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STATISTICALLY BASED DECOMPRESSION TABLES IV: EXTENSION TO AIR AND N_2-O_2 SATURATION DIVING.

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This technical report has been reviewed by the NMRI scientific and public affairs staff and is approved for publication. It is releasable to the National Technical Information Service where it will be available to the general public, including foreign nations.

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Recent analyses have examined empirical, but statistically justifiable, models for "standard" air diving and used the results to develop air decompression schedules that are equal in risk. This analysis has been extended by examining air and N_2-O_2 saturation decompression. Some 279 exposures satisfied the rigid criteria for use as data. These exposures were analyzed alone and in combination with the earlier data by a number of gas exchange models. Several models with 2 or 3 gas exchange "tissues" were found to fit the data well. One of these models was chosen to produce "optimum" stage and continuous decompression schedules at a 1% chance of decompression sickness (DCS) for air, and for two constant PO_2 mixtures at saturation depths down to 100 feet of seawater (fsw). For the same low predicted incidence of DCS, continous decompression requires many fewer hours than needed for 10 or 5 foot staged decompression. Although the most powerful use of available data supports these schedules, they need testing to verify the actual incidence of DCS.

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BACKGROUND

Report I of this series (Weathersby et al., 1985a) evaluated the results of applying several empirical decompression models to more than 1,700 reported dives. Those empirical models were a break with previous methods because a probabilistic formalism was adopted and a statistical evaluation of model success was conducted. The models are quite empirical because no specific knowledge is presumed regarding mechanisms of bubble formation, growth, etc. Nevertheless, the models were shown to be successful in summarizing a large number of decompression trials and in separating dives according to their risk of DCS. The statistical models did not consider variations in diver workload, environment (e.g., wet vs. dry), or acclimatization. The success in that analysis encouraged us to produce Report II; new sets of air decompression tables characterized by an equal chance of DCS (Weathersby et al., 1985b). The method is extended in the present report to examine the known outcome of 279 air and N_2-O_2 saturation dives using the same and similar empirical models.

MODELS

The candidate models are detailed in Report I of this series, so only a brief review is presented here. Evaluation of the safety of a dive is accomplished by relating the entire dive profile to the probability of DCS by a "risk function":

$$p(DCS) = 1.0 - \exp(-\int_0^t r \, dt') \qquad [1]$$

Here, r is one of several measures of instantaneous risk that is integrated over the entire duration of a dive, including the post dive period.

All models applied to the data from air subsaturation dives for Report I were also applied to the saturation data in this report. The first of these is expresed as:

Model 1: $r_1 = A\ (\ Ptis - Pamb)\ /\ Pamb$ [2]

Ptis by monexponential; time constant = T

2 parameters: A, T

Ptis, a tissue inert gas partial pressure calculated by treating the tissue as a single, well mixed compartment, is compared to Pamb, the current ambient pressure. As is common in decompression calculations, the metabolic gases O_2 and CO_2 and water vapor are ignored. Whenever Ptis is less than Pamb, r_1 is set to zero. The risk r_1 is proportional to the supersaturation with a proportionality parameter A in units of min^{-1} (T in min). The appearance of Pamb in the denominator follows from previous work with deep saturation/ excursion data (Weathersby, Homer, and Flynn, 1984) where it was shown that a significant decrease in DCS occurred if the same supersaturation was created at deeper depths.

The next model adds a threshold parameter, PTHR, permitting the possibility that a supersaturation can be sustained indefinitely without risk of DCS:

Model 2: $r_2 = A\ (\ Ptis - Pamb - PTHR)\ /\ Pamb$ [3]

Ptis by monexponential; time constant = T

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. 1.

Model 1 can be generalized to include a parallel "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. This model is expressed by:

Model 3: $r_3 = r_{3A} + r_{3B}$, where [4]

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

PtisA by monoexponential; time constant = TA

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

PtisB by monoexponential; time constant = TB

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 [5]

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

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

As before, negative values of r_{3A}, r_{3B}, r_{4A}, and r_{4B} are not allowed. An alternative to the "two tissue" model is one in which more complex gas exchange kinetics are used. The gas residence time function (rtf) (Weathersby et al., 1979; Weathersby et al., 1981) is an empirical multi- exponential description of gas exchange in a single tissue that has three kinetic parameters, one of which is a weighting constant, rather than the one kinetic parameter of a single exponential. This model is described by:

Model 5: r_5 = A (Ptis - Pamb) / Pamb [6]

Ptis by 2 exponentials; time constants = T1 and T2

Fraction of rtf by T1 is W1;

Fraction of rtf by T2 is 1 - W1;

4 parameters: A, T1, T2, W1

This model performed well on the more than 1,700 air decompression dives in Report I, and was used in the calculation of the new air decompression tables in Report II.

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 [7]

Ptis by 2 exponentials; time constants = T1 and T2

Fraction of rtf by T1 is W1;

Fraction of rtf by T2 is 1 - W1;

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

Models 1 through 6 were used to examine the air decompression data in the previous reports.

Figure 1 illustrates how the models apply. Ambient pressure was plotted as a solid line; the dash-dot line represents the calulated tissue PN_2 according to model 5 throughout the dive; the dashed line is the integral in Eqn. [1] that rose in value whenever the value of r in the model was greater than 0. This particular dive was from the saturation data set, with 2 cases of DCS in 2 trials, and a total decompression time of 574 min.

PROCEDURE

The data were entered on a computer (PDP 11/70) as a single entry per man- dive following the procedure in Reports I and II. Data entry included all depths and times of gas or pressure ramp change and gas switch times. As before, marginal symptoms were entered as 1/2 case of DCS (Weathersby, Homer, Flynn 1984, Report I).

A period of 24 h post-surfacing was included to assure return of (Ptis - Pamb) to zero (6 h was sufficient in Report I). Each model, Eqns. [2-7], was used to calculate p(DCS) 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. Parameter standard errors

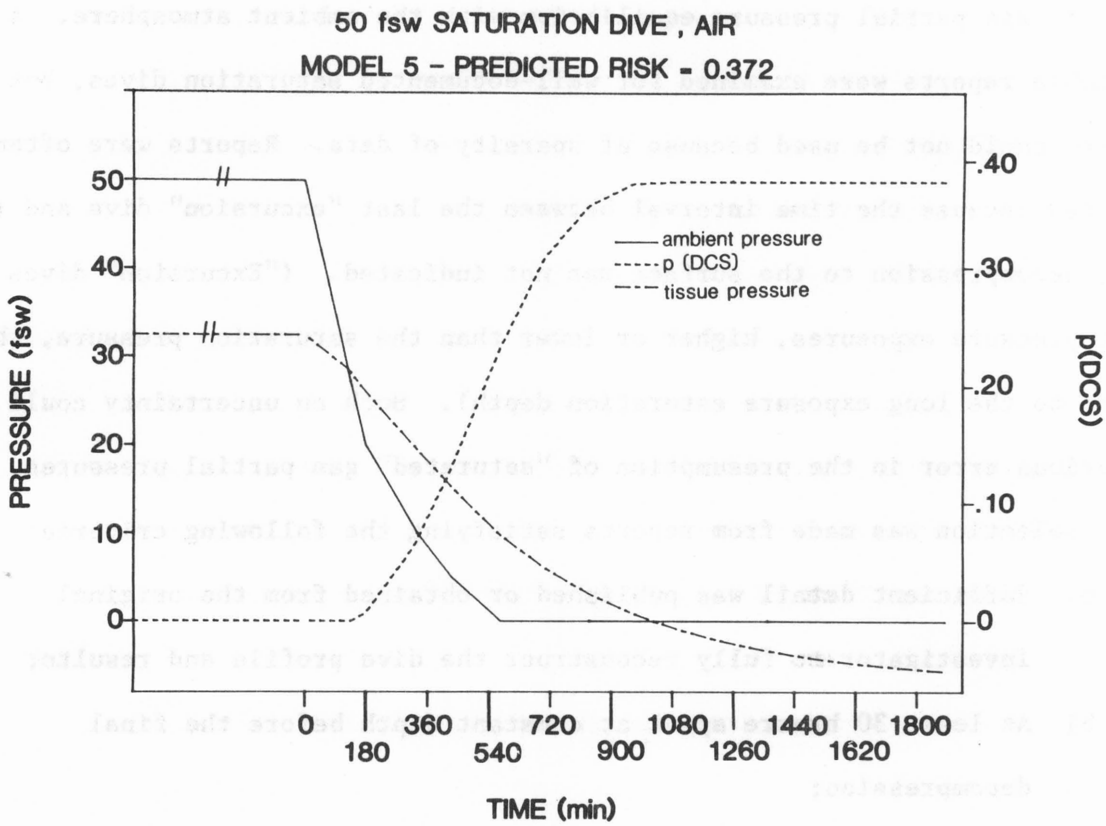

Fig. 1. Example of risk calculation. On a 50 foot saturation dive the tissue partial pressure of nitrogen starts at 32 fsw and declines throughout decompression according to the kinetics in model 5. At 130 min into the decompression, tissue pressure exceeds the ambient and stays higher until 1025 min. During that interval the probability of DCS increases according to Eqn. 1.

(Kendall and Stuart, 1979) reported in the following tables are asymptotic estimates.

SATURATION DECOMPRESSION DATA

Saturation dives are of such duration that all body tissues are assumed to be in gas partial pressure equilibrium with the ambient atmosphere. All available reports were examined for well-documented saturation dives, but most reports could not be used because of sparsity of data. Reports were often rejected because the time interval between the last "excursion" dive and the final decompression to the surface was not indicated. ("Excursion" dives are short pressure exposures, higher or lower than the saturation pressure, that return to the long exposure saturation depth). Such an uncertainty could lead to serious error in the presumption of "saturated" gas partial pressures. Final selection was made from reports satisfying the following criteria:

a) Sufficient detail was published or obtained from the original investigator to fully reconstruct the dive profile and results;

b) At least 30 h were spent at constant depth before the final decompression;

c) The breathing mixture during the saturation and decompression was air or N_2-O_2 of known composition. (Dives using 100% O_2 were excluded pending a more complete examination of how O_2 contributes to decompression stress).

