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STATISTICALLY BASED DECOMPRESSION TABLES

I. ANALYSIS OF STANDARD AIR DIVES: 1950-1970

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A large number of air dives was examined by a new methodology. Several essentially empirical models of decompression risk were considered that predicted the probability of decompression sickness (DCS) for a given pressure exposure to avoid the infinitely sharp threshold parameters that have characterized previous calculation of decompression tables. The candidate models used several distinct formulations of tissue gas exchange kinetics and summed tissue overpressures that are calculated during the dive to estimate decompression risk. The models were compared to decompression outcome data using the statistical principle of maximum likelihood.

Reported decompression trials from American, British, and Canadian Naval laboratories were examined individually and collectively to evaluate the probabilistic models and their parameters. Only two to five parameters were found to be justified by the available data (more than 1,700 individual exposures were considered). Diving data from various sources were only partially compatible; some of the discrepancy may arise from an evolution of

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diagnostic criteria over several decades. Predictions were made of the outcome for additional reported diving series, and they were only partly successful. The models were then used to estimate decompression risk for current USN air diving with a finding of a wide range of hazard. Specifically, it appears that short dives are quite safe, even to a moderately deep depth, while long exposures are very risky regardless of depth. These findings will be used to produce a set of standard air tables with a uniform and low level of DCS risk. Subsequent work will extend this approach to provide a single model for many forms of diving, thus allowing a new range of operational flexibility.

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BACKGROUND

Procedures for the safe decompression of air breathing divers have existed in many forms throughout this century. The first generally accepted set of decompression tables resulted from a study conducted by J.B.S. Haldane under commission by the Royal Navy (Boycott, Damant, and Haldane, 1908). Haldane performed a number of experiments on goats and humans, and combined his interpretation of these results with a then plausible set of assumptions that established ascent criteria for decompression. After making the initial assumption that decompression sickness (DCS) is due to excessive inert gas, Haldane argued that gas exchange is due to a constant fractional rate of exchange for each passage of gas through the lungs. The constant fraction led immediately to a single exponential term for exchange kinetics. No direct experiments on kinetics were performed, but the goats were observed to experience a roughly constant incidence of DCS after several hours of pressure exposure. This maximum time was extended slightly using arguments of human-goat relative metabolic rates, and then the maximum time was divided into five exponential half-times to allow for a spectrum of exchange rates for calculations. It appeared from these calculations that both men and goats did not suffer DCS if the ratio of calculated total internal gas tension did not exceed twice the ambient pressure. This combined "model" of five exponential components and a 2:1 rule for ascent were the basis of the Haldane Tables subsequently adopted for use by the Royal Navy. After a short trial by Stillson (1915), they were adopted for US Navy use.

The first US modification to the tables seemed to be driven by a theoretical point. A 1935 report by Hawkins, Shilling, and Hansen pointed out that a large number of empirically controlled decompressions that simulated submarine escape appeared safe under conditions that were prohibited by the

Haldane approach. (Specifically, they concluded that more than a 2:1 ascent ratio was allowed by theoretical tissues of 5 and 10 min half-times). The report (1935) proposed a revised calculation method to relax the original set of assumptions. The modification dropped the two fastest half-times of Haldane but inserted a number of depth and time dependent rules in lieu of the simpler 2:1 ascent criterion. A set of tables was revised accordingly by Yarborough in 1937. In 1951, a study of no-decompression dives reported as part of a larger surface decompression study (Van der Aue et al.) supported the growing suspicion that long dives were not sufficiently safe. A major revision and test series in 1956 (des Granges) produced the current set of air tables; the number of exponential half-times were increased to six and the ascent criteria (a set of ratios) were increased to several dozen. That very laborious exercise required five iterations of human testing and rule revision before an acceptable outcome was declared.

An extrapolation of the final rules to slightly longer dives produced the current Exceptional Exposure Tables, which had a high incidence of DCS even after five additional iterations of testing (Workman, 1957). A similar history could be described for other forms of decompression tables as well. The present U.S. Navy Diving Manual has several sets of tables for various operating environments that were calculated by methods similar to those just described (Workman, 1965). The final parameters ("surfacing rules") of the various studies are incompatible, and extrapolation from one set does not produce a reasonable approximation to any other condition. The failure of this extrapolation is not surprising as there is no model, in the mathematical sense of the word, involved. For example, in the tests of the current air tables (des Granges, 1956), the number of parameters finally used exceeded the number of cases of DCS encountered during the modification of the parameters.

This behavior is equivalent to "negative degrees of freedom" where one derives more constants than he has data. The tables in their present form do have a degree of safety, though probably not a well known or uniform degree (Berghage and Durman, 1980). They are a tribute to a lengthy trial-and-error effort and numerous dangerous trials. Modern scientific methods and statistical evaluation have yet to be applied to Navy decompression tables.

Current physiological and engineering analyses use models in a different way. The model sought is a concise mathematical description of the process under study that maintains only the important features of the process and whose parameters are justified statistically by fitting to appropriate data. By this definition, decompression tables presently used did not arise from models because the large number of half-times and decompressions rules are neither concise nor obtained in a statistically meaningful way. We have begun to apply models by the mathematical definition to the decompression problem. The first application addressed saturation-excursion dives with helium-oxygen of unlimited duration where relative safety could be defined only in terms of pressures with no explicit treatment of time (Weathersby, Homer, and Flynn, 1984). For all subsaturation dives, the models must explicitly include time functions.

MODELS

Typically, in decompression trials a schedule may produce one or more cases of DCS on any given day. The same schedule, however, will not necessarily produce the bends in another set of divers on that day or in the same divers on a different day. Thus, variability of outcome is well known and should be a feature of any model. Incorporation of variability can be assured by asserting that the <u>probability</u> of DCS is associated with a given profile, rather than that a given procedure is either completely safe or completely unsafe:

$$p(DCS) = \underline{f}(\text{Pressure, Time,...,Parameters}) \qquad [1]$$

This report concerns how a class of models, that is, a set of functions, $\underline{f}$, in Eqn. 1, can be applied to air diving. The process of applying probabilistic models to decompression data was developed by Weathersby, Homer, and Flynn (1984). Briefly, the function of Eqn. 1 is used to predict p(DCS) for any dive in which the detailed profile is known. The prediction is then used directly if the dive resulted in DCS, or is used in Eqn. 2 if we know that the dive was safe:

$$p(\text{no DCS}) = 1.0 - p(DCS) \qquad [2]$$

In either case, one predicts the actual outcome of the known dive profile. The process is repeated for each tabulated actual dive (hundreds or thousands are needed in practice). The overall success of the model is the total probability of all the known outcomes. Assuming that the results of each dive are independent, the overall probability is called the likelihood function:

$$L = p(\text{dive 1}) \cdot p(\text{dive 2}) \cdot p(\text{dive 3})... \qquad [3]$$

For the most satisfactory model, the likelihood function should be at a maximum (Kendall and Stuart, 1979). Accordingly, parameters are estimated by changing the parameters of the model until further increases in likelihood are impossible. Further presentation of this approach and some simple examples are found in work by Weathersby, Homer, and Flynn (1984).

In this report, all models will be of the class called "risk models" taken from the previous report of Weathersby, Homer, and Flynn (1984). The term "hazard function" is used in other applications (Kalbfleisch and Prentice, 1980). For these, the decompression dose-response function is provided by:

$$p(DCS) = 1.0 - \exp(-\int r\, dt) \qquad [4]$$

where r is one of several measures of instantaneous risk that is integrated over the course of dive and postdive periods. The approach of integrating risk over the course of an entire decompression differs fundamentally from the traditional practice of seeking to avoid a specific critical point (e.g., the Haldane 2:1 rule) at every instant during the decompression. The present approach embodies the assumption that a given decompression stress, r, is more likely to produce decompression symptoms if it is sustained longer. It also means that a large number of distinct decompressions from the same dive may result, after integration, in the same probability of DCS.

For this analysis, the form of r in Eqn. 4 will be essentially empirical, that is, we will not invoke specific mechanisms of bubble formation, number, volume, growth, etc. Rather the forms used will be mathematically convenient. Ptis, a computed tissue inert gas partial pressure, will be compared to Pamb, the current ambient pressure. As is common in decompression calculations, the metabolic gases O_2 and CO_2 and water vapor will be ignored totally. Whenever Ptis is less than Pamb, r will be set to zero, in keeping with the notion that DCS is somehow precipitated by a supersaturation of inert gas. This model is expressed as:

Model 1: $r_1 = A\,(\text{Ptis} - \text{Pamb})/\text{Pamb}$

Ptis by monoexponential; time constant = T [5]

2 parameters: A, T

The risk here is simply proportional to the supersaturation with a proportionality parameter A in units of min^{-1} (T is in min). Ptis is calculated by treating the tissue as a single, well mixed compartment. Details of this treatment are in Appendix 1. The appearance of Pamb in the denominator follows from our previous work with saturation-excursion data in which a significant decrease of DCS risk occurred if an equal supersaturation was created at a deeper depth (Weathersby, Homer, and Flynn, 1984). This denominator will be used in all of the present models, even though it has not been shown statistically as necessary for air diving. The data used in this report have most of the decompression near surface pressure, so we do not expect that the effect will be important, whether included or not. Not enough data were found on air saturation-excursion diving for an equivalent study to that of Weathersby, Homer, and Flynn (1984). The next model adds a threshold parameter, PTHR, that allows the possibility of a supersaturation that can be sustained indefinitely without the risk of DCS:

Model 2: r_2 = A (Ptis - Pamb - PTHR) / Pamb

Ptis by monoexponential; time constant = T [6]

3 parameters: A, T, PTHR

PTHR is a constant parameter independent of depth. Again, only positive values of the numerator will be allowed in the integration of Eqn. 4.

Model 1 can be generalized to include a "second tissue" that has its own time constant and proportionality parameter. The statistical sense of this model is that no·DCS is the joint probability of no DCS in both tissues. No anatomic identification of the second (or indeed the first) tissue is attempted, and most data provide insufficient information on location of bends symptoms to justify the search. Such a model parallels the development of a large number of tissue half-times in the post-Haldane evolution of decompression schedules. This model is expressed as:

Model 3: $r_3 = r_{3A} + r_{3B}$, where

r_{3A} = AA (PtisA - Pamb) / Pamb

PtisA by monoexponential; time constant = TA

r_{3B} = AB (PtisB - Pamb) / Pamb

PtisB by monoexponential; time constant = TB [7]

4 parameters: AA, TA, AB, TB

This "two tissue" model can also have an added threshold parameter:

Model 4: $r_4 = r_{4A} + r_{4B}$, where

r_{4A} = AA (PtisA - Pamb - PTHR) / Pamb

PtisA by monoexponential; time constant = TA

r_{4B} = AB (PtisB - Pamb - PTHR) / Pamb

PtisB by monoexponential; time constant = TB [8]

5 parameters: AA, TA, AB, TB, PTHR

As an alternative to the "two tissue" model, it is possible to use more complex gas exchange kinetics in a single tissue. Through our experiments on the kinetics of an inert gas in numerous dog tissues, we found that although a single exponential cannot describe real dog tissues over more than a tenfold range in concentration, most data were well described by an empirical two exponential gas residence time function (rtf) (Weathersby et al., 1979; Weathersby et al., 1981). The rtf is a multiexponential description of gas exchange in a single tissue that has three kinetic parameters rather than one of a single exponential. Details of this gas exchange function can be found in the two references cited directly above and in Appendix 1. This model is expressed as:

Model 5: r_5 = A (Ptis - Pamb) / Pamb

Ptis by 2 exponentials; time constants = T1 and T2

Fraction of rtf by T1 is W1;

Fraction of rtf by T2 is 1 - W1 [9]

4 parameters: A, T1, T2, W1

To parallel the previous developments, a threshold parameter can also be defined for the two exponential exchange model:

Model 6: $r_6 = A (Ptis - Pamb - PTHR) / Pamb$

Ptis by 2 exponentials; time constants = T1 and T2

Fraction of rtf by T1 is W1;

Fraction of rtf by T2 is 1 - W1 [10]

5 parameters: A, T1, T2, W1, PTHR

All six models were used to explore various data sets.

DECOMPRESSION DATA

Data were needed to evaluate the two to five adjustable parameters of the models. The eventual goal is a model with a reasonable number of parameters that could be applied to any type of pressure exposure. For present purposes, however, only "standard" air dives were chosen. These dives were single pressure exposures, with a breathing mixture of compressed air used at all times and a single monotonic decompression. Ideally, they would have all been performed under similar conditions as effects of temperature, exercise, recent diving history, body composition, and other possibly important effects were not considered by the models. As a further requirement, all should have had the same diagnostic criteria applied to DCS outcome. This was a problem because minor symptoms are so highly subjective, and standards of diagnosis may have placed more emphasis on less severe symptoms in recent times.

Although standards of diagnosis are rarely discussed explicitly in reports of diving trials, there are some indications of possible changes. Some mild cases that would be classified as decompression sickness today are not described as such in earlier reports. For example, a 1957 British trial reported only seven cases of decompression sickness but 14 mild cases are also noted in the detailed tables, including two arm "aches" (Crocker, 1957). These two cases were classified as decompression sickness for analysis in the present report. Another retrospective diagnosis was made in Data Set C for a subject in submarine escape trials who developed what was termed a migraine headache 1.5 h postdive. He had no previous history of migraine headaches (Barnard and Eaton, 1964). Other data sets analyzed in this report had sufficient information to permit similar reclassification of postdive incidents, but when less details are available, suspicion arises that some mild cases of decompression sickness may have gone unreported.

