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Relative decompression risk of dry and wet chamber air dives

P.K. WEATHERSBY, S.S. SURVANSHI, and R.Y. NISHI

Naval Submarine Medical Research Laboratory, Box 900, Naval Submarine Base New London, Groton, Connecticut 06349-5900; Naval Medical Research Institute Bethesda, Maryland 20814-5055; and Defence and Civil Institute of Environmental Medicine Downsview, Ontario, Canada M3M 3B9

Weathersby PK, Survanshi SS, Nishi RY. Relative decompression risk of dry and wet chamber air dives. Undersea Biomed Res 1990; 17(4):333–352.—The difference in risk of decompression sickness (DCS) between dry chamber subjects and wet, working divers is unknown and a direct test of the difference would be large and expensive. We used probabilistic models and maximum likelihood estimation to examine 797 dry (and generally resting and comfortable) and 244 wet (and generally working and cold) chamber dives from the Defence and Civil Institute of Environmental Medicine, supplemented with 483 wet (working, cold) dives from the Navy Experimental Diving Unit. Several analyses considered whether dry and wet data were distinguishable using several models, whether models obtained from one set of exposure conditions would correctly predict the occurrence of DCS in the other condition, and whether a single wet-dry risk difference parameter was different from zero. Although the two conditions may not produce identical risks, immersion appears to change relative risk of DCS by less than 30% and certainly involves less than a doubling of DCS risk. Uncontrolled differences in exercise and temperature stresses unavoidably complicate interpretation. Several methods are presented to extrapolate results from dry-test subjects in decompression trials to expected at-sea performance.

decompression sickness	inert gas
exercise	maximum likelihood

If we wished to directly compare the relative incidence of decompression sickness (DCS) between wet and dry exposures we could perform a trial of carefully replicated exposures on many divers, with half of them wet and the other half dry. For a specific example, suppose that the wet exposures had 8 cases of DCS in 200 dives, while the dry exposures had only 4 cases in 200 dives. This seems to say that the risk of DCS doubles with immersion. However, statistical analysis of that outcome shows that perfectly identical incidence rates for the two conditions could give this large an apparent difference over 20% of the time. Therefore, we should not claim any significant difference between the two conditions even after this rather large trial. Further examples would show that over 1000 exposures would be needed to reliably detect effects that double the risk of DCS in relatively safe exposures (under 5% DCS).

Since the resources to conduct these many replicated dives might be prohibitively expensive, can we never arrive at a confident answer?

An alternative method is available to use the power of 1000 exposures, but less directly. Potentially any dive can be used for data even if never replicated, as long as its pressure-time profile and outcome are well known, and if one is satisfied that other dive conditions are either similar or can be modeled. To combine the dives, one needs a mathematical model capable of predicting the probability of decompression sickness, P(DCS), for each known exposure. One then fits the parameters of the model to the data using the principle of maximum likelihood (1, 2). The magnitude of effects such as the difference between wet and dry is assessed by examining statistical descriptors of the fitting and the model parameters.

Here we report the examination of wet vs. dry risk in compressed air exposures using 1041 nonreplicated exposures from a Canadian laboratory, supplemented by another 483 exposures from an American laboratory. Several statistical procedures are presented for quantifying wet-dry differences, as well as exploring how the answers depend on details of models and data sources. The emphasis is on estimating the magnitude of wet-dry differences rather than on testing the hypothesis that no difference exists. Environmental effects almost certainly have some impact on decompression, but rational decisions depend on whether the expected differences are large or small.

METHODS

Data selection

The primary source of data was records of single air dives performed at the Defence and Civil Institute of Environmental Medicine (DCIEM) during 1978–1986. Records of the chamber exposures, including the pressure-time profiles and any DCS symptoms, were extracted from the CANDID data bank (3). Discrepancies in the records were resolved by examining original logs. All air exposures were selected unless excluded for one of the following reasons:

- very short or shallow exposure usually for familiarization;
- very complex pressure profile with multiple compressions and decompressions, e.g., for clearing ears or sinuses; or
- exposure with intermittent immersion, which includes "standby" divers in air decompression trials (4–6).

Included in the data were all exposures reported previously for tests of the 1971 Kidd-Stubbs (7–10) and the DCIEM 1983 decompression tables (4–6). Sixty percent of the wet exposures involved moderate work during the dive but not during or after the decompression: 75–100 W (7, 8) or 50–75% of maximum heart rate (4, 6). Water was deliberately kept cold. Dry exposures on the other hand had no activity for over 80% of the exposures and only light arm work with weights or attending hoses for the remainder. Therefore to a good approximation, "wet" can be interpreted as "wet-working-cold" and "dry" as "dry-resting-comfortable."

Each individual acceptable exposure was formatted as a sequence of pressure-time nodes. Pressure changes between nodes were assumed to be linear in time. For data entry, depth precision was ±1 fsw and rate precision within 10–15%. When necessary, depth conversion used 3 msw equals 10 fsw. A more precise depth conversion changes individual probabilities by no more than 0.2% DCS. A summary of the selected dives is presented in Table 1. Nearly 800 dry exposures were available, more than 3 times the number of wet. Depths and times were similar. Indeed, many of the dives represent exposures of wet and dry divers simultaneously. The slightly greater average depth and time of the wet data are partially explained by that simultaneity. In over half of the wet exposures a suspended wet pot chamber was used. The wet divers had the additional 3 fsw of hydrostatic pressure compared to their dry companions. Also, they typically entered the water 6 min before the chamber atmosphere was compressed (adding to bottom time by usual definition) and emerged about 3 min after the chamber was decompressed (adding to their total decompression time). Figure 1 shows the actual pressure history of one of these joint exposures.

In the total DCS outcome summary of DCIEM dives in Table 1, entries for DCS cases include 4 marginal outcomes in each category. These cases represent postdive symptoms, generally musculoskeletal aches of a fleeting nature (sometimes termed "niggles"), and not receiving recompression therapy. In two previous studies (2, 11) the choice of how to treat marginal cases (all as DCS, none as DCS, each as ½ case) were explored. The choice affected overall safety estimates for each diver since counting marginals as DCS increases the overall incidence. However, the choice did not exert an important influence on which model fit the data best nor on estimation of important effects within the data, such as the importance of oxygen (11). The present study uses the marginals as ½ case of DSC each.

