most of today's dive computers use a row of parallel exponential compartments, normally defined by the same halftime for uptake and release of the nitrogen fraction of ambient pressure. Supersaturation tolerances are usually computed according to a model, originally published by Workman [1], and, mathematically simplified, by Bühlmann [2]. This model assumes the "ceiling pressure", i. e. the lowest "allowed" ambient pressure, to be a linear function of the partial pressure of inert gas in the "leading tissue", i. e. the compartment with the highest ceiling pressure at the time of interest. In Bühlmanns model these constants are independent of ambient pressure. Thus two constants per compartment define the safety level of decompression, i. e. whether a table or computer based on this model is more or less "conservative". The 32 constants for the compartments of his ZH-L16 were derived mainly from the symptomatic outcomes of dry chamber trials.

Laymen usually cannot imagine how many DCS-free exposures are necessary to narrow down statistically expected DCS-percentages to at least 1% (fig. 1). This points to general problems of validation of mathematical decompression models:

a) No social consensus does exist on the level of residual risk acceptable in recreational diving. The answer "zero" is of course unreasonable [3].

b) Independent validation of the mathematical models implemented in today's dive computers according to recently proposed procedures [4] is obviously beyond possibilities of the manufacturers. This could be acceptable, if computer displays would stay on the conservative side of already validated tables or algorithms.

c) The handling of repetitive dives leaves some discretionary margin to the designer of a model, or repetitive system of a table, as is demonstrated by two well known examples (table 1).

Recent statistics on decompression sickness (DCS) among sport/-recreational divers [5] give no clues to specifically blame dive computers, resp. their models and parameters, for an increase in DCS cases per dive (fig. 2). But this result shall not obscure the fact, that it is the absolute number of cases which counts for grief, cost and public attention. This number really grows

TABLE 1:

Descent to 36 m in 1 min, hold for 14 min, ascent speed, hold at decompression depth and time as prescribed by table. No-D-Limits in minutes after 2 hours surface intervall.

| Table | Deco-Stops at |  |  | Total Ascent-Time [min] | No-D-Limits after 2 hours surface interval at |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  | 9m | 6m | 3m |  | 12m | 15m | 18m | 21m | 24m | 27m | 30m |
| BSAC | 0 | 1 | 0 | 4 | 44 | 24 | 15 | 10 | 8 | 0 | 0 |
| NDC | 1 | 2 | 5 | 11.6 | 105 | 60 | 30 | 20 | 13 | 10 | 7 |

Tab. 1 *Comparison of decompression schedules for a 36 m, 15 min dive and NDLs after 2 hours surface interval for the BSAC decompression tables (The British Sub Aqua Club Diving Manual, 110-114, Stanley Paul, London, 1990.) and the NDC decompression tables (Nationaal Duikcentrum, Delft, The Netherlands, 1988.)*

TABLE 2:

No-D-Limits for Bühlmann and DCIEM models.

| Depth | 12m | 15m | 18m | 21m | 24m | 27m | 30m | 33m | 36m | 39m | 42m | 45m | 48m | 51m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ZH-L16C | | | | | | | | | | | | | | |
| [min] | 188 | 93 | 62 | 44 | 32 | 25 | 20 | 16 | 14 | 11 | 10 | 9 | 8 | 7 |
| risk [%] | 2.0 | 2.7 | 3.2 | 3.4 | 3.4 | 3.3 | 3.1 | 3.0 | 2.9 | 2.7 | 2.6 | 2.6 | 2.5 | 2.5 |
| DCIEM | | | | | | | | | | | | | | |
| [min] | 180 | 64 | 36 | 25 | 19 | 15 | 12 | 10 | 9 | 8 | 7 | 6 | 6 | 5 |
| risk [%] | 2.0 | 2.4 | 2.4 | 2.2 | 2.0 | 1.9 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.9 | 2.0 |

*Tab. 2 Comparison of NDLs and pertinent DCS-risks (calculated with model 2, single air parameters from [6]) for ZH-L16C [7] and the DCIEM-model [8].*

due to the expansion of recreational diving.

Looking closer into details of reported DCS cases reveals a relative high fraction to be related to high gas loading, or repetitive or deeper than previous dives resp. combinations of these attributes. Comparison of the Bühlmann model (BM) (with recently proposed coefficients for dive computers) to outcomes of experimental chamber exposures and fish-farming dives, other models, physiological measurements and risk calculations elucidate the limits of this model:

Application of risk estimation with maximum likelihood algorithms [6] to the no-decompression limits (NDL) of ZH-L16C-coefficients [7] shows remaining DCS-risks to be highest for the depth region used most frequently by recreational divers. The NDLs of the DCIEM model [8] yield a less pronounced increase of risk for shallower dives (table 2). It must be considered as unfortunate, that the strict "no decompression dives" policy of prominent dive tuition agencies keeps dive computer manufacturers from accepting shorter NDLs for shallow dives.

High gas loading single chamber profiles [9, 10, 11], with DCS rates far beyond acceptable limits, stay well within approx. 90% of the allowed supersaturation limits of ZH-L16C (fig. 3, 4, 5).

The response of the BM to yo-yo-diving is comparable to a high(-frequency) pass, e.g. an electrical condenser fed with alternating current.

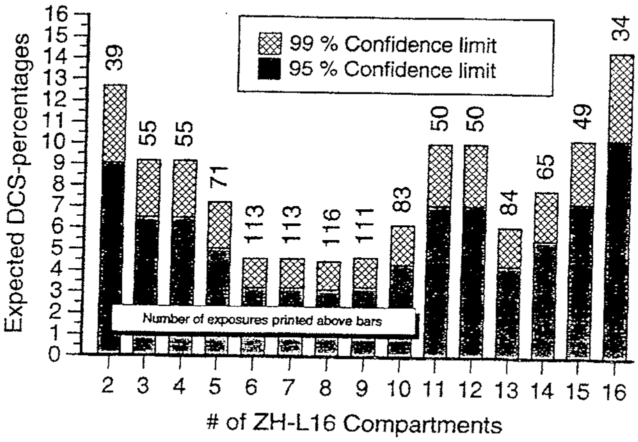


*Fig. 1 Confidence limits for the definition of coefficients of ZH-L16 [7] compartments.*

An infinite row of bounce dives to 40 m, with bottom time just within the NDL, repeated every 80 minutes, with an average depth of 5 m [12], never provoke a limiting response of the model (fig. 6). The DCIEM model, with offgassing slower than uptake, piles up increasing decompression demands for subsequent dives (fig. 7), although this probably would not suffice to prevent DCS, if such dives were made. This may be judged from the outcome of rather shallow fish-farming dives [13](fig. 8). Repetitive wet chamber dives [14], decompressed according to the BM, showed bubble grades and DCS occurrence to increase with subsequent exposures. This corresponds to the concept of decompression induced delay of nitrogen elimination [15].

Repetitive dives with increasing depths are supposed to be highly DCS-prone. In the above cited repetitive chamber dives, bubbles could be heard with ultrasound doppler after descending to 40 m on the second dive. Theoretical considerations about bubble excitation [16] lead to a distinct "punishment" of deeper-than-previous repetitive dives in the appropriate decompression model. The BM, only describing the in- and outflow of dissolved gas, does not yield this feature.

Many dive computer manufacturers, using some kind of BM, handle its shortcomings by side rules: "Do not..." and "Avoid...", which - at best - are mentioned in the instructions for use, but sometimes only can be found as remarks in diving magazines.

Steadily dropping prices for RAM- and ROM-bytes together with more powerful CPUs, still thrifty of battery life, give a chance, to gradually transfer side rules from the instructions to the decompression-algorithms - if manufacturers desist from further investments in "featurism"!

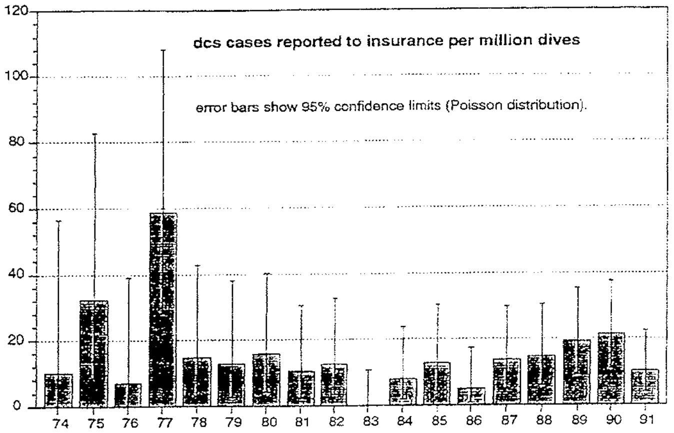


*Fig 2 Number of DCS cases reported to the (compulsory) insurance of German Sports Divers Federation (VDST), related to the approximate number of dives made by members. According to complete reports of 9.4% of the members, 16.9 dives were made per member in 1989*

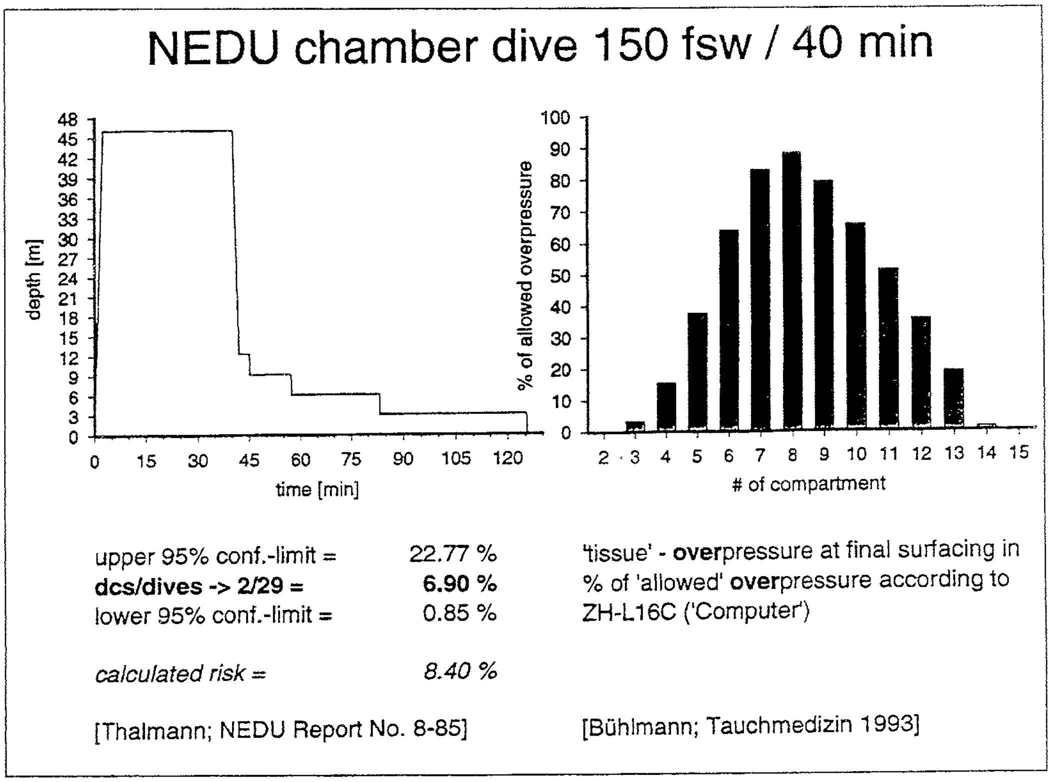
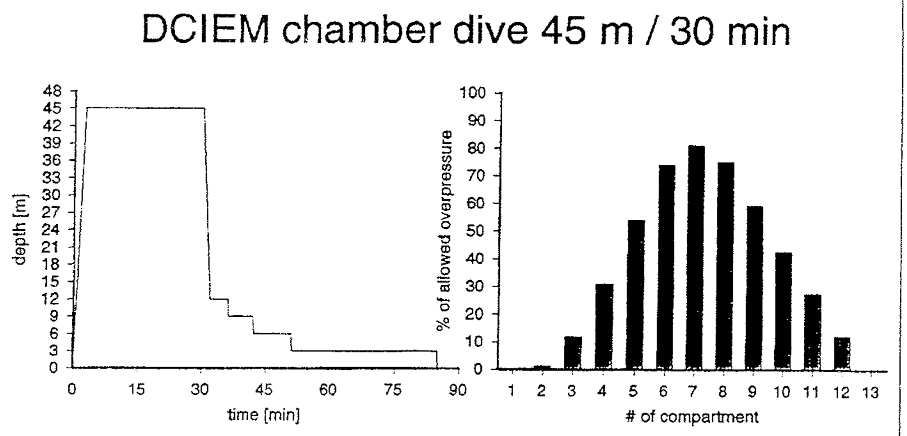


*Fig. 3 Profile and outcome of a NEDU wet chamber dive [9] and the appropriate percentages of supersaturations tolerated by ZH-L16C [7].*



upper 95% conf.-limit = 44.50 %
**dcs/dives -> 1/10 = 10.00 %**
lower 95% conf.-limit = 0.25 %

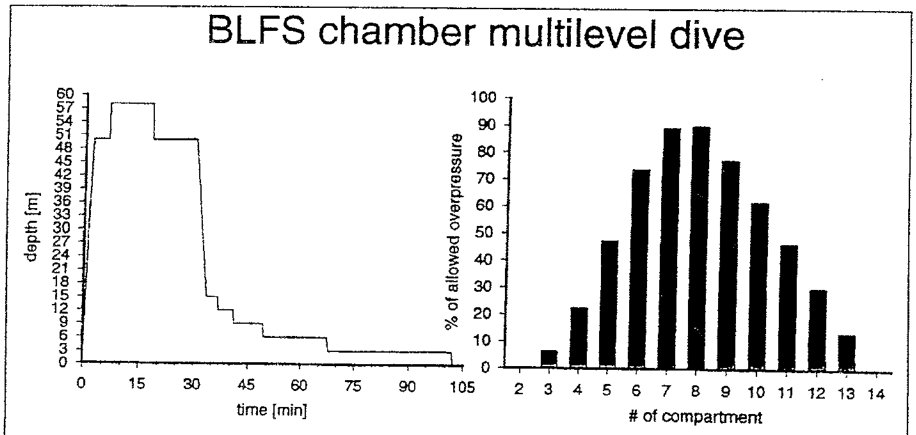
*calculated risk = 6.40 %*

[Lauckner, Nishi, Eatock;
DCIEM No. 84-R-72]

'tissue' - **over**pressure at final surfacing in % of 'allowed' **over**pressure according to ZH-L16C ('Computer')

[Bühlmann; Tauchmedizin 1993]

*Fig. 4 Profile and outcome of a DCIEM chamber dive [10] and the appropriate percentages of supersaturations tolerated by ZH-L16C.*



upper 95% conf.-limit = 55.10 %
**dcs/dives -> 4/15 = 26.67 %**
lower 95% conf.-limit = 7.79 %

*calculated risk = 8.30 %*

[Hahn; Der Tauchlehrer 4/1986]

'tissue' - **over**pressure at final surfacing in % of 'allowed' **over**pressure according to ZH-L16C ('Computer')

[Bühlmann; Tauchmedizin 1993]

*Fig. 5 Profile and outcome (only skin rashes, which disappeared without treatment, were observed) of a BLFS multilevel wet chamber dive [11] and the appropriate supersaturations tolerated by ZH-L16C.*

