

The Risk of Decompression Sickness (DCS) is Influenced by Dive Conditions

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Abstract

DAN's Project Dive Exploration (PDE) gathers data on dive profiles, conditions, and outcomes to assess DCS risk and risk factors. This report investigated the DCS risk in three dive groups: 51,497 PDE warm-water dives; 6,527 PDE cold-water dives; and 2,252 Navy chamber dives. First, DCS risk was predicted for all dives by a probabilistic decompression model that had been calibrated to Navy data. Next, predicted risk and observed incidence were compared for the groups. Finally, predicted risks were recalibrated to all dives combined. Mean observed DCS incidences were 2, 28, and 311 cases per 10,000 dives for warm-water, cold-water, and Navy dives, respectively. Original predictions overestimated observed incidences for warm and cold-water dives but not for Navy dives. With recalibration, mean predicted risk and mean observed incidence were the same. Navy dives had higher predicted risks than warm or cold-water dives, but even for a given dive profile, the groups differed significantly in both recalibrated risk and observed incidence. We conclude: (a) probabilistic models are useful for estimating risk; (b) models may not extrapolate accurately beyond their calibration data; and (c) dive conditions, in addition to dive profiles, may significantly affect risk.

Introduction

Brief sojourns at elevated pressure while breathing compressed gases are relatively safe, but extended exposures can lead to unacceptable risk of decompression sickness (DCS). The limits of safe exposure are particularly difficult to determine for multi-level, repetitive, and multi-day dives. Besides exposure, the conditions and circumstances of a dive may also affect risk. We investigated the influence of exposure and conditions on DCS risk in three groups of dives.

Project Dive Exploration

Investigation of safe diving limits requires knowledge of depth-time profiles and medical outcomes. This is the objective of Project Dive Exploration (PDE) which became possible when recording dive computers were introduced by Suunto and Orca in 1989. Seven brands of dive computer and recorder are now PDE-compatible including those made by Suunto, Uwatec, Dive Rite, Cochran, Sensus, Oceanic, and Delta P Technologies.

PDE divers are asked to describe any symptoms noted during or after a dive series. When the series is complete, the diver submits a report that reviews his or her medical condition at 48 hrs after the last dive or altitude exposure. The 48 Hour Report admits or denies symptoms, indicates whether recompression occurred, and provides information about flying after diving. If the diver was recompressed, DAN contacts the treating chamber for a case report. The report is evaluated by a diagnostic algorithm to classify the case as not all recompressed divers have DCS, (Vann 2004b).

PDE began in 1995 as a pilot study (Project Dive Safety) that was designed to develop procedures and software for collecting dive profiles from open water divers (Figure 1). Formal PDE data collection began in 1998, and to date, over 100,000 raw dive profiles have accumulated. All dives are reviewed and error checked before analysis. The 58,024 dives that have undergone this process so far are discussed below.

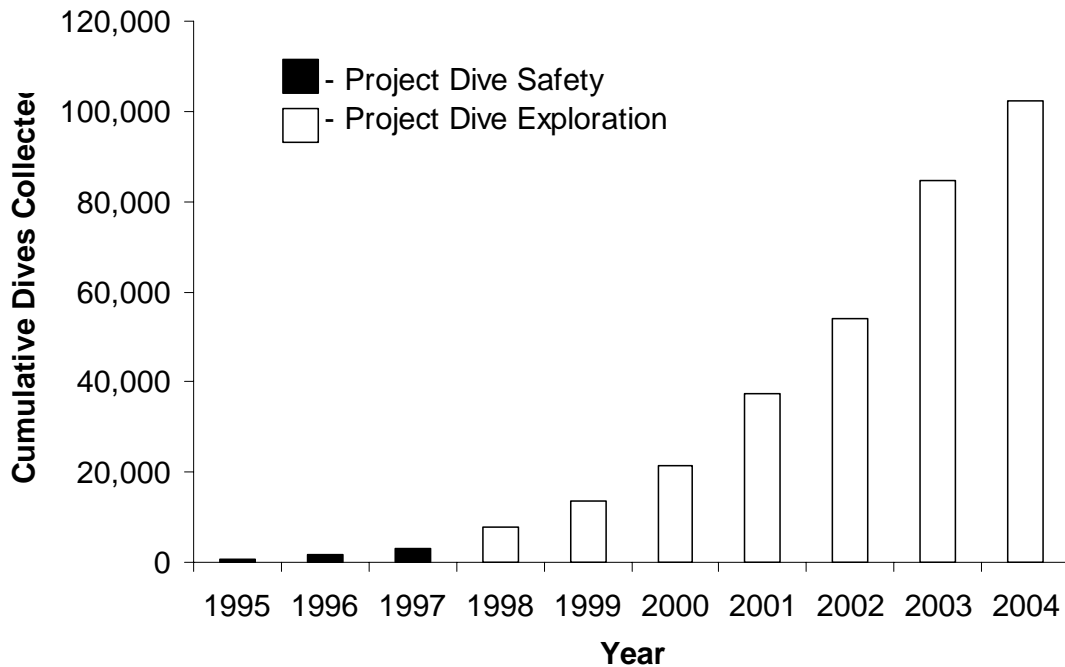


Figure 1. History of PDE data collection.