To enrich the data, some additional exposures were examined. These are single experimental air dives done at the U.S. Navy Experimental Diving Unit (NEDU) in 1984 (12). All divers were wet and exercising moderately (75 W) in 50–65°F water until the start of decompression. As seen in Table 1, compared to the DCIEM exposures the NEDU dives tended to be more hazardous, slightly shallower, but much longer in duration of both the bottom and decompression phases. The longer duration would be expected to yield kinetic parameters reflecting slower events, but other features of the data (e.g., subject population, diagnostic criteria) seem to be sufficiently comparable to warrant a combination of the data. Original data tapes of

TABLE 1
CHARACTERISTICS OF DIVING DATA

Set	DCIEM, Dry	DCIEM, Wet	NEDU, Wet
Total dives	797	244	483
Total DCS (marg)	19 (4)	8 (4)	30
Percent DCS	2.6	4.1	6.2
Depth, fsw	50–290	50–265	50–190
Average	149	154	112
Bottom time, min	2–120	3–100	14–244
Average	18	24	78
Decompression time, min	1–95	3–99	2–290
Average	23	28	102

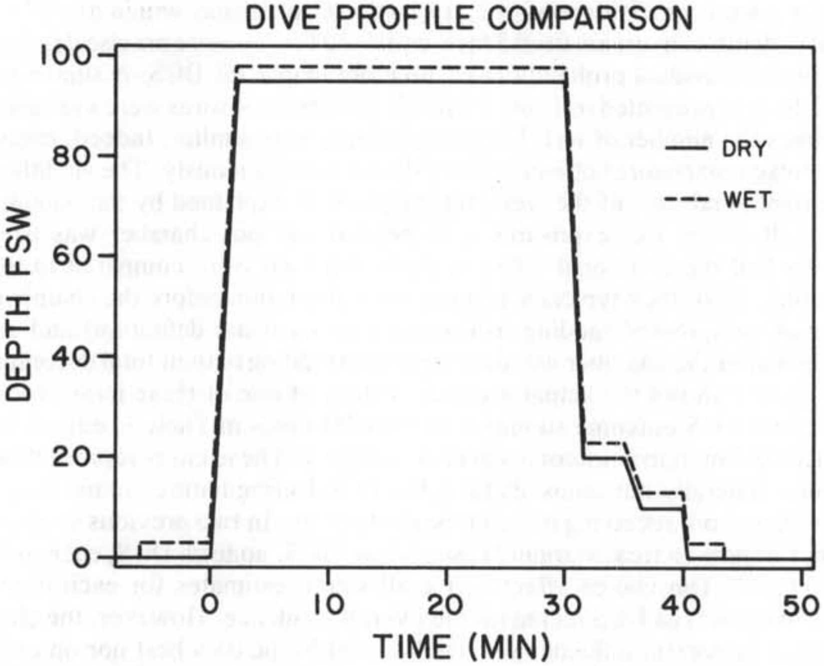

Fig. 1. Actual pressure history of a single decompression schedule test. Wet divers used a suspended wet pot which increased both the depth and duration of this exposure compared to their companions. Wet depth measured at mid-chest level on divers.

the pressure-time profiles were kindly provided by E. D. Thalmann, Naval Medicine Research Institute. Data formatting was similar to the DCIEM exposures. We emphasize that all data are actual recorded exposures rather than any planned or standard profile.

Models

A mathematical model is required to relate details of the dive profile to the chance of observing a case of DCS. For analysis, we use a family of "risk" models previously found satisfactory for description of air dives (13–15). All models are of the form:

$$P(DCS) = 1.0 - \exp(-R) = 1.0 - \exp\left(-\int^{\text{whole dive}} r\,dt\right) \qquad (1)$$

Equation *1* sets the overall probability of DCS as related to an overall risk, R, obtained by integrating an instantaneous risk, r, over the diver and a sufficient postdive interval for the instantaneous risk to decay to 0. (Negative values of r are not integrated.) This formulation differs fundamentally from traditional decompression calculations and their probabilistic counterparts, which seek to avoid a specific critical point (e.g., a specific forbidden supersaturation ratio). Note that a very small r leads to a P(DCS) near 0, whereas large or sustained values of r approach a P(DCS) of 1.0 (100%). Many different dives can lead to the same predicted P(DCS), for example one with a large risk for a short time and one with a small instantaneous risk maintained for a long time. The choice of r can be guided by theory, such as being proportional to a volume of bubbles, or it can be rather empirical and convenient computationally. In this report, r is proportional to a computed relative supersaturation:

$$r = A\,(P_{tis} - P_{amb})/P_{amb} > 0 \qquad (2)$$

The term in parenthesis is a computed nitrogen supersaturation. P_{tis} is the tissue nitrogen tension; oxygen and other gases are ignored in computing risk as supported by a recent human trial (11). Appearance of P_{amb}, the current ambient pressure, in the denominator could correspond to theoretical concepts of bubble volume, etc. Its use follows from an investigation of models applied to He-O_2 data spanning a wide range in pressure (2). In that study it was statistically shown that the same overpressure ($P_{tis} - P_{amb}$) is less dangerous as ambient pressure increases but that several formulations can accommodate that observation with similar statistical success. This normalization by P_{amb} is unlikely to be crucial in the present analysis because most of the decompression for these data occurs over a narrow range of shallow depths. Nevertheless we keep the normalization in the expectation of greater ability to fit additional data in the future. The scale factor A is needed to convert the integral into nondimensional form. For example, if a relative supersaturation of 0.5 (say P_{tis} = 1.5, P_{amb} = 1.0) maintained for 10 min produces DCS in 1% of divers, then A would be about 0.002 min^{-1}.

The models used here differ in how they calculate tissue nitrogen tension, P_{tis}. Some additional mathematical details appear in the appendix and in reference (13). The differences in the nitrogen kinetics among the models used are summarized:

Model 1 has a single exponential exchange compartment or tissue. The kinetics are controlled by a single time constant, τ (to express as a tissue half-time, multiply τ by 0.693). Some additional mathematical details regarding kinetics are in the appendix. Two parameters are estimated from the data: A and τ.