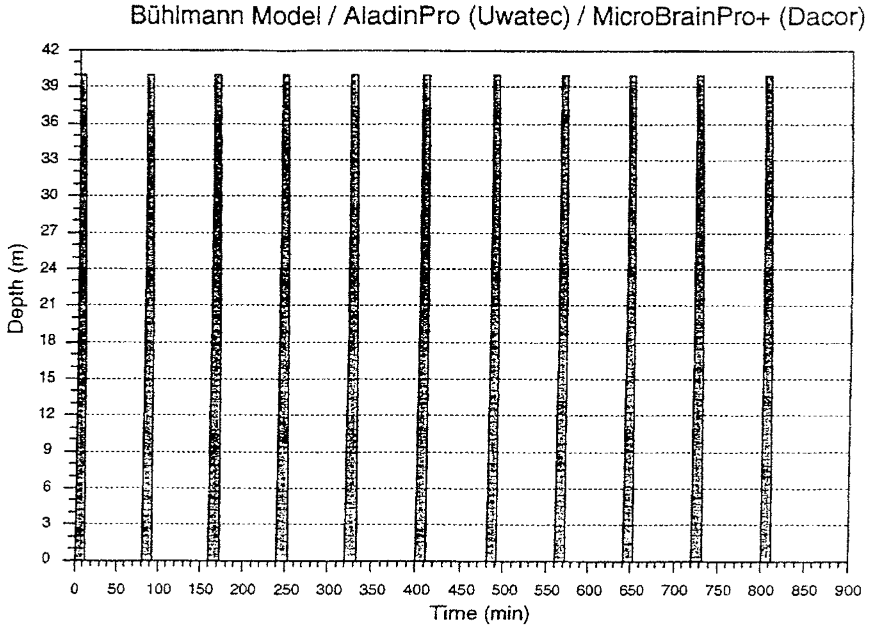


*Fig. 6 Allowed profiles according to ZH-L16C and two dive computer brands for repetitive bounce dives with an average depth of 5 m [12].*

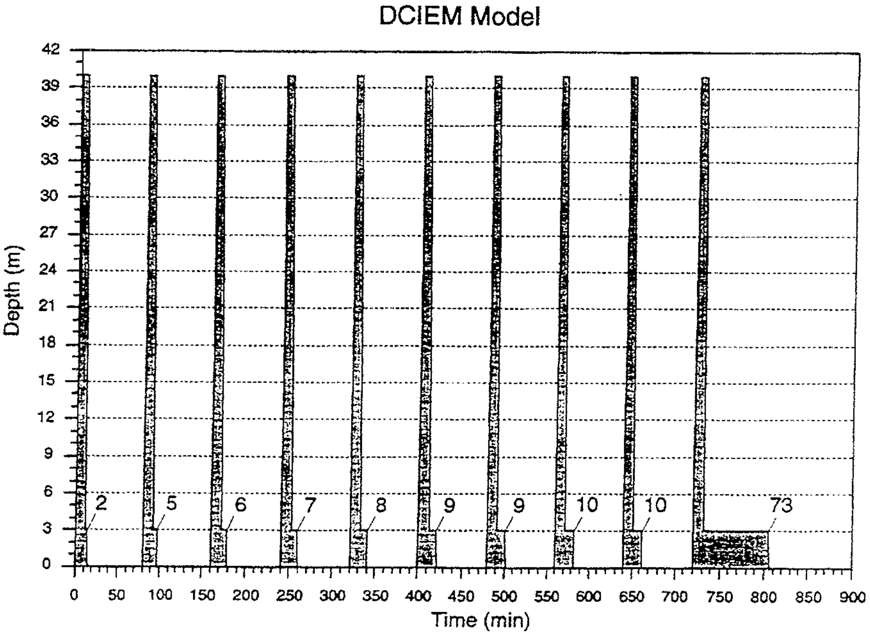
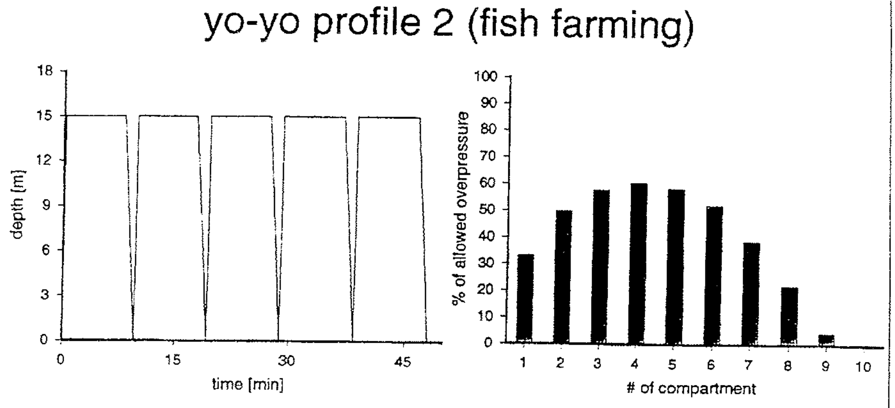


*Fig. 7 Response of the DCIEM-model [8] to the bounce dives of fig. 6.*



musculoskeletal dcs successfully treated according to US Navy table No. 6

[Douglas + Milne, BMJ, 1991, 302:1244-5]

'tissue' - **overpressure** at final surfacing in % of 'allowed' **overpressure** according to ZH-L16C ('Computer')

[Bühlmann; Tauchmedizin 1993]

*Fig. 8 Fish-farming dive profile with DCS outcome and appropriate ZH-L16C supersaturation percentages.*

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# Defining Diving Safety

R.D. Vann[1]

## What is Safety?

In an ideal world, safety is freedom from risk. Unfortunately, real-world activities such as diving have risks that are not totally avoidable. These activities are defined as "safe" when their risks are judged to be acceptable (1).

To judge the acceptability of risk and to establish safety guidelines, we must learn how risk varies with exposure. This is a three part process. First, the potential injuries are identified. Second, the risks of these injuries are related to the exposures that cause them, and third, safety guidelines are defined from exposures for which risk is judged to be acceptable.

The first two parts of this process depend upon empirical data while the third part is a subjective evaluation that weighs risk against perceived benefit. Recreational dives and experimental trials are two potential sources of empirical diving data from which safety guidelines might be derived for diving.

## Empirical Diving Data

From 1987-1990, the Divers Alert Network collected some 1,400 reports of recreational diving incidents (2-5) including both decompression sickness (DCS) and air embolism, collectively referred to as decompression illness (6). Figure 1 summarizes these incidents as a function of depth. Decompression illness (DCI) was rare after dives shallower than 10 fsw, most common after dives to 80-90 fsw, and of decreasing frequency for greater depths.

This does not mean that the maximum DCI risk occurs at 80-90 fsw and that deeper diving is safer. We cannot address questions concerning risk without knowing how many dives were made to each depth. Data on recreational diving incidents, therefore, are not useful for establishing acceptable risk and defining safety guidelines.

The type of data needed are found in the results of experimental trials which carefully document depth-time profiles and the presence or absence of symptoms (7). Such data can be used to estimate DCS risk for any exposure as illustrated in Fig. 2 for no-stop air diving. No-stop dives with estimated risks of 0.5%, 2.2%, and 5% are indicated by lines in Fig. 2 while the U.S. Navy limits are represented by dots (8).

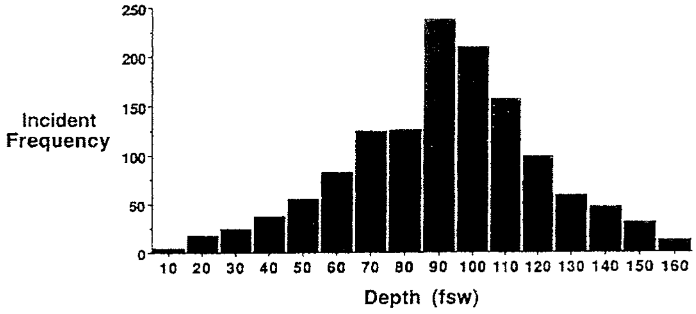

*Fig. 1*

Many of the Navy no-stop limits have estimated risks of about 2.2%. If this risk is judged to be too great, a smaller acceptable risk can be selected. The corresponding no-stop limits become "safe" by definition. Thus, diving can be as safe as desired, but increasing safety imposes greater restrictions on exposure time.

## Experimental Trials vs. Recreational Dives

Unfortunately, differences between experimental trials and recreational dives may render experimentally based risk estimates inaccurate when applied to recreational diving. Most experimental trials are conducted with bottom times at the military no-stop limits or longer (7). Thus, risk estimates for shorter recreational dives are extrapolations beyond the existing data. Recreational dives are generally short, no-stop, repetitive, and multi-level (9) while single, square, decompression dives predominate in experimental trials (7).

Ascent rates can vary widely during recreational diving but are tightly controlled during experimental trials. This might account for the apparent infrequency of air embolism during experimental dives.

While the number of dives and DCI incidents are unknown in recreational diving, an overall DCI incidence is estimated at one in 2,500-5,000 exposures (0.02-0.04%; (5)). A much higher overall DCS incidence of one in 15-23 dives (4.4-6.7%) is indicated for experimental trials (7) with risk estimates of 1-4% for the Navy no-stop limits (Fig. 2). Pain-only symptoms predominate in experimental trials (see reports listed in (7)) while neurological symptoms appear more common in recreational diving (2-5).

These apparent discrepancies in incidence and symptoms may result, in part, from under-reporting by recreational divers(8). Experimental divers are trained to report even minor symptoms during post-dive interviews. Recreational divers, on the other hand, receive little training in symptom recognition and can face social censure for admitting to symptoms (10). Thus, a 2% DCS incidence based upon experimental

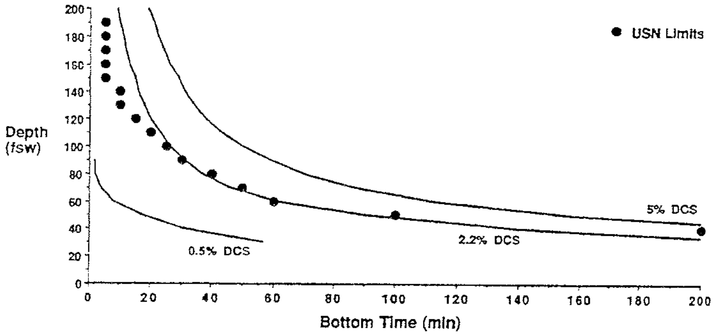

*Fig 2*

data (Fig. 2) might reflect symptoms that would be overlooked in recreational diving. If recreational diving data is to be useful for risk estimation, symptom reporting must be complete and accurate.

## The Epidemiology of Decompression Illness

The fundamental problem is ignorance of the epidemiology of decompression illness, and as long as appropriate epidemiological data are unavailable, rational safety guidelines for recreational diving will continue to be elusive. Recognizing this circumstance, the Divers Alert Network is planning a project to collect data from approximately one million dives. Project development will require 1-2 years and data gathering at least five years. Depth-time profiles will be recorded using dive computers, and divers will be interviewed concerning the presence or absence of symptoms by a network of Field Data Coordinators. Field Data Coordinators will be volunteers with a strong interest in improving diving safety. The success of this project depends upon the enthusiastic support of the recreational diving community and the dive computer industry. Orca and Suunto have indicated preliminary interest by providing software for downloading depth-time data from their dive computers. DAN has incorporated this software into a computer program for collecting information about divers, symptoms, and therapy. A description of the project (11) and a copy of the preliminary data collection program are available from DAN on request. In the coming years, Dan will work closely with the diving community to develop the information that could ultimately benefit divers around the world.

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# Using the UHMS Validation Workshop Guidelines in Development of Decompression Computers

R.W. Hamilton[1]

**HAMILTON R.W. USING THE UHMS VALIDATION WORKSHOP GUIDELINES IN DEVELOPMENT OF DECOMPRESSION COMPUTERS. DIVE COMPUTER WORKSHOP, BASEL 1992 (ED. WENDLING J./SCHMUTZ J.) P. 38-41 ISBN 3-908229-06-5. - The matter of validating decompression tables has always been troublesome. Early dive computers were produced and distributed without benefit of guidelines on how such devices should be validated. Such recommendations are now available in the form of the guidelines of the Undersea and Hyperbaric Medical Society Workshop on Validation of Decompression Tables. According to the Workshop the developing organization has the responsibility, and it is advised to appoint a Decompression Decision Board (DDB) with both the competence and the responsibility for making decisions during development. Entirely new tables or extrapolations of past experience may require traditional testing, but procedures that are interpolations of established ones can be introduced with extra precautions at the operational evaluation stage. These principles, although conceived for traditional decompression development, can apply to new dive computers. The validation may be done by the manufacturer or a user organization. Operational evaluation is done with extra training, qualified supervision, involvement of management, appropriate medical coverage, rigorous monitoring, and documentation, and feedback. This monitoring should use the computer itself as a tool, since all new dive computers are strongly urged by decompression experts to provide for detailed monitoring of dive pressure-time (and gas if other than air) profiles. Manufacturers are encouraged to distribute both the computational algorithm and the results of validation testing.**

## Introduction

Diver-carried decompression computers - conventionally called "dive computers" or "DC's" - enjoy wide acceptance among scuba divers, both recreational and professional. Early dive computer manufacturers have chosen existing computational algorithms or "models" for performing their calculations, often with some modification for the computer mode, and generally with satisfactory results (Lang and Hamilton, 1989; DAN, 1991). As dive computers with greater capabilities and higher performance move through the design process, the issue of how to validate the quality of their decompressions comes up.

A couple of decades ago, as modern diving began to develop, in order to put new or changed decompression tables to work in an ethical manner it was regarded as essential that they had to be validated by chamber tests. This consisted of exposing human experimental subjects in pressure chambers to representative examples of the new profiles or tables. As time has passed several problems with this approach have surfaced. One is a better appreciation of how little value a few tests are in predicted decompression sickness incidence in the range of fractions of a percent (Weathersby, 1989; Lehner and Palta, 1989); previously it was not widely appreciated how limited the value of a few tests were. In recent years there has been a considerable resistance also to the use of human subjects for decompression trials, especially in certain environments. Not only does this attitude cause unnecessary testing to be regarded as unethical, but it adds greatly to the cost. Another significant advance is a substantially improved ability to document field decompression exposures (Sterk and Hamilton, 1991). Perhaps the most important changes over the last 25 years, however, have been the increasing improvement in the understanding of the phenomenon of decompression as a physiological event, and the great advances in learning how to do it reliably.

One further development has been the increase in the popularity of legal litigation - law suits - particularly with regard to product liability. In the United States a concept known as "strict liability" makes a manufacturer potentially liable if a product is defective and leads to an injury; it is not necessary to prove negligence.

Validation of decompression tables, or more accurately "procedures" in the case of dive computers, has always been a sticky problem, and it remains one. A relatively new set of guidelines for systematically and ethically facing this issue offers some help.

## The UHMS Validation Workshop

In 1988 a workshop held by the Undersea and Hyperbaric Medical Society made something of a breakthrough in the question of the validation of new decompression tables, and particularly of improvements in older ones (Schreiner and Hamilton, 1989). This was a committee of 30 or so key people in decompression research and development, including almost all the leading experts of North America, and though not planned as an international workshop it was fortunate enough to include several from Europe as well. Wide representation included safety directors, the legal profession, the clergy, government and military administrators, universities, etc., with occupational safety, management, operational, medical, and research orientations. The group was well qualified to make decisions affecting all aspects of decompression development; it was not limited to the small club of decompression modelers. Their report, although it is not strictly a consensus statement, reflects the intent of the group. The Workshop dealt with several issues, including the development process itself, identifying who bears the responsibility for development, what is work and what is research, and how to make judgmental decisions.