The data sets used are summarized in Appendix II. The first (Data Set A) consists of a series of dives used to validate the present USN Standard Air Tables (des Granges, 1956). Any inconsistencies noted in that report were resolved by checking the original diving logs at the NEDU library. A total of 568 exposures were conducted using 88 different schedules and 27 cases of DCS resulted from this series. All dives were conducted with wet, working divers. The diagnostic criteria were not fully specified, but examination of the accident reports from that period indicated that the DCS cases were of a relatively serious variety. It appeared that no record was kept of those cases with marginal symptoms who did not receive recompression therapy. It should be noted that because these dives were performed for an acceptance test, they were thought to be of nearly equivalent severity at the time.

The second data set (Data Set B) consisted of the dives used to test the Exceptional Exposure Tables currently in the USN Diving Manual (Workman, 1957). In this dive series, 46 exposures were performed with 10 schedules, each schedule resulting in at least one case of DCS. These dives were long exposures: 1.5-6 h in a dry chamber. The report tabulated 13 cases of bends and nine cases of minor bends, along with a short case summary of all dives. Of the minor bends cases described, all but one involved pain in a specific joint that persisted for up to several days in the absence of recompression therapy. We considered these joint pains as DCS in our data evaluation because by current standards these men would have all received recompression therapy.

At the other extreme of air decompression, we also examined the total UK human trials of submarine escape from 1945-1970 (Donald, 1970). In these trials (Data Set C), subjects were compressed rapidly to depths up to 625 ft and then decompressed rapidly (total pressure exposure 0.8 to 4 min). The recorded timing of the pressure exposures in this dive series was to 0.01 min, as opposed to 0.1 min in the Experimental Diving Unit data and 1.0 in the data from the Defence and Civil Institute of Environmental Medicine (DCIEM) (below). As taken from a summary publication (Donald, 1970), with a few necessary corrections made by consulting a source document (Barnard and Eaton, 1964), 299 trials were reported with a total of four cases of DCS. The cases were distributed across 46 schedules and did not occur under the most extreme conditions, so the data were only marginally useful for dose-response modeling by itself. Nevertheless, the data were examined to provide information on short term events that could lead to DCS and that would not be provided by the other data sets.

Another data set was constructed based on Canadian diving experience. Since 1967, all pressure chamber exposures at the Defence and Civil Institute of Environmental Medicine have been entered into a computer data base (Kuehn and Sweeney, 1973) with detailed pressure histories and DCS outcomes. One of us (R.Y. Nishi) is responsible for maintenance of this large data base. Of the thousands of records, the dives with compressed air were selected and further restricted by removing repetitive dives, those with any recompression before surfacing (e.g., to treat skin or other symptoms), those with divers entering or leaving the wet pot, and some obviously safe dives (candidate tests, familiarization).

The data spanned several types of studies (Kidd, Stubbs, and Weaver, 1971) but only a relatively short period of time (August 1967-December 1968), so diagnostic personnel and standards might be expected to have remained constant. The exclusion of all DCS cases that occurred before surfacing where treatment was started immediately undoubtedly excluded some useful data and may have constituted a bias. This exclusion was our attempt to keep the data comparable to other data sets where no time of diagnosis was known, or where the outcome was tabulated as a complete dive even if interruption for treatment was necessary. (An important future study will apply models to dives where the time of symptoms is specifically considered.) A total of 800 exposures on 183 schedules remained for examination. The data included a large number of deep (average : 232 ft) but fairly short (average: 25 min) exposures. Those exposures resulted in 21 cases of DCS, six cases of "marginal symptoms," which were considered as one-half of a case as discussed in our previous study (Weathersby, Homer, and Flynn, 1984), and many cases of skin symptoms, which we called safe exposures.

PROCEDURE

Each data set was entered on a computer (PDP 11/70) as a single entry per man dive. At first, we approximated a dive as a series of constant pressure steps separated by infinitely sharp pressure changes. For dives of standard USN decompression format, this seemed satisfactory. The data from DCIEM, submarine escape exposures, and typical decompressions from saturation dives, however, followed rather slow "linear" pressure changes that could be approximated only by a large number of steps. The data format was then changed to pressure and time combinations, which were nodes connecting pressure ramps of constant rate. Currently, 40 of these P,t nodes are allowed in our data format. Only the very longest USN and DCIEM dives were excluded by reason of excessive nodes. The data format was also set to deal with changes in inspired gas, but only complete air exposures have been examined thus far.

The analysis programs calculated the integral of Eqn. 4 over the entire dive and over sufficient postdive time for Ptis to fall below 1 ATA as the actual time of symptom occurrence was not generally known. In principle, a straightforward calculation of Ptis at many time points during the decompression and numerical integration could be performed. To avoid unacceptably slow computation, however, analytical expressions were derived to calculate conditions at each node and integrate analytically between nodes. Also, partially recursive expressions were obtained to avoid repeating all calculations from the start of the dive for each node. A major problem to overcome was a root-finding approach to obtain all crossover times for Ptis and Pamb. More mathematical details are presented in Appendix I.

A graphical picture of how the models apply is shown in Fig. 1. Ambient pressure for an experimental dive and decompression, found in one of the data sets used, (Data Set A) was plotted as a solid line. The dash-dot line is calculated tissue P_{N_2} according to Model 5 through the dive. The dashed line labeled p(DCS) is the integral in Eqn. 4 that rose in value whenever the value of r in the model (Model 5 in this case) was greater than 0. The tissue tension remained below ambient pressure while the diver was at bottom depth and during the 50, 40, 30, and 20 ft decompression stops. During ascent to the 10 ft stop, the tissue and ambient curves crossed and the risk began to accumulate. The greatest amount of risk accrued after surfacing. Gas excretion brought the tissue down until at about 400 min when tissue P_{N_2} again fell below 1 ATA and the total risk of DCS for the diver became constant. In

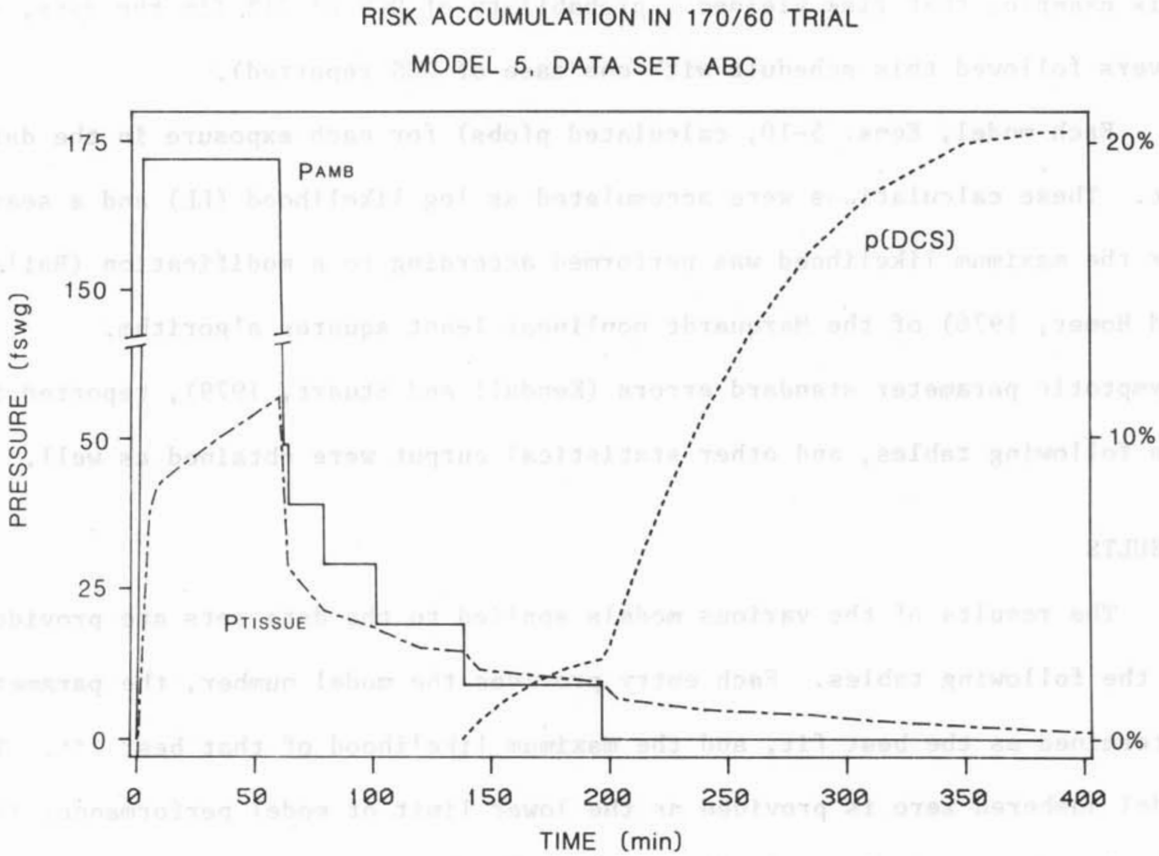

Fig. 1. Time course of ambient pressure, calculated tissue pressure, and p(DCS) during a dive. The exposure was a test of a 170 ft, 60-min dive from Data Set ABC. Model 5 was used with best-fit parameters estimated from Data Set ABC.

this example, that risk yielded a probability of DCS of 21% (in the data, six divers followed this schedule with one case of DCS reported).

Each model, Eqns. 5-10, calculated p(obs) for each exposure in the data set. These calculations were accumulated as log likelihood (LL) and a search for the maximum likelihood was performed according to a modification (Bailey and Homer, 1976) of the Marquardt nonlinear least squares algorithm. Asymptotic parameter standard errors (Kendall and Stuart, 1979), reported in the following tables, and other statistical output were obtained as well.

RESULTS

The results of the various models applied to the data sets are provided in the following tables. Each entry provides the model number, the parameters determined as the best fit, and the maximum likelihood of that best fit. The model numbered zero is provided as the lower limit of model performance; it is calculated as a single probability (C) of DCS for the data and ignores both pressure and time.

As seen in Table 1, the one exponential model was a significant improvement over the null model. This means that the two parameters of Model 1 succeeded in separating exposures according to DCS hazard. This separation is shown in Fig. 2, where all exposures were lumped into four categories based on the model's prediction of DCS probability: 0-2%, 2-5%, 5-10%, and >10%. For example, Model 1 estimated that 65 dives had a p(DCS) between 2.0 and 5.0% with an average of 3.3%. Of those 65 dives, only three cases of DCS occurred for a raw incidence of 3/65 or 4.6%. Thus, a bar graph of height 4.6% was plotted at a predicted incidence of 3.3%. Reference to tables of binomial sampling confidence limits (Diem, 1962) provides a 95% confidence limit that the raw incidence has an actual underlying incidence between 1.0 and 12.9%;

TABLE 1

Acceptance Tests of Present USN Standard Air Tables (6)

Model	Parameters (1 SE)	Log Likelihood
0. constant p	C = 0.048	-108.598
1. 1-exp, no thresh	T = 340(100),	- 91.450
	$A = 3.1(1.1) \cdot 10^{-3}$	
2. 1-exp, thresh	T = 122(50),	- 90.891
	$A = 1.6(2.4) \cdot 10^{-2}$,	
	PTHR = 11.9(7.1)	
3. 2-exp, no thresh	no unique TB	--
4. 2-exp, thresh	not applied	--
5. 2-exp RTF, no thresh	no unique set	--
6. 2-exp RTF, thresh	not applied	--

Data Set A: n = 568.

T (TA, T1, etc.) are in units of min; A (AA, A1, etc.) are in min^{-1}; PTHR is in fswg; W1 and C are dimensionless.