Model 2 [model 3 in ref (13)] has two of the monoexponential exchange compartments in parallel. Kinetics are controlled by the two time constants τA and τB. Each has its own scale factor AA and AB. The statistical sense of using two tissues is that no-DCS is the joint probability of no-DCS in tissue A and no-DCS in tissue B. Neither tissue has an anatomic identification—the tissues are labeled only by the kinetic exchange rates required to fit the data. The risks of the two tissues combine linearly:

$$r = rA + rB \qquad (3)$$

Four parameters are estimated: τA, τB, AA, and AB.

Model 3 [model 4 in ref (13)] has the two monoexponential compartments in parallel as in model 2, but the risk definition uses an absolutely safe threshold pressure, PTHR applied to both compartments:

$$rB = AB\,(P_{tis}B - P_{amb} - PTHR)/P_{amb} > 0 \qquad (4)$$

with a similar expression for compartment A. Five parameters are estimated: τA, τB, AA, AB, and PTHR.

Model 4 [model 5 in ref (13)] is conceptually similar in having a single compartment, but the kinetics within it controlled by two different time constants τ1 and τ2 weighted by a factor W1 (13, 16). This means that within the single compartment the fraction W1 of gas that enters leaves the tissue with an exponential residence time distribution (rtf) with a time constant $\tau 1$ and the remaining fraction $(1 - W1)$ leaves by another exponential distribution with time constant $\tau 2$ (*see* appendix). Four parameters are estimated: $\tau 1$, $\tau 2$, W1, and A.

The difference between the gas kinetics of models 2 and 4 is shown in Fig. 2. Model 2, *top*, has two parallel exponential tissues: one fast with $\tau A = 27$ min and the other slow with $\tau B = 749$ min (parameters are selected from the all-wet data in Table 4). The 27-min tissue builds up an 86-fsw nitrogen tension by the start of decompression and remains supersaturated until 14 min after surfacing. The slow 749-min tissue builds a P_{tis} slowly and only achieves a slight supersaturation of about 0.5 fsw max for 63 min after surfacing. The final estimated P(DCS) is 5.2%, almost all of it from the faster compartment. The double exponential tissue response of model 4 is shown for the same dive in the bottom of Fig. 2. The initial rise of tissue nitrogen tension is intermediate in response compared to the two single tissues of model 2. The apparently much slower washout of nitrogen is characteristic of the double exponential

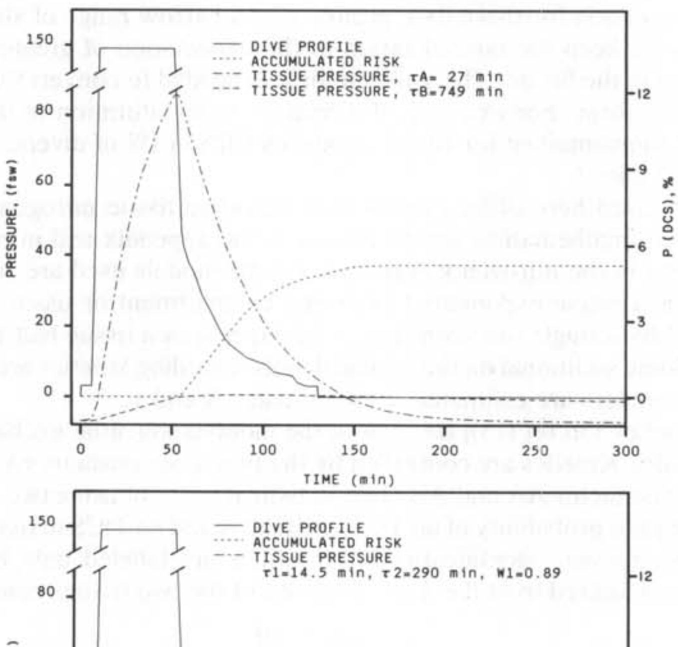

Fig. 2. Model behavior on a wet DCIEM dive to 148 fsw for 51 min with 79 min decompression time performed on 16 January 1978 (CANDID no. DD1694A). Parameters used for model 2 (*top*) and model 4 (*bottom*) are for the combined all wet data listed in Table 4. *See* text for more details.

residence time functions used to describe dog gas exchange experiments (16, 17). Supersaturation does not begin until the divers decompress to 13 fsw at 85 min. Risk is accumulated from that point until 132 min after reaching the surface where the total P(DCS) builds to 8.6%. There is no statistically significant difference in the final P(DCS) for this dive from the two models, but model 2 says the early portion of decompression is dangerous whereas model 4 raises concern about the final shallow portion.

A model variation was also explored that places any difference between wet and dry exposures into a single parameter, dW. When used, the calculations in Eq. *1* for dry dives remain as before, but for wet exposures, the overall risk is fractionally incremented by the additional parameter:

$$\text{if wet, } R = R' \,(1.0 + \text{dW}) \qquad (5)$$

Statistical procedures

Computations for each model followed every dive, decompression, and postdecompression period as illustrated before in Fig. 2. [We allowed 12 h (DCIEM data) or 24 h (NEDU data) to allow P_{tis} to fall below P_{amb}, but it seldom required more than 1–2 h and never as much as 8 h.] Some additional mathematical details of implementing the models are found in appendix A of (13). From Eq. *1* the probability of the actual outcome of each dive was obtained; directly if it resulted in DCS, or from its converse if the dive was safe:

$$P(\text{NO} - \text{DCS}) = 1.0 - P(\text{DCS}) \qquad (6)$$

The joint probability of all dives having their recorded outcomes is the product of all the individual dive probabilities. This is also called the likelihood function:

$$L = P(\text{outcome 1}) \times P(\text{outcome 2}) \times \ldots \times P(\text{last outcome}) \qquad (7)$$

Values of L depend on values of the model parameters. We desire to have the best overall prediction of all the outcomes, and this occurs when L achieves its highest value, the maximum likelihood (ML). Since each P is less than 1, it is more convenient to use the natural logarithm of L, or LL.