The first thing the Workshop did was to determine that the developing organization is responsible for decompression table development and validation. This means that neither the authority nor the liability is to be passed off to a government agency or military standard or anything like that. The concept is that decompression tables are best developed by organizations who need them and who know the requirements and limitations of a given diving mode. This is focused on commercial operations, military diving, and perhaps scientific diving, cases where the diver is an employee of the diving organization, but is generally applicable everywhere.

The Workshop defined a flow chart (Figure 1) of the decompression table development process. This was intended as much to be a snapshot of the way it currently works in a responsible organization as a hypothetical "ideal" process; it shows the necessary elements. The flow chart begins with development of a new model or concept for decompression, follows with laboratory validation when necessary, shows movement into the field for monitored provisional and operational field use, with appropriate feedback loops completing the circuit. An important point is that several of the arrows in the flow chart represent decision-making steps; the Workshop proposed a method for dealing with them.

The Workshop made the distinction between research for decompression table development and operational diving. Research is by intent research and is under medical control; it meets ethical criteria for informed consent of volunteer subjects. Operational diving is within the job description of the diver. In a given case this distinction might not be clear and judgement may be needed.

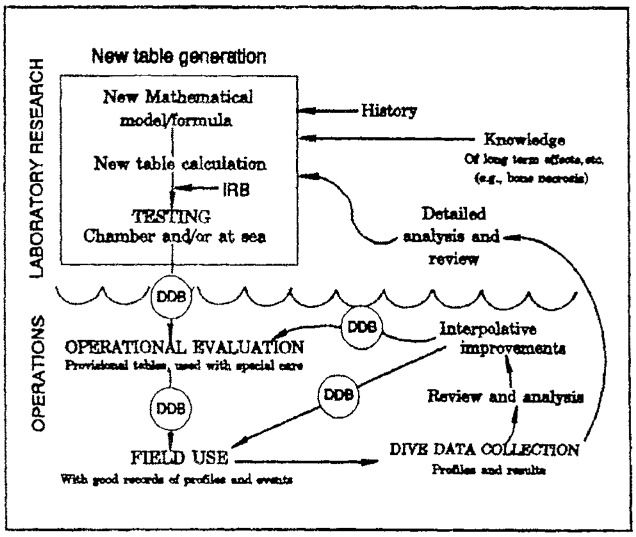

*Figure 1. Flow diagram from Validation Workshop. The DMB has been renamed to the Decompression Decision Board, DDB (Schreiner and Hamilton, 1989*

The most troublesome points in the development process are those where judgement is required, where decisions have to be made. Examples of decisions that have to be made are, when has laboratory development reached a stage that open sea provisional operational use can begin, or when is operational evaluation complete so the tables can be considered operationally ready. Or, perhaps, when is it time to go back and redo the formula because it is not working.

The Workshop noted that the ethical and legal approach to decisions of this type are that they are properly made by a "competent authority," whether in diving or in other human endeavors. The recommendation for table development is that the decisions that come up in the development process be made by a committee or board within the developing organization that is charged with the responsibility for making such decisions. This was tentatively called a "decompression monitoring board" by the Workshop, but a better term is Decompression Decision Board (DDB) since that better reflects what they do. This group is expected to have the competence to make the necessary decisions or to draw it in from elsewhere in the organization or from outside. It conceivably may be one or two people, but three or four with diverse perspectives would be better, such as the operations manager, the safety director, the decompression guru, and possibly the medical director. The makeup may change, depending on the issues involved. The description of the DDB concept by the Workshop does not mean such a mechanism has not existed before; most organizations developing decompression tables have in place a similar process, with varying degrees of formal recognition. The important conclusion of the Workshop is that a competent authority be formally designated and charged with the responsibility.

The DDB is integral to the decompression development process and makes everyday decisions; it is not a "review" board that occasionally oversees the process. Such a review or oversight committee is not a necessary part of development, but the Workshop did endorse the idea of having some sort of higher-level external review, especially where the developing organization is limited in its scope. This has been implemented in some actual situations; for example, the DAN Advisory Board reviewed the new DSAT/PADI tables (Hamilton et al, 1994), and organizations such as the U.S. Navy may have several levels of review.

Another important concept discussed by the Workshop is that of introducing tables at the operational evaluation stage. New tables that have been generated by a laboratory project or are revisions of earlier operational tables, for example, often need a phase of provisional field use before being accepted as operationally ready. This phase should be done with "special care," involving such safety oriented factors as extra training, experienced supervision, involvement of management, appropriate medical coverage, rigorous monitoring and documentation, and of course feedback. It was agreed that interpolative developments based on prior experience could be introduced at this stage without formal chamber testing, as long as the changes are within the scope of past experience and are not extrapolations into new domains. Some examples of this implementation have been with compressed air work (Faesecke KP, 1990) and in scientific diving (Hamilton, Cockrell, and Stanton, 1990).

At the operational level another process takes place, that of data acquisition, recording, and review. An essential requirement of the "op eval" process, and a highly recommended aspect of all diving operations, is monitoring of the results. This means data acquisition in terms of dive logs and pressure-gas-time profiles, review of the dive logs by the using organization, and feedback of results. This is widely implemented by various diving organizations (for example, Imbert and Bontoux, 1989; Brubakk and Jacobsen, 1991; Sterk and Hamilton, 1991).

The concepts offered by the UHMS Validation Workshop afford a logical, ethical, and recognized approach to decompression procedure development. To our knowledge they have not yet been tested in court, but they provide the kinds of things a court looks for to show that the developer has done its homework.

## Applying the Workshop principles to dive computers

It is not intuitively clear how these guidelines can be applied to the development and validation of dive computers. First consider some facts. Most current dive computers were already in existence or the development was complete at the time of the Validation Workshop, so what is said here cannot apply to them. Decompression computers, with the exception of some developed for the US Navy and the Canadian Forces, have always been dedicated to recreational diving. Dive computers have uniformly used algorithms for their computations that have been validated in field use or that are conservative modifications of established procedures. Partly because of this, in recreational diving it traditionally has not been considered critical (or possible) to perform validation testing before issuing new procedures. Most DC algorithms have been related to the US Navy Standard Air tables, and if it could be shown that they were conservative with respect to the Navy tables then they were considered acceptable.

A notable exception to the concept that recreational procedures are rarely subjected to laboratory validation is a test program performed by the DSAT, Diving Science and Technology, Inc. DSAT is a subsidiary of PADI set up for evaluating the PADI Recreational Dive Planner, "The Wheel" (Rogers, 1992; Hamilton et al, 1994). This is mentioned because it shows the considerable effort considered necessary to validate a recreational decompression algorithm that is somewhat different from previous ones. The results of this development were reviewed by an advisory committee assembled by the Diver's Alert Network.

As an aside, note that an algorithm adequate for generating "flat" tables may not necessarily be adequate for a dive computer. The reason is that most, in fact virtually all, table-based dives are submaximal; they do not extend to the full depth and time of the table. Computer dives, if they follow the computer literally, are all maximal dives. How important this is quantitatively is not known, but it represents an important distinction, and some allowance needs to be made for it either in the algorithm itself or in how the DC is used.

To begin to apply the Validation Workshop guidelines to computers it is first necessary to identify the "developing organization," the entity responsible for the development. This could go several ways. The obvious developer in most cases is the manufacturer, but some other scenarios exist. In one case a manufacturer modified a standard recreational computer specifically for an operational organization, who then performed their own operational evaluation, to validate its reliability. But let us consider that the manufacturer is the developer.

First we should consider the process of designing, producing, and marketing a new dive computer. As these things go, before the issue of a computational algorithm gets much attention the company will invest considerable effort in electronic design and miniaturization, power and power management, computational capability, packaging (which has to be rigorously waterproof as well as attractive), the display, and the overall marketing strategy (not to mention financing, manufacturing, etc.).

In order to conform to the Workshop guidelines - and this would be the best approach for any new decompression procedure development, computer or otherwise - the computer manufacturer should first establish or designate a Decompression Decision Board. This may be their resident expert in decompression, perhaps in collaboration with a product manager or safety director, or perhaps with a design engineer and maybe with one or more consultants provided such expertise is not available in house. The algorithm and its origin and track record should be documented.

Next, if the procedures produced by the new dive computer are in fact so new that they cannot be regarded as interpolations of existing experience (an unlikely event), then some type of testing program would be considered necessary. For most situations the procedures are interpolative and the validation can be done in the operational evaluation mode, in the field.

The next step is to set up methods for documentation of the op eval phase. The basic "documentation" of profiles would best be done by the computer itself. Considering the strong stand taken by another high-level workshop, the AAUS Workshop on Dive Computers (Lang and Hamilton, 1989), it would appear to be a mistake to make a new computer today that does not record the dive profiles so that they can be accessible by a desktop computer or at least be converted into hard copy. Recordings should preferably be to the nearest minute and half-metre of sea water, or very close to this, and should somehow allow an entire diving vacation to be monitored. As a minimum of dive event documentation, at least the date and starting time of every profile and the serial number of the computer should be recorded, linked firmly to the profile.

It is then part of the op eval procedure for the identity of the diver - either by name or code - and some other essential information such as the repetitive status, breathing gas (if not air), equipment, and environmental factors, etc., also to be recorded. Of course a stringent method for monitoring the outcome of the dive regarding DCS, etc., including a confirming check the day after the dive, should be in place. During the operational phase the method of recovering these profiles has to be established. Recording just the depth and bottom time is not considered adequate.

The next step is to identify the operational evaluation users. These may be volunteers to whom prototype computers are loaned for a "beta test" phase of hardware shakedown, or they may be the first eager purchasers of a new design. These people would not be considered "human volunteers" in the laboratory sense, but they should be informed of the risks involved to whatever extent that they are different from the ordinary risks of diving (they normally would not be), and of course be told what is expected of them in terms of data acquisition and reporting of outcome. For certain exposures the DDB might regard them as having a higher risk than the background level of recreational diving, and special care might need to be implemented during the initial exposures. These evaluators could be randomly selected from the population of dive computer users and requested to dive in their own style, or they could be chosen from a particular tour or resort. DAN, for example, conducts tours from which data could be acquired, under proper arrangements.

For dives in the recreational mode several thousand would be needed before an evaluation could be made. For more extreme dives such as "technical" or "commercial," a smaller number would probably suffice. It takes large numbers of dive records to establish the incidence or range of DCS probability for recreational diving because the incidence is so low. It is not necessary to establish a firm incidence if it can be shown to be suitably low. Again, this is decided by the DDB.

The analysis could consist of as little as calculating a simple incidence of a fractional percentage of DCS resulting from a given number of exposures, or could involve sophisticated statistical breakdown. Since the analysis is based on profiles involving the use of the new computer in a wide variety of situations, a good denominator for establishing an incidence level should thus be available. Note that the incidence level presumed to apply to the overall scope of recreational diving, perhaps one case of DCI in 10,000 exposures, is probably optimistic, and a level of carefully-documented near-maximal exposures would not expect such a low incidence (Lang and Vann, 1992). Whether the details of the validation are reported or not is the option of the manufacturer, but certainly it would seem the results are relevant. Paradoxically, it might be better for the liability exposure of the manufacturer for a case or two of decompression sickness to be reported in the validation testing. The reason is that if the manufacturer implies that the procedures are "safe" and that decompression sickness "is not a possibility" then it creates an unrealistic expectation on the part of the user. Likewise, if the manufacturer publishes the algorithm which is solved by the computer then his responsibility is that the computer solves the algorithm rather than that the computer prevents all decompression sickness. Decompression sickness is always a possibility in any significant diving or pressure exposure.

## Conclusion

Although the guidelines proposed by the UHMS Workshop on Validation of Decompression Tables are directed primarily at development of conventional tables by diving organizations, they offer a useful set of principles for ethical and acceptable introduction of new tables that can apply equally well to dive computers. They suggest criteria and an organizational mechanism for determining when validation testing is needed, and provide a means of putting new procedures directly into field practice when they are interpolations based on previous experience. The guidelines, as the collective opinion of the leading researchers and administrators dealing with decompression, are highly defensible. Their use is recommended for all decompression development.

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# Discussion of the presentations

**E.O Thalmann:** What I can say that I did not say before, is that in the USA for all the years that we are collecting these reports and emergency phone calls we had only 3 cases of computer failures that blacked out or something like that.

**C. Wachholz:** Yes, what has been said that we don't have enough information to point out in what one computer differs over another is true at this time. In fact, we don't know how many computers are being dived, which manufacturer them and in what quantities.

**W. Sterck:** That could mean that since the incidents of decompression sickness made with dive computers are apparently so low we could even recommend the least conservative for the longest bottom time dives and get away with it. Is that the actual state?

**A. Marroni:** The incidents of DCI seem low as a matter of fact independently of what you dive with. Its a rare event and that's why I go looking for it. This is one thing. Then there are a few considerations that appear to be relevant that happened to come up from many of us, but even if we consider the things from many different points of view that leads us to say that it appears not to be true that this current approach to the development of decompression science should be withdrawn. It seems simply not true that the new technology is not as safe as the older tables.

**E. Thalmann:** When we start talking about DCI risk level quickly, e.g. the level that was observed in the North Sea, I think that we got to be careful to find out that the reported incidents of DCI may be different than the actual incidence rate for the reasons that have nothing to do with bubbles. So a very low reporting rate doesn't necessarily mean that a computer algorithm has a low expected incident rate.

**A.O. Brubbak:** One of the obvious advantages of a computer like this is what the modern system does in making a record of what actually is going on. So, more or less educated people will look at it and say "well, is this really what I did?" and I think people's perception on what they believe to do and what they actually are doing is totally different, that's one thing.

Another thing is that I feel worried when I talk with people who dive a lot and ask them very closely what they feel after decompression. There are a lot of people who describe all kinds of aches, symptoms that do actually not give rise to treatment of decompression sickness. This arises of course the question what one should do and that is probably the danger of the computer, that gives you the feeling that it is safe to go to the limits of the tables that we have and we all know that these tables more or less break down in cases where we go to the limits. I think that is probably the danger. That would perhaps be where we should attack and try to incite on what is the reasonable approach to sports diver's diving behaviour, what kind of advice should we give them? Perhaps the advice should be "do not use decompression dives at all".

**J.L. Meliet:** From the pictures that we have seen this morning from A. Marroni and M.H. Hahn, it seems like dive computers are not unsafe. It does not give more disease cases. But we have seen a lot of evidences that on most multi-level dives and on repetitive dives you do get more time in the water. That is simply analytic as that we saw from Finland. If you would agree with me that more time spent in the water rises the risk for DCI, the answer must be somewhere else than in the computer for having no risk of DCI and what is the answer then, when more time in the water gives a higher risk for DCI?

**S. Daniels:** We got the question of modifying the dive computer slightly, there is no reason to believe that you improve the incidents of 0.1% to say 0.02% on a small modification. You may have 0.1 to 10% and all the experimental evidence suggests that it is a fairly unstable system and that such a change is what you would expect.