Methods

Dive Groups

Table 1 describes three dive groups with known depth-time profiles and medical outcomes. Two were from PDE, and one was from U.S. Navy chamber dive trials for developing decompression procedures. The first PDE group included live-aboard dive boats, day boats, and shore dives in warm water locations. The second PDE group was from cold water wreck

divers in Scapa Flow, Scotland. The U.S. Navy group included experimental dives conducted in hyperbaric chambers during which the divers were usually immersed and exercising.

Table 1. Dive population samples.

| Dive Group | # DCS Cases | # Dives | DCS per 10,000 Dives |
|----------------|-------------|---------|----------------------|
| PDE Warm Water | 8 | 51,497 | 2* ⁺ |
| PDE Cold Water | 18 | 6,527 | 28 ⁺ |
| USN Chamber | 70 | 2,252 | 311 |

* - significantly different from Cold Water

⁺ - significantly different from Navy trials

Statistics

DCS incidences between dive groups were compared by Fisher's exact test. Differences between observed incidence and DCS risk predicted by a probabilistic decompression model were evaluated by Chi-square test.

Predicting the DCS risk of a particular dive can be accomplished with a probabilistic decompression model if the depth-time profile and breathing gases are known. A probabilistic model is a mathematical rendering of a decompression theory. The parameter values of the model are statistically calibrated to empirical decompression data for which the dive profiles and medical outcomes are known. We used a probabilistic model of bubble growth and resolution calibrated to a dataset that included the Navy chamber dives of Table 1 (Gerth and Vann, 1997).

Each dive group of Table 1 was divided into sub-groups, and the mean predicted risk and mean observed incidence were computed for each of the sub-groups. Trendlines to the sub-groups were determined by linear regression. Logistic regression was used to investigate the relationship of predicted DCS risk to observed DCS incidence based on the individual dives.

A p-value of less than 0.05 was accepted as an indication of statistical significance for all tests.

Results

The mean DCS incidence for each dive group was significantly different from the other groups (Table 1).

For each group, the mean DCS risk predicted by the model was compared with the mean observed DCS incidence. The difference between predicted and observed was not significant for the Navy dives, as might be expected since these dives were part of the model calibration data, but the predicted means were significantly greater than the observed means for both PDE groups (Table 2).

Table 2. The observed DCS incidence and the DCS incidence predicted by the probabilistic model of reference (1) for the three dive groups of Table 1.

| Dive Group | Mean Observed Incidence (DCS per 10,000 Dives) | Mean Predicted Risk (DCS per 10,000 Dives) |
|----------------|------------------------------------------------|--------------------------------------------|
| PDE Warm Water | 2 | 51* |
| PDE Cold Water | 28 | 75* |
| USN Chamber | 311 | 351 |

*observed and predicted differ significantly

The Navy dives were sorted in order of predicted DCS risk, divided into six equal sub-groups of 375 dives, and the mean risk and mean observed incidence were determined for each sub-group. The observed incidences were plotted against the predicted risks in Figure 2. If the predictive model were perfect, the points would fall exactly on the line of identity. The model under-predicted slightly at high risks and over-predicted slightly at low risks, but with an R-square of 0.98, the trendline indicated a good simulation of the Navy dives.