To obtain a ML for each model we use a general nonlinear estimation program (18) based on the Marquardt algorithm (19). The highly nonlinear nature of the problem usually requires multiple attempts with different starting parameter values before achievement of a ML can be declared. Estimated parameter precision is taken from the covariance matrix (1, 18). Confidence limits for parameters obtained by exploring the likelihood surface are generally larger than these estimates, and are generally asymmetric about the best fit parameter.

Hypothesis testing uses a likelihood ratio (LR) test (1, 13, 18). The test statistic is calculated as twice the difference in LL between a specific model and a more general model having additional parameters. The additional parameters are accepted if the test statistic exceeds the critical value of the chi-square distribution with degrees of freedom corresponding to the number of additional parameters. Thus for two additional parameters at a $P < 0.05$ level of significance, the critical chi-square is 5.99, meaning we need a log likelihood increase of about 3.0 to accept the additional parameters. LR tests are used here in two contexts. The first asks whether additional risk model parameters are needed to describe a particular data set: e.g., are the two tissues of model 2 required or is model 1 sufficient? The second application asks about data: For a given model are two different groups of parameters required to describe the two data sets, or is one group of parameters sufficient for the overall data? In that case, the LR is constructed from the sum of LL from fits to individual data sets and from LL of fitting the combined data.

We also include results for a "null" model, which states the P(DCS) is equal for all dives in the data set without regard for depth or time. The null model would equal the performance of a rational decompression model only in the rare circumstances where all dives in the data had identical safety. The value of LL for the null model is a convenient number to compare to the LL of other models. Absolute values of LL have no meaning by themselves.

RESULTS

DCIEM wet vs. dry

We first examine the DCIEM dry data alone. The null model ML of -97 is significantly surpassed by model 1 with an LL of -81 with only 1 additional parameter (Table 2). Addition of a second parallel compartment in model 2 is not quite statistically justified, but it implicates a risk generated from both faster (τ = 84 min) and slower (τ = 407 min) kinetics than the single 123-min time constant of model 1. Addition of an absolute threshold of 13 fsw in model 3 is also not fully justified statistically, but it has an excellent fit to the data and focuses attention on even faster events (τ = 18 min) than models 1 and 2. Model 4 is not quite as attractive as model 2 or 3 by LL, but it is much better than a null model. As discussed previously, model 4 has appeal to us because it matches features of actual mammalian gas exchange kinetics not provided by single exponential models in parallel (17). We cannot perform any formal statistical tests on differences between models 2 and 4 except to observe any large differences in LL. Despite apparently large differences in parameters, predictions of safety on some individual dives are comparable. For instance, the "worst" profile in the dry exposures resulted in 3 cases of DCS among 10 men following a 40-min dive to 150 fsw with 85 min of decompression using the DCIEM 1983 table (6). For that profile models 1–4 predicted 11, 16, 14, and 11% DCS, respectively.

Analysis of the DCIEM wet exposures ("Wet" column in Table 2) showed the more limited information provided by a smaller data set. Models 2–4 were all improvements over the null model, although to a less impressive extent (*P* in range of 0.03–0.05 from LR test rather than the $P < 0.001$ in dry data set). The time constants indicate somewhat faster kinetics than estimated from the dry data including some kinetics requiring about 1 min. Standard errors of the parameters are sometimes greater than the parameter values, consistent with the overall marginal performance of modeling. Other experience with small data sets is consistent with the present inability to reach precise conclusions.

In Table 2 the column labeled "Combined" uses both dry and wet data lumped together. All 4 models were again used, and all are tremendous improvements over the null model by LR tests. Within the models, only addition of a second parallel

TABLE 2
ANALYSIS OF DCIEM DATA[a] [b]

Model	Exposures	Dry, n 797	Wet, n 244	Combined, n 1041	Test for Combination
0. Null	LL	−97.084	−41.738	−139.466	—
1. 1 Monoexponential	τ, min	123 ± 22	46 ± 28	97 ± 20	LR = 3.65
	A, min^{-1}	$2.8 \pm .8 \times 10^{-3}$	$2.1 \pm 0.7 \times 10^{-3}$	$2.4 \pm 0.6 \times 10^{-3}$	P = 0.16
	LL	−81.306	−40.595	−123.725	
2. 2 Monoexponentials paralled	τA, min	84 ± 72	0.39 ± 0.15	3.0 ± 14	LR = 7.99
	AA, min^{-1}	$1.2 \pm 1 \times 10^{-3}$	0.55 ± 0.85	$2.7 \pm 14 \times 10^{-3}$	P = 0.09
	τB, min	407 ± 160	360 ± 180	255 ± 74	
	AB, min^{-1}	$1.1 \pm 1 \times 10^{-2}$	$9.7 \pm 14 \times 10^{-3}$	$5.6 \pm 2.5 \times 10^{-2}$	
	LL	−79.592	−36.514	−120.100	
3. 2 Monoexponentials parallel with threshold	τA, min	18 ± 18	0.78 ± 0.74	4.9 ± 7	LR = 7.33
	AA, min^{-1}	$1.5 \pm 1 \times 10^{-3}$	$0.34 \pm .84$	$3.8 \pm 5 \times 10^{-3}$	P = 0.20
	τB, min	141 ± 90	76 ± 110	91 ± 36	
	AB, min^{-1}	$3.8 \pm 5 \times 10^{-2}$	$2.8 \pm 8 \times 10^{-2}$	$4.5 \pm 4 \times 10^{-2}$	
	PTHR, fsw	9 ± 7	13 ± 18	13 ± 5	
	LL	−79.381	−35.529	−118.576	
4. 2 Weighted exponentials	τ1, min	34 ± 220	1.6 ± 4	20 ± 33	LR = 8.53
	τ2, min	175 ± 500	160 ± 160	200 ± 250	P = 0.07
	W1	0.48	0.991	0.72	
	A, min^{-1}	$4.2 \pm 8 \times 10^{-3}$	$5.8 \pm 23 \times 10^{-2}$	$6.2 \pm 8 \times 10^{-2}$	
	LL	−81.239	−37.054	−122.556	

[a]Error estimates are approximately 1 SE; [b]No error on W1 in model 4 is usually given as it is large and very assymmetric. For example, in the DCIEM combined where the best W1 is 0.72, the 1 SE band is from 0.54 to 0.84.

compartment (model 2 over model 1) has strong statistical justification. Kinetic parameters tend to be intermediate between those of dry and wet alone. Estimates of the parameters in Table 2 show an apparently poor precision, with many standard errors similar in magnitude to the parameters themselves. However, some specific calculations may actually be more precise. For example, the kinetic parameters in model 4 are strongly correlated ($\tau 1$ and $\tau 2$ have a correlation coefficient of -0.924). When propagation of error formulas are used to accept a covariance matrix in estimating uncertainty in calculations, individual predictions can contain better precision (20). These parameters predict P(DCS) of 15.8% for the profile of Fig. 2. The 95% confidence band about that prediction is 8–33%.

