



DECOMPRESSION CHAMBER—In a NASA decompression chamber, Dr. Johnny Conkin of the National Space Biomedical Institute of the Baylor College of Medicine, tests Laura A. Thompson, ISSO post-doctoral research fellow, in oxygen pre-breathe protocols instituted by NASA to minimize decompression sickness. During the course of 484 extravehicular activities, researchers estimate that at least one person will suffer serious decompression sickness and suffer debility.

Determination of Risk of Serious Decompression Sickness among Astronauts Involved in Space Extravehicular Activities

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Abstract—

NASA follows specified oxygen pre-breathe protocols that astronauts must

complete prior to their extravehicular activities (EVA). Exercise during prebreathe protocols accelerates the process of denitrogenation and so reduces the prebreathe time. NASA needs to evaluate prebreathe protocols with and without the option of exercise to determine their efficacy in mitigating decompression sickness (DCS) risk. Currently, NASA estimates the probability of serious DCS based upon a model derived from physiological concepts and statistically fitted to DCS data from 258 altitude chamber tests given in 73 published or reported studies. A new model has been developed based on statistical considerations that uses a random effect term to account for excess variability across the various test studies. This model appears to fit the data better, and hence, is considered more reliable in predicting the outcome of serious DCS.

Researchers incorporate the random effects model into a simulation procedure which simulates the uncertainty in the estimation of the probability of at least one case of serious DCS in the lifespan of the International Space Station (approximately 484 EVAs) for prebreathe protocols that involve exercise. The estimated probabilities and their upper confidence limits (UCL) show that with 95 percent confidence, the actual probability lies below 0.428 for the 2-hr + exercise prebreathe, and lies below 0.418 for the 2-hr 20-min + exercise prebreathe.

For the prebreathe protocols that do not involve exercise, the use of a simulation procedure is not required, and the probability of at least one serious DCS case is estimated directly from the random effects model. The estimated probabilities and UCLs for these protocols show that all of the estimated probabilities and the upper confidence limits exceed those in the case of prebreathe protocols with exercise.

A MODEL PROPOSED BY DR. JOHNNY CONKIN¹ DESCRIBES THE probability of serious decompression sickness (DCS) during extra-vehicular activity (EVA) to be a nonlinear function of the three variables:

1. TR180 = Tissue ratio in the 180-minute half-time compartment (denitrogenation dose)
2. T_{alt} = Time at Altitude (duration of the EVA)
3. EXER = Binary indicator variable for the presence (1) or absence (0) of exercise at altitude.

TR180 is estimated from another model and is then input into Conkin's model. The entire process of estimation of the probability of serious DCS requires a sequence of steps.

To account for the uncertainty inherent in the sequence of estimations described above, McWhorter and LaMotte² simulated the process using the statistical properties of the estimates involved. Their simulation assumed that EVAs will last six hours and will involve exercise at altitude. Table 1 summarizes their results (after 10,000 simulations) for the two prebreathe protocols that involve exercise. The fourth column of Table 1 gives the estimated probability of at least one case of serious DCS in 484 EVAs, and the fifth column gives the upper 95 percent confidence limits on this probability.

Thus, according to the simulation procedure that uses Conkin's model, with 95 percent confidence, this probability lies below 0.146 for the 2-hr + exercise prebreathe, and lies below 0.110 for the 2-hr 20-min + exercise prebreathe.

Random Effects Model as Alternative to Conkin's Model

Conkin's model was based on certain physiological considerations, but it also incorporated the statistical concept of hazard as a function of T_{alt} and was formulated by multiplying terms involving the three explanatory variables, TR180, T_{alt} , and EXER. The model fit to the data from 258 altitude chamber test studies showed that all three parameters associated with the explanatory variables were highly significant, and thus, a significant amount of variability in the occurrence of serious DCS was explained by the model.

An alternative approach to modeling data with a binary response (as occurrence or nonoccurrence of serious DCS) is to characterize its risk probability in terms of a logistic function using the three variables TR180, T_{alt} , and EXER. However, an

examination of the data revealed a relatively high amount of test-to-test variability that exceeded the variability accounted for by only these three explanatory variables. A random effects model is used to capture excess variability.

The number of serious DCS cases in the i th test was modeled as binomially distributed, with probability given in Equation (1):

$$\Pr(\text{Serious DCS in test } i) = \frac{\exp(\beta_0 + \sum_{j=1}^4 x_{ij}\beta_j + b_i)}{1 + \exp(\beta_0 + \sum_{j=1}^4 x_{ij}\beta_j + b_i)}, \quad (1)$$

where

$b_i \sim Normal(0, \sigma_b^2)$; b_i represents the random effect for the i th test

$x_1 = EXER (=1,0)$

$x_2 = TR180$

$x_3 = (T_{alt} - \bar{T}_{alt})$ \bar{T}_{alt} = sample mean of T_{alt}

$x_4 = (T_{alt} - \bar{T}_{alt})^2$

In comparison with Conkin's Model, the random effects model better describes the data. In particular, a numerical measure of general goodness-of-fit, called Akaike's Information Criterion (AIC), is much lower for the random effects model (AIC = 513.6) than for Conkin's Model (AIC = 854.7). A lower value of this criterion implies a better relative model fit when comparing two different model fits.