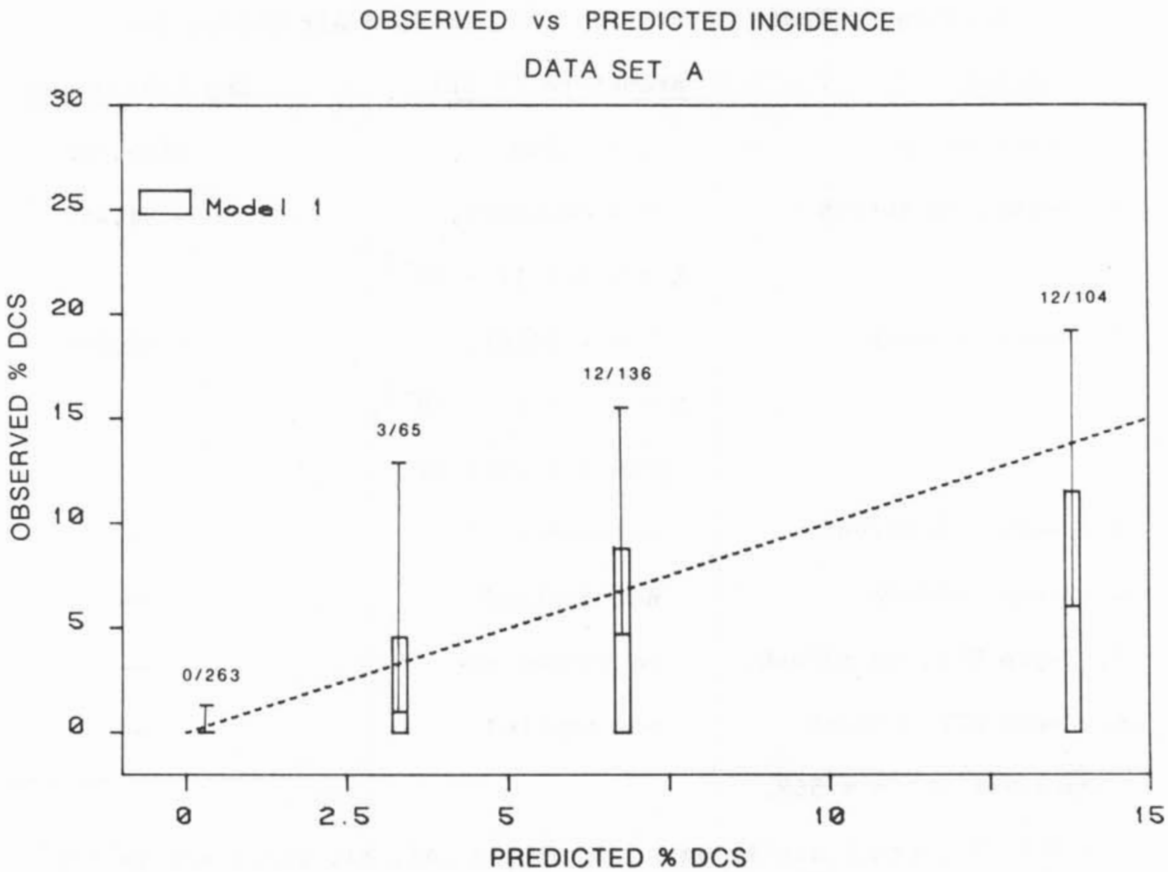

Fig. 2. Bar graph comparing predicted and observed incidence of DCS in four categories of predicted p(DCS): < 2%, 2-5%, 5-10%, and > 10%. Results presented for Model 1 applied to Data Set A. The dotted line is the condition of perfect agreement.

these limits are shown as an error band on the bar. The same procedure was followed for other categories of predicted incidence. In examining Fig. 2, the predictions clearly appear to be in ascending order but with some overlap of confidence limits, which was expected for this fairly small sample size. The actual incidence for each category was rather close to the midpoint of each interval: well within the 95% binomial limits in all cases. There was some indication, however, that the model predicted somewhat higher risk than was actually encountered in both the safest (0-2%) and most hazardous (>10%) dives (both categories fell below the dotted line in Fig. 2 that shows a "perfect" prediction).

Statistical significance among models was assessed by the likelihood-ratio test (Weathersby, Homer, and Flynn, 1984): twice the difference in LL between a general and a specific model was compared to the chi-square distribution for the difference in degrees of freedom between the models. For example, compare Models 1 and 2 in Table 1. The log likelihood improved by -90.891 - (-91.450) = 0.559 when a nonzero threshold was estimated by the data. Because 2(.559) = 1.018 was less than the $p < 0.05$ limit of chi-square at 1 degree of freedom (3.84), the improvement was not judged significant. Thus, there appeared no statistical need to presume a threshold parameter in the simple one exponential model.

None of the more elaborate gas exchange models were required here to achieve a good description of the data. When a second tissue was added in Models 3-6, no improvement in LL was achieved and no specific entries were made in Table 1. This ability of a one tissue model to describe the data well stands in sharp contrast to the six tissues presumed to be equally important in calculating the decompression tables tested. Limited use of the four and five parameter models (Models 3-6) showed that a range of additional time constants could be added without significantly hurting the likelihood. For example, a wide range of parameters was found to be satisfactory for Model 5, but no parameters fit the data overall better than Models 1 and 2.

The second data set (Set B), although not very extensive, allowed the simpler models to deal with the occurrence of DCS after long dives. Table 2 shows the results. As in Set A, the two parameter model was a significant improvement over Model 0, which denies the effects of pressure and time. Only one time constant was required to describe this data set: Use of Models 3-6 did not produce a second term with any statistically significant improvement of the likelihood. Bar graphs were not presented for these data because the small sample numbers made binomial confidence limits exceedingly large. The time constant, empirical scale factor, and threshold estimated for these data appeared close to those found for Data Set A. In fact, the estimated confidence limits for all parameters overlapped, and a likelihood ratio test for the necessity of different parameters for the two sets failed to achieve significance. Thus, the two sets could be combined and treated together. Rather surprisingly, an allowance for a threshold in the data sets combined did not lead to an improvement in likelihood despite the improvment seen in Data Set B alone in Table 2. Note that the two studies interpreted by nonstatistical use of over 50 parameters could be described usefully by only two or three parameters.

At the other extreme of air diving are the very short and deep exposures used to simulate crew escape from a disabled submarine (Set C). We plunged into these data with the knowledge that the actual tissues that produced bends in such short exposures may differ from those in long exposures, and that the assumption that there is no pulmonary or circulatory delay in gas transport kinetics may be violated seriously. Examination of those data is provided in Table 3.

TABLE 2

Acceptance Tests of Present USN Exceptional Exposure Tables (22)

Model	Parameters (1 SE)	Log Likelihood
0. constant p	C = 0.435	- 31.492
1. 1-exp, no thresh	T = 650(420),	- 27.502
	$A = 3.0(0.7) \cdot 10^{-3}$	
2. 1-exp, thresh	T = 320(50),	- 23.957
	$A = 6.0(4.0) \cdot 10^{-2}$,	
	PTHR = 14.0(2.0)	
3. 2-exp, no thresh	no unique TB	--
4. 2-exp, thresh	no unique TB	--
5. 2-exp RTF, no thresh	not applied	--
6. 2-exp RTF, thresh	not applied	--

Data Set B: n = 46.

T (TA, T1, etc.) are in units of min; A (AA, A1, etc.) are in min^{-1}; PTHR is in fswg; W1 and C are dimensionless.

TABLE 3

UK Submarine escape trials (8)

Model	Parameters (1 SE)	Log Likelihood
0. constant p	C = 0.013	- 21.230
1. 1-exp, no thresh	T = 12.2(20.4), $A = 4.8(5.9) \cdot 10^{-3}$	- 19.225
2. 1-exp, thresh	T = 1.04(0.94), $A = 7.0(27) \cdot 10^{-2}$, PTHR = 79(82)	- 18.093
3. 2-exp, no thresh	no unique TB	--
4. 2-exp, thresh	not applied	--
5. 2-exp RTF, no thresh	T1 = 2, T2 = 75, W1 = 0.88(0.19), $A = 3.5(7.4) \cdot 10^{-2}$	- 18.911
6. 2-exp RTF, thresh	not applied	--

Data Set C: n = 299.

T (TA, T1, etc.) are in units of min; A (AA, A1, etc.) are in min^{-1}; PTHR is in fswg; W1 and C are dimensionless.

No standard errors are provided for T1 and T2 in Model 5 because they were held constant at the values shown.

The time constants estimated here were considerably shorter than those found in the previous data sets. Thus, simply combining these data with the previous data could not be accomplished with the one exponential Models 1 or 2. As in the previous two sets, only the two parameter model was statistically justifiable for this data set by itself. No evidence existed of monoexponential gas exchange (Models 5,6) or a second tissue (Models 3,4). Also, as before, the addition of extra gas exchange terms did not force the likelihood to reach extreme values. The entry for Model 5 in Table 3 was not a statistically significant improvement over Models 1 or 2, but showed that the addition of a different exchange model with a provision for slow gas excretion could still describe the data well.

The combination of all three data sets provided a wide range of exposures and a data base of nearly 1,000 man dives. We hope that the British data were subjected to diagnostic criteria similar to American data, thereby justifying the assumption that our data represents a very large and broad trial. The results of fitting to this set are provided in Table 4.

For these combined data, a single time constant, with or without a threshold, was a bad description: both Models 1 and 2 were worse than the null Model 0. Allowance of a second "tissue" in Model 3 improved the fit substantially. The two time constants estimated were quite close to the ones found in the UK and US data examined individually. The numerical values of the two time constants in Models 5 and 6 shared the same resemblance. Thus, there was a noticeable similarity in time constants for the different gas exchange models as well. Note by the likelihood of Models 2, 4, and 6 that none of the models had a statistically significant threshold. Could this mean that the threshold was a mathematical trick of occasionally useful descriptive value but little underlying demand in large data sets? The differences in LL

TABLE 4

Combined Data of Sets A, B, C

Model	Parameters (1 SE)	Log Likelihood
0. constant p	C = 0.056	- 199.496
1. 1-exp, no thresh	T = 33.7(1.2),	- 221.046
	A = 3.1(0.4) $\cdot$ 10^{-3}	
2. 1-exp, thresh	T = 34.9(5.9),	- 221.046
	A = 2.8(0.9) $\cdot$ 10^{-3},	
	PTHR = 0(1.1)	
3. 2-exp, no thresh	TA = 0.66(1.6),	- 139.529
	AA = 6.7(19) $\cdot$ 10^{-3},	
	TB = 365(50),	
	AB = 3.6(6.3) $\cdot$ 10^{-3}	
4. 2-exp, thresh	TA = 0.68(1.5),	- 139.420
	AA = 7.3(19) $\cdot$ 10^{-3},	
	TB = 290(105)	
	AB = 5.3(3.9) $\cdot$ 10^{-3}	
	PTHR = 2.5(4.3)	
5. 2-exp rtf, no thresh	T1 = 1.5(2.3),	- 139.289
	T2 = 265(30),	
	W1 = 0.99(0.08)	
	A = 1.18(0.57) $\cdot$ 10^{-2},	
6. 2-exp rtf, thresh	T1 = 1.2(2.5),	- 139.181
	T2 = 285(80),	
	W1 = 0.99(0.15)	
	A = 1.05(0.66) $\cdot$ 10^{-2},	
	PTHR = 1.1(4.2)	

Data Set ABC: n = 913.

T (TA, T1, etc.) are in units of min; A (AA, A1, etc.) are in min^{-1}; PTHR is in fswg; W1 and C are dimensionless.

between Models 3 and 5 were so small that the data could not allow one to choose between two "tissues" or multiexponential kinetics in one tissue. The Model 5 estimate of kinetics yielded a mean residence time of 4.2 min and a variance to mean square ratio of 81, which were not typical of dog tissues in our previous study of ^{133}Xe exchange (Weathersby et al., 1981).

The success of these models in separating the risk of the combined data is shown in bar graph format in Fig. 3. Because estimates of threshold were nearly zero, prediction of dive risk by Models 1 and 2 was nearly identical as it was for model pairs 3,4 and 5,6. Thus, only the results of three models were plotted. The separation of dives by category of risk was not successful for Model 1, as we expected for such low values of likelihood. Models 3-6 performed well in separating risk and came quite close to matching the incidence of actual DCS in all categories. The low and mid-risk categories were mixed dives from Data Sets A and C; the high prediction category included nearly all dives from Data Set B. A formal treatment for evaluating categorized predictions is the Pearson's goodness-of-fit test (Kendall and Stuart, 1979). The observed and predicted numbers of DCS cases in each category (0-2%, 2-5%, 5-10%, >10%) were used to generate a chi-square statistic. The resulting statistics were 186 for Model 1, 0.99 for Model 3, and 3.54 for Model 5. Only the Model 1 results exceeded the value required ($\chi^2_{.01}$ > 11.34 for 3 degrees of freedom) to declare failure of the data to fit the model distribution of hazard. The slightly better performance of Model 3 was due to the closer match with the 5-10% category.

Can the data sets be fitted in combination as well as each set was fitted separately? The very poor performance of Models 1 and 2 demonstrated that the kinetics needed to describe this wide range of dives did not consist of one exponential. Models 2-6, however, did very well. Combined values of maximum

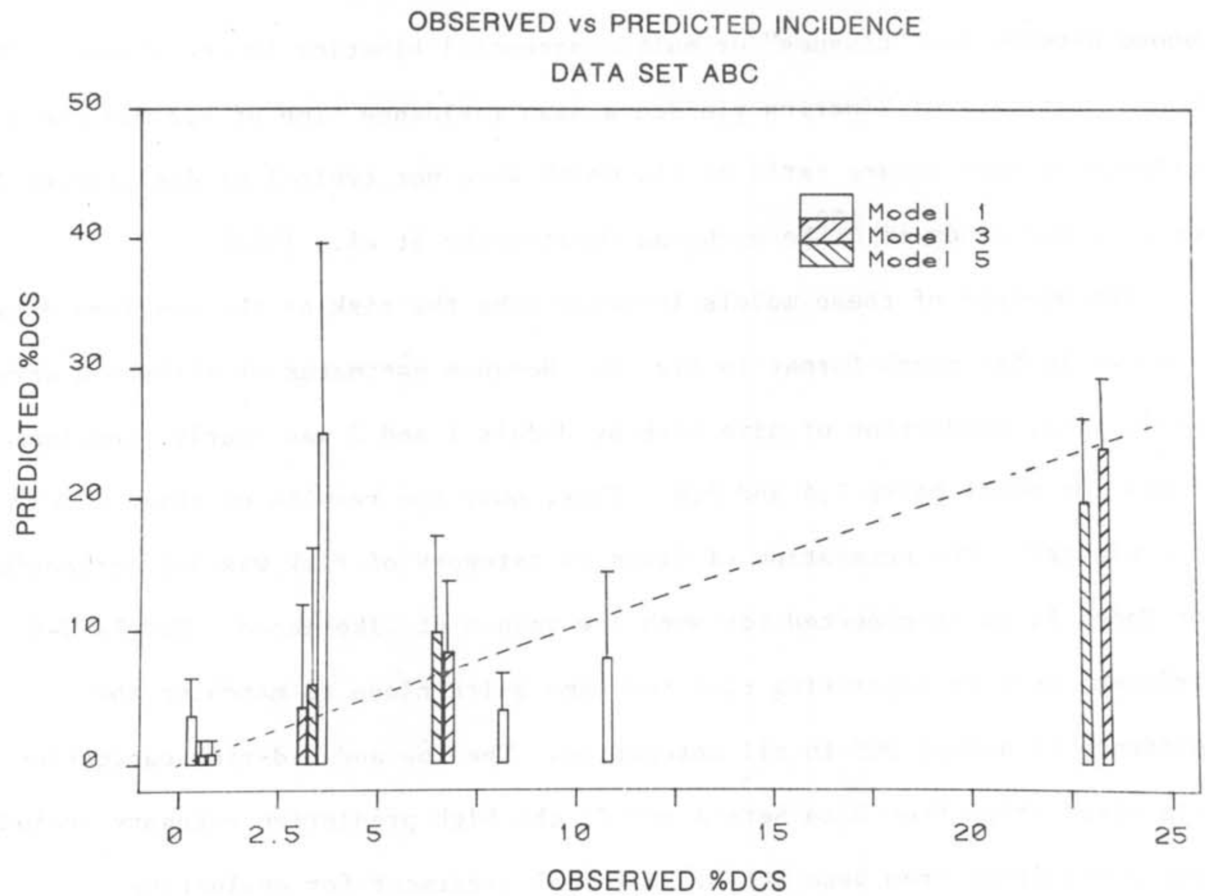

Fig. 3. Bar graph comparing predicted and observed incidence of DCS in four categories of predicted p(DCS): < 2%, 2-5%, 5-10%, and > 10%. Results are presented for Models 1, 3, and 5 applied to combined Data Set ABC. The dotted line is the condition of perfect agreement.

likelihood for Model 1 from each data set individually (Tables 1-3) yielded a total of -138.177. This was very close to the results of Models 3-6, and a likelihood ratio test did not support the use of three separate sets of single exponential models in preference to combined data sets of Models 3-5 in Table 4. Therefore, we concluded that adding the data together is a useful and justifiable practice.