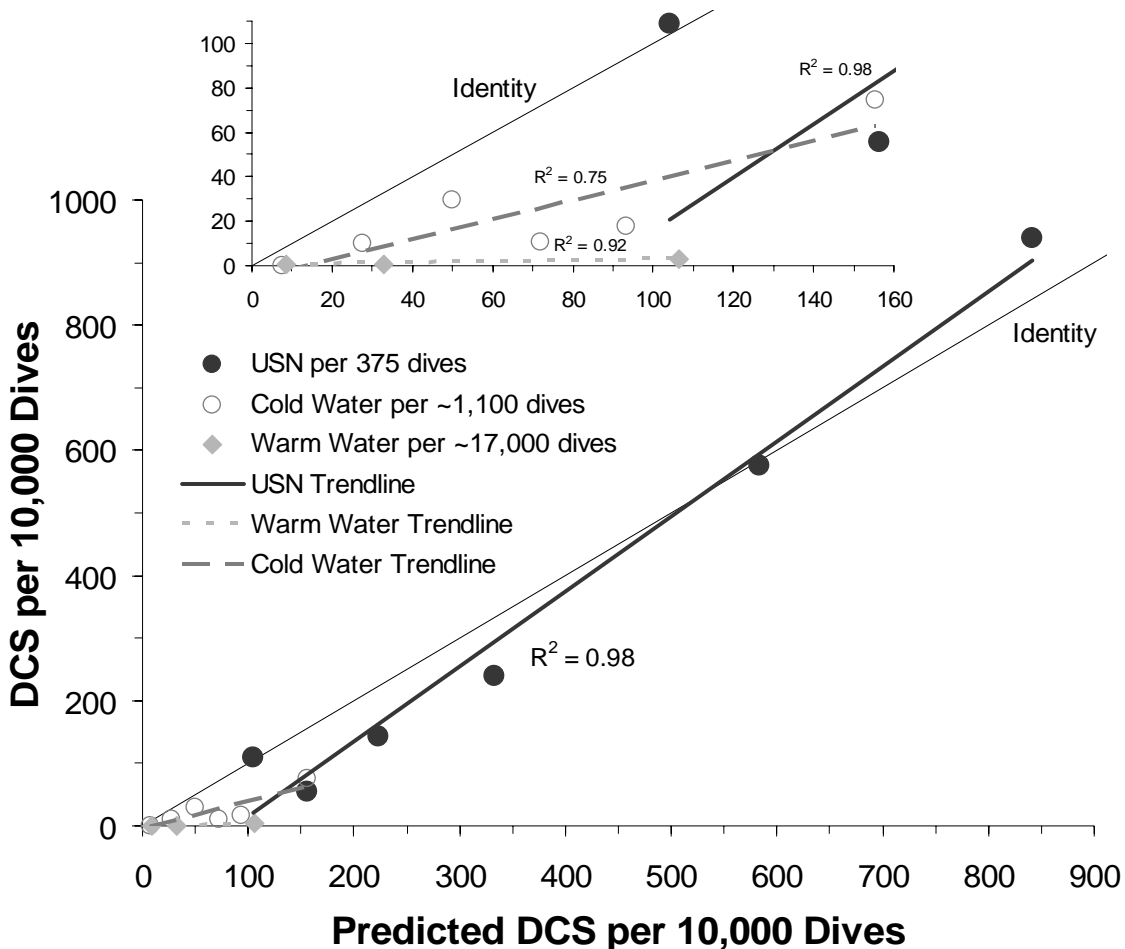


Figure 2. Observed DCS incidence and predicted DCS risk for the Navy and PDE dives. The inset shows the lower left corner of the main plot.

Trendlines were found in a similar manner for the PDE Cold Water dives (six sub-groups of ~1,100 dives each) and PDE Warm Water dives (three sub-groups of ~17,000 dives each).

The trendlines showed that the Navy dives had higher predicted risks than either PDE group. This is best seen in the inset that expands the low risk corner of Figure 2 where the PDE dives were concentrated. Over-prediction of the Navy DCS incidence was small, but the Cold Water DCS was over-predicted by a factor of about two, and Warm Water DCS was over-predicted by a factor of about 30. The R-square values for PDE trendlines were lower than for the Navy trendline, but the observed DCS incidences for the PDE dives were ordered reasonably well by the predicted risks, and most so for the Warm Water dives.

Although predicted risk was a poor measure of observed DCS incidence for the PDE dives, the trendlines of Figure 2 suggested that there might be a functional relationship between predicted and observed DCS. We tested this hypothesis by applying logistic regression to the combined PDE and USN data. This recalibrated the relationship of predicted to observed DCS, in effect, by treating predicted risk as a decompression stress rather than an absolute risk. Individual adjustments were made for each dive group to represent possible (but not necessarily known) differences in dive conditions between the groups.