# Round Table on Controversial Topics

Participants: Brubakk A.O., Bühlmann A.A., Daniels S., Hahn M.H., Hamilton R.W., Marroni A., Meliet J.-L., Nishi R.Y., Thalmann E.D., Wachholz C., Wendling J. (Chairman)

## Introduction

**There is a general consensus that about 85% of the divers from Malta, Switzerland, Germany, Italy are using dive computers. In all other countries the use of dive computers is increasing as well.**

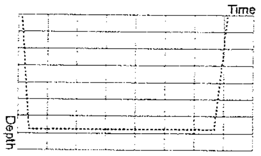
**Dive computers are used as standard tools in research laboratories, for teams revising or creating diving tables, in sports diving and, rarely in professional diving, but even there indications for some special conditions exist. Therefore the aim of the actual workshop cannot be to discuss, whether dive computers were a benediction or rather a devil tool. We have to accept that sport divers use the computer but we - doctors - may have some objections in the way they use it.**

**The following questions answered and discussed by all of the participants focus on some of the typical problems sport divers face in using the dive computer.**

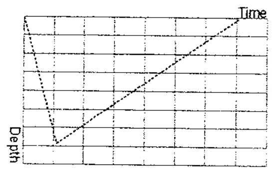
### Question 1: Multiple level diving with dive computers

a) **Do the participants think that this type of dive profile**
   - **should be forbidden in general?**
   - **would only be acceptable for selected types of dive profiles (for instance asymmetric V-shape profiles)?**
   - **should be allowed without any restrictions?**

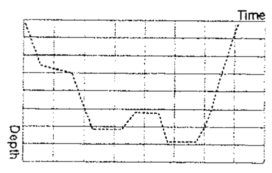
b) **In rough sea conditions decompression stops can be performed at depths of 7 to 4 meters instead of 3 meters using computers which adjusts the decompression time according to the unusual decompression level. Do the participants accept that this is a help for safer diving or do they have objections?**



Rectangular profile
(Table standard)



Asymetric V profile
(Multilevel)



Irregular profile
(multilevel)

**A.A. Bühlmann:** I have no objections to multi-level diving with the computer. The computers calculate the decompression with the actual depth, if you take 7 meters it will calculate the 7 meters and give adequate correct decompression instructions. Therefore, decompression stops on unusual levels are acceptable as well.

**E. Thalmann:** I cannot answer this question without knowing what the algorithm is. A good model should not require any restrictions. If the model is good, there should be no objections to multi-level dives. Although I would say, like Dr. Bühlmann, that a good model should allow you to take your last decompression stop where you want it and the risk of decompression sickness should be the same no matter where that stop is taken.

**R.Y. Nishi:** I agree with Dr. Thalmann. There should be no restriction, but I think that what the diver needs is better education on how to use the computer properly. For example staying at 7 to 4 meters during decompression would be good as long as the diver understood to stay at 7 to 4 meters and decompress correctly. This is the key for safer diving with dive computers.

**A. Marroni:** There should be no restriction even if the V-shape, and even better the asymmetric V-shape profile, might be recommended as a procedure. Decompression diving for recreational divers should be discouraged in general and specially when the sea is very rough aware recreational diver should avoid diving, but in the case he dives, the computer would take over and calculate the stops appropriately.

**A.O. Brubbak**: I think I agree with most of what has been said. I cannot see any reason why there should be any restriction. For the second part of the question, it is difficult for me to take a position because I think, for those cases a different model for calculation of deeper decompression stops would be required, which probably could not calculate the stops at time accurately enough. So it would on no condition be safe. If a computer does it well, yes, let it do the calculation.

**S. Daniels:** There is no point to put restrictions on dive profiles. Decompression stops in rough seas are foolish in my opinion, but nevertheless let the machine calculate them.

**M. Hahn:** I would make no restrictions for multi-level diving, neither for unusual decompression stops if the algorithm is capable of doing the calculation well. Otherwise it should be mentioned in the instructions for use if the decompression algorithm is considered not to be safe enough in that case.

**J. Meliet** : I am not sure that "no restrictions" would be a good solution because there are biological restrictions, which are specially important in the case of repetitive diving. I therefore prefer the prescription of a V-shape dive profile. If the model allows spending decompression stops at 7 meters why not use it for the eventual case.

**R.W. Hamilton**: As long as the diver tends to turn his brain off when he turns his computer on we might need restrictions. I tend to agree with Dr. Meliet with the second choice, that is the prescription of a V-shape profile. If, rather than having it being unrestricted, you define a multi-level dive as a dive in which the deepest part of the profile is first, then you can do those without restriction. I agree that the use of unusual decompression stops can be done with the help of a good computer and that this could increase safety under special conditions.

**C. Wachholz**: I would recommend no restrictions concerning dive profiles. There are some situations where one might need to go deeper later in the dive. There are many variables and factors and I am not even sure that manufacturers could cover all the bases, all the possible problems that you would want to restrict. ❖

## Question 2: Repetitive (multiday) diving

**An increasing number of divers is performing repetitive dives, specially during holidays in tropical sites, far away from treatment facilities. No limit diving is offered by many dive masters. Does the computer help to make that kind of diving safer or should it be restricted, for example in one of the following ways:**

- **More than one repetitive dive within 24 hours should not be allowed.**
- **The diver should add 50% or 100% to the DECO stop-times of the first dive in order to reduce primary bubble production to a minimum. The following dive could be performed following the computer indications.**
- **The diver can do the first dive normally following the computer indications but should be warned to use the dive computers informations for the following dives, because, due to the bubbles in the circulatory system, the algorithm calculating on a dissolved model is not correct any more. What corrections would you suggest (calculating perfusion changes due to silent bubbles)?**

**C. Wachholz:** I don't see there should be a restriction to one repetitive dive within 24 hours. This is not going to be followed, at least in the recreational community. People want to make more dives and they are just going to. That should be accepted. The diver should however be instructed to make progressively shallow dives after the first dive and not to dive more than 3 or 4 times a day, things that we are promoting through DAN currently.

**R.W. Hamilton:** As the US Dive Computer Workshop of 1991 shows this topic has something from the American football called "punt" which simply means they did not really definitively answer this important and interesting question. It requires special studies because repetitive diving means too many different things and you cannot do it in a unrestricted way. If you go out and do multiple 40-meter dives quickly with very short intervals between them, you are going to get into trouble. We pretty well agree with that so to be unrestricted is not realistic. It requires some education.

To restrict repetitive diving to a single repetition would improve safety but there are sometimes recreational situations, certainly also some scientific situations, where you need to do more repetitive diving. Then you try to do it as conservatively as possible. You might add some J-factors on the first dive so that it would make the second one better, which corresponds to your second proposal. The decompression models of the computers do not deal with bubble formation as an item at least at the present stage and therefore the only way to dive safely in a repetitive way is to add J-factors to imitate bubbles, so the calculation can follow the model.

**J. Meliet:** I totally disagree with the solutions modifying either the first or the following dives. If you give a computer to a diver, you should not tell him to do free style computing in his head in place of the computer. So I prefer the more logical way of restricting repetitive diving to a defined number of repetitions following the safety of your computer algorithm and system and corresponding to the diver you sell your computer to. So you could even produce and sell computers being able to calculate for only 3 or 4 dives in a day.

**J. Wendling:** The proposals 2 and 3 for modifying the way of using the computer indications are not necessarily recommendations for the diver himself, it could be recommendations for the producer. They are thought as ways how to adapt, how to make things go better or safer.

**M. Hahn:** If the manufacturer has the feeling that today's knowledge is not enough to have equal risk for many exposures in a day, he should state that each exposure, each ascent adds to the risk and so keep it as low as possible. However no J-factors or what ever else should be applied, otherwise the use of the computer would be useless.

**S. Daniels:** I think we have to be practical. I cannot imagine being told if I would do 3 or 4 dives in a day. Therefore the first proposal is not realistic. I also reject the second proposal, modifying decompression time of the first dive to imitate silent bubble production. I just don't believe that it would be possible to stop bubble production essentially adding 50 or 100% to the decompression times. We therefore need to go towards the third solution. We need to do a lot more work to allow the manufacturers to correct the algorithm of the machine to compensate for the effects of bubble production.

**A.O. Brubbak:** I agree with Hahn. One should recommend not to do repetitive diving and if you do it, do it as well as possible. The first advice is therefore the best. You cannot prevent divers from doing more dives but you can certainly give them advice. I don't think furthermore that adapting the algorithms or interpretation of the computers following the second or third proposals would add much to the safety of repetitive diving.

**A. Marroni:** Multiple repetitive dives are actually largely done in recreational area, especially by scuba instructors. They will not do it less just because it is not reommended but they will continue doing it because it is their work. They should be informed that multiple multi-day diving is a little more dangerous than diving without at least some intervals, let us say every 24 or 36 hours, as it has been brought up recently in numerous workshops. The proposals for modification of the computer indicated procedures are acceptable as recommendations for manufacturers but under no circumstances these recommendations should be offered as a basis for personal real-time interpretation and interpolation of the data by the diver, this is dangerous.

**R. Nishi:** The advantage of the dive computer is that it allows doing more than one dive in a day. You cannot restrict that. For the diver to modify the first dive, there is no way for the diver to make a proper judgement on how to improve his own situation. So I don't agree with the second proposal. The third proposal might be a possibility, but the correction should be performed by the algorithm so that the diver can follow the computer displays without interpreting them.

**E. Thalmann:** If the computer doesn't give a good advice the diver should not be using it. I can't answer the question how to correct for multiple diving without knowing what the algorithm is, but if the computer is not giving the diver good advice from the time he turns it on to the time he turns it off, then he should not dive with it.

**A.A. Bühlmann:** The first proposal (only 2 dives a day) is unrealistic, the second is dangerous, the third part is possible. We have the same tendency with the decompression computers as with the table: we become more and more conservative. If we have a conservative modern decompression computer the diver can do the first dive normally and then he can make the repetitive dives according to the computer (supposing it has a good model for repetitive diving).

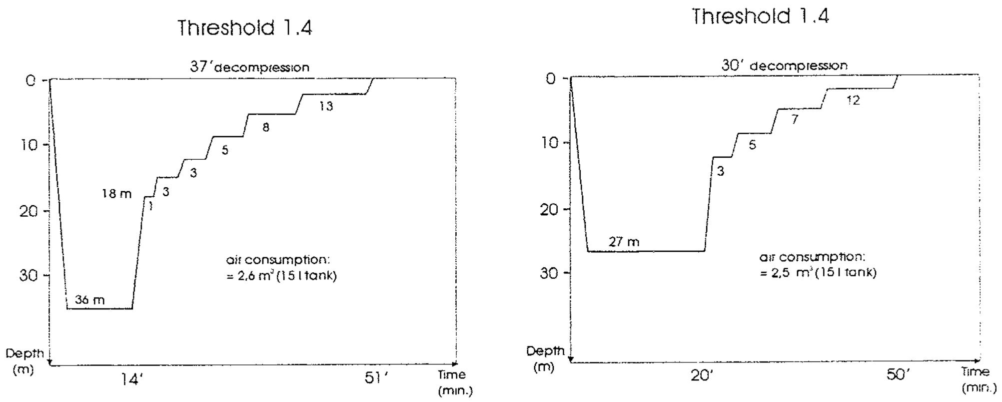
**R.W. Hamilton:** Dr. Arntzen has shown in his presentation (EUBS Congress Proceedings 1992 p. 187 ff) how the adaptation of the algorithm might be done. In other words, you hold, you freeze the outgassing of the diver for a few minutes at the end of the decompression time... That is only one technique for making the model do what it is supposed to do. ❖

## Question 3. Risk of a patent foramen ovale (PFO)

**Let's take a diver who had a decompression illness after a correctly performed dive and there is clear evidence and proof of a PFO. How could a dive computer help this diver to increase his individual safety?**

- **He should not dive any more.**
- **He might only do no decompression dives and for that purpose use the dive computer in a usual way.**
- **The diver could go back to dive safely if the decompression stress at any moment would be below the bubble growth threshold. Software adaptation for those cases could be easily done by the manufacturer. Should we stimulate the manufacturers to offer such adapted computers or computer modes for the special cases?**

**Dr. Hahn was so kind to calculate and present me a set of possible tables with a threshold of 1.0, which shows that it is not very realistic to go diving with such a table. However, if we accept a bubble threshold of 1.4, (which is a quasi consensus of the UHMS Workshop...) it looks somehow more realistic. Calculated on that base, tables would allow a diver who really wants to dive, to go back to the sea but performing very conservative and not very deep dives which however are still realistic (see fig 1). Should we promote that kind of adaptations?**



*Dive profiles calculated for a critical tolerable oversaturation of 0,4 bar (by Max Hahn on the basis of the ZHL 16 algorithm modifying the a and b values. More detailed description follows in Annex 1).*

**A.A. Bühlmann**: I am not able to answer the question, but the market is not big enough to make special models for calculations for foramen ovale. There are 30% of our people with an open foramen ovale but only some cases with decompression sickness. In my opinion if you make a gas embolism through a foramen ovale, it is not so much a question of the decompression profile.

**J. Wendling**: It is an important question because theses divers normally are highly motivated and routined divers. They want to dive and we just have to decide whether we can declare them fit to dive or not. If there was a table based on a algorithm that avoids even silent bubbles production, could we tell them that they can go to dive again or do we just say no?

**A.A. Bühlmann**: My position is to say to the individual what he could do to increase his safety while diving, but this is not a question for the manufacturer.

**E. Thalmann**: My advice is that if an individual has a patent foramen ovale and has a history of DCS on dives where other people do not get it, he should not dive any more. Patent foramen ovale is one of many risk factors for DCS but so long as it is not associated with an unusually high occurrence or severity of decompression sickness it is not a contra-indication to diving. Even if tables of a much lower risk than normal tables where used by divers with PFO, it is unlikely that enough data could be obtained from their use to distinguish between the increased table safety and normal variations in observed incidence of decompression sickness.

**J. Wendling**: I must stress that there is a difference between sports diving and professional diving. Recreational divers are diving at their own risk even if we (doctors) say they should not dive. They will do it anyway. So sometimes we can help them if we say: you should not dive, but if you go, do it in the following way....

**A. Marroni**: There were two reports on patent foramen ovale during the EUBS Congress (1992, Basel) and actually we got evidence that there is no significantly increased risk for people with patent foramen ovale. We only know that many of us have such a residual of our embryology and I would not call it a pathological aspect as it is so frequent (more than 30%). The normal recommendation should be to perform only no-decompression dives. Diving below bubble-threshold should be a normal recommendation to any diver. Regarding the possibility of having a specially customised computer where you could switch to the special program, I think it is unrealistic.

**A.O. Brubbak**: I would have no objections for going back to dive even with a patent foramen ovale after DCS. I don't think there is any clear evidence that there is a relation between the risk of decompression sickness and patent foramen ovale. If a diver has several episodes of DCS, then he could perhaps have a risk factor and that makes the decision more difficult. Manipulating the table doesn't work. All my data that I have from the animal work indicate that even a very low increase in pulmonary arterial pressure which we will have with a very low bubble load will let gas bubbles go into the arterial side. So you simply cannot do that. You should tell your diver rather that probably his risk will increase for having a problem not only because of a patent foramen ovale, but because of the problem related to decompression in general with doing long deep dives.

**S. Daniels**: The evidence seems to indicate that the patent foramen ovale doesn't substantially increase the risk factor. So go back to diving without any limitations.

**J. Meliet**: For me, diving with a patent foramen ovale should be forbidden, because if one has the knowledge of patent foramen ovale, one should be aware of the risk factor and its not allowed to play with hazards in this case.