Finally, we examined 17 months of Canadian experience. The results of model fitting to this data set are provided in Table 5. For this data set, each model had a specific message similar to that of Table 4. The simplest risk model was better than none (compare Model 1 to Model 0). A two exponential rtf description of gas exchange was better than a one exponential description (compare Model 5 to Model 1), as was a two "tissue" model (Model 3). A slight threshold of about 5 fsw improved the fit for Model 4 but not for Model 6. Bar graphs of these results are provided in Fig. 4. Models 3, 4, and 5 achieved a respectable ordering of incidence, subject to the substantial uncertainty inherent in the fairly small numbers. The values of Pearson's test supported the visual impression that all three models fit satisfactorily the categories (χ^2 values of 2.65, 0.37, and 3.45, respectively).

The parameters estimated from the Canadian data can be compared to the previous results. The time constants were of a similar magnitude as those established before, but they were neither quite as short or as long. This was not surprising as the DCIEM data did not include extremely rapid dives such as those in Set C, nor the very long dives included in Set B. The scale factors (A's in Table 4) are of a similar magnitude.

In passing, we also examined some additional DCIEM data. Preliminary analysis indicated that the models behaved differently from the results in

TABLE 5

DCIEM Chamber Dives 1967-1968

Model	Parameters (1 SE)	Log Likelihood
0. constant p	C = 0.030	- 107.794
1. 1-exp, no thresh	T = 221(58),	- 103.426
	$A = 1.26(0.31) \cdot 10^{-3}$	
2. 1-exp, thresh	T = 214(85),	- 103.390
	$A = 1.35(1.0) \cdot 10^{-3}$,	
	PTHR = 0.7(3.5)	
3. 2-exp, no thresh	TA = 3.91(4.5),	- 100.630
	$AA = 6.15(11) \cdot 10^{-3}$,	
	TB = 382(170),	
	$AB = 1.26(0.63) \cdot 10^{-3}$	
4. 2-exp, thresh	TA = 6.64(5.4),	- 97.246
	$AA = 5.6(6) \cdot 10^{-3}$,	
	TB = 253(107),	
	$AB = 7.83(11) \cdot 10^{-2}$,	
	PTHR = 5.9(5.1)	
5. 2-exp rtf, no thresh	T1 = 8.96(3.2),	- 100.072
	T2 = 227(35),	
	W1 = 962(0.013),	
	$A = 2.35(1.2) \cdot 10^{-2}$	
6. 2-exp rtf, thresh	T1 = 8.96(2.9),	- 100.072
	T2 = 227(29),	
	W1 = 0.962(0.014),	
	$A = 2.35(1.4) \cdot 10^{-2}$,	
	PTHR = 0.5(0.9)	

Data Set D: n = 800.

T (TA, T1, etc.) are in units of min; A (AA, A1, etc.) are in min^{-1}; PTHR is in fswg; W1 and C are dimensionless.

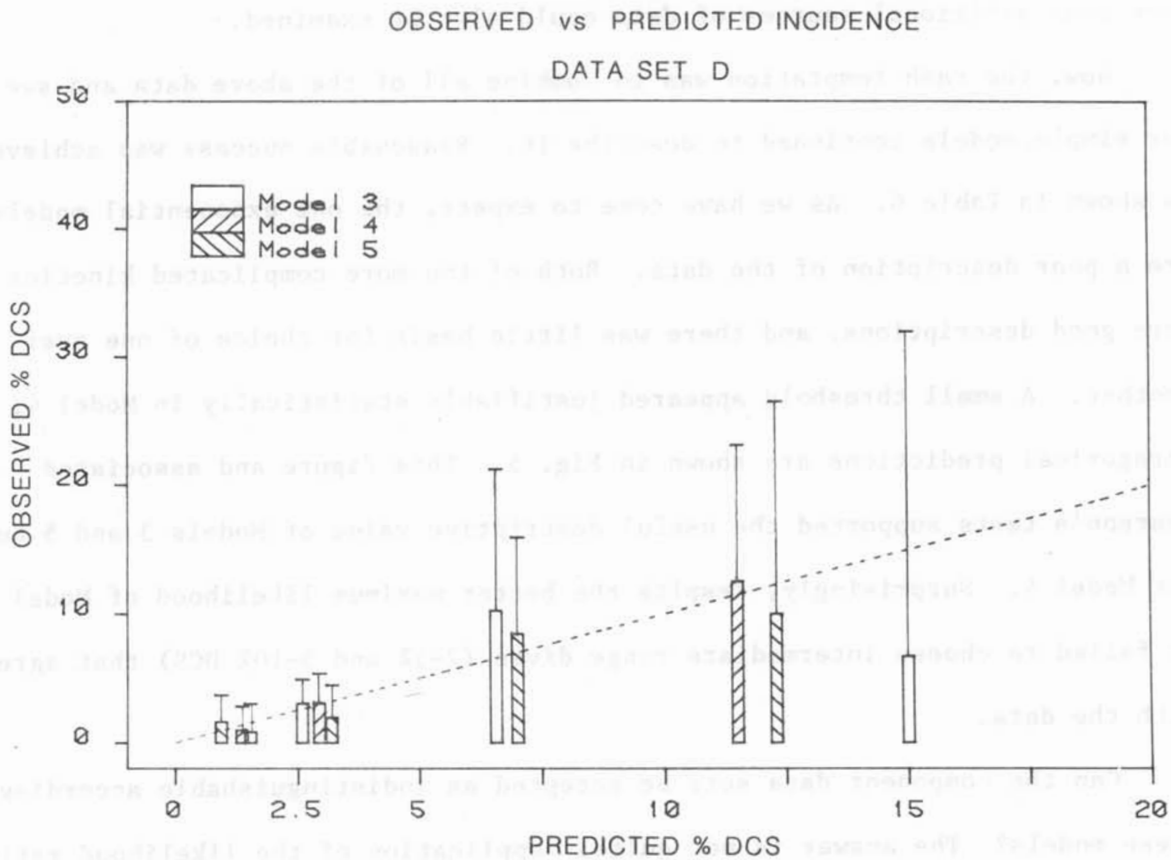

Fig. 4. Bar graph comparing predicted and observed incidence of DCS in four categories of predicted p(DCS): < 2%, 2-5%, 5-10%, and > 10%. Models 3, 4, and 5 were applied to Data Set D. The 5-10% and > 10% categories from Model 4 had so few dives that the two categories were combined. The dotted line is the condition of perfect agreement.

Table 5. Further consideration of that possibility was deferred until a later time when additional sources of data could also be examined.

Now, the rash temptation was to combine all of the above data and see if our simple models continued to describe it. Reasonable success was achieved, as shown in Table 6. As we have come to expect, the one exponential models are a poor description of the data. Both of the more complicated kinetics were good descriptions, and there was little basis for choice of one over another. A small threshold appeared justifiable statistically in Model 4. Categorical predictions are shown in Fig. 5. This figure and associated Pearson's tests supported the useful descriptive value of Models 3 and 5 but not Model 4. Surprisingly, despite the better maximum likelihood of Model 4, it failed to choose intermediate range dives (2-5% and 5-10% DCS) that agreed with the data.

Can the component data sets be accepted as indistinguishable according to these models? The answer is not quite: application of the likelihood ratio test to combining Data Set ABC with Data Set D using Models 3-5 produced likelihood ratios of 14, 11, and 15, respectively, for the addition of four or five parameters. These numbers made the probability of the data not being identical about 0.01. Thus, the combined fit was not as good as the fit to the individual data sets.

Some attempt should be made to explain this finding other than the simple failure of the models to describe that broad a range of dives. The individual data set most likely to disagree with the others is the submarine escape trial where both time course and type of symptom elicited appears different from longer exposures. Therefore, we now present model results with those data excluded in Table 7.

TABLE 6

Combined Data of Sets A, B, C, D

Model	Parameters (1 SE)	Log Likelihood
0. constant p	C = 0.044	- 311.049
1. 1-exp, no thresh	T = 33.5(1.3),	- 337.348
	$A = 2.08(0.24) \cdot 10^{-3}$	
2. 1-exp, thresh	T = 33.5(5.3),	- 337.348
	$A = 2.08(0.58) \cdot 10^{-3}$,	
	PTHR = 0.0(1.2)	
3. 2-exp, no thresh	TA = 2.43(1.7),	- 247.085
	$AA = 3.19(1.9) \cdot 10^{-3}$,	
	TB = 383(44),	
	$AB = 2.73(0.45) \cdot 10^{-3}$	
4. 2-exp, thresh	TA = 6.17(1.9),	- 242.250
	$AA = 3.16(1.2) \cdot 10^{-3}$,	
	TB = 260(39),	
	$AB = 7.63(3.0) \cdot 10^{-3}$,	
	PTHR = 5.03(1.7)	
5. 2-exp rtf, no thresh	T1 = 3.73(1.1),	- 246.873
	T2 = 265(14),	
	W1 = 0.974(0.009),	
	$A = 1.06(0.19) \cdot 10^{-2}$	
6. 2-exp rtf, thresh	T1 = 3.95(1.8),	- 246.873
	T2 = 266(14),	
	W1 = 0.973(0.019),	
	$A = 1.06(0.18) \cdot 10^{-2}$,	
	PTHR = 0.0(0.6)	

Data Set ABCD: n = 1,713.

T (TA, T1, etc.) are in units of min; A (AA, A1, etc.) are in min^{-1}; PTHR is in fswg; W1 and C are dimensionless.

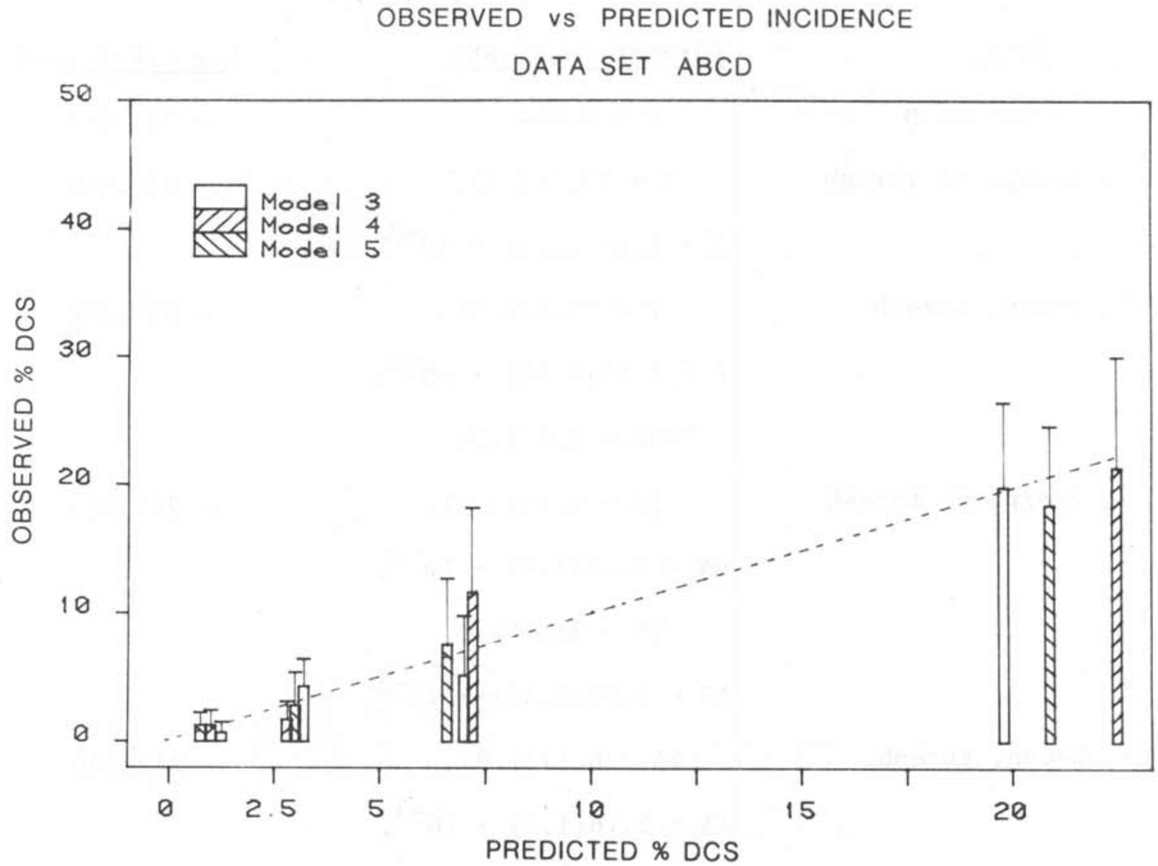

Fig. 5. Bar graph comparing predicted and observed incidence of DCS in four categories of predicted p(DCS): < 2%, 2-5%, 5-10%, and > 10%. Results are presented for Models 3, 4, and 5 applied to combined Data Set ABCD. The dotted line is the condition of perfect agreement.