A formal test of whether wet and dry data are readily combinable under these models was then performed. The final column in Table 2 lists LR tests for combining the 2 data sets under each model. The LR is constructed by doubling the difference in LL between the combined data and the sum of the LL for fits to dry and wet data separately. The statistical question is whether P(DCS) can be calculated with exactly the same parameters for wet and dry dives. The resulting statistics show that that hypothesis cannot be rejected: samples of identical data would produce LL differences this large from 7–20% of the time. With 2–5 degrees of freedom and a fairly small wet data set this test of combining data is fairly weak. Furthermore the test cannot provide an estimate of how different a DCS risk these data could support.

A more direct test of relative risk is provided by using model parameters evaluated from only one set of data to predict the outcome for different data. We used the larger dry data to predict the outcome of the wet exposures. If we had many replications of a given decompression schedule we could compare the predictions and outcome directly for each profile. For the diverse collection of nearly unreplicated dives we made the comparison only on the total. After getting a P(DCS) for each wet profile, we added the individual probabilities to get a total number of expected DCS cases. These predictions are tabulated in Table 3. Despite differences in model features that gave varying predictions on individual profiles, the total cases predicted in the wet exposures are all about 8. This compares well with the 8 definite and 4 marginal cases actually recorded among the wet dives. Using our definition of marginals as ½ case, the ratio of actual wet DCS cases to cases predicted from only dry dives is about 1.2 as shown in the table. Thus the immersed subjects seem to have about a 20% higher

TABLE 3
PREDICTIONS OF TOTAL DCS WET CASES BASED ON DCIEM DRY EXPOSURES ONLY [a]

Model	Predicted Wet Cases	Relative Risk Wet-Dry	95% Confidence Limits on Predicted Cases
1	8.44	1.18	5–12
2	8.30	1.21	5–12
3	8.58	1.17	5–12
4	8.34	1.20	5–12

[a]Actual wet cases were 8 + 4 marginal (score as 10 total). Relative risk defined as ratio of actual wet cases to predicted wet cases from dry dive data.

chance of DCS than dry subjects. The uncertainties in the predictions [last column in Table 3 generated by propagation of errors (20)] indicate that the range of possible predictions (5–12 cases) allows immersion to result in about a 20% lower risk as well as one as high as doubling the risk estimated from dry exposures. (The doubling would be seen as 5 cases predicted vs. the 10 observed.)

The final technique for assessing relative risk used the variant of models 2 and 3 that adds a parameter for incremental risk in wet exposure (Eq. 5). When fitted to the 1041 DCIEM exposures, the estimates of dW were 0.27 ± 0.57 and 0.20 ± 0.53. In neither case did the additional parameter pass a LR test for its addition at $P < 0.05$. We can also estimate the maximum increased risk of immersion is about 2.6 times higher than dry since the upper 95% confidence limit on dW is about 1.6, based on an examination of the likelihood surface. The magnitude of the estimated risk difference is illustrated in Fig. 3 which was generated using the dW variant of model 2. For 5 no-decompression dives to 100 fsw dives performed by both wet and dry subjects, immersion adds less than 1% to predicted P(DCS). The wet-dry difference is much less than the uncertainty in the predictions themselves obtained by propagation of errors. Uncertainty in predictions is slightly greater for the wet dives, which is consistent with the smaller number of dives in that data category. The uncertainty increases with longer times, as the predictions cross outside the range covered in the raw data. (In the data, 35 exposures were to about 100 fsw with rapid decompression, but the bottom times averaged 18 min with a maximum of 28 min.) The figure also shows visually the power of the analysis. Differences in risk less than about two- or threefold in relative risk would have overlapping confidence limits. A plot using model 3 (not shown) appears similar.

The various analyses then all give a consistent answer that wet dives could be about 15–30% more hazardous than dry dives, but that substantial uncertainty is associated with that estimate. The uncertainty will still allow rejection of the possibil-

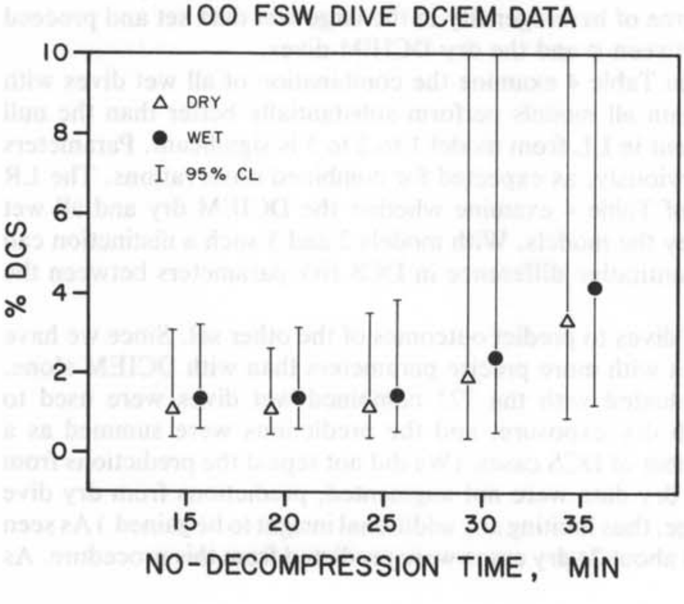

Fig. 3. Comparison of predicted P(DCS) for no-decompression dives either wet or dry to 100 fswg for 15, 20, 25, 30, and 35 min. Predictions are from model 2 using only DCIEM data.

ity that wet dives are more than 2–3 times as hazardous. The relatively few wet exposures limit the precision of these conclusions.

