Descriptive Model of the Influence of Thermal Exposure on Diver Susceptibility to Decompression Sickness

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INTRODUCTION

Divers who ascend from depth too quickly risk occurrence of decompression sickness (DCS). This risk is mitigated with insertion of decompression stops. The numbers and lengths of such stops in current U.S. Navy diving decompression tables are explicitly based on only the maximum dive depths and times at those depths.

Other potentially modifiable factors such as diver thermal status may also affect DCS risk. For example, the *U.S. Navy Diving Manual* advises “jumping” a schedule if the diver is exceptionally cold or the workload is relatively strenuous during a dive.

Unfortunately, schedule jumping is imprecise, and successive jumps can be made on the basis of trial and error before the DCS incidence in a given diving operation is reduced to an acceptable level. Safer and more efficient techniques for determining appropriate decompressions require establishment and quantification of the influence of diver thermal conditions on DCS risk.

We here report a quantitative model of how diver thermal exposure during different dive phases influences the incidence of DCS.

METHODS

The model is based on results of an NEDU man trial[1] in which diver thermal exposure was independently controlled during dive bottom time (BT) and decompression time (Figure 1). Dives were characterized by their depths, bottom times, and thermal conditions during BT and decompression. The data are summarized in Table 1.

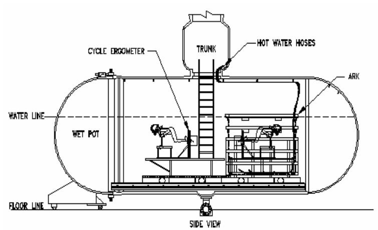

Figure 1. Schematic of setup for independent control of diver thermal conditions during dive bottom time and decompression. Divers wore only t-shirts and swim trunks while immersed in warm (W, 97 °F; 36 ° C) or cold (C, 80 °F; 27 °C) water. To change thermal conditions during a dive, divers exchanged locations between Ark and Wet Pot at different water temperatures during the 2 minutes before starting decompression.

Table 1. Summary of DCS Outcomes (Ref. 1)

Series[a]	Thermal Condition Pair	Depth (fsw)/ Bottom Time (min)	# DCS/ # Exposures	DCS Incidence % (95% C.L.)
1	C/W	120/30	0/80	0.0 (0.0 – 3.7)
3		120/50	0/8	0.0 (0.0 – 31.2)
4		120/70	2/158	1.3 (0.2 – 4.5)
2	W/C	120/30	7/32[r]	21.9 (9.3 – 40.0)
5		120/25	4/80	5.0 (1.4 – 12.3)
6	W/W	120/70	4/24[r]	16.7 (4.7 – 37.4)
7	C/C	120/60	4/18[r]	22.2 (6.4 – 47.7)
		Subtotals:	21/400	
8	C/W	150/60	1/84	1.2 (0.3 – 6.4)
		Grand Totals	22/484	

[a] Series 1-7 dives decompressed with the 120 fsw/70 min U.S. Navy Standard Air schedule
Series 8 dives decompressed with the 150 fsw/60 min U.S. Navy Standard Air schedule

[r] Testing stopped with attainment of reject criterion

Quantitative expressions of observed thermal effects during different dive phases were obtained after controlling for differences in bottom time and dive depth in the test profiles with logistic regression analyses. The final two models were

$$\text{logit} = \beta_0 + \beta_1 \ln(\text{BT}) + \beta_2 T_{W,B} + \beta_3 T_{W,D} \qquad \text{(Model 1)}$$

$$\text{logit} = \beta_0 + \beta_1 \ln(\text{BT}) + \beta_2 T_{W,B} + \beta_3 T_{W,D} + \beta_4 \ln(Depth) + \beta_5 \ln(R_A) \qquad \text{(Model 2)}$$

where

β_i = linear coefficient for i^{th} factor
BT = Bottom Time (min)
$T_{W,B}$ = water temperature during BT (°C)
$T_{W,D}$ = water temperature during decompression (°C)
Depth = dive depth (fsw)
R_A = *Depth*/total decompression time
= average ascent rate (fsw/min)

Model fits were evaluated with likelihood ratio tests and chi-square analyses, and significances of the coefficients were evaluated with univariate Wald test statistics.