The dive conditions of the 279 exposures that met these criteria are presented in Table 1. Appendix 1 provides more experimental detail of the reported dives. Prominent omissions from this list include: SHAD III (Hamilton et al., 1982) failed criterion b; PREDICTIVE STUDIES (Lambertsen and Bardin, 1973) failed criterion c; and the Swiss studies (Buhlmann et al., 1967) failed criterion a. The OI/NOAA dive (observations 276-279) was

TABLE 1

Saturation Data Summary

OBS#	DIVES	BENDS (marg)	DEPTH (fsw)	GAS	DEC.TIME (min)	REFERENCE SOURCE	
1,2	2	2	50	Air	574.0	Pre-SHAD (Hamilton et al., 1982)	
3,4	2	0	50	Air	810.0	SHAD-I (")	
5,6	2	0	60	Air	1690.0	SHAD-II (")	
7-9	3	0	198	.3ATA	9703.0	NISAT-I (")	
10-54	45	0	23.1	.4ATA	2.5	ISLANDER (Bell, 1984)	
55-79	25	4	26.4	.4ATA	2.5	" (")	
80-99	19	0(5)	25.5	Air	1.0	MINISAT (Eckenhoff, 1985)	
99-113	15	4(3)	29.5	Air	1.0	" (")	
114-123	10	4	60	.5ATA	1260.0	TT-7 Trial (Thalmann, 1985)	
124-126	3	3	60	Air	1620.0	" (")	*
127-136	10	1	60	Air	1620.0	" (")	
137	1	1	60	Air	740.0	" (")	**
138-148	11	1	60	Air	1621.0	" (")	
149-158	10	0	60	18%02	1762.0	" (")	
159-168	10	1	60	18%02	1762.0	" (")	
169-178	10	0	60	18%02	2162.0	" (")	
179-187	9	0(1)	60	Air	1840.0	" (")	
188	1	0	60	Air	1840.0	" (")	
189-199	11	1	60	Air	1200.0	AIRSAT 1 (Eckenhoff, Vann, 1985)	
200-211	12	2	60	Air	1200.0	AIRSAT 2 (")	
212-235	24	6	60	Air	1035.0	(Philp et al., 1979)	
236-238	3	0	111	.4ATA	4010.0	AIRSAT 5A (Harvey, 1985)	
239-241	3	0	111	.4ATA	4010.0	AIRSAT 5B (")	
242-244	3	0	111	.4ATA	3710.0	AIRSAT 5C (")	
245	1	1	111	.4ATA	2515.0	AIRSAT 5D (")	**
246-248	3	3	111	.4ATA	2.0	AIRSAT 5E (")	**
249-252	4	1	111	.4ATA	3710.0	AIRSAT 5F (Harvey, 1986)	***
253-255	3	3	111	.4ATA	2.0	AIRSAT 5G (")	**
256,257	2	0	203	.4ATA	7860.0	BISAT82 (Withey, Florio, 1985)	
258-275	18	1	132	.5ATA	3908.0	AIRSAT 4 (Eckenhoff, Vann, 1985)	
276-279	4	4	165	.5ATA	3911.0	OI/NOAA (Barry et al., 1984)	**

Notes:

Gas entry when not air refers to the pre-decompression oxygen concentration or partial pressure.

* Seven dives excluded due to recompressions. See text.

** Nineteen dives excluded due to recompressions. Dives truncated at last depth before recompression. See text.

*** One Dive truncated at last depth before recompression.

included as an exception to criterion b. Storage depth for this dive was 165 fsw with a breathing mixture of 0.5 ATA pO_2. Daily excursions were made to 200 fsw on air. Because the nitrogen level on the excursions and at storage depth was the same, this dive was entered as if they had remained at a constant depth throughout the entire dive.

Two problems arose in attempting to analyze some of the dives in the same manner as Report I (* in Table 1). Because of the nature of saturation diving, unaffected divers are sometimes recompressed along with those being treated for DCS. Since symptoms of DCS may manifest themselves many hours after surfacing, it is possible that these clinically well, but recompressed, divers might have developed DCS later. The outcome of their planned dive to the surface is simply unknown, and the partially completed dive was not included in this data set. This occurred with all of the dives flagged in Table 1. The two NEDU TT-7 trials that are flagged had ten divers on each team, AIRSAT 5D had three divers, AIRSAT 5E and 5G had four divers, and the OI/NOAA dive had a 10 diver team. Only 18 divers total appear in Table 1 for these dives. The 26 divers excluded from Table 1 were recompressed before the final outcome of their dive could be determined. If the recompressed divers were included in the data set and counted as not having DCS, they would prejudice predictions of the probability of DCS by making the dives appear safer than they might actually be.

The other problem arose in dealing with subjects who were recompressed before reaching surface pressure (1 ATA) and declared to have DCS. This occurred in the last six dives flagged in Table 1. For purposes of calculating the risk of DCS their recompression was ignored, and the data were entered as if the divers had remained at the last pressure before recompression. Twenty-four hours were added at the final pressure to assure inclusion of all risk accumulated at that pressure, just as 24 h were included at 1 ATA at the conclusion of all other dives.(In data for Report I, the same procedure was followed, but the shorter dives in that case required less than 24 h.)

Full use of maximum likelihood estimation technique could in principle treat all of the problem dives as they actually occurred, even though defining the probability of the different outcomes would be complex. That goal was not attained in this report for several reasons. The risk model used in estimation is capable of accepting "truncated" observations where the decompression was interrupted for treatment. We chose not to truncate the risk calculation at the appearance time of symptoms, nor have we yet put the time of occurrence to full use. These questions as well as use of high oxygen breathing and recompression invoke conceptual and numerical problems that need careful study in the future, as discussed in Report I. We accept as conflicting biases the possibility that divers ignored because of unnecessary recompression would be free of symptons, while divers treated before surfacing might have accumulated more risk by our models if they had been allowed to continue their planned dives.

RESULTS

Models 1-6, along with a null model that assumes a constant probability irrespective of details of the dive, were applied to the 279 saturation dives previously described (Table 2). Each model achieved a much better LL than that of the null model. Therefore, all are a better description of the data than Model 0. Models 2 and 5 each performed equally well, but Model 5 encountered severe numerical problems that made achieving a final set of paramenters difficult. Model 6 degenerated into Model 2 by placing all of the weight on T2 by making W2 arbitrarily large, and had an almost identical LL as Model 2. Statistical significance between models that are subsets of a more general model, such

TABLE 2

Results of Fitting Models To Air Saturation Data

Model	Parameter (1 SE)	Log Likelihood
0. constant p	C = 0.1667	-125.707
1. 1-exp, no thresh	T = 447 (22), A = 2.50 (0.52) $\cdot 10^{-3}$	-119.636
2. 1-exp, thresh	T = 649 (55), A = 5.06 (1.21) $\cdot 10^{-3}$, PTHR = 6.01 (1.18)	-113.534
3. 2-exp, no thresh	TA = 0.49 (.20) AA = 18.20 (38) TB = 490 (51) AB = 1.53 (0.54) $\cdot 10^{-3}$	-115.526
4. 2-exp, thresh	TA = 609 (56), AA = 1.33 (0.42) $\cdot 10^{-2}$, TB = 1194 (769), AB = 3.15 (6.5) $\cdot 10^{-4}$, PTHR = 8.44 (1.10)	-109.012
5. 2-exp, rtf, no thresh	T1 = 19 (397), T2 = 514 (188), W1 = .834 (1.00), A = 3.11 (1.54) $\cdot 10^{-3}$	-119.376
6. 2-exp, rtf, thresh	no unique W1	

n = 279

T (TA, T1, etc.) are in min; A (AA, A1, etc.) are in min-1; PTHR is in fsw; W1 and C are dimensionless.

Models 3 and 4, may be assessed by the likelihood-ratio test (Kendall and Stuart, 1979). Twice the difference of the log likelihoods between two models is compared to chi-square distribution. Degrees of freedom for the test correspond to the number of parametric constraints in the hypothesis being tested. In the case of models 3 and 4,

$$2(-109.012 - (-116.947)) = 15.870,$$

which is greater than the $p < 0.05$ limit of chi-square for one degree of freedom (3.84), and so the improvement with Model 4 was significant. It is not possible to compare Models 4 and 5 in this fashion, because the models are not a subset of a more general model.

The air saturation exposures and decompression times found in the data used in this report are considerably longer than the exposures found in the subsaturation data used for Reports I and II. Thus, it is no big surprise that the time constants found in Table 2 are consistently longer than those reported in Table 6 of Report I. For example, TA and TB for Model 4 in Report I were 6.17 min and 260 min, respectively, whereas TA is 609 min and TB is 1194 min for the saturation data. However, there was some consistency in the fitting of the models to the different data sets. In Report I and in this report, Model 4 showed the best likelihood, but had a substantial threshold (5.03 fsw and 8.44 fsw, respectively).