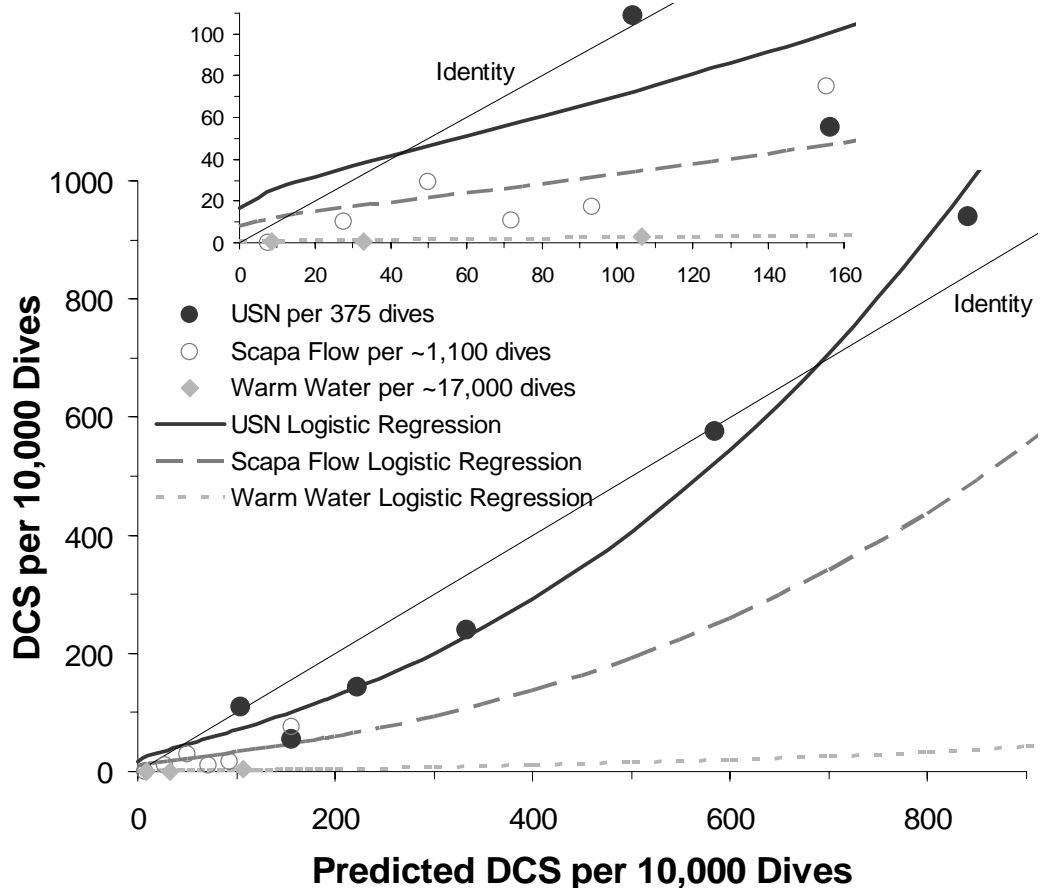


Figure 3. Logistic regression model of the Navy, Cold Water, and Warm Water dives. The inset shows the lower left corner of the main plot.

Predicted risk was significantly associated with DCS, and Warm Water dives were significantly different from Cold Water dives and from Navy dives. Recalibration brought

the mean observed and predicted DCS into agreement for each dive group at 8, 18, and 70 cases for the Warm Water, Cold Water, and Navy dives, respectively (Table 1). Figure 3 is similar to Figure 2 but shows the logistic regression model of observed DCS after recalibration. The inset in Figure 3 expands the low risk corner of the main figure.

Discussion

What are the implications of this analysis for a familiar dive such as a no-decompression exposure on air to the U.S. Navy limit of 60 min at 60 fsw? After recalibration by logistic regression, a 60 min no-decompression dive to 60 fsw had an estimated DCS risk of 4 DCS per 10,000 dives for Warm Water, 59 DCS per 10,000 dives for Cold Water, and 132 DCS per 10,000 dives for Navy trials.

If these estimates are correct, the conditions and circumstances of a dive may have important effects on DCS risk even for dives of identical depth-time profile. While we refer to “Warm Water,” “Cold Water,” and “U.S. Navy” dives, these are better described as labels for the entire set of conditions that apply for each dive group. The conditions may be unmeasured or unknown and might include water temperature, thermal protection, and pre-, during, and post-dive exercise.

Our analysis demonstrated a significant effect for each dive group by assigning a separate parameter value to each group in the logistic regression. While we cannot confirm the underlying causes for differences between groups, exercise and temperature are known to have profound effects on inert gas exchange and bubble formation (Vann 2004a and 2004b), with magnitudes that vary according to the phase of the dive (pre-dive, at depth, during decompression, or post-dive), and recent evidence has demonstrated that thermal stress is an important determinant of decompression risk (Ruterbusch *et.al.*, 2004). One might speculate that long, cold, decompression dives put the Navy divers at higher risk than short, no-decompression Warm Water dives. The difference was smaller for the Cold Water dives at Scapa Flow (for which most divers wore drysuits) that involved thermal stress and some decompression diving.

A final conclusion is that probabilistic decompression models should be calibrated to the type of diving for which they are to be used. While the probabilistic model that was calibrated to the Navy trials did well at predicting the high risk Navy dives (Gerth and Vann, 1997), there were few low risk dives under conditions of low thermal stress in the Navy calibration data. The ideal approach would be to calibrate probabilistic models to a dataset that included both high and low risk data. This could be achieved by calibration data that included both the Navy and PDE dives.

Literature Cited

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