DEPTH SCALING OF SEVERAL GAS SUPER-SATURATION DECOMPRESSION MODELS

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INTRODUCTION

Since the first publication of a probabilistic decompression sickness (DCS) model based on survival analysis by Weathersby et. al [1], several forms of the hazard function have been explored in the literature [2,7,8,9,10]. The hazard function is the mathematical model for conversion of measurable or predictable parameters into a probability of an event occurring. Previous work exploring the hazard function have adjusted the function to better account for observed DCS incidence rates. The performance and properties of the hazard function is an important aspect related to the accuracy of any probabilistic model. A systematic approach exploring the performance differences between hazard functions may identify superior or inferior risk definitions. One major limitation of current DCS models is a noted inability to accurately scale increasing risk with depth [9], for example in profiles related to submarine escape. Adjustment of the hazard function may be one avenue through which accurate risk scaling may be accomplished. In the present work, we explore 16 published and new hazard functions with the goal of identifying the best overall form.

METHODS

Our previously published three compartment EE1 model was used as a base for the 16 hazard function definitions explored [11]. All three compartments were potentially risk-bearing. Models were fitted to the Navy BIG292 data set including 190 DCS incidents in 1038 dive profiles [10]. Because of our previous identification of the irrelevance of marginal DCS incidents on fit quality [2], marginal cases were not considered in the fit. Model fitting was performed with the use of failure times [3]. Optimization was performed on the log likelihood function using Nelder-Mead (NM) and Simulated Annealing (SA) techniques [4]. 256 solutions were obtained for each model using NM, then the best solution was further refined using SA. We quantified the extrapolation quality using both Pearson's group χ2 test and the Akaike Information Criterion (AIC) [6]. The best resulting models were used to generate an AIC weighted multi-model.

MODELS

$$\mathrm{DS}:\sum_{i=1}^{3}\left(P_{T_i}-P_{abs}-R_B t+P_{FVG}\right) \qquad \mathrm{DST}:\sum_{i=1}^{3}\left(P_{T_i}-P_{abs}-R_B t-Thr+P_{FVG}\right)$$

$$\mathrm{DSE}:\sum_{i=1}^{3}\left(P_{T_i}-P_{abs}-R_B t+P_{FVG}\right)^{n} \qquad \mathrm{DSET}:\sum_{i=1}^{3}\left(P_{T_i}-P_{abs}-R_B t-Thr+P_{FVG}\right)^{n}$$

$$\mathrm{DSR}:\sum_{i=1}^{3}\frac{\left(P_{T_i}-P_{abs}-R_B t+P_{FVG}\right)}{P_{abs}+R_B t} \qquad \mathrm{DSRT}:\sum_{i=1}^{3}\frac{\left(P_{T_i}-P_{abs}-R_B t-Thr+P_{FVG}\right)}{P_{abs}+R_B t}$$

$$\mathrm{DSRE}:\sum_{i=1}^{3}\left(\frac{P_{T_i}-P_{abs}-R_B t+P_{FVG}}{P_{abs}+R_B t}\right)^{n} \qquad \mathrm{DSRET}:\sum_{i=1}^{3}\left(\frac{P_{T_i}-P_{abs}-R_B t-Thr+P_{FVG}}{P_{abs}+R_B t}\right)^{n}$$

$$\mathrm{DSREN}:\sum_{i=1}^{3}\frac{\left(P_{T_i}-P_{abs}-R_B t+P_{FVG}\right)^{n}}{P_{abs}+R_B t} \qquad \mathrm{DSRENT}:\sum_{i=1}^{3}\frac{\left(P_{T_i}-P_{abs}-R_B t-Thr+P_{FVG}\right)^{n}}{P_{abs}+R_B t}$$

$$\mathrm{DSE111}:\sum_{i=1}^{3}\left(P_{T_i}-P_{abs}-R_B t+P_{FVG}\right)^{n_i} \qquad \mathrm{DSE111T}:\sum_{i=1}^{3}\left(P_{T_i}-P_{abs}-R_B t-Thr+P_{FVG}\right)^{n_i}$$

$$\mathrm{DSRE111}:\sum_{i=1}^{3}\left(\frac{P_{T_i}-P_{abs}-R_B t+P_{FVG}}{P_{abs}+R_B t}\right)^{n_i} \qquad \mathrm{DSRE111T}:\sum_{i=1}^{3}\left(\frac{P_{T_i}-P_{abs}-R_B t-Thr+P_{FVG}}{P_{abs}+R_B t}\right)^{n_i}$$

$$\mathrm{DSRE111N}:\sum_{i=1}^{3}\frac{\left(P_{T_i}-P_{abs}-R_B t+P_{FVG}\right)^{n_i}}{P_{abs}+R_B t} \qquad \mathrm{DSRE111NT}:\sum_{i=1}^{3}\frac{\left(P_{T_i}-P_{abs}-R_B t-Thr+P_{FVG}\right)^{n_i}}{P_{abs}+R_B t}$$

i : Tissue number t : Time

P_t : Tissue pressure P_{FVG} : Fixed venous gas

P_{abs} : Ambient pressure n : Fitted exponent

R_B : Ambient rate Thr : Tissue threshold

Table 1. Functional forms of all models tested in the work.