Results from these models as applied to the saturation data were grouped by their predictions of DCS probability into 0-5%, 5-15%, 15-25%, and > 25% intervals to show the way in which they separate the data by DCS risk. The results of this process are depicted in Fig. 2. Reference to binomial distribution confidence limits (Diem, 1962) provide 95% confidence limits for the observed incidence of DCS. The limits are quite broad because each group had a small number of observations. The dotted line represents the line of "perfect" agreement, i.e. predicted probability of DCS is equal to the

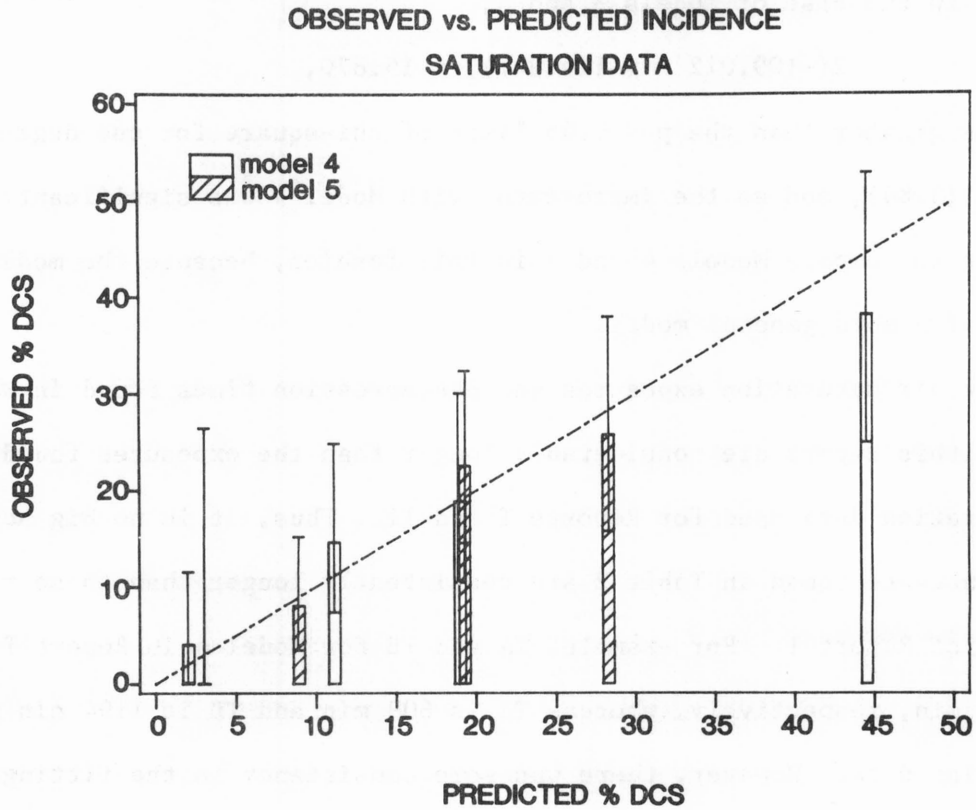

Fig. 2. Bar graph comparing predictions of models 4 and 5 and actual outcome in various risk categories for the saturation data of 279 dives. For each of the 4 categories (< 5%, 5-15%, 15-25%, and > 25%) a bar is plotted at the x-axis position of the average predicted incidence. Bar height is the actual incidence for each prediction category. Error bars are 95% confidence limit for binomial outcome. The dash-dot line corresponds to perfect prediction.

observed probability. Model 4 predicted a somewhat lower incidence of DCS in the 0-5% and 5-15% intervals than actually encountered, and a higher incidence than encountered in the > 25% range. Model 5 predicted a lower incidence in the 15-25% interval than observed, and a higher incidence in the 0-5% and > 25% ranges. However, both models exhibited a high degree of agreement with observed DCS hazard throughout the entire data set. No groups of predictions are contradicted by being outside the confidence limits of the data.

Several problems were encountered in applying these models to the data. T1 and W1 in Model 5 were highly correlated (r > .99), which means that the maximum likelihood algorithm had difficulty in separating the effects of these two parameters in fitting the data. This was also the case with TA and AA in Model 3. Another problem occurred when we attempted to estimate upper and lower bounds on p(DCS) predictions of Models 3-5 through a propagation of error technique (Ku,1968). To derive these upper and lower bounds for a particular dive, the partial derivative of each parameter is numerically calculated. The error is then found by summing all possible products of these partial derivatives taken in pairs with the corresponding entry in the covariance matrix, which is part of the output from the maximum likelihood algorithm. The upper bound on predicted p(DCS) for some of the dives in the original data set exceeded 1, indicating a large degree of uncertainty in the results. Such large uncertainty usually means an original data set is too small or not well suited for evaluation of the model.

DATA COMBINATION

It would be ideal if a single model could describe a wide range of decompression data. This objective, together with the numerical problems encountered in estimation using only the limited amount of saturation data, encouraged us to pursue the possibility of estimating parameters using a combination of the present saturation data and the previously studied subsaturation air decompression data.

We wished to determine if Model 5, the model used for the final tables in Report II, considered saturation dives and air subsaturation dives similar events. That is, we needed to know if the combination of air subsaturation dives and saturation data greatly decreased the agreement of the model with either set of data. In early attempts to fit the combined data using Model 5, the large number of air dives seemed to overwhelm the smaller saturation subset, that is, the values of the parameters seemed to closely resemble the values obtained for the air data alone.

In an attempt to determine whether or not these data could be combined under the model, we randomly subdivided the 1,713 air decompression dives into 6 sets of 250 dives each without repetition. This selection was made because 250 was the size of the saturation data set at the time of this test (close, but not identical, to the data in Table 1). Model 5 was applied first to the air subsets, and then to a combination of each air subset and the saturation data. The likelihood-ratio test previously described was applied to these results. In this case, the likelihood-ratio compares the fits for the combination of one of these subsets with the saturation data to the fits for each subset alone. The resulting test statistic can then be compared to the chi-square distribution at 4 degrees of freedom to determine if there is a difference between estimating the data sets separately and in combination. In half of the six subsets, the likelihood-ratio test statistic was greater than the chi-square limit for $p < 0.01$ with 4 degrees of freedom (13.277), and in another case was greater than the limit for $p < 0.05$ (9.488). Therefore, the selected short dives and the saturation data are not combinable under Model 5. The question of whether these subsets were combinable under other models was not examined. In other words, the addition of short air diving data decreased the ability of Model 5 to describe the saturation data, and was therefore not a good candidate as a model for the combination of the two sets.

MODELS OF ALL DIVES

A new model was sought to describe the combination of the short air decompression and saturation data. Four new models (numbered 7-10) were developed in a fashion similar to the development of the first 6 models. As in previous models, only positive or zero values of instantaneous risk were allowed in each "tissue."

Model 3 was extended to include "three tissues" in parallel rather than the "two tissues" previously described. No DCS is the joint probability of no DCS in all three tissues. The new model is expressed by:

Model 7: $r_7 = r_{7A} + r_{7B} + r_{7C}$, where [8]

r_{7A} = AA (PtisA - Pamb) / Pamb

PtisA by monoexponential; time constant = TA

r_{7B} = AB (PtisB - Pamb) / Pamb

PtisB by monoexponential; time constant = TB

r_{7C} = AC (PtisC - Pamb) / Pamb

PtisC by monoexponential; time constant = TC

6 parameters: AA, TA, AB, TB, AC, TC

Once again, a threshold parameter can be added:

Model 8: $r_8 = r_{8A} + r_{8B} + r_{8C}$, where [9]

r_{8A} = AA (PtisA - Pamb - PTHR) / Pamb

PtisA by monoexponential; time constant = TA

r_{8B} = AB (PtisB - Pamb - PTHR) / Pamb

PtisB by monoexponential; time constant = TB

r_{8B} = AC (PtisC - Pamb - PTHR) / Pamb

PtisC by monoexponential; time constant = TC

7 parameters: AA, TA, AB, TB, AC, TC, PTHR

Model 5 was extended by creating a "two tissue" model, each tissue having the more complex rtf gas exchange kinetics:

Model 9: $r_9 = r_{9A} + r_{9B}$, where [10]

$r_{9A} =$ AA (PtisA - Pamb) / Pamb

PtisA by 2 exponentials; time constants = T1A and T2A

Fraction of rtf by T1A is W1A;

Fraction of rtf by T2A is 1 - W1A;

$r_{9B} =$ AB (Ptis - Pamb) / Pamb

PtisB by 2 exponentials; time constants = T1B and T2B

Fraction of rtf by T1B is W1B;

Fraction of rtf by T2B is 1 - W1B;

8 parameters: AA, T1A, T2A, W1A, AB, T1B, T2B, W1B

Adding a threshold parameter yields:

Model 10: $r_{10} = r_{10A} + r_{10B}$, where [11]

$r_{10A} =$ AB (PtisA - Pamb - PTHR) / Pamb

PtisA by 2 exponentials; time constants = T1A and T2A

Fraction of rtf by T1A is W1A;

Fraction of rtf by T2A is 1 - W1A;

$r_{10B} =$ AB (PtisB - Pamb - PTHR) / Pamb

PtisB by 2 exponentials; time constants = T1B and T2B

Fraction of rtf by T1B is W1A + W1B;

Fraction of rtf by T2B is 1 - W1B;

9 parameters: AA, T1A, T2A, W1A, AB, T1B, T2B, W1B, PTHR

A comparison of the parameters and likelihood values for each model as applied to the combination of the shorter air dives and the saturation data is given in Table 3. Models 1 and 2 did worse than the null model, which ignores