TABLE 7

Combined Data of Sets A, B, D

Model	Parameters (1 SE)	Log Likelihood
0. constant p	C = 0.051	- 284.516
1. 1-exp, no thresh	T = 323(24),	- 229.201
	A = 2.48(0.35) $\cdot 10^{-3}$	
2. 1-exp, thresh	T = 258(47),	- 228.260
	A = 3.44(0.93) $\cdot 10^{-3}$,	
	PTHR = 1.8(1.4)	
3. 2-exp, no thresh	TA = 10.1(47),	- 227.405
	AA = 5.60(22) $\cdot 10^{-4}$,	
	TB = 392(63),	
	AB = 2.72(0.46) $\cdot 10^{-3}$	
4. 2-exp, thresh	TA = 17.6(22),	- 221.415
	AA = 1.13(1.05) $\cdot 10^{-3}$,	
	TB = 258(41),	
	AB = 8.10(3.5) $\cdot 10^{-3}$,	
	PTHR = 5.3(1.9)	
5. 2-exp rtf, no thresh	T1 = 179(33),	- 223.241
	T2 = 1,160(490),	
	W1 = 0.87(0.08),	
	A = 6.2(1.7) $\cdot 10^{-3}$	
6. 2-exp rtf, thresh	not applied	--

Data Set ABD: n = 1,414.

T (TA, T1, etc.) are in units of min; A (AA, A1, etc.) are in min^{-1}; PTHR is in fswg; W1 and C are dimensionless.

For this collection of normal air dives, all models worked well. The parameters were similar to those obtained from the overall combined data set (see Table 6), and thus the submarine escape data do not appear to be the single culprit in the discrepancy among the data. Some difference is apparent with Model 5, which required longer kinetics. Attempts to use Model 6 were abandoned because of numerical problems. The problem with combining data is probably a combination of the models, which we know are naive, and the data which we know were not obtained under identical circumstances. Further resolution of this discrepancy does not seem worth pursuing at this point. We will take the answers from the largest data set and tentatively use them as our best summary of air diving risk.

EVALUATION OF OTHER DECOMPRESSION REPORTS

We examined several other data sets that were too small for useful parameter estimation in themselves and too dissimilar for naive merging. These were examined by prediction using the results presented above but were not used for fitting. The first data set is a sea trial of British schedules in 1957 (Crocker) that had a much higher incidence of DCS than an earlier chamber trial (Set E). The second is a 1949 US series of air dives that emphasized the stress of heavy exercise after the dives (Van der Aue, Kellar, and Brinton) (Set F). The third is part of a large US trial of surface decompression procedures (Van der Aue et al., 1951) that included a number of no-decompression exposures (Set G). Finally, Set H is a 1952 British chamber trial of prospective trials whose tables were too conservative to be adopted as official (Hempleman, Crocker, and Taylor). For each dive in these reports, the best reconstruction of the actual dive data was entered in the same format as the other data already used. A variety of the models and parameter sets evaluated with the previous parameters (Tables 1-6) were applied to each data set to obtain a prediction of p(DCS) for each dive. These probabilities were summed for each trial to calculate the expected number of cases in the total trial.

The results of this pure prediction are provided in Table 8. For each of the new (never used for parameter estimation) data sets, the total number of dives and the number of reported cases of DCS are tabulated as well as the predicted number of total cases of DCS according to our analysis. The notation in the prediction columns provides both the model (i.e., Models 1-5) and the data set used for parameter estimation (e.g., Data Set ABC from Table 4).

Table 8 shows that projection of total cases in these trials is mixed. The predictions are consistently lower for Sets E and F, and slightly higher for Set H. There is reasonable agreement between predicted and observed incidence of bends for Sets G and H. A series of chi-square tests of one degree of freedom to check the predictions verifies this impression: Set G (4/D prediction) and all Set H predictions are within the range of the observed value (at $p < 0.05$). As would be expected, the models do best with data similar to those to which they were fitted. Sets G and H involved dives with depths, bottom times, and total decompression times in the same range as dives in Sets A and D. Set G, which shows close agreement between observed incidence and that predicted by 4/D, has the widest range of depths and bottom times of these four sets.

Significance of a single case of bends is obviously limited, but it is interesting that the only such case of Data Set H occurred on the one profile predicted by all models to be about twice as dangerous as all other profiles of that dive series. The more homogeneous dive profiles of Data Sets E and F mean that a lack of predictive accuracy in a single profile will be reflected

TABLE 8

Projection of Risk in Additional Data

Data Set	Dives	DCS Cases	Cases Predicted by Model/Data 1/AB	3/ABC	5/ABC	4/D	3/ABCD
E	50	9	0.8	0.8	0.7	1.8	0.8
F	141	42	3.9	3.6	4.3	7.3	3.4
G	143	9	0.9	1.1	1.3	7.5	1.7
H	192	1	3.2	3.7	3.9	5.5	3.8

in a major loss of predicted accuracy for the data set as a whole. More importantly, the types of diving represented by these two data sets are not well represented in Data Sets A,B,C, and D. Dives in Data Set E are similar to standard air dives in Set A, but the total decompression time for almost all dives was significantly shorter than that called for in the USN Standard Air Decompression Table. The dives of Data Set F were explicitly intended to produce an incidence of bends approaching 50%. It is not surprising that the outcome of such stressful dives was not well predicted by models fitted to an entirely different range of diving conditions.

SAFETY OF USN SCHEDULES

The models evaluated from the data sets were applied to current USN procedures. The calculation of p(DCS) for current no-stop dives, standard air dives, and exceptional exposure dives is shown in Appendix 3. Dive depth and bottom time are tabulated as well as the total decompression time specified in the U.S. Navy Diving Manual (1973). The remaining five columns represent the predicted incidence of DCS according to several of the models and parameters obtained above. First is the single tissue model that was shown in Tables 1 and 2 to describe well the acceptance tests of these schedules. It basically predicted all short dives are safe and all long dives are dangerous, as we expected for a single 6-h time constant. The next two columns represented combined EDU and submarine escape data using Models 3 and 5. The models were equally successful (similar likelihood) in describing the 913 dives used for data and they yielded very similar predictions when applied to the Diving Manual decompression schedules. These two sets of predictions were also very similar to the first set, indicating that the ability to describe extremely short dives does not affect the prediction of safety for longer dives. The next column represents parameters from the DCIEM data. These entries are similar for long exposures, but they assign higher risk to shorter dives. The final column represents the parameters of the largest data set, and it agrees rather well with the other columns.

The message of Appendix 3 is clear: air dives shallower than 150 ft and shorter than 40 min are quite safe: the risk of DCS is less than one-half of 1%. Dives longer than 2 h and up to 80 ft in depth, longer than 1.5 h in the 90-120 ft range, and longer than 40-60 min and deeper than 120 ft should produce bends at least 10% of the time. Dives that are both deep and long can result in DCS more often than not.

Are these incidences borne out in fleet practice? Berghage and Durman (1980) assembled seven years of Navywide experience based on reports of the Navy Safety Center. Problems existed with that data base that could easily produce both too high and too low predictions of DCS incidence. Widespread underreporting, errors in completion and keypunching of the elaborate form, and entry of only the deepest depth reached regardless of how much time was spent at shallower depths were serious problems. Nevertheless, the report merits a brief examination. Berghage found that only 20 of the 295 decompression schedules included as many as 200 reported dives, so no records exist on the operational safety of most schedules. These 20 frequently used schedules were sufficient to derive an estimate of incidence. The results for schedules that reported more than 200 exposures in a seven year period are provided in Table 9.

The tabulated experience in Table 9 can be used very loosely for a comparison with Appendix 3. A detailed, line-by-line comparison is unwarranted. In general, the longer dives were about as unsafe as predicted, at least within a factor of two. Short dives were even closer to the

TABLE 9

DCS Incidence of Present Tables in Operational Use

Depth	Time	No. Dives	No. Bends	% Reported Incidence Range (95% binomial confidence limits)
100	50	549	3	0.1 - 1.6
110	20	209	0	< 1.8
110	30	455	4	0.2 - 2.3
110	50	1,198	4	0.1 - 0.8
120	30	244	3	0.3 - 3.5
120	50	474	2	0.1 - 1.5
130	15	227	1	< 2.4
130	50	226	2	0.1 - 3.2
150	10	686	2	0.1 - 1.0
160	30	270	3	0.2 - 3.2
170	10	854	4	0.1 - 1.2
170	15	494	2	0.1 - 1.5
180	15	396	2	0.1 - 1.8
180	20	397	6	0.5 - 3.2
190	10	473	5	0.4 - 2.7
200	10	1,458	13	0.5 - 1.4
200	15	257	5	0.6 - 4.6
210	10	345	0	< 1.0
290	10	511	9	0.8 - 3.4
300	10	668	13	1.0 - 3.2

predictions of Appendix 3. Only the 110/50 entry appeared to be definitely safer than the approximately 3% predicted in Appendix 3. That could arise through a somewhat more conservative use of this schedule. For example, if the actual dive was only for 101 ft for 41 min with a 110/50 decompression (as specified by the Diving Manual), the predicted risk would be 0.9% by Model 4 Data Set ABCD rather than 2.5% listed in Appendix III for the full time and depth. Because the Safety Center did not record the actual times and depths the divers used, the value of this comparison is minimal.

CONCLUSIONS

Previous development of decompression tables has been characterized by ad hoc adjustment of necessary parameters with little regard for agreement with actual data. Application of probabilistic models and maximum likelihood estimation now allows calculations to be justified statistically by available diving data. The models used here were definitely simplistic and empirical, but did show a significant ability to describe the outcome of thousands of dives. Even this naive approach could be used to calculate new decompression tables in a "conservative manner", that is, by extrapolating the models into hypothetical decompression schedules with an acceptably low risk of DCS. As that would represent an unabashed extrapolation of an overly simple model, initial success with the new tables cannot be assured without actual tests. Improved models, more satisfactory data, and more extensive computer time should produce better predictions.

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Hobbs

Mathematical Details

Gas Exchange: General

The treatment of tissue gas exchange follows the formalism presented in Weathersby et al., 1979. The tissue residence time distribution function, f(t), is a linear transfer function relating the venous outflow of the tissue, Y(t), to its arterial inflow concentration, X(t). The tissue concentration, Q'(t), is proportional to the accumulated arterial-venous difference since the previous steady state.

$$Q'(T) = G \int_o^T [X(t) - X(t) * f(t)]\, dt \qquad [I-1]$$

The symbol * is the convolution operator. We will ignore the slight contributions of pulmonary O_2, CO_2, and H_2O, as well as the pulmonary and cardiac transport lag, and assume directly that X(t) is equal to inspired inert gas partial pressure.

During an air dive the time course of X(t) can become rather complicated. We have chosen to describe the dive as a series of ramps characterized by a change in rate of compression or decompression.

$$X(t) = X_o + \sum_{i=1}^{n} k_i\, (t - T_i) \quad \text{for } T_n < t \qquad [I-2]$$

Here, k_i is the change in rate that occurred at time T_i. Note that by this convention, maintenance of a steady condition (i.e., constant depth) means $\Sigma\, k = 0$, not $k = 0$. Evaluation of Eqn. I-1 depends on choice of tissue exchange function f(t).

Monoexponential Gas Exchange

The simplest common exchange function is one exponential with a single parameter.

$$f(t) = 1/\tau \;\; \exp\,(-t/\tau) \qquad [I-3]$$

The pre-exponential term is necessary for the integral of f(t) out to infinity to equal one, which is a necessary condition for treatment of f(t) as a probability density function (see Weathersby et al., 1979). As another computational convenience, inclusion of the inverse of the mean residence time (= τ for 1 exponential) into the constant G in Eqn. I-1 results in G = 1. The units of Q are the same partial pressure units as X, so $Q_o = X_o = 0.79$ ATA.

Substitution of Eqn. I-3 into Eqn. I-1 for a single ramp of slope k_1 leads to

$$Q\ (t > T_1) = X_o + k_1(t - T_1) - k_1\tau + k_1\tau\exp[-(t-T_1)/\tau] \qquad [I\text{-}4]$$

which shows the overall response consists of a constant, a linear term, and a decaying exponential. In general, for a tissue after the n^{th} ramp is imposed:

$$Q(t > T_n) = X_o + \sum_{j=1}^{n} k_j\ (t-T_j) - \tau\sum_{j=1}^{n} k_j + \tau\sum_{j=1}^{n} k_j\exp[-(t-T_j)/\tau] \qquad [I\text{-}5]$$

This equation uses linear superposition, but much greater computational speed is achieved if calculations for each ramp do not require an explicit summation of all ramps since the beginning of the dive. Such a partially recursive formula is given below:

$$Q(t > T_n) = X(T_n) - \tau\sum_{j=1}^{n} k_j + (\sum_{j=1}^{n} k_j)(t - T_n) + \phi(t > T_n)$$

$$\phi(t > T_n) = [k_n\tau + \phi(T_n)]\ \exp[-(t - T_n)/\tau]$$

$$\phi(T_n) = \phi(t > T_{n-1})$$

$$\phi(T_1) = 0 \qquad [I\text{-}6]$$

This gas exchange equation is used for Models 1 and 2 described in the text. Calculations for Models 3 and 4 are exactly the same, except that two τ's are followed in parallel, τ_A and τ_B. (In the text these parameters appear as TA and TB).