Combining NEDU data

Additional data from NEDU were examined in an attempt to bolster the size of the wet-diver data base. Parameters estimated from the NEDU data alone are shown in the first numerical column of Table 4. All risk models are better than the null model, and two compartments are a significant improvement over one. The threshold in model 3 is also a significant improvement. Other trends within the parameters seem similar to the DCIEM results. Kinetic parameters seem longer; up to 12 h for time constants. The long time constants are required by some DCS cases that occurred following very long dives (up to 6 h in the water, much longer than DCIEM exposures). The larger time constants are not surprising but they will confound the analysis slightly by placing some emphasis on DCS hazard in kinetically slow regions that are not stressed greatly in the shorter DCIEM dives.

Also in Table 4 are parameters obtained from wet data added from both institutions. Although the test conditions appear similar with regard to immersion, exercise, and breathing equipment, comparisons across institutions increase the uncertainty that data can be merged. Thus, evidence of failure in combining data could be a modeling failure or it could reflect unexpected differences in subject population, DCS diagnostic standards, or other factors. A decision to combine data involves some chance that the analyses will become less decisive after averaging dissimilar dives, and some chance that effects could be misidentified (for example, a difference in subject population could masquerade as a wet-dry difference). With these 727 combined wet exposures, model 1 failed to fit better than the null model and is therefore useless for drawing inferences, but the others all performed well. Likelihood ratio tests for combining the two sets of wet dives (not shown) gave a probability of only about 5% that parameters are identical for the two sets. That result indicates a difference between the data sets which can be seen as the slower kinetics required by the NEDU dives. We accept that degree of heterogeneity in the large wet data set and proceed to examine differences between it and the dry DCIEM dives.

The final two columns in Table 4 examine the combination of all wet dives with the DCIEM dry data. Again all models perform substantially better than the null model, and the improvement in LL from model 1 to 2 to 3 is significant. Parameters are in the range found previously, as expected for combined observations. The LR tests in the final column of Table 4 examine whether the DCIEM dry and all wet dives are distinguishable by the models. With models 2 and 3 such a distinction can be made, supporting a quantitative difference in DCS risk parameters between the exposure conditions.

We also used one set of dives to predict outcomes of the other set. Since we have an enlarged set of wet data with more precise parameters than with DCIEM alone, all model parameters evaluated with the 727 combined wet dives were used to calculate P(DCS) for each dry exposure, and the predictions were summed as a prediction of the total number of DCS cases. (We did not repeat the predictions from dry conditions. Since the dry data were not augmented, predictions from dry dive paramters would not change, thus limiting any additional insight to be gained.) As seen in Table 5, between 17 and about 24 dry cases were predicted from this procedure. As

TABLE 4
ANALYSIS OF WET DATA[a]

Model	Exposures	NEDU Wet 483	All Wet 727	All Together 1524	Test for Combination Dry + All Wet
0. Null	LL	−112.413	−154.881	−256.074	
1. 1 Monoexponential	τ, min	173±40	92±17	105±13	
	A, min^{-1}	$2.2\pm.4\times10^{-3}$	$2.2\pm0.4\times10^{-3}$	$2.3\pm0.3\times10^{-3}$	LR = 1.19
	LL	−109.919	−153.867	−235.766	P=0.55
2. 2 Monoexponentials parallel	τA, min	22±30	27±15	77±21	
	AA, min^{-1}	$1.7\pm2\times10^{-3}$	$1.8\pm0.6\times10^{-3}$	$1.7\pm0.3\times10^{-3}$	
	τB, min	730±200	749±195	808±260	
	AB, min^{-1}	$9.4\pm8\times10^{-3}$	$9.7\pm8\times10^{-3}$	$9.5\pm12\times10^{-3}$	LR = 12.11
	LL	−104.006	−145.246	−230.892	P= 0.02
3. 2 Monoexponentials parallel with threshold	τA, min	26±34	27±10	47±8	
	AA, min^{-1}	$2.8\pm1.5\times10^{-3}$	$3.3\pm0.9\times10^{-3}$	$4.0\pm0.9\times10^{-3}$	
	τB, min	325±60	335±67	335±80	
	AB, min^{-1}	$6.4\pm4\times10^{-2}$	$6.9\pm4\times10^{-2}$	$8.8\pm6\times10^{-2}$	
	PTHR, fsw	6.6±1	6.6±1	7±1	LR = 11.43
	LL	−100.934	−142.210	−227.308	P= 0.05
4. 2 Weighted exponentials	τ1, min	2.2±1.4	14.5±8	26±13	
	τ2, min	310±40	290±60	254±90	
	W1	0.991±0.008	0.89±0.06	0.78±0.07	
	A, min^{-1}	$4.9\pm5\times10^{-2}$	$9.2\pm3\times10^{-3}$	$6.0\pm2\times10^{-3}$	LR = 7.78
	LL	−105.594	−147.704	−232.833	P=0.10

[a]Error estimates are approximately 1 SE.

TABLE 5
PREDICTIONS OF TOTAL DCS DRY CASES BASED ON ALL WET EXPOSURES [a]

Model	Predicted Dry Cases	Relative Risk Wet-Dry	95% Confidence Limits on Predicted Cases
1	21.4	1.02	13–30
2	24.0	1.14	11–37
3	23.2	1.10	11–35
4	16.7	0.80	8–26

[a]Actual dry cases were 19 + 4 marginal (score as 21 total). Relative risk defined as ratio of predicted dry cases from wet data to actual dry dive data.

the observed total was 21 cases, agreement was close but not exact. The ratio of predicted cases from wet data to observed dry cases of DCS vary from 0.80 to 1.14, with the most successful models (2 and 3) being highest. This seems consistent with the trend in earlier predictions in Table 3 that give a slightly higher risk of DCS under wet conditions. Again the cumulative uncertainty in the total number of cases predicted precludes a precise prediction, but a doubling risk from immersion can again be rejected. (In Table 5 a doubling of risk would be seen as prediction of double the actual dry cases, about 42, which definitely is outside the listed confidence limits.)