TABLE 3

Results of Fitting Models To Air Saturation and Subsaturation Data

Model	Parameter (1 SE)	Log Likelihood
0. constant p	C = .0615	-460.280
1. 1-exp, no thresh	T = 371 (6), A = 3.17 (0.30) $\cdot 10^{-3}$	-525.940
2. 1-exp, thresh	T = 371 (9), A = 3.17 (0.38) $\cdot 10^{-3}$, PTHR = 0.00 (0.17)	-525.860
3. 2-exp, no thresh	TA = 3.92 (1.77), AA = 2.79 (1.37) $\cdot 10^{-3}$, TB = 435 (13), AB = 2.81 (0.32) $\cdot 10^{-3}$,	-367.966
4. 2-exp, thresh	TA = 4.23 (2.20), AA = 2.71 (1.29) $\cdot 10^{-3}$, TB = 436 (16), AB = 2.85 (0.49) $\cdot 10^{-3}$, PTHR = 0.07 (.58)	-367.960
5. 2-exp, rtf, no thresh	T1 = 1.26 (0.51), T2 = 351 (3), W1 = .955 (.015), A = 4.88 (0.53) $\cdot 10^{-3}$	-437.031
6. 2-exp, rtf, thresh	T1 = 1.26 (.51), T2 = 351 (4), W1 = .955 (.020), A = 4.21 (0.40) $\cdot 10^{-3}$, PTHR = 0.00 (.09)	-437.031
7. 3-exp, no thresh	TA = 2.54 (1.68) AA = 3.20 (1.9) $\cdot 10^{-3}$, TB = 391 (43), AB = 2.72 (0.57) $\cdot 10^{-3}$, TC = 1165 (3400), AC = 8.23 (45) $\cdot 10^{-5}$	-366.443
8. 3-exp, thresh	TA = 6.42 (1.77), AA = 3.46 (1.24) $\cdot 10^{-3}$, TB = 229 (25), AB = 7.87 (2.85) $\cdot 10^{-3}$, TC = 702 (60), AC = 3.16 (1.04) $\cdot 10^{-3}$, PTHR = 6.27 (1.10)	-355.484

TABLE 3
(continued)

Results of Fitting Models To Air Saturation and Subsaturation Data

Model	Parameter (1 SE)	Log Likelihood
9. 4-exp, rtf, no thresh	T1A = 0.07 (0.02), T2A = 409 (50), W1A = .99994 (.00002), AA = 1.41 (1.21) T1B = 154 (42), T2B = 704 (126), W1B = .805 (.07), AB = 3.35 (0.45) $\cdot 10^{-3}$,	-355.822
10. 4-exp, rtf, thresh	T1A = 0.07 (0.02), T2A = 409 (51), W1A = .99993 (.00004) AA = 1.28 (1.35) T1B = 153 (43), T2B = 719 (153), W1B = .814 (.09), AB = 3.56 (0.82) $\cdot 10^{-3}$, PTHR = 0.15 (0.55)	-355.787

n = 1,992

T (TA, T1, etc.) are in min; A (AA, A1, etc.) are in min-1; PTHR is in fsw; W1 and C are dimensionless.

details of the dive. Model 7 did no better than Models 3 or 4, and Models 5 and 6 were much worse, as predicted by likelihood ratio test of the previous section. Models 8, 9 and 10 all performed well. The threshold value was found to be different from zero only in Model 8. It should be noted that the same parameters (W1 and T1) correlated highly in Models 9 and 10 as in model 5 when fitting to the saturation data alone. However, these problems did not produce difficulty in determining upper and lower bounds for the predictions of p(DCS).

The parameter values for Model 9 appear to be different from the values for other models. T1A has a value of .07 min, or about 4 sec, whereas T2A has a value of 154 min. In only a few cases were the original data entered to a greater precision than the nearest minute, so it seems unusual that the model would chose such a small value for one of the time constants. However, the model does produce a better likelihood value with this incredibly small value than with a seemingly more reasonable value, such as 1 min. The selection of these parameters means that we have one "tissue" that responds quickly to a change in pressure by way of the .07 time constant, but still takes a relatively long time to completely dissipate, as can be seen from the 410 min T2A. The other "tissue" responds very slowly to pressure changes with T1B equal to 154 min, and requires an extremely long time to dissipate with T2B equal to 704 min. Upon examining individual dives, we found that the tissue with the 4 sec time constant plays an important role in risk accumulation for dives with quick pressure drops, such as the AIRSAT 5 series.

Both Models 8 and 9 with the parameters of Table 3 do a very good job of describing saturation data alone. The log likelihood portion for Model 8 on the saturation data is -112.916, and Model 9 has a log likelihood of -116.234. These are comparable to fits of simpler models to that data alone, Table 2. Models 8 and 9 also describe the more than 1700 short dives well. Model 8's

TABLE 4

Comparison of Model Predictions

OBS#	DIVES	BENDS	DEPTH	TIME	M2a	M4a	M5a	M8b	M9b
1	2	2	50	574.0	.628	.348	.372	.352	.334
3	2	0	50	810.0	.384	.271	.288	.272	.253
5	2	0	60	1690.0	.135	.111	.132	.117	.107
7	3	0	198	9703.0	.021	.120	.015	.001	.009
10	45	0	23.1	2.5	.118	.012	.109	.046	.105
55	25	4	26.4	2.5	.177	.132	.174	.145	.164
80	19	2.5	25.5	1.0	.178	.133	.174	.147	.164
99	15	5.5	29.5	1.0	.235	.308	.238	.264	.224
114	10	4	60	1260.0	.255	.414	.280	.284	.255
124	3	3	60	1620.0	.154	.115	.165	.134	.151
127	10	1	60	1620.0	.066	.027	.062	.026	.063
137	1	1	60	740.0*	.072	.015	.057	.032	.029
138	11	1	60	1621.0	.064	.037	.064	.026	.051
149	10	0	60	1762.0	.177	.063	.189	.134	.170
159	10	1	60	1762.0	.177	.065	.190	.140	.172
169	10	0	60	2162.0	.041	.031	.036	.006	.030
179	9	0.5	60	1840.0	.092	.024	.075	.034	.090
188	1	0	60	1840.0	.035	.006	.025	.000	.036
189	11	1	60	1200.0	.248	.211	.267	.266	.240
200	12	2	60	1200.0	.260	.210	.267	.297	.248
212	24	6	60	1035.0	.283	.184	.294	.234	.235
236	3	0	111	4010.0	.146	.396	.139	.246	.152
239	3	0	111	4010.0	.146	.397	.139	.247	.153
242	3	0	111	3710.0	.213	.628	.220	.411	.523
245	1	1	111	2515.0*	.212	.606	.219	.411	.519
246	3	3	111	2.0*	.259	.713	.271	.506	.816
249	4	1	111	3710.0	.214	.633	.221	.411	.525
253	3	3	111	2.0*	.212	.600	.219	.411	.519
256	2	0	203	7860.0	.271	.321	.267	.309	.261
258	18	1	132	3908.0	.062	.166	.063	.220	.091
276	4	4	165	3911.0*	.072	.220	.065	.165	.050

Legend: OBS# - observation number of the first dive of each set; DIVES - number of dives in that set; BENDS - number of cases of DCS; DEPTH - depth of dive in fsw; TIME - total decompression time in min; M2a - predictions of model 2 using saturation data only; M4a - predictions of model 4 using saturation data only; M5a - predictions of model 5 using saturation data only; M8b - predictions of model 8 using combined data; M9b - predictions of model 9 using combined data.

* Dives truncated at last depth before recompression.

likelihood for the shorter exposures is -242.568, whereas Model 9 has a likelihood of -239.591. It is interesting that the likelihood in Report I for Model 5 in fitting the air subsaturation data was -246.873, and so Model 9 is a significant ($p < 0.05$) improvement in fit to the previous air subsaturation data.

Of the models which fit the entire data sets well, which ones have similar predictions of individual dives? A comparison of the predictions of Models 2, 4 and 5 estimated from the saturation data alone, and Models 8 and 9 estimated from the combined data is given in Table 4 for all the saturation dives. Most of the predictions of p(DCS) for each model fell well within the 95% confidence limits for the raw data. Predictions that did not fall within these limits were those of Models 2, 5 and 9 on observations 10-54, Model 2 on observations 246-248, and all models on observations 276-279. Model predictions appear to differ greatly on all of the AIRSAT 5 dives, with predictions ranging from 15-40% on AIRSAT 5A (observations 236-238) and from 26-82% on AIRSAT 5F (observations 246-248). However, the 95% confidence levels on the raw data for these dives are 0-71% and 29-100%, respectively. On many of the other dives the predictions of p(DCS) made by the models are almost identical. Model 4a tended to be more pessimistic about safety of the deeper dives. Also note that observations 55-79 and 80-98 have essentially the same inspired nitrogen so predictions for both groups are nearly identical.

The way in which Models 8 and 9 separate the dives according to groupings of DCS hazard is displayed in Fig. 3. All exposures were grouped into four categories based on the models' prediction of DCS probability: 0-2%, 2-5%, 5-10%, and > 10%. Reference to binomial sampling confidence limits provide error bars to show the 95% confidence limit for the raw data. These error bars are smaller than those in Fig. 2, because the data set is now seven times