**A.O. Brubbak**: I would like to make a comment to that. I would like to make clear that it has not been defined up to now that the patent foramen ovale is a hazard. It might be that it is a hazard but the present data do not show it.

**J. Meliet**: Until the proof of the contrary I consider it as a hazard.

**R.W. Hamilton**: I agree with Brubbak and Daniels that until we know better, we should go on without restrictions.

**C. Wachholz**: DAN generally tells to the divers to give up diving when they had a DCS and patent foramen ovale. Whether they do it or not is an other question. We have this position because some work on patent foramen ovale has been done at Duke University. ❖

## Question 4: Future modifications of dive computers

**We all agree that the ideal computer would give the correct informations about how to behave specifically how to decompress, even under exceptional conditions. As we observe an increasing tendency towards unconventional dive methods like inwater oxygen decompression or mixed gas diving, for instance with enriched air, we would be interested to know the opinion of the participants about what should optionally be modified in the next computer generation. Some evident options are:**

a) **Adaptation for pure oxygen decompression. Should there be an optional button to reduce the nitrogen partial pressure in the algorithm for oxygen breathing?**

b) **Could we even go further and wish an adaptation for mixed gases like enriched air with variable PN2 (nitrogen partial pressure)?**

c) **In case of a catastrophic ascent, the display of the computer display should not be frozen. Most of the diving computers do not continue giving data on the display although this could be very helpful in case of a rescue management, mainly for the medical staff.**

d) **Decompression stress should be displayed in addition or instead of the zero stop time especially in the interval between repetitive dives. This would give an estimation of where you are on the way of denitrogenation, which is not possible with giving just time in minutes on a display. deco-stress means giving some coefficient like it was in the old GERS tables (for instance 1,4 or 1,7) after a big dive. This would not mean necessarily the exact saturation of a partial tissue or something precise.**

**C. Wachholz**: DAN is not involved in mixed gas diving or oxygen decompression, thus I would not comment on that. In England, there is a computer which does calculate mixed gases: it would appeal to enriched air-divers to use a computer with that capability. As far as the display options during a catastrophic ascent are concerned, I can't see any reason why the display should be stopped. The more information the diver has, the better. If the idea would be to keep the divers from going back to the water, I don't think that they will behave so. As far as the last part of the question, I think that if a deco-stress parameter can be easily understood by the diver and used correctly for his safety, it should be displayed.

**R.W. Hamilton**: As you could imagine from what I said earlier, I would suggest a most important modification of computers and that is recording the whole dive profile. Whether the recreational dive computers should deal with oxygen breathing and enriched air diving is another question which depends mainly of the market strategy. There are two computers that do calculate for enriched air diving. Computers that give you many more capabilities would generally be too complicated and cannot be used in what we define as recreational diving.

Absolutely, the display should continue the dive logging and should continue to calculate the decompression. This was a strong recommendation of a formal dive computer workshop. The original Edge Computer showed gas loadings in its graphically display giving you an idea about the decompression stress. For unknown reasons, the new model does not include this display any more. I think it was a good idea to display it, but if I am not sure that most people who had that computer were able to use that information effectively.

**S. Daniels**: In an uncontrolled ascent, the computer should continue to calculate and display. Of course, the person should not be allowed to continue the dive, but it is sometimes useful to have information for purposes of treatment, especially for someone who gets hurt after the dive.

**J. Meliet:** I also think that the display should not interrupt. Adaptation for gas mixtures and enriched air seems more to be for professional use than for recreational diving and it is in fact a question of marketing. If you increase the number of functions that the decompression computer can do, you increase the risk of misuse and mistakes as well. So it is rather an ergonomic problem than a mathematical or technical one.

**M. Hahn**: What concerns adaptation for the case of enriched air or oxygen decompression, I think that is a question of marketing policy of the computer manufacturers. If these techniques were to spread among sports divers, the manufacturers would be capable of monitoring this kind of dive. However, concerning non-regular ascent, I would say all vital information must be supplied to the diver in any case, but the registration of the profile and probably a specific mark if the limits of decompression were disregarded should be kept in the memory of the computer, so it can be reviewed somehow.

A display of a deco-stress factor is not necessary because most computer users have a feeling of it, if the no-d-limit and no-flight-time is displayed. They would be able to judge what factor this is about.

**S. Daniels**: The question about enriched gas diving made us aware that there is a diving computer for enriched air diving. I was astonished that recreational divers would want to use this kind of thing. In case of rapid ascent, dive computers should continue to display and continue to record. That data could be vital for a treatment centre.

The deco-stress is not to be indicated on the display. I am not sure what you mean by that indicator. I would want to know the gas loading, how many bubbles there were, what the rate of the accumulation has been, what the elapsed time was. The computer cannot calculate the gas loading properly and it does not measure the bubbles, so I don't see that as something meaningful.

**A.O. Brubbak:** One should not encourage dives with longer bottom times and more complicated diving procedures for sports divers. Development of such modifications should not be encouraged. It makes things more complicated and I think a recreational diving computer should be a simple device. Obviously the computer display should continue to calculate even in case of irregular ascent. Concerning the deco-stress indication, I have the same comments as Daniels. I would say that if you have the serial zero-stop-time, that would be enough.

**A. Marroni**: Modification for calculating on enriched gases would not be recommended. This would imply the risk that one could use the wrong computer for a certain dive. It is a problem similar to the one of using different gases. In this case for instance, there are fittings for different gases so that you are protected against mistakes. Unless we restrict the marketing of these objects to the holders of certain certificates, the use of such computers would mean a unacceptable risk. Monitoring should continue in case of rapid ascent.

There are actually dive computers using deco-stress indicators. The Edge computers use a display with bars and there is another, I think by Techna, with a little man that fills up and gets empty again. Such indications could be a precious help to the divers.

**R. Nishi:** Mixed gas diving is not recommended for the recreational diver. Perhaps for the professional diver, procedures such as oxygen decompression is necessary. I do not think that many recreational divers are aware of the problems that can exist with enriched air diving with high oxygen content, and therefore, I do not recommend adapting dive computers for mixed gas for the recreational market. I support the continued display of information in case of an exceptional ascent. The display should not be stopped. I agree that the diver has to be told in some way what he should do in case he has a problem. The deco-stress indicator is a nice idea if you can do it properly. It would be information that could indicate to the diver how to increase the safety.

**E. Thalmann**: I would support the development of computers that can take enriched gas breathing and oxygen breathing into account. However, this is something best confined to professional divers and should not be generally used in sports diving. An important condition is that the algorithm must have been tested on enriched gas mixes, it simply should not be extrapolated from air diving, which could be dangerous. Interruption of display in exceptional situations is never acceptable. Decompression computers should never turn off. They could flash a warning light if conditions warrant but they should always provide the diver with decompression advice, if they turn off they are not useful.

As far as a deco-stress indicator, you can display anything you want, a little man, bar graphs of tissue tension, or a number of some sort. Unless the algorithm has been calibrated to actually computer the time course of DCS risk, these things are useless. In most cases the next zero-stop-time at a specified depth is probably the most useful indicator in planning repeat dives.

**J. Wendling**: You could also display the probabilities according to your probabilistic model.

**E. Thalmann**: Well you could, that is quite credible, but that has not been tested yet.

**A.A. Bühlmann**: I agree with Thalmann. ❖

## Question 5: Are there applications for diving computers in professional diving?

**Could the diving computers found on the market, or the ones to come, be a help either for the worker to get more safety or to the employer to get more working time, or are there other arguments for the use of diving computers in the professional field?**

**A.A. Bühlmann:** A diving computer is useful for the professional diver as much as it is for a recreational diver. For a tunnel worker, it is unnecessary. The tunnel caisson is managed from the outside and regarding the professional diver in a bell he is also directed from the outside.

**E. Thalmann**: My comments on this question are my own and not the opinion of the U.S. Navy. I think that every professional diver should have a decompression computer. There are some restrictions:

1) The computer decompression advice needs to be displayed to topside personnel for tethered divers.

2) Whatever algorithm is used, it must be well tested and the testing thoroughly documented.

3) The confidence limits on the algorithm predictions and any restrictions have to be well known.

Being able to update the algorithm based on actual experience is important. I think the main advantage of using a dive computer professionally is recording the actual dive profile. If this information is combined with the observed DCS incidence a method of constantly improving safety is available.

The diver should always be able to get as much time on the bottom as possible for a given amount of decompression, if is safe for him to do so. Bottom time is productive, decompression time is not. In my conversations with Navy divers, the main limiting factors in diving are fatigue and cold stress. Therefore the faster the diver can get out of the water after having completed his job the better.

**R.Y. Nishi**: I think that for the professional diver, a dive computer could be useful, if controlled from the surface. Because the diver may be cold and tired, he may not be able to excercise correct judgement to control his own decompression by computer. So in this case, it could be done much better from the surface-support team. For tunnel work, the computer could be useful, not for the worker, but for the inspector who will go into the tunnel to inspect the job.

**A. Marroni**: For the commercial diver, as for example in oil diving, which is normally run from the surface, probably the use of a computer as we see it is not advisable. Scientific diving and professional teaching activity, as for example in tourism centres, have a benefit by using computers. So we have to define what sort of professional divers we are speaing about. What Prof. Bühlmann says is very correct, if the diver is in the water on his own judgement, he is his master and the computer is fine: if the diver is not the master of himself, the computer may not be useful.

**A.O. Brubbak:** The most useful part of decompression computer is simply that of a recorder, recording the time and depths which is not only good for professional dives and it should definitively be used more. The ability to calculate profiles would be less useful for a professional diver because a large portion of those jobs will be preplanned and the decompression will be preplanned to some extent, but the recording and the ability to get information back to the ones who are running the dive, that information is very useful. So retrospectively we could see for instance that the ascent was a little more rapid than was allowed, that this guy has been jumping up and down and doing things that are not recommended. I have to remark on an important fact that has been observed many times in practical work with our professional sites, where dive computers are used all the time but with the computer kept topside to record the dives of the workers. People look at the displays and tend to believe what they see. When the depth is displayed 27,34 meters, they think it is 27,34 meters. In the old days, they said "well, that is approximately 30 meters, let's be conservative, use a 31 m-table" and nowadays they go much closer to the actual limits. For some reasons they believe much more what they see with 2 digits than what they see as an analog value.

**S. Daniels**: What Jean-Pierre Imbert showed us adequately in his presentation (EUBS Congress Proceedings 1992, Basle, p. 203-205).

**M.H. Hahn**: I have the same attitude as Dr. Marroni, it depends on what kind of professionalism it is applied. There are professional divers like diving instructors who use computers in the same way as recreational divers do. Others, maybe divers who are operated from the surface, who don't need the computer and probably can't read it (zero visibility, welding).

**J. Meliet**: I would say the same thing.

**R.W. Hamilton**: I agree that if you have a computer like Imbert says it would be a big help. I would like comment that a computer does not necessarily give you more bottom time. If you are going down working at a worksіde and then coming back when you are finished you are going to get the same result with a computer or a table, we get maybe a tiny little difference. For divers doing an inspection or with a lot of swimming up and down, the computer could give them much more efficient decompression than the tables.

**E. Thalmann**: I mean if you happen to drop your brush to the bottom of the harbor at 60 feet and you have been on 30 feet all the day, you are on a 65 feet table - then the computer may be very very handy.

**J. Wendling**: So I would like to thank all to participants. We came to a kind of consensus even if the opinions are not all the same for everybody, which is not suspected to be; there is no rough disagreement I think, but we need more investigations to arrive at standards. ❖

Presentation held at the XVIIIth Annual Meeting of EUBS, September 1992, Basel (Switzerland)

# Guidelines for Dive Computer Algorithms

A.J. Arntzen[1]

**ARNTZEN A.J. GUIDELINES FOR DIVE COMPUTER ALGORITHMS. PROC. XVIIITH MEETING EUBS, BASEL 1992 ISBN 3-908229-00-6. Experience indicates that dive computers, although based on apparently conservative decompression models, seems to introduce a increased risk for decompression sickness. An analysis of the general working principles of the dive computer, compared with the use of diving tables reveals that there are weaknesses in the dive computers program that may increase the risk of decompression sickness for certain types of dives. Changes to the computers algorithm are therefore desirable.**

## Introduction

The small dive computers on the market today have an impressive capacity. They seem to be able to calculate and display almost any information needed for a safe decompression, whether this includes stops or not.

Typical information are

- depth
- dive time
- maximum depth
- water temperature
- minutes left of no stop time at current depth
- information on minimum safe ascent depth
- correct speed of ascent
- decompression stops
- time at stops
- repetitive dive info
- automatic diving at altitude corrections
- flying after diving info
- recall of diving data
- etc, etc.

Dive computers as such are accurate and reliable. Experience, however, has clearly shown that following a dive computer is no guaranty to avoid decompression sickness. For certain dives, and especially for repetitive dives it seems to represents an increased risk for decompression sickness, compared to many diving tables.

This is perhaps a bit strange, because most dive computers are based on decompression tables which is supposed to be quite conservative. If we take a dive computer and compare the no decompression times for a single dive with the no decompression times on various diving tables we will see that they are at far more conservative than the US Navy table, and more in line with tables like Royal Navy, Canadian Navy, Bühlmann, PADI and others. The no decompression times does not tell the whole story, but to some extend it is a good guide line.

A sport diver who uses a dive computer will not have to concentrate on tables, time and depth, because all the information he needs will be displayed for him. An other advantage is that a dive computer will normally give more dive time on a typical sport diver profile. It does so because it integrates the divers depth through small time intervals, and from that calculates the "exact" loading of the various tissues, and hence the decompression stops if needed. In this way the dive computer allows the diver to go to the limit of the table (i.e. table model) on which it is based without rounding off the depth and bottom time to the nearest greater table values (as the rules are when using tables).

Based on the difference in ambient pressure and the immediate saturation pressure in the various tissues, the computer will make small corrections to the tissue saturation with few seconds interval. With the high calculation capacity there is no problem for the dive computer to track tissues with 12 different half times.

Calculation of the desaturation follows the same well known model whether the diver is in the water or during surface intervals. This means that the dive computer gives "full credit" for any reduction in the ambient pressure less than the tissue saturation. This may be correct if the rate of inert gas elimination is a function of the difference between the theoretical tissue saturation and the ambient inert gas pressure. The algorithms of most diving tables are based on this assumption.

However, the algorithm has been gradually changed since the dive computers first appeared on the market, resulting in shorter and shorter "no decompression time". This reflects the experience that even if a dive computer program is based on rather conservative or safe tables, it is not as safe as the tables in practical use.

## Discussion

There may be many reasons for this difference. But it does not mean that there is always a greater risk for DCS when diving with a dive computer. Using one of the newer dive computers for a single dive, with reasonable work load and what we could call a "normal" dive profile (no yo-yo diving) is probably a very safe procedure.

The basic problem with dive computers is that the model assume that tissue saturation is a function of time and depth only, and that desaturation will follow the same basic principles as long as the pressure differences are within given M values or similar criteria. Such a model is very useful in table work, because it is easily understandable and it allows us to manipulate the constants to let the answer match practical experience.

There are much experience to show that a dive with one or more short surface intervals, so called "yo-yo diving" represents a greater risk for DCS than if the diver had spent all the time (including the surface intervals) at depth. If you dive with a table you will at least let the time run till the final ascent. But if you use a dive computer, you will get credit for the short trip(s) to the surface.