Two Exponential Residence Time Tissue Exchange

As described in Weathersby et al., 1981, one exponential does not provide a very good description of gas exchange in dog tissues, but two or three exponentials do. The residence time distribution function that has two exponentials is:

$$f(t) = \frac{1}{M}\left[W_1 \exp(-t/\tau_1) + (1 - W_1)\exp(-t/\tau_2)\right] \qquad [I-7]$$

where $M = W_1\tau_1 + (1 - W_1)\tau_2$, the mean residence time.

For a single ramp of slope k_1 imposed at T_1, substitution of Eqn. I-2 and Eqn. I-7 into Eqn. I-1 yields:

$$Q(t > T_1) = X_o + k_1(t - T_1) - k_1\,(W_1\tau_1^{\,2} + (1 - W_1)\tau_2^{\,2})/M$$
$$+ \frac{k_1 W_1 \tau_1^{\,2}}{M} \exp\left[-(t - T_1)/\tau_1\right] + \frac{k_1(1 - W_1)\tau_2^{\,2}}{M} \exp\left[-(t-T_1)/\tau_2\right] \qquad [I-8]$$

Superposition can be used to calculate the tissue tension after the n^{th} ramp:

$$Q(t > T_n) = X_o + \sum_{j=1}^{n} k_j(t - T_j) - \left[W_1\tau_1^{\,2} + (1 - W_1)\tau_2^{\,2}\right]\left(\sum_{j=1}^{n} k_j\right)/M$$
$$+ \left(\frac{1}{M}\sum_{j=1}^{n} k_j W_1 \tau_1^{\,2} \exp\left[-(t - T_j)/\tau_1\right]\right) + \left(\frac{1}{M}\sum_{j=1}^{n} k_j (1 - W_1)\tau_2^{\,2} \exp\left[-(t - T_j)/\tau_2\right]\right) \qquad [I-9]$$

Finally, a recursive formula can be derived from Eqn. I-9

$$Q(t > T_n) = X(T_n) + \left(\sum_{j=1}^{n} k_j\right)(t - T_n) - \frac{1}{M}\left(\sum_{j=1}^{n} k_j\right)\left(W_1\tau_1^{\,2} + (1 - W_1)\,\tau_2^{\,2}\right)$$
$$+ \phi(t > T_n) + \Theta(t > T_n)$$

$$\phi(t > T_n) = \left[\frac{1}{M} k_n W_1 \tau_1^{\,2} + \phi(T_n)\right] \exp\left[-(t - T_n)/\tau_1\right]$$

$$\Theta(t > T_n) = \left[\frac{1}{M} k_n (1 - W_1)\tau_2^{\,2} + \Theta(T_n)\right] \exp\left[-(t - T_n)/\tau_2\right]$$

$$\phi(T_1) = \theta(T_1) = 0 \qquad [I-10]$$

Risk Integral

Once the tissue partial pressure is known, it is necessary to evaluate the risk integral (Eqn. 4) according to which risk definition is chosen (Eqns. 5-8). This integration is performed for each ramp whenever the definition of r is positive. Suppose the time during which this occurs is T' to T" (which may not be equal to T_n to T_{n+1}; see next section).

$$R_n = \int_{T'}^{T''} r\,dt' = \int_{T'}^{T''} \frac{A + Bt' + C\exp(-t'/\tau)}{Pon + \ell t}\,dt' \qquad [I-11]$$

where $t' = t - T_n$; Pon = ambient pressure at $t = T_n$;

$A = X(T_n) - \tau\sum_{j=1}^{n} k_j$ - Pon - PTHR; ℓ = rate of ambient pressure change

$B = \sum_{j=1}^{n} k_j - \ell$; $C = k_n\tau + \phi\,(T_n)$

For models 1, 3, and 5 the value of PTHR is 0.

For the case of constant pressure, $\ell = 0$, the integral is direct.

$$R_n = \frac{A}{Pon}(T'' - T') + \frac{B}{2Pon}(T''^2 - T'^2) + \frac{C\tau}{Pon}(e^{-T'/\tau} - e^{-T''/\tau}) \qquad [I-12]$$

The case of $\ell \neq 0$ is more complex because of the time function in the denominator. It is useful to substitute ambient pressure for time as follows:

$$p = Pon + \ell\,t'$$

$$\text{and} \quad \frac{dp}{dt'} = \ell, \quad p' = Pon + \ell T', \quad p'' = Pon + \ell T'' \qquad [I-13]$$

with these substitutions

$$R_n = \int_{p'}^{p''} \left[\frac{A}{\ell}\frac{1}{p} + \frac{B}{p\ell}\frac{(p-Pon)}{\ell} + \frac{C}{\ell p}\exp\left[-\frac{1}{\tau\ell}(p-Pon)\right]\right] dp \qquad [I-14]$$

The final risk integral expression is:

$$R_n = \frac{B}{\ell^2}(p''-p') + \left(\frac{A}{\ell} - \frac{BPon}{\ell^2} + \frac{Ce^{Pon/\tau\ell}}{\ell}\right)\ln\left(\frac{p''}{p'}\right)$$

$$+ \frac{Ce^{Pon/\tau\ell}}{\ell}\sum_{i=1}^{\infty}\left[\frac{\left(\frac{-p''}{\tau\ell}\right)^i - \left(\frac{-p'}{\tau\ell}\right)^i}{i\ i!}\right] \qquad [I-15]$$

A similar development is necessary for the two exponential case.

$$R_n = \int_{T'}^{T''} r dt' = \frac{A + Bt' + C_1 \exp(-t'/\tau_1) + C_2 \exp(-t'/\tau_2)}{Pon + \ell t'} \; dt' \qquad [I-16]$$

where B is the same as in Eqn. I-11 and

$$C_1 = \frac{k_n W_1 \tau_1^2}{M} + \phi(T_n) \text{ and } C_2 = -\frac{k_n (1 - W_1)\tau_2^2}{M} + \Theta(T_n)$$

$$A = X(T_n) - \frac{(W_1\tau_1^2 - (1 - W_1)\tau_2^2)}{M} \sum_{j=i}^{n} k_j - Pon - PTHR$$

The steps leading to an analytical integration formula are identical to those above, but the extra exponential term is carried as well.

The final result for $\ell = 0$ is:

$$R_n = \frac{A}{Pon}(T'' - T') + \frac{B}{2Pon}(T''^2 - T'^2) + \frac{C_1\tau_1}{Pon}(e^{-T'/\tau_1} - e^{-T''/\tau_1})$$

$$+ \frac{C_2\tau_2}{Pon}(e^{-T'/\tau_2} - e^{-T''/\tau_2}) \qquad [I-17]$$

For $\ell \neq 0$

$$R_n = \frac{B}{\ell^2}(p'' - p') + \left(\frac{A}{\ell} - \frac{BPon}{\ell^2} + \frac{C_1 e^{Pon/\tau_1\ell} + C_2 e^{Pon/\tau_2\ell}}{\ell}\right) \ln\left(\frac{p''}{p'}\right)$$

$$+ \frac{C_1 e^{Pon/\tau_1\ell}}{\ell} \sum_{i=1}^{\infty} \left[\frac{\left(\frac{-p''}{\tau_1\ell}\right)^i - \left(\frac{-p'}{\tau_1\ell}\right)^i}{i\, i!}\right]$$

$$+ \frac{C_2 e^{Pon/\tau_2\ell}}{\ell} \sum_{i=1}^{\infty} \left[\frac{\left(\frac{-p''}{\tau_2\ell}\right)^i - \left(\frac{-p'}{\tau_2\ell}\right)^i}{i\, i!}\right] \qquad [I-18]$$

The evaluation of terms containing i! in the integral is dangerous for large absolute values of $(p/\tau\ell)$. We can avoid numerical problems by careful association of operations, and thereby preserve stability when $-100 < (p/\tau\ell) < 20$.

The other major numerical difficulty arises from determination of integration limits T' and T". The problem is one of determining the roots of the numerator of Eqn. I-11 or Eqn. I-14. Two roots are possible in Eqn. I-11 and three in Eqn. I-14. Our strategy has been to first decide on the maximum number of roots by knowing whether an odd number of roots exist [$r(T_n)$ and $r(T_{n+1})$ have a different sign], and then searching for maxima and minima in r(t). Once a region is known to have exactly one root, its location is found by a combination of bisection and Newton search.

Data Summaries

DATA SET A

Study: Des Granges, M
Standard Air Decompression Table
EDU Research Report 5-57, Dec. 1956

Pressure exposure	
Dry or wet	Wet
Frequency of diving for individual subjects	Not specified
Descent rate	Not stated; assume 75 fsw/min
Bottom depth	From 40 to 300 fswg; avg. = 167 fswg
how measured	Chamber pressure
how reported	Chamber + 10 fsw for wet pot (Subtract 3 fswg from bottom depth and 1 fswg from stop depth to approximate diver chest depth).
Bottom time	Tabulated as start of descent to start of ascent; range: 10-240 min; avg. = 39 min
Ascent rate	60 fsw/min
Gas breathed	Air
Other factors	
Exercise	Swimming/weight lifting
Subject background	USN, EDU, and UDT divers
Water temperature	No control; "generally comfortable"
Results	
How bends defined	Not stated but all treated
Incidence of bends	27/568 on 88 schedules
Distribution of symptoms	Not stated

Comments:
(1) Data from Appendices A, C, G. Following discrepancies between C,G resolved from original logs in NEDU library. 130/50 (attempt #1):1bends/4dives; 140/80 (attempt #1): 2bends/4dives. 170/30 (attempt #1):1bends/4dives; NOT IN SAME LOG - assume elsewhere.
(2) Four iterations for safety; first defined as 0 bends/4 dives.
(3) Source of present USN Standard Air Tables.

EDU557N.DAT

DATA SET B

Study: Workman, RD
Calculation of Air Saturation Decompression Tables
EDU Research Report 11-57, June 1957

Pressure exposure	
Dry or wet	Dry
Frequency of diving for individual subjects	Not specified
Descent rate	Not stated; assume 75 fsw/min
Bottom depth	All 140 fswg
how measured	Chamber pressure
Bottom time	Start of descent to start of ascent; range: 90-360 min; avg. = 205 min
Ascent rate	60 fsw/min
Gas breathed	Air
Other factors	
Exercise	No
Subject background	USN and EDU divers
Water temperature	No control; "generally comfortable"
Results	
How bends defined	All described; summarized as bends/mild. (Details on each case allow some mild bends involving joint pain and spontaneous resolution to be scored as bends now).
Incidence of bends	13 bends/9 mild: 46 dives on 10 scheds. (Text shows 8 minor bends as joint pain; count as bends).
Distribution of symptoms	Knee, ankle pain mostly. Also hip, shoulder, back pain, nystagmus, weakness.
Treatment	Recompression; 2 weeks no diving

Comments: (1) Data from Tables 2 and 4.
(2) Five iterations for safety; never attained.
(3) Source of present USN Exceptional Exposure Air Tables.

EDU1157N.DAT

DATA SET C

Study: Donald, KW
A review of submarine escape trials from 1945 to 1970 with a particular emphasis on decompression sickness
Donald KW. MRCUP Report 290, 1970

Pressure exposure	
Dry or wet	Some of each
Previous exposure	Some subjects repeat at > 1 week
Descent rate	Varied (given) >100 fsw/min; some geometric, entered at each pressure doubling
Bottom depth	From 60 to 625 fswg; avg.= 320 fswg
how measured	Chamber pressure or sub depth
Bottom time	Given; 4 min or less; avg. = 1.0 min
Ascent rate	Given; varies
Gas breathed	Air
Other factors	
Exercise	No
Subject background	Royal Navy divers and submariners
Water temperature	No control; "generally comfortable"
Doppler monitoring done?	No
Results	
How bends defined	Serious symptoms; one case of "migraine" after dive now entered as bends
Incidence of bends	4/299 on 46 schedules
Distribution of symptoms	Stated; mostly CNS

Comments:
(1) Data from Table II, but follows changes made after seeing original report, Barnard and Eaton, RNPL 7/64:
- 5 exposures to 500 fsw had 20 s bottom time
- 4 more exposures at 450 fsw and 20 s bottom time with 1 bends from Barnard and Eaton Appendix 2
- in 350 fsw group (misprint in B&E as 360?) a migraine 1.5 h postdive in person with no history now scored as bends

(2) Compendium of all UK sub escape experiments from six studies.
(3) Data entered with time to 0.01 min.