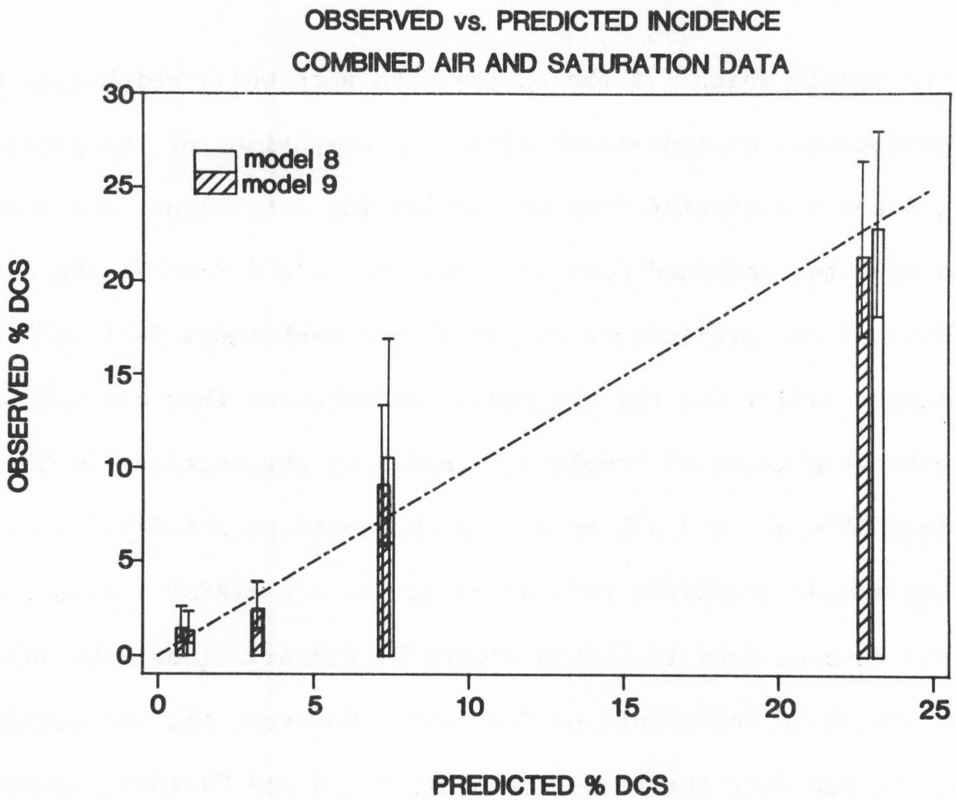

Fig. 3. Bar graph for prediction and outcome for combined short duration and saturation diving, total 1992 dives. Categories were < 2%, 2-5%, 5-10%, and > 10%.

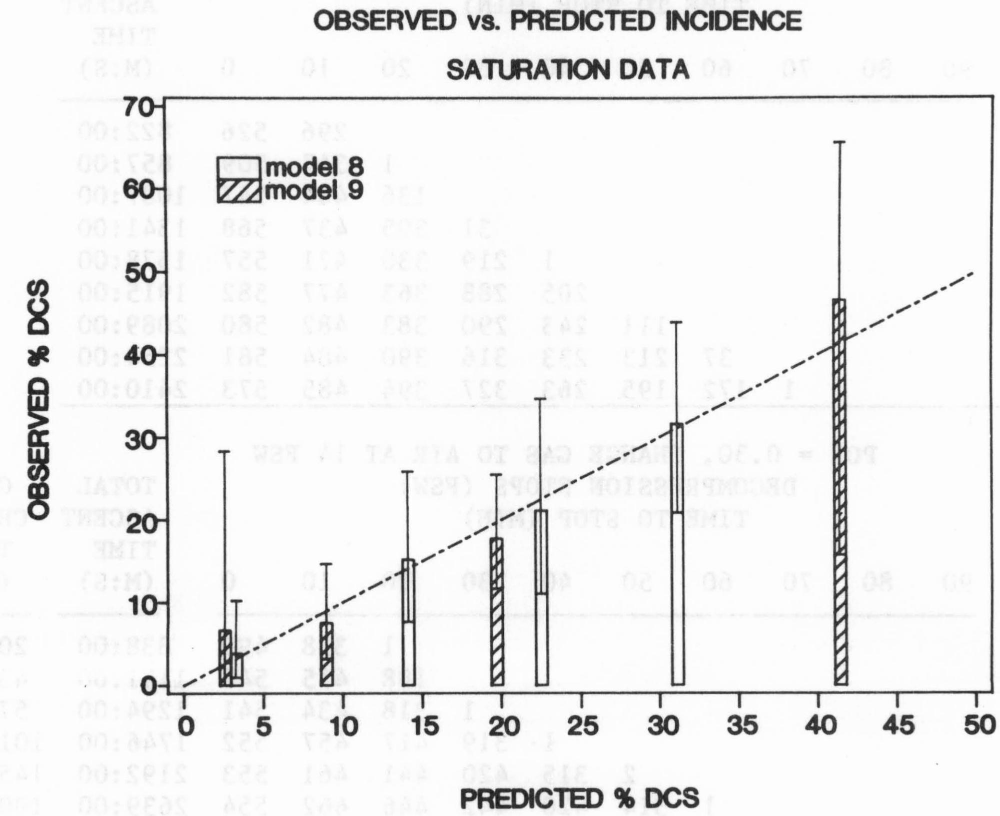

Fig. 4. Bar graph of same analyses as Fig. 3, but with categories of < 5%, 5-15%, 15-25%, and > 25%.

TABLE 5

Decompression From Air Saturation Dives For 1% Incidence of DCS
Continuous Decompression, 10 ft intervals
UNTESTED

AIR

DEPTH (FSW)	DECOMPRESSION STOPS (FSW) TIME TO STOP (MIN) 90	80	70	60	50	40	30	20	10	0	TOTAL ASCENT TIME (M:S)
30									296	526	822:00
35								1	347	509	857:00
40								136	404	547	1087:00
50							31	305	437	568	1341:00
60						1	219	330	471	557	1578:00
70						205	288	363	477	582	1915:00
80					111	243	290	383	482	580	2089:00
90				37	213	233	316	390	484	581	2254:00
100			1	172	195	263	327	394	485	573	2410:00

PO2 = 0.30, CHANGE GAS TO AIR AT 14 FSW

DEPTH (FSW)	DECOMPRESSION STOPS (FSW) TIME TO STOP (MIN) 90	80	70	60	50	40	30	20	10	0	TOTAL ASCENT TIME (M:S)	GAS CHANGE TIME (M:S)
30								1	338	499	838:00	203:48
35								188	415	548	1151:00	437:00
40							1	318	434	541	1294:00	579:24
50						1	319	417	457	552	1746:00	1011:12
60					2	315	420	441	461	553	2192:00	1454:36
70				1	314	420	442	446	462	554	2639:00	1900:12
80			1	314	420	441	447	447	462	554	3086:00	2347:12
90		1	308	422	442	447	447	447	461	557	3532:00	2790:36
100	1	302	426	441	447	447	448	447	461	559	3979:00	3235:36

PO2 = 0.40, CHANGE GAS TO AIR AT 30 FSW

DEPTH (FSW)	DECOMPRESSION STOPS (FSW) TIME TO STOP(MIN) 90	80	70	60	50	40	30	20	10	0	TOTAL ASCENT TIME (M:S)	GAS CHANGE TIME (M:S)
35								18	371	527	916:00	6:00
40								219	422	553	1194:00	109:30
50							190	335	454	576	1555:00	190:00
60						187	306	351	475	582	1901:00	493:00
70					177	309	310	374	479	587	2236:00	796:00
80				165	313	312	329	379	480	590	2568:00	1119:00
90			153	316	312	330	334	380	481	591	2897:00	1445:00
100		121	343	305	329	334	335	381	481	596	3225:00	1767:00

Decompression stops are depths at which rate of ascent is changed.

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TABLE 6

Decompression From Air Saturation Dives For 1% Incidence of DCS
Continuous Decompression, 5 ft intervals
UNTESTED

Air
DECOMPRESSION STOPS (FSW)
TIME TO STOP(MIN)

DEPTH (FSW)	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10	5	0	TOTAL ASCENT TIME (M:S)
30																39	191	244	229	703:00
35															1	157	186	276	232	852:00
40															142	203	199	283	259	1086:00
50													29	168	143	196	235	297	264	1332:00
60											1	104	119	149	182	214	246	315	229	1559:00
70										25	154	99	143	169	195	222	250	302	269	1828:00
80								1	104	88	115	135	158	180	202	226	251	312	244	2016:00
90							21	146	72	111	129	148	166	185	205	227	252	301	274	2237:00
100					1	108	64	93	107	123	139	155	171	188	206	228	252	313	243	2391:00

PO2 = 0.3 ATA, CHANGE GAS TO AIR AT 14 FSW
DECOMPRESSION STOPS (FSW)
TIME TO STOP(MIN)

DEPTH (FSW)	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10	5	0	TOTAL ASCENT TIME (M:S)	GAS CHANGE TIME (M:S)
30															1	148	185	280	211	825:00	186:00
35														1	148	177	210	295	225	1056:00	368:00
40													1	148	177	199	224	305	226	1280:00	569:48
50											1	148	177	199	213	219	234	310	228	1729:00	1003:48
60									1	147	177	199	213	219	222	223	235	312	227	2175:00	1448:00
70							1	147	177	199	213	219	222	223	223	224	236	312	226	2622:00	1895:12
80					1	147	177	199	213	219	222	223	223	224	224	223	236	313	224	3068:00	2342:12
90			1	147	177	199	213	219	222	223	223	224	224	223	224	224	236	309	233	3521:00	2790:12
100	1	146	177	199	213	219	222	223	223	224	224	223	224	224	224	223	236	311	230	3966:00	3236:12

PO2 = 0.4 ATA, CHANGE GAS TO AIR AT 30 FSW
DECOMPRESSION STOPS (FSW)
TIME TO STOP(MIN)

DEPTH (FSW)	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10	5	0	TOTAL ASCENT TIME (M:S)	GAS CHANGE TIME (M:S)
35															38	170	190	281	234	913:00	12:40
40														25	161	165	219	294	246	1110:00	16:40
50												1	156	126	171	207	242	301	262	1466:00	157:00
60										1	151	123	144	163	192	220	249	304	263	1810:00	419:00
70								1	148	125	144	154	160	174	199	224	251	307	256	2143:00	732:00
80						1	151	123	144	154	160	164	166	177	201	225	251	306	259	2482:00	1063:00
90				1	148	125	144	154	160	164	166	167	167	178	201	225	251	308	255	2814:00	1396:00
100		1	145	126	145	154	160	164	166	166	168	167	168	178	201	225	252	307	256	3149:00	1730.00

Decompression stops are depths at which rate of ascent is changed.