RESULTS

Results are summarized in Table 2 and Figure 2.

Model 1 fit the 120 fsw dive data (Series 1–7) with log likelihood (LL) significantly higher than the null model LL (P<<0.0001) and significant chi-square goodness-of-fit. With two additional terms to accommodate data from dives to different depths with different decompression schedules, model 2 fit all data (Series 1–8) with similar success. Additional interaction terms were explored in each model and found insignificant. Coefficients for bottom time and temperature terms in the two models were statistically indistinguishable.

For Model 1, the DCS odds ratio (*OR*) for a 10 °C increase in $T_{W,B}$ was 23.8 (95% CI = 3.77–132), while the *OR* for a 10 °C increase in $T_{W,D}$ was 0.010 (95% CI = 0.002–0.114). The DCS *OR* for a doubling of BT was 33.3 (95% CI = 5.05–194).

DCS risks estimated with the BVM(3)[2] and NMRI98[3] probabilistic models, representing experience from a large body of laboratory man-dives,[4] lie between the observed and estimated DCS incidences at the tested extremes of thermal exposure.

Table 2. Logistic Regression Results

Model	Data	P(chi-square)	Factor	Coefficient	S.E.	P	Odds Ratio		95% CI
1	Series 1–7, N = 400	0.85, d.f. 6	constant	-18.56	5.31	< 0.0005			
			ln(BT)	5.06	1.35	< 0.0002	33.34	(ea. doubling)	(5.05–193.85)
			$T_{W,B}$ (°C)	0.32	0.09	< 0.0005	23.79	(ea. 10 °C)	(3.77–131.51)
			$T_{W,D}$ (°C)	-0.44	0.11	< 0.0001	0.01	(ea. 10 °C)	(0.002–0.114)
2	Series 1–8, N = 484	0.93, d.f. 7	constant	-1950.66	5.31	< 0.00001			
			ln(Depth)	187.32	3.15	< 0.00001	***		
			ln(BT)	5.25	1.34	< 0.0001	38.16	(ea. doubling)	(6.17–235.96)
			$T_{W,B}$ (°C)	0.33	0.09	0.00024	27.59	(ea. 10 °C)	(4.69–162.42)
			$\ln(R_A)$	3738.96	57.47	< 0.00001	***		
			$T_{W,D}$ (°C)	-0.45	0.11	< 0.00005	0.01	(ea. 10 °C)	(0.001–0.097)

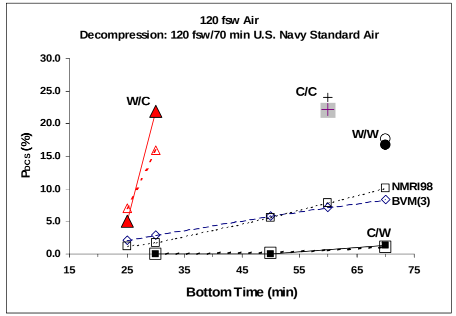

Figure 2. Observed DCS incidences in 120 fsw air dives (solid or shaded symbols) compared to DCS risks estimated with the BVM(3) and NMRI98 probabilistic models without explicit consideration of any thermal effects. DCS risks estimated for tested profile/thermal condition pairs with the descriptive logistic Model 1 are shown as open symbols.

CONCLUSIONS

Cold exposure during BT and warm exposure during decompression (C/W) are optimal for minimizing DCS risk and maximizing bottom time. Warm exposure during BT and cold exposure during decompression are unfavorable.

The inverse of the *OR* for a 10 ºC increase in $T_{W,D}$ was about five times the *OR* for the same increase in $T_{W,B}$, indicating that beneficial effects of warm conditions during decompression predominated over deleterious effects of warm conditions during BT.

Effects of a 10 °C increase in $T_{W,D}$ were comparable to effects of halving BT.

It has been shown in earlier work[5] that diver thermal exposure can be controlled in operational settings with presently available technology to exploit the presently quantified thermal effects.

LITERATURE CITED

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