UPS290.DAT

DATA SET D

Study: Nishi R, Kuehn LA, Kidd DJ, Stubbs RA et al.
Air dives done at Defence and Civil Institute of Environmental Medicine, Ontario, Canada
CANDID data base access numbers DD0453A to DD0814A

Pressure exposure	
Dry or wet	Dry
Frequency of diving for individual subjects	Not specified
Descent rate	Varies; in data file
Bottom depth	From 100 to 340 fswg; avg. = 240 fswg; 22% < 200 fsw, 40% > 299 fsw
how measured	Chamber pressure
how reported	Chamber pressure
Bottom time	From 4 to 360 min, avg. = 24 min
Ascent rate	In data; varies
Surface interval	None; repet. dives excluded
Recompression?	None; dives with recompr. excluded
Gas breathed	Air
Other factors	
Exercise	Little or none
Subject background	? many DCIEM military, civilians
Results	
How bends defined	Requiring recompression
Incidence of bends	21 bends; 6 marginal out of 800 exposures on 183 schedules (1-16 divers per schedule)
Distribution of symptoms	Some cases with comment

Data selection procedure:

(1) Access all air dives > 70 fswg depth from Aug. 1967 to Dec. 1968.

(2) Discard dives not wanted in this data set:

a. any divers in water

b. any recompression interrupting the decompression profile (some apparently to treat skin or Type I symptoms; others unknown)

c. any very safe training dives, e.g., 100 fsw/15 min

(3) Discard Dives requiring > 40 ramps for profile (only 2).

(4) Dives annotated as "marginal bends" entered as 0.5 (6 cases).

DC3B.DAT

DATA SET E

Study: Crocker, WE
Investigation into the decompression tables.
VII. Sea trials of proposed new diving tables.
RNPL Report 2/57, Feb. 1957

<u>Pressure exposure</u>

Dry or wet	Wet (at sea)
Frequency of diving for individual subjects	> 24 hours
Descent rate	Variable; specified for each dive
Bottom depth	120, 140, 160 fswg; avg. = 128 fswg
how measured	Not specified; assume shot line; (Subtract 3 fswg from given depth to approximate diver chest depth.)
Bottom time	From 25 to 50 min; avg. = 34 min
Ascent rate	60 fswg/min

<u>Gas breathed</u> Air

<u>Other factors</u>

Exercise	Moderate work (cutting, searching)
Subject background	RN divers
Water temperature	Not specified; diving off Sicily

<u>Results</u>

How bends defined	Each case listed
Incidence of bends	7 treated; 2 "aches" (53 man dives)
Distribution of symptoms	Each case listed

Comments:
(1) Probably some deviation due to at-sea conditions. Each dive listed along with results and overshoots.
(2) Three dives (Nos. 1,5,28) not entered because of lack of sufficient data. None of those three had bends.
(3) Proposed tables were rejected as a result of this trial.

RNP257.DAT

DATA SET F

Study: Van Der Aue, OE et al.
The effect of exercise during decompression from increased barometric pressures on the incidence of decompression sickness in man
EDU Report 8-49, 1949

Pressure exposure

Dry or wet	Dry
Frequency of diving for individual subjects	Not specified
Descent rate	Not specified; assume 75 fsw/min
Bottom depth	100 and 150 fswg; avg. = 120 fswg
how measured	Manometer in chamber
Bottom time	From 27 to 60 min; avg. = 42 min
Ascent rate	25 fsw/min

Gas breathed — Air

Other factors

Exercise	Rest during dive; half rested postdive; half exercised
Subject background	US Navy divers

Results

How bends defined	"Bends" and "mild bends" (former were "severe enough to require recompression therapy"; latter were not treated)
Incidence of bends	From 0/8 to 16/32; overall 42 out of 141
Distribution of symptoms	Listed for each bends case

Comments:
(1) Purpose was to look at effect of postdive exercise.
(2) Sixty dives were also made in this trial at shallow depths (33-40 fswg) for 12 h and are not considered here.
(3) From the brief descriptions in text, almost all of the "mild bends" cases would receive recompression therapy by today's standards and were therefore graded as 1 rather than 0.5.

EDU849.DAT

DATA SET G

Study: Van Der Aue, OE et al.
Calculation and testing of decompression tables employing the procedure of surface decompression and the use of oxygen
EDU Report 13-51, 1951

Pressure exposure	
Dry or wet	Wet pot in chamber
Frequency of diving for individual subjects	Not specified
Descent rate	Not specified; assume 75 fsw/min
Bottom depth	40 to 210 fsw; avg. = 118 fsw
how measured	Not clear; assume four more feet than listed for wet pot
Bottom time	From 5 to 205 min; avg. = 35 min
Ascent rate	25 fsw/min
Gas breathed	Air
Other factors	
Exercise	Lifting and lowering lead bucket - "moderately heavy work"
Subject background	EDU divers
Water temperature	Avg.: 66.9 °F (listed for each)
Results	
How bends defined	Listed for each dive
Incidence of bends	9 of 143 dives

Comments: (1) Many "minor bends" cases not recompressed.
(2) Part of trial of present surface decompression tables with O_2. No dives with surface recompression included here.

ED1351N.DAT

DATA SET H

Study: Crocker, WE and Hempleman, HV
Investigation into the decompression tables. A method of calculating decompression stages and the formulation of new diving tables.
RNPL Report III, Part B, 1952

Pressure exposure

Dry or wet	Dry
Frequency of diving for individual subjects	Not specified
Descent rate	60 fsw/min
Bottom depth	50 to 300 fsw; avg. = 130 fsw
how measured	Not specified
Bottom time	From 11 to 90 min; avg. = 34 min
Ascent rate	60 fsw/min

Gas breathed — Air

Other factors

Exercise	Yes; type specified in paper
Subject background	"Divers, medical officers and civilian scientific staff"

Results

How bends defined	Not specified
Incidence of bends	1 of 192 dives
Distribution of symptoms	Elbow and knee

RNPL52B.DAT

Estimated Risk of USN Air Decompression Schedules

Depth (fsw)	Time, min (Bot)	(Decomp)	p(DCS) by Model/Data 1/AB	3/ABC	5/ABC	4/D	4/ABCD
35	310	0.6	0.118	0.118	0.125	0.080	0.094
40	200	0.7	0.071	0.071	0.075	0.043	0.052
50	100	0.8	0.015	0.016	0.012	0.011	0.008
60	60	1.0	0.000	0.002	0.005	0.017	0.010
70	50	1.2	0.000	0.002	0.006	0.022	0.013
80	40	1.3	0.000	0.002	0.006	0.028	0.016
90	30	1.5	0.000	0.003	0.005	0.033	0.019
100	25	1.7	0.000	0.003	0.005	0.038	0.022
110	20	1.8	0.000	0.003	0.005	0.042	0.024
120	15	2.0	0.000	0.003	0.005	0.043	0.025
130	10	2.2	0.000	0.003	0.005	0.038	0.023
140	10	2.3	0.000	0.003	0.005	0.043	0.026
150	5	2.5	0.000	0.004	0.004	0.025	0.016
160	5	2.7	0.000	0.004	0.004	0.028	0.017
170	5	2.8	0.000	0.004	0.005	0.030	0.019
180	5	3.0	0.000	0.004	0.005	0.033	0.020
190	5	3.2	0.000	0.004	0.005	0.036	0.022
40	210	2.7	0.080	0.079	0.083	0.049	0.059
40	230	7.7	0.095	0.094	0.100	0.059	0.072
40	250	11.7	0.110	0.110	0.118	0.073	0.087
40	270	15.7	0.125	0.124	0.134	0.085	0.101
40	300	19.7	0.146	0.145	0.158	0.104	0.122
50	110	3.8	0.024	0.024	0.017	0.010	0.011
50	120	5.8	0.034	0.034	0.029	0.014	0.017
50	140	10.8	0.056	0.056	0.056	0.029	0.037
50	160	21.8	0.077	0.077	0.081	0.047	0.057
50	180	29.8	0.098	0.098	0.106	0.065	0.078
50	200	35.8	0.119	0.118	0.131	0.084	0.099
50	220	40.8	0.139	0.139	0.154	0.103	0.120
50	240	47.8	0.160	0.159	0.175	0.120	0.139
60	70	3.0	0.004	0.005	0.003	0.014	0.008
60	80	8.0	0.013	0.013	0.007	0.009	0.006
60	100	15.0	0.037	0.037	0.033	0.017	0.021
60	120	27.0	0.064	0.064	0.066	0.039	0.046
60	140	40.0	0.090	0.090	0.098	0.062	0.072
60	160	49.0	0.116	0.116	0.130	0.086	0.099
60	180	57.0	0.143	0.143	0.161	0.111	0.128
60	200	71.0	0.169	0.168	0.186	0.133	0.154
70	60	9.2	0.005	0.006	0.002	0.013	0.007
70	70	15.2	0.016	0.016	0.010	0.011	0.008
70	80	19.2	0.030	0.031	0.026	0.017	0.017
70	90	24.2	0.046	0.046	0.046	0.028	0.032
70	100	34.2	0.062	0.062	0.064	0.041	0.047
70	110	44.2	0.078	0.077	0.081	0.053	0.061
70	120	52.2	0.094	0.093	0.101	0.066	0.076
70	130	59.2	0.110	0.109	0.120	0.079	0.092

Estimated Risk of USN Air Decompression Schedules

Depth (fsw)	Time, min (Bot)	(Decomp)	p(DCS) by Model/Data 1/AB	3/ABC	5/ABC	4/D	4/ABCD
70	140	65.2	0.126	0.125	0.139	0.093	0.109
70	150	71.2	0.143	0.142	0.159	0.110	0.128
70	160	86.2	0.157	0.156	0.170	0.118	0.138
70	170	99.2	0.172	0.171	0.183	0.129	0.151
80	50	11.3	0.003	0.004	0.002	0.016	0.009
80	60	18.3	0.015	0.016	0.009	0.015	0.010
80	70	24.3	0.032	0.032	0.028	0.022	0.021
80	80	34.3	0.050	0.050	0.049	0.033	0.036
80	90	47.3	0.070	0.069	0.071	0.045	0.053
80	100	58.3	0.089	0.088	0.094	0.061	0.071
80	110	67.3	0.107	0.107	0.117	0.078	0.090
80	120	74.3	0.127	0.126	0.141	0.097	0.112
80	130	83.3	0.147	0.146	0.163	0.116	0.133
80	140	96.3	0.166	0.165	0.183	0.132	0.152
80	150	110.3	0.183	0.182	0.200	0.147	0.168
90	40	8.5	0.000	0.002	0.001	0.024	0.013
90	50	19.5	0.011	0.012	0.006	0.019	0.011
90	60	26.5	0.028	0.029	0.024	0.024	0.021
90	70	38.5	0.051	0.051	0.049	0.034	0.037
90	80	54.5	0.073	0.073	0.076	0.050	0.057
90	90	67.5	0.095	0.094	0.102	0.069	0.079
90	100	76.5	0.116	0.116	0.129	0.090	0.102
90	110	86.5	0.139	0.138	0.155	0.111	0.126
90	120	101.5	0.161	0.160	0.178	0.131	0.149
90	130	116.5	0.184	0.183	0.202	0.150	0.171
100	30	4.7	0.000	0.001	0.001	0.033	0.019
100	40	16.7	0.004	0.005	0.002	0.023	0.013
100	50	27.7	0.021	0.021	0.014	0.022	0.016
100	60	38.7	0.045	0.045	0.043	0.032	0.033
100	70	57.7	0.070	0.070	0.073	0.051	0.056
100	80	72.7	0.095	0.095	0.102	0.073	0.081
100	90	84.7	0.119	0.119	0.132	0.093	0.105
100	100	97.7	0.146	0.145	0.163	0.117	0.134
100	110	117.7	0.172	0.172	0.189	0.139	0.159
100	120	132.7	0.197	0.196	0.217	0.163	0.185
110	25	4.8	0.000	0.002	0.001	0.037	0.022
110	30	8.8	0.000	0.002	0.001	0.033	0.019
110	40	24.8	0.010	0.011	0.004	0.025	0.014
110	50	35.8	0.034	0.034	0.029	0.028	0.025
110	60	55.8	0.062	0.062	0.063	0.047	0.050
110	70	73.8	0.089	0.089	0.095	0.070	0.076
110	80	88.8	0.118	0.117	0.130	0.092	0.104
110	90	107.8	0.148	0.148	0.163	0.119	0.135
110	100	125.8	0.177	0.176	0.195	0.146	0.166
120	20	4.0	0.000	0.002	0.002	0.043	0.025
120	25	8.0	0.000	0.002	0.001	0.038	0.022