TABLE 7

Decompression From Air Saturation Dives For 1% Incidence of DCS
Step Decompression, 10 ft stops
UNTESTED

Air

DEPTH (FSW)	TM TO FIRST STOP (M:S)	90	80	70	60	50	40	30	20	10	TOTAL ASCENT TIME (M:S)
		DECOMPRESSION STOPS (FSW) STOP TIMES (MIN)									
30	0:10								495	1123	1618:30
35	0:05							17	737	1174	1928:35
40	0:10							238	826	1184	2248:40
50	0:10						92	528	888	1185	2693:50
60	0:10					6	354	619	905	1198	3083:00
70	0:20					226	439	651	912	1210	3439:10
80	0:20				141	322	484	661	918	1221	3748:20
90	0:20			80	246	369	500	662	913	1209	3980:30
100	0:20		33	196	288	394	507	663	914	1211	4207:40

PO2 = 0.30, CHANGE TO AIR AT 14.0 FEET

DEPTH (FSW)	TM TO FIRST STOP (M:S)	90	80	70	60	50	40	30	20	10	TOTAL ASCENT TIME (M:S)	GAS CHANGE TIME (M:S)
		DECOMPRESSION STOPS (FSW) STOP TIMES (MIN)										
30	0:10								885	1280	2165:30	885:16
35	0:05							480	1125	1394	2999:35	1605:21
40	0:10							888	1157	1413	3458:40	2045:26
50	0:10						915	1131	1225	1522	4793:50	3289:36
60	0:10					933	1139	1187	1281	1613	6155:00	4540:46
70	0:10				948	1144	1186	1233	1329	1692	7533:10	5840:56
80	0:10			959	1149	1185	1225	1274	1370	1762	8925:20	7163:06
90	0:10		967	1153	1184	1220	1261	1310	1407	1825	10326:30	8503:16
100	0:10	975	1156	1184	1215	1251	1293	1343	1441	1881	11740:40	9859:26

PO2 = 0.40, CHANGE TO AIR AT 30.0 FEET

DEPTH (FSW)	TM TO FIRST STOP (M:S)	90	80	70	60	50	40	30	20	10	TOTAL ASCENT TIME (M:S)	GAS CHANGE TIME (M:S)
		DECOMPRESSION STOPS (FSW) STOP TIMES (MIN)										
35	0:05							85	767	1178	2030:30	0:05
40	0:10							335	845	1168	2348:40	0:10
50	0:10						312	589	904	1204	3009:50	312:20
60	0:10					310	558	634	926	1249	3678:00	866:30
70	0:10				304	549	599	639	934	1266	4292:10	1542:40
80	0:10			300	544	593	607	642	944	1293	4924:20	2044:50
90	0:10		298	539	588	600	611	644	954	1318	5553:30	2637:00
100	0:10	295	536	584	596	604	614	646	963	1343	6182:40	3230:10

Rate between stops = 60 feet/minute.

TABLE 8

Decompression From Air Saturation Dives For 1% Incidence of DCS
Step Decompression, 5 ft stops
UNTESTED

Air

DEPTH (FSW)	TM TO FIRST STOP (M:S)	DECOMPRESSION STOPS (FSW) TIME TO STOP(MIN) 90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10	5	TOTAL ASCENT TIME (M:S)
30	0:10															43	201	280	277	801:30
35	0:10														6	168	237	308	290	1009:35
40	0:15														124	197	264	323	295	1203:40
50	0:15												52	143	188	241	292	335	300	1551:50
60	0:20											109	140	178	220	261	302	340	305	1856:00
70	0:20									56	109	136	168	201	234	268	304	340	304	2121:10
80	0:20							14	88	108	132	158	185	212	240	270	306	341	306	2361:20
90	0:25						58	88	106	126	149	171	194	217	242	272	306	342	30/	2579:30
100	0:25				23	74	87	104	121	141	159	178	198	219	243	272	306	342	308	2776:40

PO2 = 0.30 ATA, CHANGE GAS TO AIR AT 14 FSW

DEPTH (FSW)	TM TO FIRST STOP (M:S)	DECOMPRESSION STOPS (FSW) TIME TO STOP(MIN) 90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10	5	TOTAL ASCENT TIME (M:S)	GAS CHANGE TIME (M:S)
30	0:10															165	243	306	291	1005:30	408:16
35	0:10														162	231	278	325	301	1297:35	671:21
40	0:10													162	230	264	295	335	310	1596:40	951:26
50	0:10											161	228	262	279	288	305	344	325	2192:50	1523:36
60	0:10									160	226	259	276	284	289	293	307	348	335	2778:00	2094:46
70	0:10							158	225	257	274	282	286	289	292	295	308	351	343	3367:10	2666:56
80	0:10					158	224	256	273	281	284	287	289	292	294	297	309	354	352	3951:20	3245:06
90	0:10			158	224	256	272	280	283	285	288	290	291	294	296	299	310	357	361	4545:30	3827:16
100	0:10	158	223	255	271	279	282	284	286	288	289	292	293	295	298	300	311	359	361	5125:40	4405.26

PO2 = 0.40, CHANGE GAS TO AIR AT 30 FSW

DEPTH (FSW)	TM TO FIRST STOP (M:S)	DECOMPRESSION STOPS (FSW) TIME TO STOP(MIN) 90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10	5	TOTAL ASCENT TIME (M:S)	GAS CHANGE TIME (M:S)
35	0:10														40	176	245	313	292	1066:35	0:05
40	0:10													37	155	211	274	328	296	1301:40	0:10
50	0:10											31	137	167	208	254	299	340	306	1742:50	168:20
60	0:10									28	135	159	178	199	230	267	305	342	310	2154:00	500:30
70	0:10							27	134	157	176	190	197	209	236	270	307	346	316	2566:10	881:40
80	0:10					26	132	156	175	187	195	199	203	211	238	271	309	348	320	2971:20	1273:50
90	0:10			25	132	155	174	186	194	198	200	202	204	212	239	272	311	350	327	3382:30	1671:00
100	0:10	24	131	154	172	185	193	196	199	200	202	203	205	212	239	273	311	352	331	3783:40	2065:10

Rate between stops = 60 feet/minute.

larger. Both models seem to predict well for all intervals. The dotted line in Fig. 3 represents a "perfect" prediction, i.e., the points at which predicted probability and observed probability agree. Figure 4 shows how these models separate risk for the saturation data alone. Intervals of 0-5%, 5-15%, 15-25% and > 25% were chosen; the same as those chosen for Fig. 2. Figure 4 illustrates that both predict well for the saturation data.

EQUAL RISK DECOMPRESSION TABLES

Tables of predicted equal risk decompressions were calculated for saturation dives of 30 to 100 fsw for continuous and step-wise decompressions. Three sets are presented, for breathing mixtures air and constant PO_2 of 0.3 and 0.4 ATA. Each schedule was chosen by a computer search designed to find decompression schedules wherein the total decompression time is minimized. The algorithm of Appendix 2 in Report II and the parameters estimated for Model 9 were used for obtaining staged decompression schedules (Tables 7 and 8). For the continuous decompression tables (Tables 5 and 6), the algorithm was modified for a maximum (continuous) decompression rate between specified depths instead of the minimum time at each decompression stop. Both 10 ft and 5 ft intervals are used in Tables 5 through 8 for a target 1% incidence of DCS. As expected, use of constant controlled pO_2 of .4, or especially .3 ATA, increases the total decompression time substantially since more nitrogen is inspired than with air at the same total pressure.

If 5 ft intervals (Table 6) are used between changes in rate for a continuous decompression instead of 10 ft intervals (Table 5), total decompression time can be decreased by as much as two hours. The decrease in total decompression time using 5 ft intervals rather than 10 ft intervals is greater for shallower dives. However, for a step-wise or stage decompression, 10 ft stops seem to be inadaquate to achieve decompression from saturation in a reasonable amount of time. In many cases, the total decompression time for a step decompression with 10 ft stops

(Table 7) is more than twice as long as the time needed to decompress using 5 ft stops (Table 8). A step-wise decompression is somewhat longer than a continuous decompression from the same depth. For example, a decompression from a 60 ft air saturation with 1% incidence of DCS can be accomplished, using Table 6, by traveling to 40 ft in 1 min (a rate of .05 min/ft), to 35 ft in 104 min (20.8 min/ft), to 30 ft in 119 min (23.8 min/ft), to 25 ft in 149 min (29.8 min/ft), and so forth, taking a total of 25 h and 59 min to decompress. However, if a step-wise decompression is necessitated due to operational constraints, the decompression would take almost 31 h with 10 foot stops.

EVALUATION OF CURRENT PRACTICE

Model 9 was applied to the decompression schemes currently advocated by NOAA (NOAA Diving Manual, second edition, December, 1979, Table 12-10), UEG (Hennessy et al, 1985) and to the USN Treatment Table 7 (US Navy Diving Manual, 1985). The USN Treatment Table 7, which is used for air decompressions from 60 ft and includes 36 h of decompression time, is predicted to be extremely safe (risk < 0.1%). The UEG tables, also with risk < 0.1%, seem to be quite conservative, requiring 46 h to decompress from 60 ft, breathing a .5 ATA PO_2 from 60 to 50 ft. Results from the analysis of NOAA Table 12-10 are given in Table 9. Decompression from shallow depths is predicted to be fairly safe for the NOAA table, but risk increases to > 15% as saturation depth approaches 50 ft. A graph showing how Model 9 predicts risk for a NOAA Table 12-10 decompression from 50 ft is given in Fig. 5. Our analysis indicates that the NOAA rate is too slow at deeper depths and too fast near the surface. In long field use of the NOAA habitat at 42 ft, several hours of O_2 breathing are added to Table 12-10 and a DCS rate of approximately 2% is attained (Shane, 1985). In comparing NOAA Table 12-10 to the decompression schedules given in Tables 5 and 6, it should be noted that Model 9 predicts that about 6 h of well chosen additional decompression time is necessary to acheive a risk level of 1%.