Repetitive diving is an other problem. At surface dive computers will calculate desaturation in each tissue according to the model. Because sport dives are normally rather short dives the controlling tissues for the first as well as for the repetitive dives will have relatively short half times. That means a quick reduction of the calculated saturation level in these tissues, and thus very little penalty for the repetitive dives.

There is no compensation for the accumulative effect of repetitive dives. The magnitude of the accumulative effect is most difficult to predict. The main reason is probably great individual variation. There is also reason to believe that relatively small variations in the previous dive, such as increased speed of ascent, heavy work load etc. may give a great accumulative effect. On the other hand, the relatively short no decompression times, which has been shortened several times, reflects the problem and will to some extent compensate for both yo-yo diving and for not considering the accumulative effect on repetitive dives.

When diving on tables we can compensate for variations in each dive. This is most commonly done by reducing the actual bottom time compared to the table time. The reason for doing so may be heavy workload cold water, the divers age or physical condition etc. With a dive computer this possibility is much more limited. As long as we are diving within the no decompression limits we can compensate for such variations by surfacing while there is still time left of the no decompression time. But if the dive needs decom-pression stops, there is no easy solution.

## Recommendations

There are many ways to make tables or dive computers safer. The most easy way is probably, as we have seen, to reduce the M-value which will give shorter no decompression time and longer decompression stops. But that puts the same restrictions on all dives and is therefore not a good solution. If you are making a single dive without surface intervals or great depth variations, the dive would probably be safe even to increase the M-value to some extent, and thereby the no decompression times.

A better solution would therefore be to make more logic changes to the program to compensate for yo-yo diving and fast ascent rates. The changes to the program should give penalty instead of credit for this *(increase in tissue saturation instead* of reduction). The criteria for magnitude of the penalty should be based on the tissue saturation compared to depth. A proposed limit for maximum ascent rate without penalty is 10 m/min.

To compensate for the accumulative effect of repetitive dives, the calculated desaturation of the different tissues should be slowed down. A way of doing this is to increase the half-times of the tissues by a factor (suggesting 2) as soon as the diver is on the surface. This will result in more penalty (time added to the actual bottom time) after the same surface interval.

Various external factors like workload, temperature etc., as well as individual variations should also be compensated for. In order to make such adjustments as simple as possible there should only be a limited number of choices. There should be a default mode, which requires no extra action. In addition the choice of for example two levels of compensation, which eventually had to be set prior to each dive. Guidelines for what to compensate for should be given in the users guide. The result of choosing one of the compensation levels could be that the dive computer used a set of reduced M-values in the calculation.

The recommendations presented here is not meant to be a complete study of what is needed to compensate for the short comings of the dive computers on the marked today. But it probably indicates that certain improvements are possible without developing completely new and complicated programs. I also understand that people in the diving equipment industry are aware of the problems and are considering solutions.

Although much of the traditional concept of supersaturation is maintained in this paper, it is reasonable to believe that we in the future will reconsider the validity of this model. The result may be deeper stops and slower speed of ascent.

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# Comparison of No-stop and Deco Stop Times of Dive Computers

P. Mattila[1]

**MATTILA P. COMPARISON OF NO-STOP AND DECO STOP TIMES OF DIVE COMPUTERS. PROC. XVIIITH MEETING EUBS, BASEL 1992 ISBN 3-908229-00-6. A comparison of no-stop and deco stop times of current dive computers reveals significant differencies between dive computers of different manufacturers (fig.1 and 2). As a simple "safety index" of a dive computer or a dive table one can use the sum of no-stop times at different depths (fig.3). Correspondingly one can add the total ascent times of selected deco stop schedules. If these indexes match with indexes of latest dive tables one can at least suppose that those dive computers are reasonably safe when making single dives with square profiles. Another interesting topic is to compare the no-stop and deco stop times on gradually ascending multilevel dives. The difference between the most conservative and the most liberal dive computer is astounding (fig.4 and 5). Of course if a dive computer gives clearly shorter no-stop times and longer deco stop times the probability of DCS is smaller than with a more liberal dive computer. The measurements were made mostly only once with a certain dive computer model, so the results should be considered more as direction giving than exact values. Although comparing different dive computers is interesting to users and manufacturers we need more research on how safe current dive computers are in multiday repetitive diving and how long should the no flight time be. Another important area of investigation is the effect of so called risk dive profiles and how the model should take them into account.**

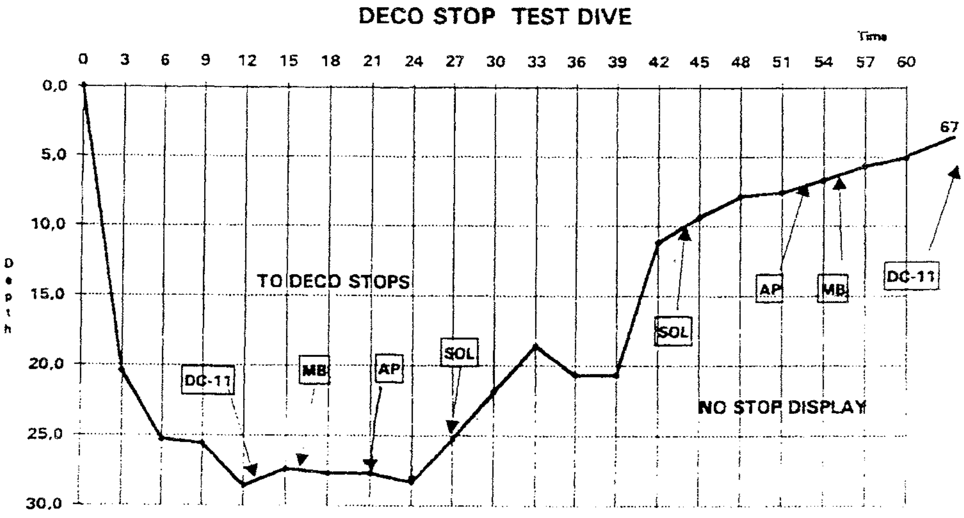

*Fig. 1 Test dive with 4 dive computers. The first series of arrows (about 27 m depth) shows the endpoint of zero stop time of the different devices. the second series (between 10 – 5 m) shows the end of deco stop time. Typically for realtime logging devices the end of deco time may be displayed even before arriving to the indicated deco level, because offgasing begins much deeper. Note that the difference between "DC-11" and "Sol" is about 2:1. DC-11 = Scubapro, MB = Dacor MB Pro. AP = Aladin pro, Sol = Sununto Solution*

| COMPARISON OF DIVE COMPUTER DEC TIMES | | | | | | |
|---|---|---|---|---|---|---|
| No stop times during descent | | | | | DIVEPROFILE | |
| | | | | | Time | Depth |
| Depth | SCUBAPRO | DACOR | ALADIN | SUUNTO | 3 min | 20,4 |
| 21 m | 24 | 15-30 | 33 | 37 | 6 min | 25,3 |
| 25,7 m | 9 | 8-15 | 17 | 23 | 9 min | 25,6 |
| 30 m | 2 | 4-8 | 9 | 12 | 12 min | 28,6 |
| | | | | | 15 min | 27,4 |
| | | | | | 18 min | 27,7 |
| To deco stops, max deco need and return to no stop display | | | | | 21 min | 27,7 |
| | | | | | 24 min | 28,3 |
| | SCUBAPRO | DACOR | ALADIN | SUUNTO | 27 min | 25,3 |
| To deco stops: | | | | | 30 min | 21,9 |
| Scubapro | (13 min) | NST 2 | NST 7 | NST 11 | 33 min | 18,6 |
| Dacor | 3 m / 4 min | (16 min) | NST 4 | NST 8 | 36 min | 20,7 |
| Aladin | 6 m/ 7 min | 3 m/ 4 min | (21 min) | NST 3 | 39 min | 20,7 |
| Suunto | 6 m/ 14 min | 3 m/ 7 min | 3 m/ 5 min | (27 min) | 42 min | 11,2 |
| | | | | | 45 min | 9,4 |
| Max deco need: | 6 m/ 24 min | 3 m/ 12 min | 3 m/ 8 min | 3 m/ 5 min | 48 min | 7,9 |
| | | | | | 51 min | 7,6 |
| Max depth: | 29,0 m | 29,5 m | 30,1 m | 28,7 m | 54 min | 6,7 |
| | | | | | 57 min | 5,7 |
| No stop display: | | | | | 60 min | 5,1 |
| Suunto | 3 m/ 20 min | 3 m/ 10 min | 3 m/ 5 min | (44 min) | | |
| Aladin | 3 m/ 17 min | 3 m / 6 min | (53 min) | | | |
| Dacor | 3 m/ 15 min | (56 min) | | | | |
| Scubapro | ( 67 min) | | | | | |

NTS' = No stop time

*Fig. 2 Table of displayed times during the dive of fig. 1*

| DIVETABLE AND COMPUTER COMPARISONS | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| No stop times | | | | Scubapro | Dacor | Uwatec | Suunto | Orca | Sherwood | |
| Depth | USN | FSDF | BUHLM. | DC-11 | MBPRO+ | AL PRO | SOLUTIO | SK. DIPPE | SOURCE | MAX DIFF |
| 15 | 100 | 65 | 75 | 58 | 64 | 70 | 72 | 77 | 78 | 20 |
| 18 | 60 | 45 | 51 | 36 | 44 | 49 | 52 | 53 | 55 | 19 |
| 21 | 50 | 35 | 35 | 22 | 31 | 35 | 37 | 40 | 40 | 18 |
| 24 | 40 | 25 | 25 | 15 | 20 | 25 | 29 | 32 | 31 | 17 |
| 27 | 30 | 20 | 20 | 12 | 15 | 20 | 23 | 24 | 25 | 13 |
| 30 | 25 | 15 | 17 | 9 | 12 | 16 | 18 | 20 | 20 | 11 |
| 33 | 20 | 10 | 14 | 8 | 10 | 14 | 13 | 13 | 17 | 9 |
| 36 | 15 | 5 | 12 | 7 | 8 | 12 | 11 | 11 | 13 | 6 |
| 39 | 10 | 5 | 10 | 6 | 7 | 10 | 9 | 9 | 11 | 5 |
| | 350 | 225 | 259 | 173 | 211 | 251 | 264 | 279 | 290 | |
| Total ascent times on decostop dives | | | | | | | | | | |
| 30/30 | 5 | 15 | 12 | 31 | 21 | 15,5 | 15 | 11 | 10,5 | 20,5 |
| 36/25 | 8 | 20 | 17 | 35 | 25 | 20,5 | 21 | 16 | 14 | 21 |
| 45/15 | 6 | 20 | 13 | 26 | 14 | 12,5 | 14 | 8 | 14 | 18 |
| 51/15 | 10 | 25 | 19 | 37 | 23 | 20 | 20 | 13 | 20 | 24 |
| | 29 | 80 | 61 | 129 | 83 | 68,5 | 70 | 48 | 58,5 | |

ESTIMATED TIME, BECAUSE SOURCE GOES ON ERROR AFTER 4 MINUTES OF DIVE TIME!

*Fig. 3 Comparison of No Stop times of three dive tables and six dive computers*

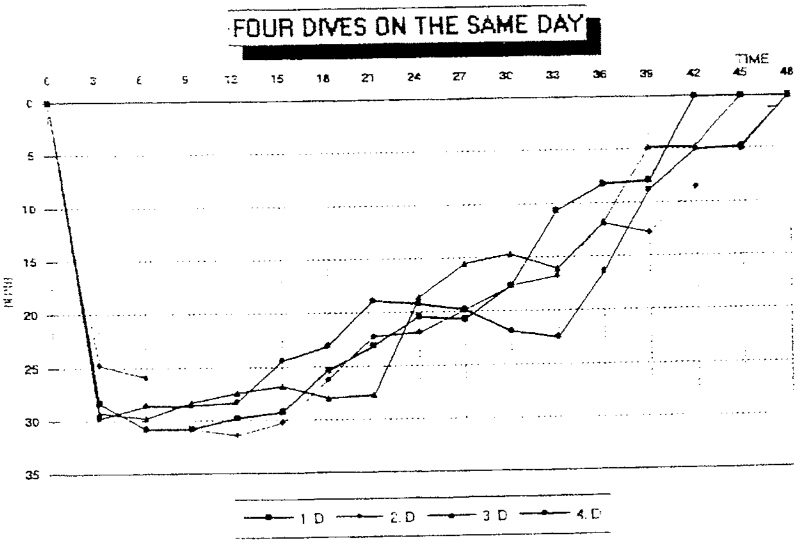

*Fig. 4 Gradually ascending multilevel dive profiles used as a tesr in a repetitive dive*

| REPETITIVE DIVE TEST LOG | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | | 20.3.91 | | | | | 21.3.91 | | | |
| Site | Little Cayman | | | | | | | | | |
| | | Dive 1 | Dive 2 | Dive 3 | Dive 4 | | Dive 1 | Dive 2 | Dive 3 | Dive 4 |
| Surface interval | | - | 3:02 | 1:50 | 2:21 | | 11:08 | 2:06 | 2:12 | 2:17 |
| Dive started | | | | | | | | | | |
| ended | | | | | | | | | | |
| Total dive time | | 0:56 | 0:46 | 0:42 | 0:52 | | 0:41 | 0:45 | 0:44 | 0:46 |
| Max. depth | | | | | | | | | | |
| ALADIN PRO | | 28,4 | 29,9 | 29,6 | 24,9 | | 31,5 | 31,9 | 30,5 | 30,5 |
| DACOR MB Pro | | 28,0 | 29,5 | 29,3 | 24,5 | | 31,0 | 31,5 | 30,0 | 30,0 |
| SUUNTO SOL | | 27,7 | 29,1 | 29,0 | 24,4 | | 30,8 | 31,2 | 29,9 | 29,5 |
| Max. deco need | | | | | | | | | | |
| Desaturation time | | | | | | | | | | |
| ALADIN | | 13:02 | 16:20 | 18:19 | 19:13 | | 15:42 | 18:34 | 19:47 | 20:46 |
| DACOR | | 9 h | 16 h | 19 h | 22 h | | 19 h | 23 h | 25 h | 27 h |
| SUUNTO | | 14:43 | 20:17 | 23:32 | 25:23 | | 22:02 | 25:15 | 27:00 | 28:14 |
| No flight time | | | | | | | | | | |
| ALADIN | | 3 h | 6 h | 8 h | 9 h | | 8 h | 8 h | 10 h | 11 h |
| DACOR | | 2 h | 9 h | 12 h | 16 h | | 12 h | 16 h | 18 h | 20 h |
| Dive profile | | | | | | | | | | |
| | Time | | | | | | | | | |
| | 3 | 16,7 | 15,5 | 16,4 | 9,4 | | 28,5 | 24,7 | 29,2 | 29,8 |
| | 6 | 21,9 | 23,3 | 25,6 | 17,9 | | 30,8 | 25,9 | 29,8 | 28,6 |
| | 9 | 25,9 | 28,0 | 26,8 | 19,3 | | 30,8 | 30,8 | 28,3 | 28,6 |
| | 12 | 27,7 | 28,0 | 28,9 | 18,3 | | 29,8 | 31,4 | 27,4 | 28,3 |
| | 15 | 18,9 | 28,9 | 28,3 | 20,4 | | 29,2 | 30,2 | 26,8 | 24,4 |
| | 18 | 23,1 | 28,6 | 27,7 | 19,2 | | 25,3 | 26,2 | 28,0 | 23,1 |
| | 21 | 25,6 | 25,6 | 26,8 | 18,9 | | 23,1 | 22,2 | 27,7 | 18,9 |
| | 24 | 25,0 | 23,1 | 20,1 | 13,7 | | 20,4 | 21,9 | 18,6 | 19,2 |
| | 27 | 25,0 | 20,4 | 20,7 | 13,4 | | 20,7 | 19,8 | 15,5 | 19,8 |
| | 30 | 24,7 | 14,0 | 12,8 | 21,3 | | 17,6 | 17,6 | 14,6 | 21,9 |
| | 33 | 17,0 | 10,6 | 7,6 | 24,4 | | 10,6 | 16,7 | 16,1 | 22,5 |
| | 36 | 10,0 | 8,2 | 8,5 | 16,4 | | 8,2 | 11,8 | 11,8 | 16,4 |
| | 39 | 9,4 | 4,5 | 6,4 | 12,5 | | 7,9 | 12,8 | 4,8 | 8,8 |
| | 42 | 10,0 | 6,4 | 4,5 | 14,6 | | END | 8,5 | 4,8 | 5,1 |
| | 45 | 9,4 | 6,1 | END | 15,2 | | | 5,1 | END | 4,8 |
| | 48 | 8,8 | END | | 14,9 | | | END | | END |
| | 51 | 13,1 | | | 5,7 | | | | | |
| | 54 | 7,8 | | | END | | | | | |
| | 57 | END | | | | | | | | |
| | 60 | | | | | | | | | |