The overall combined data were also examined by the variant of models 2 and 3 that include the wet-dry difference parameter, dW, of Eq. 5. Again a small effect was estimated: for model 2, dW $= -0.24 \pm -0.25$ and for model 3, dW $= -0.19 \pm -0.26$. Within 95% confidence limits this parameter allows the immersion effect to range from a modest increase in risk to a more substantial degree of relative safety to an additional risk of about 60% (maximum dW is about 1.6). Sample results of these models are also shown in Fig. 4 using the same dives as in Fig. 3, but in this

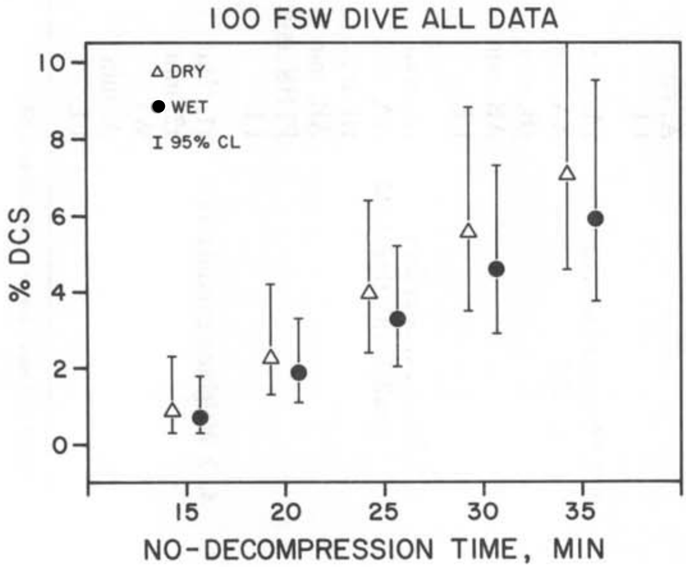

Fig. 4. Comparison of predicted P(DCS) for no-decompression dives either wet or dry to 100 fswg for 15, 20, 25, 30, and 35 min. Predictions are from model 3 using all data from DCIEM and NEDU.

case the predictions of the dW variant of model 3. (Model 2 leads to similar conclusions.) The general dose-response upward trend using this model is sharper than Fig. 3, as we have seen in other models with threshold parameters. Because of the negative sign in dW, P(DCS) is predicted to be lower for the wet exposures. Again the dry-wet difference is much less than the uncertainty in the predictions themselves. The magnitude of the error bars is somewhat less than when only the DCIEM data were used, reflecting the advantage of larger data sets. However, the strict numerical advantage has been partially lost due to the need to cover different diving durations and other possible factors that are different in the data and are reflected only in parameter imprecision. Again, Fig. 3 shows that a relative change in risk of almost twofold would be required to separate conditions by more than the error bars.

Taken together, the analyses support a strong similarity in DCS risk between wet and dry exposures. The combined 1524 dives examined point to a range of possible small differences with immersion, between 25% safer and 15% more hazardous than dry exposures. With consideration of confidence limits in the analyses, twofold differences can be confidently rejected.

DISCUSSION

Tests of new decompression tables historically have preferred divers under wet working conditions. Pressure chambers for the tests usually limit wet exposures to 1–3 subjects per test. With the hundreds of exposures necessary to document safety, use of dry subjects who could be grouped 6–12 per test would be a substantial increase in efficiency with a large economic benefit. However, we would need to know the magnitude of any difference in DCS risk between dry and wet exposure. Some statistically significant differences have been reported between dry and warm-immersed altitude exposures (21) and between working and resting divers (some dry, some wet) undergoing surface decompression (22). There are lesser indications, many claims, and theoretical expectations that exercise, temperature, and immersion may have some effect alone or in combination; but the size of any effect is certainly not available [for a review *see* (23)].

The present analysis indicates that for "typical" air dives any difference is small. None of the estimates showed a difference as great as 30% and nearly all answers overlap each other. The major conclusions can be seen graphically in Figs. 3 and 4. Estimates of the difference in risk due to immersion may be slightly greater or slightly less, depending on the specific model and data sets used. The estimated difference is less than the difference among individual dives (e.g., 20 vs. 40 min, bottom time on a 100-fsw dive) and less than the uncertainty of a given prediction of P(DCS). From the confidence bounds on the analyses, a relative difference of about twofold can be rejected by the data. Thus we can comfortably assert that immersion does not double DCS risk.

A more quantitative appreciation of the magnitude of risk difference can also be sensed from these results. If we refer to Fig. 3 and desire a target DCS of 2% DCS, then a no decompression time of 30 min would be specified for dry diving but only 27 min for wet dives. Of course these numbers cannot be statistically separated. However, reliable predictions based on more data and probabilistic models would eventually allow a more detailed risk-benefit analysis.

The present analysis relied on many different statistical approaches to estimating a wet-dry difference. Despite the use of over 1500 exposures, the conclusions carry more uncertainty than a recent examination of an oxygen effect in DCS risk using less than 500 exposures (11). An advantage in the O_2 study was control of experimental design that avoids confounding influences such as the longer times in the NEDU exposures compared to the DCIEM dives. Variations in data that occur when the "experiment" is unplanned can be partially controlled by use of additional parameters, such as the multiple gas kinetic parameters necessitated by combining the present data. However, since the additional parameters must also be estimated from the data, the uncertainty of more complex models with modest data sets leaves less precision for parameters of more direct interest, such as dW.

Limitations on using more complex models dissuaded us from exploring models with more physiology, such as specific treatment of reported immersion differences in exchange kinetics of inert gas (24). The present analysis also did not allow separate consideration of exercise and thermal effects (23, 25). Almost invariably the wet subjects were exercising, and in most cases the dry subjects were not. The finding of no large effect then implies but not confirms that exercise is not a very strong factor. A similar argument could be used for the factor of thermal conditions because immersed subjects were generally in cold water. The overall small difference due to conditions means that either all three "stresses" are less important than sometimes thought, or that the stresses somehow act to offset each other's effect when combined. Either explanation makes the specification of "worst case" conditions for testing more problematic since the choice of "worse" between dry-resting-comfortable and wet-working-cold is this small.