TABLE 9

Predicted p(dcs) for NOAA Table (12-10) for air decompression from air saturation to depths up to 50 fsw

DEPTH (fsw)	TOTAL DECOMPRESSION TIME	p(DCS)	ESTIMATED ERROR ON p(DCS)	
			HIGH	LOW
50	975	0.159	0.186	0.136
45	945	0.113	0.134	0.095
40	915	0.076	0.092	0.063
35	885	0.047	0.059	0.038
30	855	0.025	0.033	0.019
25	741	0.009	0.013	0.005

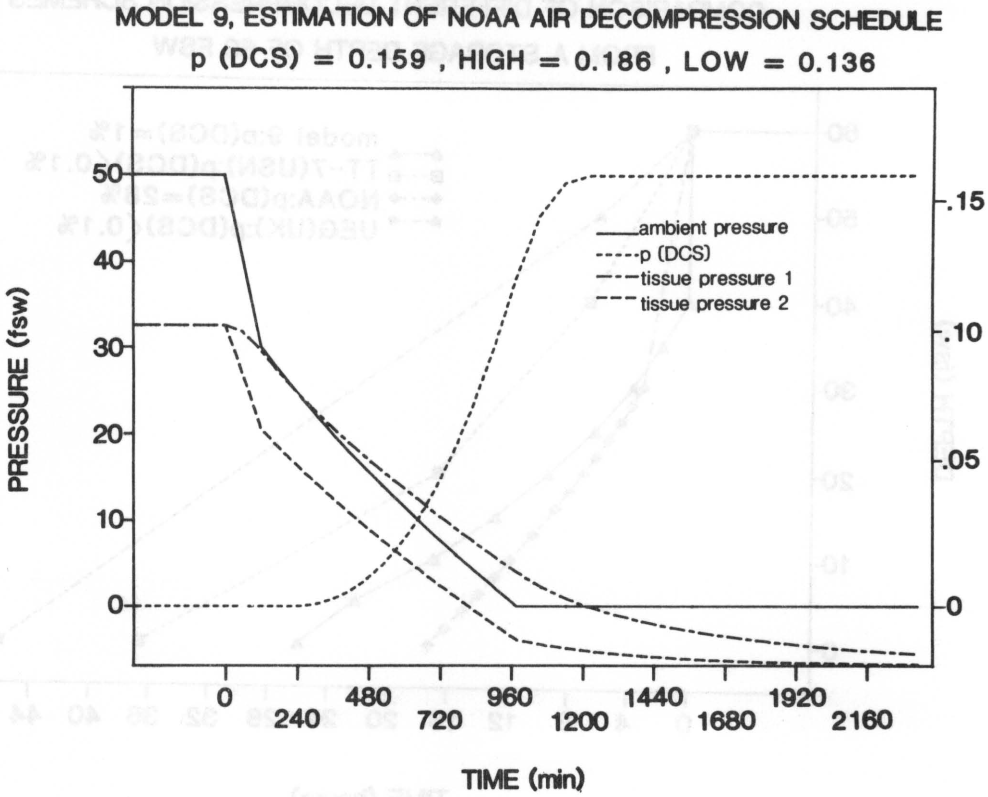

Fig. 5. Evaluation of NOAA decompression from 50 foot air saturation. Ambient pressure never exceeded calculated nitrogen pressure in Tissue 2, but the nitrogen pressure in Tissue 1 exceeded during the interval of 230 to 1210 min after starting decompression. Integrating the risk over this period predicts a 16% chance of DCS.

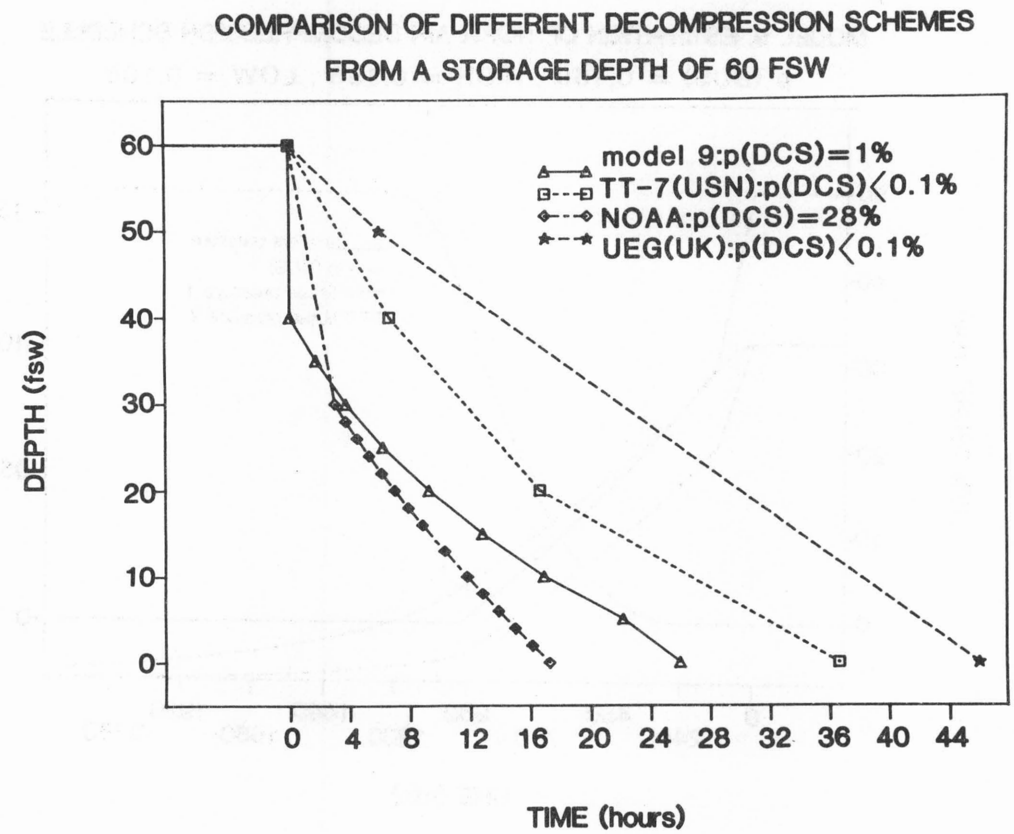

Fig. 6. Comparison of DCS risk for several proposed decompression schedules from 60 feet. Sources of proposed tables are given in the text.

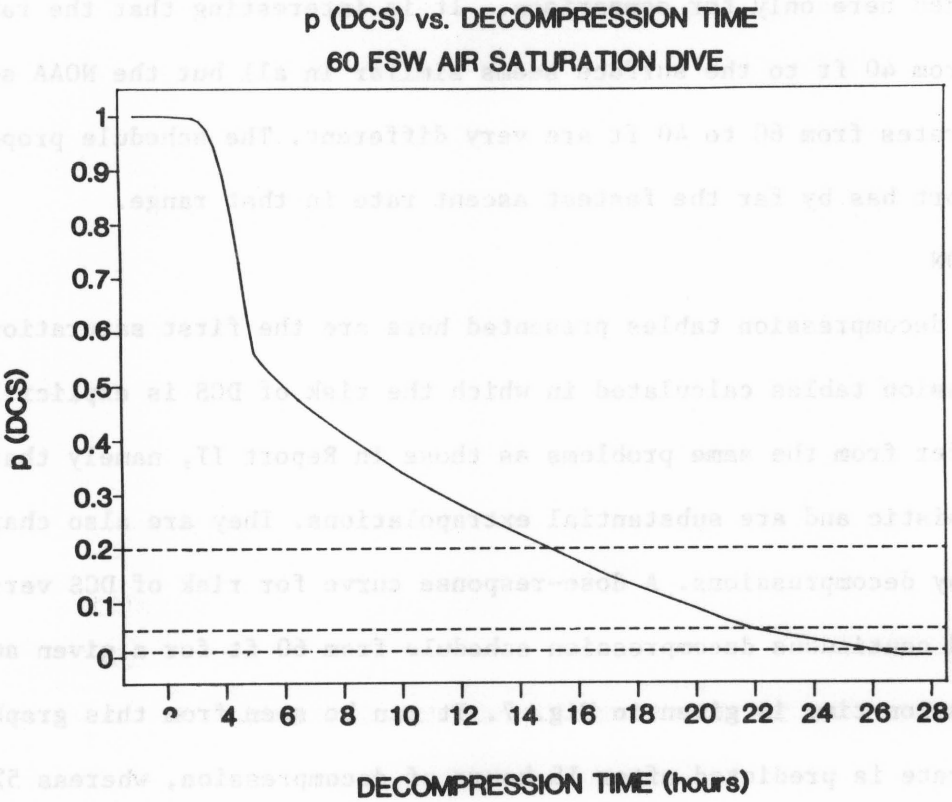

Fig. 7. Decompression dose response curve after saturation at 60 feet breathing air. The total decompression time plotted assumes the most efficient use of variable ascent rates as described in the text. Dashed lines show possible target risks of 20%, 5% and 1%. Nearly a full day is required to achieve a DCS risk of 5%.

A graph demonstrating the differences between the decompression schemes proposed by this report and those previously mentioned is given in Fig. 6. Although NOAA does not advocate air saturation diving deeper than 50 ft, the decompression schedule shown is in keeping with the style of Table 12-10, and is provided here only for comparison. It is interesting that the rate of ascent from 40 ft to the surface seems similar in all but the NOAA schedule, but the rates from 60 to 40 ft are very different. The schedule proposed in this report has by far the fastest ascent rate in that range.