Estimated Risk of USN Air Decompression Schedules

Depth (fsw)	Time, min (Bot)	(Decomp)	p(DCS) by Model/Data 1/AB	3/ABC	5/ABC	4/D	4/ABCD
120	30	16.0	0.001	0.003	0.002	0.032	0.018
120	40	32.0	0.019	0.019	0.011	0.026	0.017
120	50	48.0	0.048	0.048	0.046	0.039	0.038
120	60	71.0	0.079	0.078	0.082	0.062	0.067
120	70	89.0	0.110	0.110	0.121	0.088	0.097
120	80	107.0	0.144	0.143	0.160	0.118	0.133
120	90	132.0	0.175	0.174	0.191	0.145	0.163
120	100	150.0	0.205	0.205	0.227	0.176	0.197
130	15	3.2	0.000	0.002	0.003	0.045	0.027
130	20	6.2	0.000	0.002	0.001	0.044	0.025
130	25	12.2	0.000	0.002	0.002	0.038	0.022
130	30	23.2	0.004	0.005	0.001	0.031	0.018
130	40	37.2	0.029	0.029	0.023	0.031	0.024
130	50	63.2	0.063	0.063	0.064	0.051	0.053
130	60	86.2	0.097	0.097	0.104	0.077	0.084
130	70	103.2	0.133	0.132	0.147	0.111	0.123
130	80	131.2	0.169	0.168	0.185	0.141	0.158
130	90	154.2	0.204	0.203	0.225	0.173	0.195
140	15	4.3	0.000	0.002	0.002	0.048	0.028
140	20	8.3	0.000	0.002	0.001	0.046	0.026
140	25	18.3	0.000	0.002	0.000	0.036	0.021
140	30	28.3	0.008	0.009	0.003	0.033	0.019
140	40	46.3	0.041	0.041	0.037	0.038	0.035
140	50	76.3	0.078	0.077	0.080	0.064	0.067
140	60	97.3	0.116	0.115	0.128	0.097	0.105
140	70	125.3	0.156	0.155	0.171	0.130	0.145
140	80	155.3	0.195	0.195	0.214	0.164	0.185
150	10	3.5	0.000	0.002	0.003	0.044	0.027
150	15	5.5	0.000	0.002	0.001	0.051	0.030
150	20	11.5	0.000	0.001	0.000	0.044	0.025
150	25	23.5	0.003	0.004	0.001	0.037	0.021
150	30	34.5	0.014	0.015	0.008	0.034	0.020
150	40	59.5	0.053	0.053	0.051	0.048	0.045
150	50	88.5	0.093	0.093	0.099	0.077	0.082
150	60	112.5	0.135	0.135	0.150	0.115	0.127
150	70	146.5	0.179	0.179	0.196	0.151	0.169
150	80	173.5	0.219	0.218	0.242	0.191	0.213
160	10	3.7	0.000	0.002	0.003	0.048	0.029
160	15	7.7	0.000	0.001	0.000	0.050	0.029
160	20	16.7	0.000	0.001	0.000	0.042	0.024
160	25	29.7	0.006	0.007	0.002	0.038	0.022
160	30	40.7	0.022	0.022	0.015	0.034	0.023
160	40	71.7	0.065	0.065	0.065	0.058	0.057
160	50	98.7	0.109	0.108	0.119	0.094	0.100
160	60	132.7	0.156	0.155	0.170	0.132	0.146
170	10	4.8	0.000	0.002	0.002	0.050	0.030

Estimated Risk of USN Air Decompression Schedules

Depth (fsw)	Time, min (Bot)	(Decomp)	p(DCS) by Model/Data 1/AB	3/ABC	5/ABC	4/D	4/ABCD
170	15	9.8	0.000	0.001	0.000	0.050	0.029
170	20	21.8	0.000	0.002	0.000	0.043	0.025
170	25	34.8	0.011	0.011	0.004	0.037	0.021
170	30	45.8	0.030	0.031	0.024	0.038	0.029
170	40	81.8	0.077	0.076	0.079	0.068	0.069
170	50	109.8	0.124	0.124	0.137	0.109	0.117
170	60	152.8	0.179	0.178	0.196	0.153	0.170
180	10	6.0	0.000	0.002	0.001	0.052	0.031
180	15	12.0	0.000	0.001	0.000	0.050	0.029
180	20	26.0	0.002	0.003	0.000	0.043	0.024
180	25	40.0	0.017	0.017	0.009	0.037	0.023
180	30	53.0	0.040	0.040	0.036	0.046	0.038
180	40	93.0	0.090	0.090	0.095	0.080	0.082
180	50	128.0	0.144	0.143	0.158	0.124	0.135
180	60	168.0	0.197	0.196	0.215	0.171	0.189
190	10	7.2	0.000	0.002	0.000	0.052	0.031
190	15	14.2	0.000	0.001	0.000	0.050	0.029
190	20	31.2	0.004	0.005	0.001	0.043	0.025
190	25	44.2	0.023	0.024	0.016	0.039	0.027
190	30	63.2	0.050	0.049	0.047	0.053	0.046
190	40	103.2	0.104	0.103	0.112	0.092	0.095
190	50	147.2	0.163	0.162	0.176	0.139	0.153
190	60	183.2	0.217	0.216	0.239	0.192	0.212
200	5	4.3	0.000	0.003	0.003	0.036	0.022
200	10	8.3	0.000	0.002	0.000	0.054	0.032
200	15	18.3	0.000	0.001	0.000	0.047	0.027
200	20	40.3	0.008	0.008	0.002	0.043	0.025
200	25	49.3	0.031	0.031	0.025	0.044	0.033
200	30	73.3	0.059	0.058	0.057	0.060	0.055
200	40	112.3	0.117	0.116	0.128	0.104	0.109
200	50	161.3	0.180	0.180	0.196	0.157	0.172
200	60	199.3	0.236	0.235	0.262	0.213	0.234
200	90	324.2	0.378	0.377	0.417	0.364	0.396
200	120	473.2	0.458	0.459	0.453	0.406	0.446
200	180	685.2	0.548	0.550	0.449	0.422	0.473
200	240	842.2	0.593	0.596	0.402	0.394	0.456
200	360	1058.3	0.634	0.639	0.302	0.308	0.388
210	5	4.5	0.000	0.003	0.003	0.039	0.024
210	10	9.5	0.000	0.001	0.000	0.054	0.032
210	15	22.5	0.000	0.001	0.000	0.048	0.028
210	20	40.5	0.012	0.013	0.005	0.043	0.024
210	25	56.5	0.039	0.039	0.034	0.049	0.039
210	30	81.5	0.068	0.068	0.068	0.068	0.064
210	40	124.5	0.131	0.130	0.144	0.117	0.124
210	50	174.5	0.197	0.196	0.215	0.174	0.191
220	5	5.7	0.000	0.002	0.001	0.039	0.024

Appendix 3

Estimated Risk of USN Air Decompression Schedules

Depth (fsw)	Time, min (Bot)	(Decomp)	p(DCS) by Model/Data 1/AB	3/ABC	5/ABC	4/D	4/ABCD
220	10	10.7	0.000	0.002	0.000	0.056	0.033
220	15	26.7	0.000	0.001	0.000	0.049	0.028
220	20	42.7	0.017	0.017	0.009	0.044	0.027
220	25	66.7	0.047	0.047	0.043	0.054	0.046
220	30	91.7	0.079	0.078	0.081	0.075	0.073
220	40	140.7	0.147	0.146	0.159	0.130	0.139
220	50	190.7	0.213	0.212	0.232	0.188	0.207
230	5	5.8	0.000	0.002	0.002	0.042	0.025
230	10	12.8	0.000	0.001	0.000	0.053	0.031
230	15	30.8	0.001	0.003	0.000	0.049	0.028
230	20	48.8	0.023	0.023	0.015	0.044	0.029
230	25	74.8	0.054	0.054	0.051	0.061	0.053
230	30	99.8	0.089	0.088	0.093	0.084	0.083
230	40	156.8	0.161	0.160	0.172	0.141	0.152
230	50	202.8	0.229	0.229	0.253	0.208	0.227
240	5	6.0	0.000	0.003	0.002	0.044	0.027
240	10	14.0	0.000	0.001	0.000	0.054	0.032
240	15	35.0	0.003	0.004	0.001	0.049	0.028
240	20	53.0	0.029	0.029	0.022	0.048	0.034
240	25	82.0	0.063	0.062	0.061	0.067	0.061
240	30	109.0	0.099	0.099	0.105	0.093	0.093
240	40	167.0	0.177	0.176	0.191	0.157	0.170
240	50	218.0	0.246	0.246	0.272	0.225	0.246
250	5	7.2	0.000	0.002	0.000	0.043	0.026
250	10	16.2	0.000	0.001	0.000	0.054	0.031
250	15	38.2	0.006	0.006	0.001	0.049	0.028
250	20	59.2	0.036	0.036	0.030	0.052	0.039
250	25	92.2	0.072	0.072	0.072	0.073	0.068
250	30	116.2	0.109	0.108	0.117	0.103	0.104
250	40	178.2	0.191	0.190	0.207	0.170	0.185
250	60	298.2	0.334	0.334	0.370	0.319	0.347
250	90	514.2	0.467	0.468	0.456	0.411	0.452
260	5	7.3	0.000	0.002	0.000	0.045	0.027
260	10	19.3	0.000	0.001	0.000	0.051	0.030
260	15	42.3	0.009	0.009	0.003	0.047	0.027
260	20	67.3	0.042	0.042	0.037	0.056	0.044
260	25	99.3	0.080	0.080	0.081	0.080	0.076
260	30	126.3	0.121	0.120	0.130	0.112	0.115
260	40	190.3	0.204	0.203	0.221	0.183	0.199
270	5	8.5	0.000	0.002	0.000	0.046	0.028
270	10	22.5	0.000	0.001	0.000	0.051	0.030
270	15	46.5	0.012	0.013	0.005	0.047	0.027
270	20	74.5	0.048	0.048	0.044	0.060	0.050
270	25	106.5	0.090	0.089	0.093	0.087	0.085
270	30	138.5	0.134	0.133	0.145	0.124	0.129
270	40	204.5	0.220	0.219	0.240	0.197	0.215

Estimated Risk of USN Air Decompression Schedules

Depth (fsw)	Time, min (Bot)	(Decomp)	p(DCS) by Model/Data 1/AB	3/ABC	5/ABC	4/D	4/ABCD
40	360	23.7	0.187	0.187	0.204	0.142	0.164
40	480	41.7	0.244	0.244	0.258	0.189	0.215
40	720	69.7	0.308	0.309	0.304	0.227	0.259
60	240	82.0	0.222	0.222	0.256	0.197	0.221
60	360	140.0	0.325	0.325	0.360	0.292	0.324
60	480	193.0	0.386	0.387	0.398	0.328	0.365
60	720	266.0	0.451	0.453	0.414	0.339	0.384
80	180	121.3	0.240	0.239	0.279	0.219	0.243
80	240	179.3	0.318	0.318	0.358	0.298	0.329
80	360	280.2	0.420	0.420	0.431	0.372	0.410
80	480	354.2	0.480	0.481	0.455	0.397	0.440
80	720	455.2	0.529	0.532	0.416	0.360	0.414
100	180	202.7	0.317	0.316	0.358	0.302	0.331
100	240	283.7	0.394	0.394	0.420	0.366	0.401
100	360	416.7	0.489	0.490	0.462	0.417	0.460
100	480	503.7	0.541	0.543	0.461	0.419	0.468
100	720	613.7	0.585	0.588	0.402	0.370	0.432
120	120	176.0	0.262	0.262	0.302	0.245	0.271
120	180	284.0	0.384	0.384	0.421	0.368	0.401
120	240	396.0	0.457	0.458	0.458	0.410	0.450
120	360	551.0	0.537	0.539	0.457	0.425	0.473
120	480	654.0	0.578	0.581	0.419	0.401	0.459
120	720	773.0	0.617	0.621	0.348	0.339	0.411
140	90	166.3	0.233	0.232	0.268	0.214	0.237
140	120	240.3	0.320	0.320	0.360	0.305	0.335
140	180	386.2	0.436	0.436	0.447	0.396	0.435
140	240	511.2	0.504	0.505	0.464	0.422	0.467
140	360	684.2	0.571	0.574	0.426	0.407	0.464
140	480	801.2	0.603	0.607	0.363	0.361	0.429
140	720	924.2	0.639	0.644	0.297	0.296	0.377
160	70	166.7	0.203	0.202	0.223	0.175	0.195
170	70	183.8	0.224	0.224	0.248	0.197	0.219
170	90	246.8	0.307	0.306	0.345	0.292	0.320
170	120	356.7	0.393	0.393	0.415	0.363	0.399
170	180	535.7	0.501	0.502	0.465	0.423	0.467
170	240	681.7	0.555	0.557	0.442	0.416	0.469
170	360	873.7	0.609	0.613	0.366	0.367	0.435
170	480	1007.7	0.632	0.636	0.292	0.294	0.375
280	5	8.7	0.000	0.002	0.000	0.047	0.028
280	10	25.7	0.000	0.001	0.000	0.050	0.029
280	15	49.7	0.016	0.016	0.009	0.047	0.028
280	20	81.7	0.055	0.054	0.051	0.065	0.055
280	25	113.7	0.099	0.098	0.104	0.096	0.095
280	30	150.7	0.145	0.144	0.154	0.131	0.138
280	40	218.7	0.234	0.233	0.255	0.211	0.230
290	5	9.8	0.000	0.002	0.000	0.047	0.028

Appendix 3

Estimated Risk of USN Air Decompression Schedules

Depth (fsw)	Time, min (Bot)	(Decomp)	p(DCS) by Model/Data 1/AB	3/ABC	5/ABC	4/D	4/ABCD
290	10	29.8	0.000	0.001	0.000	0.050	0.029
290	15	52.8	0.020	0.020	0.013	0.048	0.030
290	20	89.8	0.062	0.062	0.059	0.069	0.061
290	25	120.8	0.107	0.106	0.113	0.103	0.102
290	30	162.8	0.157	0.156	0.166	0.141	0.149
290	40	228.8	0.248	0.247	0.272	0.227	0.247
300	5	11.0	0.000	0.002	0.000	0.047	0.028
300	10	32.0	0.000	0.001	0.000	0.051	0.030
300	15	57.0	0.026	0.025	0.018	0.050	0.034
300	20	97.0	0.070	0.070	0.069	0.074	0.068
300	25	129.0	0.117	0.116	0.125	0.111	0.112
300	30	172.0	0.168	0.167	0.178	0.151	0.160
300	40	231.0	0.265	0.265	0.300	0.255	0.275
300	60	460.0	0.410	0.410	0.406	0.359	0.396
250	120	684.2	0.535	0.537	0.453	0.421	0.470
250	180	931.2	0.601	0.604	0.381	0.377	0.443
250	240	1109.1	0.632	0.636	0.307	0.313	0.392
300	90	693.0	0.531	0.532	0.451	0.420	0.468
300	120	890.0	0.583	0.586	0.399	0.388	0.449