*Fig. 5 Desaturation time and no flight interval after each of the repetitive dives of fig. 4*

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# Dive Computers and Commercial Diving

J.P. Imbert[1]

**IMBERT J-P. DIVE COMPUTERS AND COMMERCIAL DIVING. PROC. XVIIITH MEETING EUBS, BASEL 1992 ISBN 3-908229-00-6. The dive computers and their success in recreational diving have been ignored by commercial diving. The reason is that the diving procedures are different, and Comex attempted to design a system specifically defined for commercial diving, that is named DIVA.**

**The tables available in DIVA are not computed on line but drawn from a data bank of official tables. The dive parameters can be fed directly from a diver's monitoring system or simply typed in by the diving supervisor as in a normal diving log. The system allows a better control of the dive profile but also assists in computing deviations to the normal procedures such as altitude diving, nitrox diving, split level diving or repetitive diving. The system is now under evaluation on worksites. It benefits from the present interest of operational people to computer techniques and the large availability of personal laptops.**

## Introduction

Diving computers are good pieces of conversation. Their recognized advantages are

- they replace the old watch and depth gauge system,
- they eliminate the need for taking decision on the decompression.
- they allow fancy diving profiles with multi-levels, longer bottom times or repetitive dives.

Diving computers have invaded the recreational diving world but not the commercial one.

The limit to their progression is neither the tradition nor a narrow minded attitude towards computers. Commercial divers have already proved their capacity of adaptation and have integrated all sort of electronics, such as monitoring systems or dive recorders. However, when it comes to the decompression, they have their specific requirements. Most of the time, offshore divers

- don't use watches and depth gauges,
- don't take decision on tables,
- don't do fancy diving.

Although the way they dive is different, they understand that dive computers are convenient to use and thus may contribute to the overall safety. Comex attempted to define what could be the specifications of a commercial dive computer and presented a first tentative model, the DIVA system.

## Specific character of commercial diving operations

Commercial diving procedures have specific constraints that make the eventual use of a dive computer different. These constraints refer in this paper to the North Sea standards of diving and may differ from other professional diving activities, in other locations (Hardy 1988).

The first difference is the dive procedures. SCUBA diving is not considered as a professional method of intervention. What is associated with freedom and ease by recreational divers is regarded as unsafe practice by professional divers the gas supply is limited, there is no communication to conduct the job and no link with the surface in emergency. When it comes to surface diving, commercial divers use umbilicals and diving baskets. The umbilical provides an unlimited gas supply, communications, heating, video camera and a solid link in case of trouble. It also allows monitoring of depth and time. Even if the Rolex watch has become a status teller for offshore divers, they do not really need it. It is the supervisor who logs the different phases of the dive and monitors the depth using a pneumofathommeter. In commercial diving, the dive monitoring function is directed from surface and there is no need for any wrist gauge or indicator.

The second difference is the dive responsibilities. Commercial diving philosophy relies on the diving team organization. The basic assumption is that the responsibility of the dive is taken over by the diving supervisor. He is the one who monitors the diver's depth and time, selects the tables and controls the decompression stops. No initiative is left to the diver whose only responsibility is the conduct of the job. This philosophy implies that if any dive computer was proposed, it would have to be designed as a help to the supervisor.

The last difference comes from the tables. In some countries, like in France, the tables are published in the diving legislation and becomes statutory requirements. In others, because of the employer's liability, the diving company must use well referenced decompression procedures, such as the US Navy ones, to demonstrate that they do not expose their employees to any undue risk. In both cases, there is little flexibility in selecting the decompression schedules, which must belong to official or approved tables. The system does not allow for interpolations and extrapolations because each dive must be referenced to a printed document. The implication is that on-time calculation is not conceivable in commercial diving, because the principle is to look up in documents. A commercial dive computer should work from a databank, providing easy access to accepted protocols than a real time calculator.

## Specific needs of commercial diving

Monitoring systems have been developed for deep diving operations, others have been designed for the control of the saturation systems (Imbert et al. 1991). Although the basic structure of diving operations follows the "man in the loop" principle and never relies on electronics only, it is well recognized that computers could efficiently assist the conduct of the operations.

The first obvious advantage could be to save on the site documentation. Diving manuals usually come in large format and heavy binders and there is no way to reduce their thickness because the site requires documented procedures for a large span of situations air or mixed gas diving, surface supplied or bell diving tables, normal or emergency situations, ... It is recognized that the hundred of decompression schedules printed could be easily stored on a 3" disk, saving both the rain forest recession and the supervisors' complaints.

Another potential interest would be the efficient determination of the dive conditions. Computer can be easily interconnected and it makes sense establishing a link between a diver's monitoring system and a decompression monitoring system. However, it must be admitted that a monitoring system is quite an expensive equipment to buy and maintain. Its use is restricted to large projects or permanent installations such as DSV (and DSV don't do much air diving operations). Therefore, the practical implication of such combined systems is expected to remain limited, except perhaps for diving equipment with built in monitoring functions (Lemasson Y. and J.C. Le Péchon 1991).

The important application of dive computer could be the accurate selection and control of the decompression schedule. A survey performed on Comex dive reports has shown that many mistakes are made in subtracting the time of descent to the time of ascent, to calculate the divers' bottom time (around 1%). There, a computer would give 100% reliability. More rarely but still a problem, errors are made in the selection of the correct schedule (stops time are read on the wrong line or deep stop are forgotten). These are inherent drawbacks of document reading that could be eliminated when done by a computer.

The last possible application could be the calculations required for the adaptation of the procedures. This includes the determination of equivalent depths or bottom times for nitrox diving, altitude diving or mud diving. It also includes new procedures for the determination of multilevels diving decompressions that have become frequently used for inspections works. In addition, the system could provide assistance on a variety of calculations such as gas mixing, partial pressure, percentage, units conversion.

## Development of the DIVA project

The idea behind the Comex DIVA project was that a dive computer would minimize the human factors and thus improve the overall safety of the offshore operations. It also would save time and help the diving supervisor in his task. The system was defined with the following specifications.

- The first problem was to chose a support.

Commercial divers spend long standby periods on sites and many fancy computers as a hobby. It has now become usual to see a portable computer in a dive control room. The supervisors run word processor softwares for writing their reports, or a series of home made programmes, which they use to manage the gas stocks or the helmets maintenance programme. It is a new fact, but computers are well spread on sites and the people have learnt how to use them. These personal computers were chosen as the frame for the development of DIVA, which imposed strict limitations on the hardware (low speed 286 processor, small memory and available disk space, no mouse).

- The second problem was to define the ergonomy.

We know by experience that the man/machine interfaces are critical for the users' acceptance. For one thing, DIVA was constructed with nice colorful screens. Then, because the end users were suspected not to be very keen in reading a manual, all the documentation was built in the software. Finally, all the inputs were designed to minimize typing. A lot of information became available as select menu or "F key" functions.

- The last problem was to define the procedures to include in the system.

Fortunately, the DIVA project came along with the publication of the new French diving legislation (Décret du 28 Mars 1990) that contains a complete set of diving instructions and tables. These official procedures were integrated into the system files and provide air diving as well as mixed gas diving instructions that can be used without any commercial reference or liability.

The technical difficulties related to these dive computer specifications made the delight of smart young computer engineers who finally came out with the adequate prototype, which includes a blend of database, optimization techniques and expert system technologies.

This validation process or "Beta test" was handed over to Comex operational personnel. The system has been sent to Comex worksites in June 1992 for evaluation and up to now has received a warm welcome. The system is expected to be operational and become commercially available next year.

## Conclusion

After conducting the exercise of defining the pro's and con's of dive computers and their possible application to commercial diving, the answer came as a system quite different from the ones used in recreational diving. This system does put the emphasis on the monitoring of the dive profile nor the selection and computation of the decompression. It is adapted to the structure of professional diving which is based of a one man in charge at surface of all the operations. Because of the heavy responsibilities of this man, diving computers can assist him efficiently and are expected to develop. They will never take any decision or be given the function of the automatic conduct of the dive. Their role will be mainly to provide information, assist in selection and control of procedures. However, doing this, they will relieve the supervisor from minor tasks that require attention and allow him to concentrate on the overall progress of the dive, thus improving safety.

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[1] Comex Services, Marseille, France.

Decompression Tables for Tolerable Oversaturatin 0.4 bar

# No-Bubbles - Decompression Tables

M. Hahn, J. Wendling

## Introduction

The bubbles appear, as we know from doppler monitoring of divers, even after uneventful dives following the usual decompression tables. The number of bubbles is proportional to the decompression stress at the end of the dive. This means that even after no-decompression dives a large number of bubbles may appear while after a longer dive needing a decompression stop bubbles can be almost absent when the ascent was very slow and exceeding decompression stops have been performed. There is a consensus among specialists that the most dangerous symptoms of decompression sickness, namely the cerebral symptoms arise from embolic bubbles. These embolic bubbles may get into arteries through different pathways, one of which is possibly the one through an open foramen ovale.

The way of bubble development, growth and transport has been studied by many research teams. During the UHMS workshop on the physiological basis of decompression (ed R.D. Vann, 1989) there was a quasi-consensus that threshold over-saturation for bubble release to the circulation would be about 1.4 which means 40% over-saturation (thermodynamically speaking ). So we wanted to test whether diving tables specially calculated on the basis of a reduced threshold will still be useful for sports diving.

## Rationale:

On the basis of three highly debated hypotheses we decided to calculate a set of tables which should on a theoretical basis permit the divers to dive without producing circulating bubbles during and after decompression.

1. The patent foramen ovale is a haemodynamically possible way of bubble shunting from the right to the left side of the heart thus by passing the lung filter. The importance of this frequently found anatomic variation (30%) is not yet clear, however it remains a possible way to explain neurological decompression sickness after correctly performed dives. If we have diving tables which would guarantee that there are no circulating bubbles after decompression or during the decompression phase the presence of a PFO would not be an argument any more to declare a diver unfit to dive.

2. The presence of a gas phase within the circulation in form micro-bubbles does influence the gas washout of the body after a compression phase. This is a main criticism against the value of the perfusion limited decompression model used by Haldane, Workman, Dwyer and Bühlmann for the calculation of diving tables. If we calculate the tables in a way that there are not even silent bubbles in the circulation, the algorithm would be much closer to reality and thus more credible.

3. The fact that the majority of decompression disorders are seen in divers that have performed an uneventful dive following the accepted tables, means that the susceptibility is very difficult to determine from known values (see probabilistic approach). The main factor inducing an unforeseeable variable in the physiology of the diver is probably the presence distribution and migration of micro-bubbles. Avoiding the presence of micro-bubbles in the circulation the remaining susceptibility of diving individuals would be much more homogeneous.

## The tables:

The following tables are calculated using a software for implementation of the 16 tissue model of Bühlmann 1986. The parameters are modified corresponding to a tolerable over-saturation of 0.4 bar. The calculations are done on the assumptions of

- altitude 0 m, breathing gas: air, respiratory minute volume 20 l/min, ascent velocity 10 m/min.

## Decompression Table for Tolerable Oversaturation 0.4 bar

| Depth (m) | Bottom time (min) | Decompression stops (min) (m) | | | | | | | | | Asc. Time (min) | Air-Cons. ($m^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 27 | 24 | 21 | 18 | 15 | 12 | 9 | 6 | 3 | | |
| 9.0 | | | | | | | | | | | | |
| | 25.0 | | | | | | | | | | 0.90 | 0.98 |
| | 50.0 | | | | | | | | | 1 | 1.90 | 1.96 |
| | 75.0 | | | | | | | | | 1 | 1.90 | 2.92 |
| | 100.0 | | | | | | | | | 2 | 2.90 | 3.90 |
| 12.0 | | | | | | | | | | | | |
| | 18.0 | | | | | | | | | 3 | 4.20 | 0.91 |
| | 36.0 | | | | | | | | | 5 | 6.20 | 1.76 |
| | 54.0 | | | | | | | | | 8 | 9.20 | 2.63 |
| | 72.0 | | | | | | | | | 11 | 12.20 | 3.51 |
| | 90.0 | | | | | | | | | 14 | 15.20 | 4.38 |
| 15.0 | | | | | | | | | | | | |
| | 16.0 | | | | | | | | | 5 | 6.50 | 0.98 |
| | 32.0 | | | | | | | | 3 | 8 | 12.50 | 1.96 |
| | 48.0 | | | | | | | | 4 | 12 | 17.50 | 2.90 |
| | 64.0 | | | | | | | | 6 | 16 | 23.50 | 3.87 |
| | 80.0 | | | | | | | | 7 | 21 | 29.50 | 4.84 |
| 18.0 | | | | | | | | | | | | |
| | 10.0 | | | | | | | | | 4 | 5.80 | 0.72 |
| | 20.0 | | | | | | | | 4 | 7 | 12.80 | 1.50 |
| | 30.0 | | | | | | | 1 | 6 | 10 | 18.80 | 2.24 |
| | 40.0 | | | | | | | 2 | 7 | 14 | 24.80 | 2.98 |
| | 50.0 | | | | | | | 2 | 9 | 17 | 29.80 | 3.68 |
| | 60.0 | | | | | | | 3 | 11 | 20 | 35.80 | 4.43 |
| | 70.0 | | | | | | | 4 | 12 | 24 | 41.80 | 5.17 |
| | 80.0 | | | | | | | 4 | 14 | 27 | 46.80 | 5.87 |
| 21.0 | | | | | | | | | | | | |
| | 6.0 | | | | | | | | | 3 | 5.10 | 0.52 |
| | 12.0 | | | | | | | | 4 | 5 | 11.10 | 1.08 |
| | 18.0 | | | | | | | 2 | 4 | 8 | 16.10 | 1.61 |
| | 24.0 | | | | | | | 3 | 6 | 10 | 21.10 | 2.14 |
| | 30.0 | | | | | | | 4 | 7 | 13 | 26.10 | 2.66 |
| | 36.0 | | | | | | 1 | 4 | 9 | 15 | 31.10 | 3.20 |
| | 42.0 | | | | | | 1 | 5 | 10 | 18 | 36.10 | 3.72 |
| | 48.0 | | | | | | 1 | 6 | 12 | 20 | 41.10 | 4.25 |
| | 54.0 | | | | | | 1 | 7 | 13 | 23 | 46.10 | 4.77 |
| | 60.0 | | | | | | 1 | 8 | 14 | 25 | 50.10 | 5.27 |
| 24.0 | | | | | | | | | | | | |
| | 5.0 | | | | | | | | | 3 | 5.40 | 0.51 |
| | 10.0 | | | | | | | | 4 | 5 | 11.40 | 1.03 |
| | 15.0 | | | | | | | 3 | 5 | 7 | 17.40 | 1.57 |
| | 20.0 | | | | | | 1 | 4 | 6 | 10 | 23.40 | 2.11 |
| | 25.0 | | | | | | 2 | 5 | 7 | 13 | 29.40 | 2.64 |
| | 30.0 | | | | | | 3 | 5 | 9 | 15 | 34.40 | 3.15 |
| | 35.0 | | | | | | 3 | 6 | 11 | 18 | 40.40 | 3.67 |
| | 40.0 | | | | | | 4 | 7 | 12 | 21 | 46.40 | 4.20 |
| | 45.0 | | | | | | 5 | 8 | 13 | 24 | 52.40 | 4.74 |
| | 50.0 | | | | | | 5 | 9 | 15 | 25 | 56.40 | 5.21 |
| | 55.0 | | | | | | 6 | 9 | 17 | 28 | 62.40 | 5.74 |