CONCLUSION

The decompression tables presented here are the first saturation decompression tables calculated in which the risk of DCS is explicitly used. They suffer from the same problems as those in Report II, namely that they are nonmechanistic and are substantial extrapolations. They are also characterized by lengthy decompressions. A dose-response curve for risk of DCS versus an optimized continuous decompression schedule from 60 ft for a given amount of decompression time is given in Fig. 7. It can be seen from this graph that a 20% DCS rate is predicted after 15 hours of decompression, whereas 5% takes 22 h and 1% takes 26 h.

We have presented a single model (Model 9) that describes an extremely wide range of dives, with exposures from less than one minute to more than a week. Care was taken so that the data was appropriate to the models at this stage of development. Dives were entered as they actually occurred, not as planned, and divers who were treated but showed no symptoms of DCS were not counted as completing the dive successfully. The tables are not "final," as additional data would change predictions, even if only to a small degree. Further, substantial testing is necessary before these tables should be put into widespread use. One feature of these tables is that they attempt to minimize total decompression time while attaining a specified predicted risk of DCS. This is in contrast to USN Treatment Table 7 and the UEG tables which, although very safe, require tremendous amounts of decompression time. Treatment Table 7 may be cautious by design since it is intended for use in returning patients from very difficult recompression treatments. Further, the models developed here could be used to design decompression schemes when less than the time required for safe decompression is available. We submit that these tables are currently the most promising of any known tables, because they are based on the most complete analysis of known data.

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Hobbs

Study: Hamilton, RW, et al.
SHAD-NISAT
NSMRL Report 985, August 1982

Pressure exposure	Pre-SHAD	
Time at depth	2 days	
Time from last excursion to decompression		
depth & duration of last excursion		no excursions
Bottom depth	50 fsw	
Ascent rate	574 min decompression	
Pressure exposure	SHAD I	
Time at depth	29.5 days	
Time from last excursion to decompression		41 hr
depth & duration of last excursion		200 fsw, 26 min
Bottom depth	50 fsw	
Ascent rate	810 min decompression	
Pressure exposure	SHAD II	
Time at depth	26 days	
Time from last excursion to decompression		57 hr
depth & duration of last excursion		200 fsw, 27 min
Bottom depth	60 fsw	
Ascent rate	1690 min decompression	
Pressure exposure	NISAT I	
Time at depth	7 days	
Time from last excursion to decompression		no excursions
depth & duration of last excursion		
Bottom depth	198 fsw	
Ascent rate	9703 min decompression	
Gas breathed	air for SHAD dives, 0.3 ATA oxygen for NISAT I	
Other factors		
exercise	Up to 20 min on some days on a Collins ergometer	
subject background	US Navy divers	
Results		
incidence of bends	2 of 2 on pre-SHAD, no others (2 on SHAD I, 2 on SHAD II, and 3 on NISAT I ok)	
distribution of symptoms	left knee, right tibia and ankle	

Comments: Skins bends and joint pain occurred early in SHAD II during excursions, none treated. Mild shoulder tenderness during 12 fsw stop of SHAD II which disappeared overnight, not scored as a bend.

Study: Bell, PY, private communication
ISLANDER

Pressure exposure

Time at depth	48 hrs
Time from last excursion to decompression	no excursions
depth & duration of last excursion	none
Bottom depth	1.7 and 1.8 bar (1.3 & 1.4 bar N_2)
Ascent rate	"2-3 min period"

Gas breathed: 0.4 bar O_2, remainder N_2; 30 dives (15 of each) had 2% CO_2

Other factors

exercise	very little activity
subject background	RN submariners

Results

incidence of bends	4(2), all in 1.8 bar group, out of 70--45(15) 1.7 bar,25(15) 1.8 bar (number in parentheses for 2% CO_2 group)
distribution of symptoms	all knee bends

Comments: Ascent assumed to be 2.5 min

Study: Eckenhoff, RG, SF Osborne, JW Parker, and KR Bond.
Direct ascent from shallow air saturation exposures.
Undersea Biomedical Research 13:305-316, 1986.
MINISAT

Pressure exposure

Time at depth	48 hrs
Time from last excursion to decompression	no excursions
depth & duration of last excursion	no excursions
Bottom depth	25.5 and 29.5 FSW
Ascent rate	"about 2 minutes"

Gas breathed: air

Other factors

exercise	none
subject background	US Navy divers or chamber personnel

Results

incidence of bends	4 (at 29.5 FSW) out of 34 (19 at 25.5 FSW, 15 at 29.5 FSW) 8 questionable cases
distribution	Knee and ankle. Questionable cases included fatigue, headache, malaise.

Comments: (1) Questionable cases of DCS were scored as 0.5 in data set
(2) Time of ascent entered in data set as one minute; subsequent manuscript indicates "about 2 minutes".

Study: Thalmann, ED, private communication
trials leading to USN Treatment Table 7

Pressure exposure

Time at depth	from 45 to over 90 hrs
Time from last excursion to decompression	over 44 hrs
depth & duration of last excursion	165 fsw for 45 or 60 min for 20 divers, rest made no excursions
Bottom depth	60 fsw
Ascent rate	decompression time ranged from 1260 to 2162 min

Gas breathed: air for most, 18% oxygen during decompression of three dives

Other factors

exercise	none
subject background	US Navy divers

Results

incidence of bends	11 out of 75 divers One questionable case.
distribution of symptoms	Knee, shoulder, ankle, elbow

Comments:
(1) Questionable cases of DCS were scored as 0.5 in data set.
(2) 16 additional divers were recompressed before the outcome of their dive was determined. They are not included in the data set. One diver was recompressed for onset of symptoms before reaching surface, and his dive was included in the data set as if it had ended at the final pressure before recompression. See discussion in text under Data.

Study: Eckenhoff, RG, and RD Vann.
Air and nitrox saturation decompression: a report of 4 schedules and 77 subjects.
Undersea Biomedical Research 12:41, 1985.

Pressure exposure		
Time at depth	over a week	
Time from last excursion to decompression		44 & 47 hr
depth & duration of last excursion		100' (8:15), 150' (4:40)
Bottom depth	60 FSW	
Ascent rate	1200 min decompression	
Gas breathed	air	
Other factors		
exercise	30 minutes on bicycle ergometer during excursions.	
subject background	US Navy divers.	
Results		
incidence of bends	2 out of 23 (one treated, one not)	
distribution of symptoms	knee pain	

Study: Philp, RB, et al.
Effects of aspirin and dipyridamole on platelet function, hematology, and blood chemistry of saturation divers.
Undersea Biomedical Research 6:127, 1979.

Pressure exposure		
Time at depth	31 hr	
Time from last excursion to decompression		no excursions
depth & duration of last excursion		no excursions
Bottom depth	60 fsw	
Ascent rate	1035 min decompression	
Gas breathed	air	
Other factors		
exercise	none reported	
subject background	college students	
Results		
incidence of bends	6 out of 24 (one not treated)	
distribution of symptoms	all "Type I"	

Comments: (1) Numbers too small to decide drug effects.

(2) The 31 hour bottom time was the shortest of any group of dives evaluated.

Study: Harvey, CA, private communication
Airsat 5 series

Pressure exposure

Time at depth	48 hrs
Time from last excursion to decompression	no excursions
depth & duration of last excursion	no excursions
Bottom depth	111 fsw
Ascent rate	rapid ascent to an intermediate depth (70, 60, or 55 fsw), followed by a 12 hr hold, then a slow decompression to surface

Gas breathed: 0.4 ATA oxygen

Other factors

exercise	none
subject background	US Navy divers

Results

incidence of bends	8 of 20 divers
distribution of symptoms	knee pain, blurred vision

Comments: Five divers were recompressed along with companions with DCS; their dives of unknown outcome are not included in the data set. The divers who were recompressed before reaching the surface were included in the data set. Their dives are entered as if they had ended at the last pressure before recompression took place. See discussion in text under Data.

Study: Withey, R and J Florio, private communication
BISAT 82

Pressure exposure

Time at depth	6 days	
Time from last excursion to decompression		no excursions
depth & duration of last excursion		no excursions
Bottom depth	203 fsw	
Ascent rate	7860 min decompression	

Gas breathed 0.4 ATA oxygen

Other factors

exercise	none
subject background	

Results

incidence of bends	two subjects, no bends
distribution of symptoms	none

Study: Eckenhoff, RG, and RD Vann.
Air and nitrox saturation decompression: a report of 4 schedules and 77 subjects.
Undersea Biomedical Research 12:41, 1985.

Pressure exposure

Time at depth	2.5 days
Time from last excursion to decompression	no excursions
depth & duration of last excursion	no excursions
Bottom depth	132 fsw
Ascent rate	3908 min decompression

Gas breathed: 0.3 ATA oxygen for first 12 hours at, depth, air for the remaining time. 0.5 ATA oxygen on decompression to 50 fsw, air thereafter.

Other factors

exercise	none
subject background	US Navy divers

Results

incidence of bends	1 out of 18
distribution of symptoms	bilateral knee pain

Study: Barry, P, et al.
Decompression from a deep nitrogen/oxygen saturation dive - a case report.
Undersea Biomedical Research 11:387, 1984.

Pressure exposure

Time at depth	4.5 days	
Time from last excursion to decompression		6 hours
depth & duration of last excursion		200 fsw on air, 2 hours
Bottom depth	165 fsw	
Ascent rate	3911 min decompression	

Gas breathed 0.5 ATA oxygen

Other factors

exercise	none
subject background	"experienced divers"

Results

incidence of bends	4 out of 4
distribution of symptoms	ankle, elbow, knee, and thigh pain

Comments: Six divers were recompressed along with companions with DCS; their dives of unknown outcome are not included in the data set. The divers who were recompressed before reaching the surface were included in the data set. Their dives are entered as if they had ended at the last pressure before recompression took place. See discussion in text under Data.