Also, a comparison of the predicted, versus observed, incidence of serious DCS across the 258 tests shows that the random effects model picks up much of the test-to-test variability that is left

Table 1. Risk Probabilities Based on Conkin's Model for Prebreathe Options that Include Exercise

Prebreathe Options	Estimated TR180	Estimated P(serious DCS)	Estimated P(at least 1 serious DCS case)	95% UCL
2-hr + exercise	0.774	0.00036	0.1600	0.146
2-hr 20-min + exercise	0.7186	0.00025	0.1140	0.110

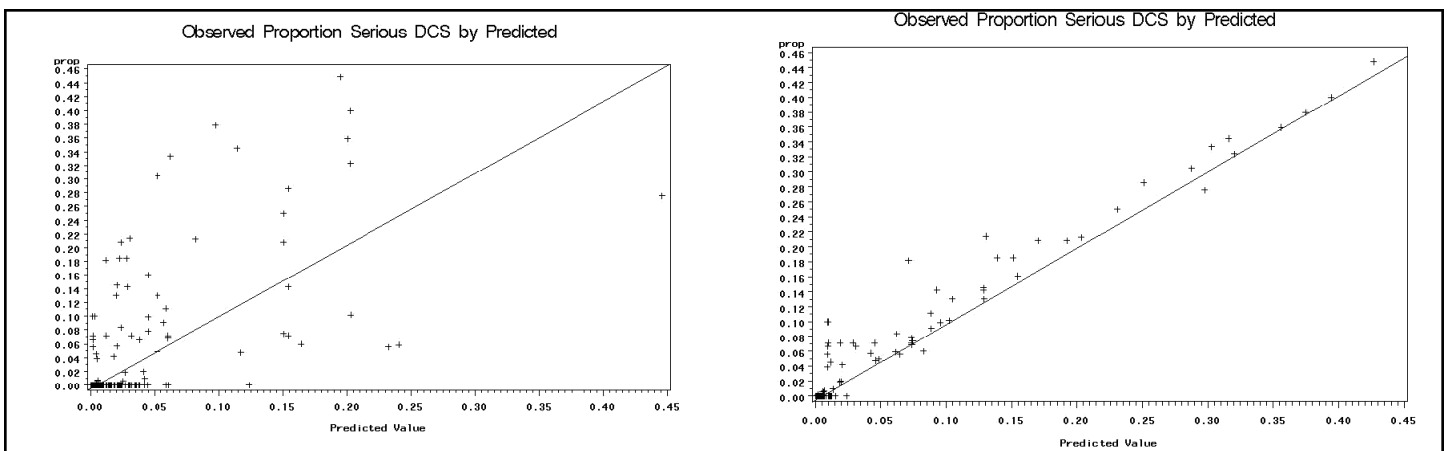


Figure 1. Panel 1a (left) shows the observed proportion (prop) of serious DCS cases within each test by the predicted probability of serious DCS using Conkin's Model. Panel 1b (right) shows the observed proportion (prop) of serious DCS cases by the predicted probability of serious DCS using the random effects model.

Table 2: Risk Probabilities Based on Random Effects Model for Prebreathe Options that Include Exercise

Prebreathe Options	Estimated TR180	Estimated P(serious DCS)	Estimated P(at least 1 serious DCS case)	95% UCL
2-hr + exercise	0.774	0.00058	0.2462	0.428
2-hr 20-min + exercise	0.7186	0.00051	0.2197	0.418

unaccounted for in Conkin’s model. Figures 1a and 1b plot, respectively, the observed, versus predicted, probability of serious DCS across the 258 tests. The solid lines running through the plots are identity lines. The predicted values used for Figure 1b come from Equation (1), with the maximum likelihood estimates of the parameters.

Estimating the Probability of At Least One Case of Serious DCS in 484 EVAs

Using the random effects model in place of Conkin’s model in the simulation procedure we obtained the nine percent upper confidence limits, as shown in Table 2, for the two prebreathe procedures that entail exercise during prebreathe. Also, other probabilities similar to those given in Table 1 are given in Table 2. The probability estimates are .2462 and .2196, respectively, for the two prebreathe protocols. Estimates of the associated uncertainty derived from the simulation procedure (after 10,000 simulations) lead to upper 95 percent confidence limits, as shown in the right-hand columns of Table 2.

Thus, assuming an EVA to last six hours, with exercise at altitude, the 95 percent upper confidence limit on the probability of at least one serious DCS case in 484 EVAs is .428 and .418 for the two prebreathe protocols. These 95 percent UCL’s are higher than those for Conkin’s model. However, the random effects model fits the data better. Thus, Conkin’s model may underestimate the upper limit on the probability of at least one case of serious DCS.

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