## Decompression Tables for Tolerable Oversaturatin 0.4 bar

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 27.0 | | | | | | | | | | | | |
| | 5.0 | | | | | | | | | 5 | 7.70 | 0.61 |
| | 10.0 | | | | | | | 2 | 4 | 6 | 14.70 | 1.21 |
| | 15.0 | | | | | | 2 | 4 | 5 | 9 | 22.70 | 1.86 |
| | 20.0 | | | | | | 3 | 5 | 7 | 12 | 29.70 | 2.46 |
| | 25.0 | | | | | 1 | 4 | 5 | 9 | 15 | 36.70 | 3.07 |
| | 30.0 | | | | | 2 | 4 | 7 | 10 | 19 | 44.70 | 3.70 |
| | 35.0 | | | | | 2 | 5 | 8 | 12 | 22 | 51.70 | 4.30 |
| | 40.0 | | | | | 3 | 5 | 9 | 14 | 25 | 58.70 | 4.90 |
| | 45.0 | | | | | 3 | 6 | 10 | 16 | 28 | 65.70 | 5.50 |
| | 50.0 | | | | | 3 | 7 | 11 | 18 | 31 | 72.70 | 6.10 |
| 30.0 | | | | | | | | | | | | |
| | 6.0 | | | | | | | | 4 | 4 | 11.00 | 0.84 |
| | 10.0 | | | | | | 1 | 3 | 4 | 7 | 18.00 | 1.40 |
| | 14.0 | | | | | | 3 | 4 | 6 | 10 | 26.00 | 1.99 |
| | 18.0 | | | | | 2 | 3 | 5 | 7 | 13 | 33.00 | 2.56 |
| | 22.0 | | | | | 3 | 4 | 5 | 10 | 16 | 41.00 | 3.15 |
| | 26.0 | | | | 1 | 3 | 4 | 7 | 11 | 19 | 48.00 | 3.72 |
| | 30.0 | | | | 1 | 3 | 5 | 8 | 13 | 22 | 55.00 | 4.27 |
| | 33.0 | | | | 1 | 4 | 5 | 9 | 14 | 24 | 60.00 | 4.68 |
| | 36.0 | | | | 1 | 4 | 6 | 10 | 15 | 26 | 65.00 | 5.09 |
| | 39.0 | | | | 1 | 5 | 6 | 10 | 17 | 28 | 70.00 | 5.50 |
| | 42.0 | | | | 2 | 4 | 7 | 12 | 17 | 31 | 76.00 | 5.94 |
| 33.0 | | | | | | | | | | | | |
| | 6.0 | | | | | | | 1 | 4 | 5 | 13.30 | 0.96 |
| | 10.0 | | | | | | 2 | 4 | 5 | 8 | 22.30 | 1.62 |
| | 14.0 | | | | | 2 | 3 | 4 | 7 | 12 | 31.30 | 2.28 |
| | 18.0 | | | | 1 | 3 | 4 | 5 | 9 | 15 | 40.30 | 2.96 |
| | 21.0 | | | | 2 | 3 | 4 | 7 | 10 | 18 | 47.30 | 3.46 |
| | 24.0 | | | | 2 | 3 | 5 | 8 | 11 | 20 | 52.30 | 3.89 |
| | 27.0 | | | | 3 | 3 | 6 | 8 | 13 | 23 | 59.30 | 4.39 |
| | 30.0 | | | | 3 | 4 | 6 | 10 | 14 | 25 | 65.30 | 4.86 |
| | 33.0 | | | | 3 | 5 | 7 | 10 | 16 | 28 | 72.30 | 5.36 |
| | 36.0 | | | 1 | 3 | 5 | 7 | 12 | 17 | 31 | 79.30 | 5.87 |
| 36.0 | | | | | | | | | | | | |
| | 6.0 | | | | | | | 3 | 4 | 5 | 15.60 | 1.10 |
| | 10.0 | | | | | 1 | 3 | 4 | 5 | 10 | 26.60 | 1.85 |
| | 14.0 | | | | 1 | 3 | 3 | 5 | 8 | 13 | 36.60 | 2.59 |
| | 18.0 | | | | 3 | 3 | 4 | 6 | 11 | 17 | 47.60 | 3.36 |
| | 21.0 | | | 1 | 3 | 3 | 5 | 8 | 12 | 20 | 55.60 | 3.93 |
| | 24.0 | | | 1 | 3 | 4 | 6 | 8 | 14 | 23 | 62.60 | 4.44 |
| | 27.0 | | | 2 | 3 | 4 | 7 | 10 | 15 | 26 | 70.60 | 5.02 |
| | 30.0 | | | 2 | 3 | 5 | 7 | 11 | 17 | 29 | 77.60 | 5.52 |
| | 33.0 | | | 2 | 4 | 5 | 8 | 12 | 18 | 32 | 84.60 | 6.05 |
| 39.0 | | | | | | | | | | | | |
| | 6.0 | | | | | | 1 | 3 | 4 | 6 | 17.90 | 1.23 |
| | 10.0 | | | | | 2 | 4 | 4 | 6 | 11 | 30.90 | 2.09 |
| | 14.0 | | | | 2 | 3 | 4 | 6 | 8 | 15 | 41.90 | 2.89 |
| | 18.0 | | | 2 | 2 | 4 | 5 | 7 | 12 | 19 | 54.90 | 3.78 |
| | 21.0 | | | 2 | 3 | 4 | 6 | 8 | 14 | 23 | 63.90 | 4.38 |
| | 24.0 | | 1 | 2 | 3 | 5 | 7 | 9 | 16 | 26 | 72.90 | 5.02 |
| | 26.0 | | 1 | 3 | 3 | 5 | 7 | 11 | 17 | 29 | 79.90 | 5.47 |
| | 28.0 | | 1 | 3 | 4 | 5 | 8 | 12 | 18 | 31 | 85.90 | 5.89 |

### Decompression Table for Tolerable Oversaturation 0.4 bar

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 42.0 | | | | | | | | | | | | |
| | 6.0 | | | | | | 2 | 4 | 4 | 7 | 21.20 | 1.40 |
| | 9.0 | | | | | 3 | 3 | 4 | 6 | 11 | 31.20 | 2.08 |
| | 12.0 | | | | 3 | 3 | 3 | 6 | 8 | 15 | 42.20 | 2.81 |
| | 15.0 | | | 2 | 3 | 3 | 5 | 7 | 10 | 19 | 53.20 | 3.54 |
| | 18.0 | | 1 | 2 | 3 | 4 | 5 | 9 | 13 | 22 | 63.20 | 4.22 |
| | 20.0 | | 1 | 3 | 3 | 4 | 7 | 9 | 14 | 25 | 70.20 | 4.69 |
| | 22.0 | | 2 | 2 | 4 | 5 | 7 | 10 | 16 | 27 | 77.20 | 5.17 |
| | 24.0 | | 2 | 3 | 4 | 5 | 7 | 12 | 17 | 30 | 84.20 | 5.63 |
| 45.0 | | | | | | | | | | | | |
| | 6.0 | | | | | | 3 | 4 | 4 | 8 | 23.50 | 1.53 |
| | 8.0 | | | | | 3 | 3 | 4 | 6 | 11 | 31.50 | 2.05 |
| | 10.0 | | | | 2 | 3 | 4 | 5 | 8 | 14 | 40.50 | 2.61 |
| | 12.0 | | | 2 | 2 | 3 | 4 | 6 | 10 | 16 | 47.50 | 3.11 |
| | 14.0 | | | 3 | 3 | 3 | 5 | 7 | 11 | 20 | 56.50 | 3.67 |
| | 16.0 | | 1 | 3 | 3 | 4 | 5 | 9 | 13 | 22 | 64.50 | 4.20 |
| | 18.0 | | 2 | 3 | 3 | 4 | 7 | 9 | 14 | 25 | 71.50 | 4.69 |
| | 20.0 | 1 | 2 | 3 | 3 | 5 | 7 | 10 | 17 | 28 | 80.50 | 5.25 |
| | 22.0 | 1 | 2 | 3 | 4 | 5 | 8 | 12 | 17 | 31 | 87.50 | 5.72 |
| 48.0 | | | | | | | | | | | | |
| | 6.0 | | | | | 2 | 3 | 3 | 6 | 9 | 27.80 | 1.75 |
| | 8.0 | | | | 2 | 3 | 3 | 4 | 7 | 12 | 35.80 | 2.30 |
| | 10.0 | | | 1 | 3 | 3 | 4 | 5 | 9 | 15 | 44.80 | 2.87 |
| | 12.0 | | | 3 | 3 | 3 | 5 | 7 | 10 | 19 | 54.80 | 3.49 |
| | 14.0 | | 2 | 2 | 3 | 4 | 5 | 8 | 13 | 21 | 62.80 | 4.03 |
| | 16.0 | 1 | 2 | 3 | 3 | 4 | 7 | 9 | 14 | 25 | 72.80 | 4.66 |
| | 18.0 | 1 | 3 | 2 | 4 | 5 | 7 | 10 | 17 | 27 | 80.80 | 5.20 |
| | 20.0 | 2 | 2 | 3 | 4 | 6 | 8 | 11 | 18 | 31 | 89.80 | 5.77 |

Figure 1 to 3 give examples of dives, that can be performed realistically using a 15 liters compressed air cylinder (2 + 3) or a double 10 liter tank (fig 1). One should avoid to speak of no-decompression time in these tables, because a staged decompression is the most important element of avoiding the bubbles in the circulation, which should be combined with a very slow ascent rate. The tables printed here are calculations on the basis of theoretical considerations. They have not undergone any validation with test-dives and should not be used by divers as such.

If we try to further reduce the threshold value to 1.0 which means that we allow the tissue $N_2$ concentration not to be more than 100 % saturation, the calculated diving profile is not realistic any more (fig 4).

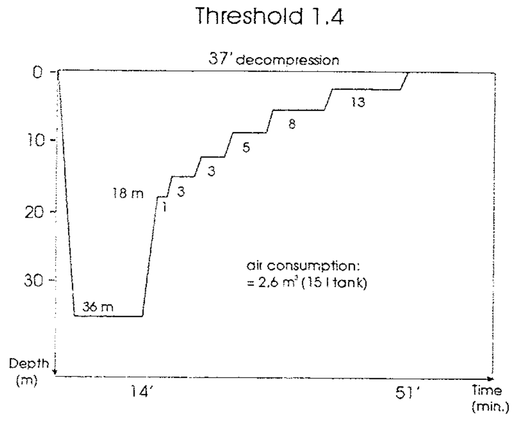

*Fig. 1*

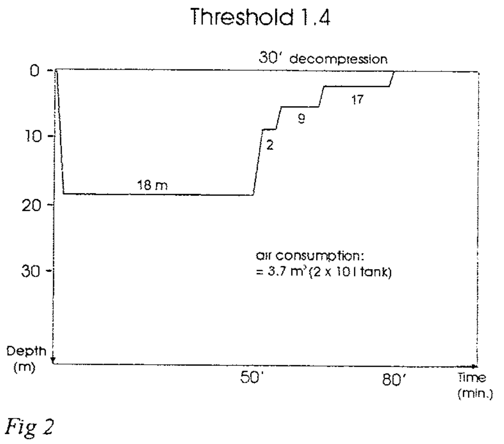

*Fig 2*

**Decompression Tables for Tolerable Oversaturatin 0.4 bar**

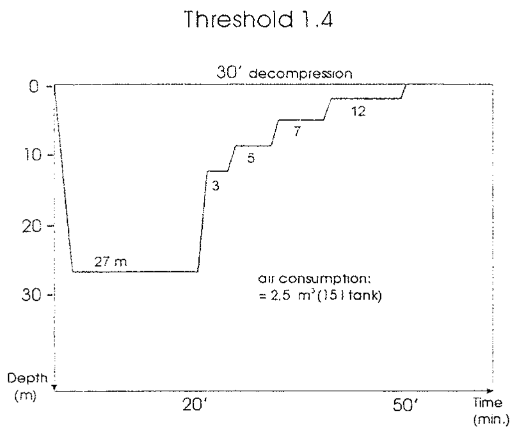

*Fig. 3*

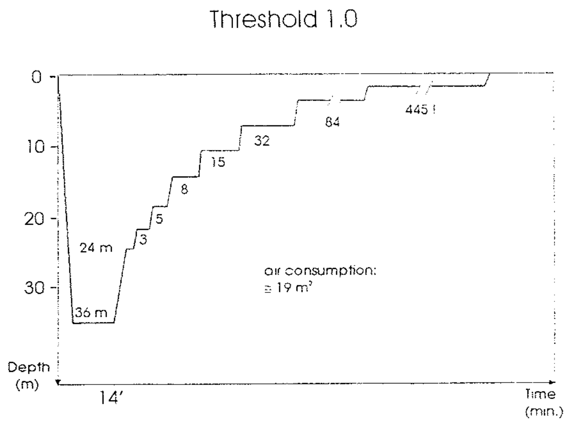

*Fig. 4 Theoretical dive profile for threshold 1.0*

## Discussion

- Tables produced for a threshold of 1.4 clearly show that recreational diving is still possible within the usual depth range and overall diving time.

- The profiles however become a more V-shaped form compared to the classical rectangular dive profile which is normally used.

- The dives become constringently decompression-dives. For many divers this might be a problem because of incompatibility with the dogma that only no-decompression-dives are safe. Of course it is reasonable not to enter into the deco-zone of the tables in sports diving as this avoids problems like getting short in air and being hit by inert gas narcosis doing deep dives. It is however wrong to believe that zero stop dives are particularly safe as to the DCI risk. Sometimes the opposite is true. The deco stress during the ascent and after the dive is reduced by a very slow ascent rate and doing deeper deco stops than normally.

- We propose therefore that research is done to study the bubble development or hopefully absence in dives performed following the 1.4 threshold table. It is possible that the threshold will have to be further reduced to avoid bubble formation, but if validated the modified tables could be a solution for safe diving in divers with individually higher risk for DCI.

## References

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