How might these results be used to test decompression tables? The least conservative approach would be to conduct exclusively dry trials and expect that subsequent wet dives would have the same safety within about 30%. A greater degree of conservatism would use the present result having greater confidence: the rejection of a twofold difference. An example of this approach would be the testing of tables that needed a 4% or less DCS rate at sea by using dry trials until a safety of <2% DCS was established. Even this procedure would be subject to additional uncertainties arising from its basis in a single class of models (one can compare model performance but can never be certain of having the "best" model) and its basis in a limited range of air diving (Table 1). The later uncertainty would increase as one extrapolates into other diving conditions. For procedures outside the range of the data examined here, even a twofold safety factor cannot be applied without a real sense of caution.

APPENDIX
Computational details of the models

For models 1–3 the calculation of nitrogen tension, P_{tis}, is relatively simple. For a single exponential time constant, τ, the response to a *step* change in inspired nitrogen from P_0 to P_1 at time T_0 is

$$P_{tis} = P_{tis_0} + (P_1 - P_0)\{1.0 - \exp[-(t - T_0)/\tau]\} \qquad (A1)$$

where P_{tis_0} is the tissue-nitrogen tension at time T_0. Thus, tissue response to a step change in pressure is a smooth exponential approach to the new inspired level. For air dives, inspired levels are taken to be 79% of ambient pressure.

The data used in this report are coded as pressure-time nodes with a linear pressure change assumed between nodes. Pressure changes are then treated as ramps. The slope of the ramp, k, is easily obtained from the pressure and time modes at the beginning, T_0 and P_0 and the end of the ramp, T_1 and P_1

$$k_1 = \frac{P_1 - P_0}{T_1 - T_0} \qquad (A2)$$

Calculation of the tissue nitrogen tension during the ramp is obtained from

$$P_{tis} = P_{tis_0} + k_1(t - T_0) - k_1\tau + k_1\tau \cdot \exp[-(t - T_0)/\tau] \qquad (A3)$$

The tissue response is thus a smooth approach to a ramp parallel to the inspired pressure but offset by an amount $(-k_1\tau)$. For positive ramps, $k_1 > 0$, the tissue tension will approach a value lower than inspired, while for negative ramps (decompression), $k_1 < 0$, the eventual tension is higher than inspired. Of course, those generalities only hold for "long" ramps where the exponential term has decayed: $(t - T_0)$ much longer than τ.

Each actual dive consists of many nodes and many ramps. The tissue nitrogen tension is calculated as the linear superposition of the response to each ramp. That is, under the assumption that the tissue deals with inert gas in the same manner throughout the dive, response to all ramps is simply added. To simplify notation slightly, define k'_j as the *change* in slope of inspired gas on the jth ramp compared with the previous slope:

$$k'_j = k_j - k_{j-1} \qquad (A4)$$

Using that definition, the response of the tissue during the nth ramp which started at time T_n is:

$$P_{tis} = P_{tis_0} + \sum_{j=1}^{n} k'_j\,(t - T_j) - \tau \sum_{j=1}^{n} k'_j + k'_j\,\tau \sum_{j=1}^{n} \exp[-(t - T_j)/\tau] \qquad (A5)$$

This equation shows the same type of constant, linear, and exponential terms as Eq. *A3* but with the additive nature of the coefficients. As seen in plots of real dive profiles such as Fig. 2 *(top)* there is a smooth response of tissue tension during the dive. Also as expected, faster (small τ) tissues track closer to the inspired gas pressure than do slower (large τ) tissues.

The gas kinetics used in model 4 are slightly more complicated in that response within a single tissue is governed by the weighted combination of two exponential terms. The additional complexity is worth exploring since the kinetics are closer to those experimentally observed in small regions of actual animal tissues (13, 17). Instead of the step response of Eq. *A1* we have the following:

$$P_{tis} = P_{tis_0} + (P_1 - P_0)\left\{1.0 - \frac{W1\tau1}{M}\exp[-(t - T_0)/\tau1] - \frac{(1 - W1)\tau2}{M}\exp[-(t - T_0)/\tau2]\right\} \qquad (A6)$$

where the mean exchange time, M, is the weighted average of the two component exponentials

$$M = W1\tau1 + (1 - W1)\tau2 \qquad (A7)$$

Rather than showing the single exponential response, the tissue has an initially rapid response (assuming $\tau1 < M$) followed by a slower approach ($\tau2 > M$) to the new inspired level. In animal experiments $\tau2$ was typically 5 times or more slower than $\tau1$ (17).

Response to a ramp in inspired pressure for the two-exponential kinetics is similar to Eq. *A3*:

$$P_{tis} = P_{tis_0} + k_1(t - T_0) - k_1\,[w1\tau1^2 + (1 - W1)\tau2^2]/M + \frac{k_1\,W1\tau1^2}{M}\exp[-(t - T_0)/\tau1] + \frac{k_1\,(1 - W1)\tau2^2}{M}\exp[-(t - T_0)/\tau2] \qquad (A8)$$

Again the tissue approaches a ramp parallel to the inspired pressure, but there are two transient exponential terms rather than one.

For a complex dive of many ramps, linear superposition is again applied, and using the slope change definition of Eq. *A4* we obtain:

$$P_{tis} = P_{tis_0} + \sum_{j=1}^{n} k'_j\,(t - T_j) - [W1\tau1^2 + (1 - W1)\tau2^2]\left(\sum_{j=1}^{n} k'_j\right)/M + \frac{1}{M}\sum_{j=1}^{n}\{k'_j W1\tau1^2 \exp[-(t - T_j)/\tau1]\} + \frac{1}{M}\sum_{j=1}^{n}\{k'_j\,(1 - W1)\tau2^2 \exp[-(t - T_j)/\tau2]\} \qquad (A9)$$

With the basic Eqs. *1* and *2* of the main text, it is possible now to calculate P(DCS) for any air dive of arbitrary complexity. To increase speed of computation in lengthy analyses, we developed some additional formulas equivalent to Eqs. *A4* and *A9* [appendix 1 in ref (13)]. We also worked on formulas for the integration of text Eq. *1* after substitution of Eqs. *2–4* and the kinetic expressions given here. For those with a preference for full numerical integration, simpler derivative formulations can be applied, for example (15).

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