Model	Best L.L.	Total DCS	Pears. χ^2
DS	-971.03	189.93	6.23
DST	-967.22	188.77	6.10
DSR	-977.06	190.23	10.86
DSRT	-967.88	189.82	7.04
DSE	-969.00	190.28	5.56
DSET	-965.40	189.7	5.52
DSRE	-974.60	189.22	8.74
DSRET	-967.90	189.09	7.23
DSREN	-970.68	191.16	7.17
DSERENT	-963.66	189.55	7.03
DSE111	-962.00	182.35	7.70
DSE111T	-961.98	187.26	6.77
DSRE111	-960.83	189.59	7.99
DSRE111T	-959.63	190.2	7.59
DSRE111N	-957.89	189.02	6.29
DSRE111NT	-957.76	192.01	6.49
AIC	N/A	189.90	6.34

Table 2. Summary of model fitting results. All models over-predicted DCS risk for profiles shallower 100 fsw and under-predicted risk for profiles deeper than 100 fsw. Pearson χ2 results based on dive profile did not have an identifiable trend. LL improvements using SA were generally small (~ 3 LL units) over NM, suggesting the NM algorithm alone may be sufficient for model optimization.

RESULTS

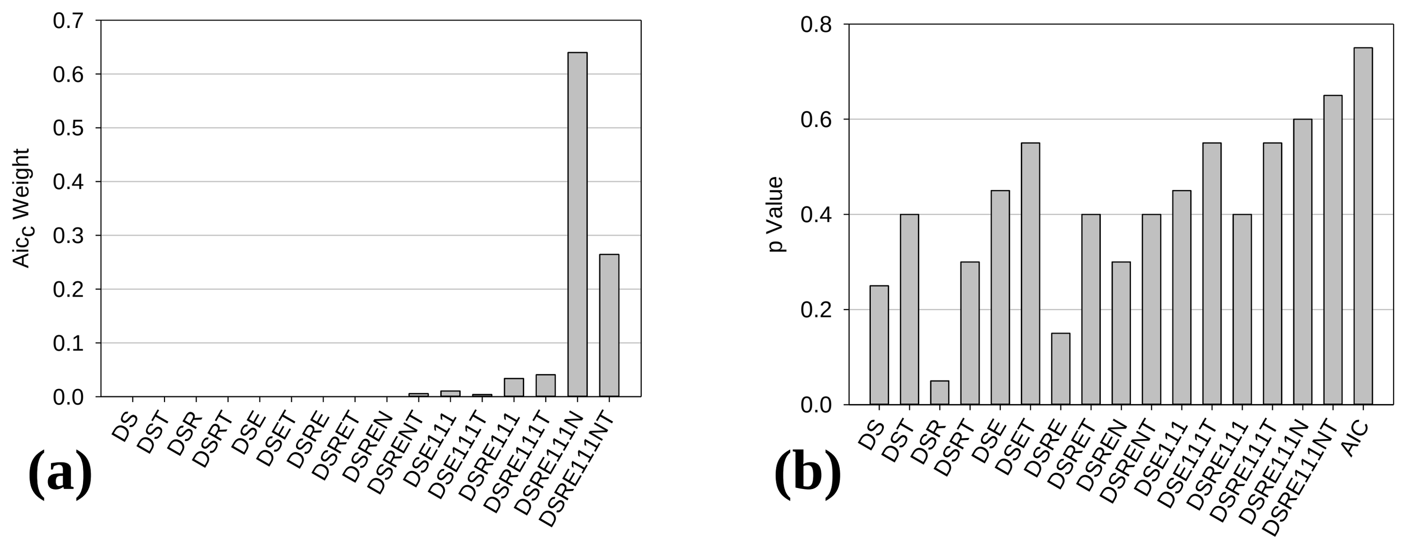

Figure 1. Model fit comparison for the BIG292 calibration data set. **(a)** The DSRE111N and DRE111NT were the two largest AICc contributors (>90%). **(b)** The AICc multi-model, developed using a weighted average of these two models, out-performed all other models in Pearson's group χ2 test.

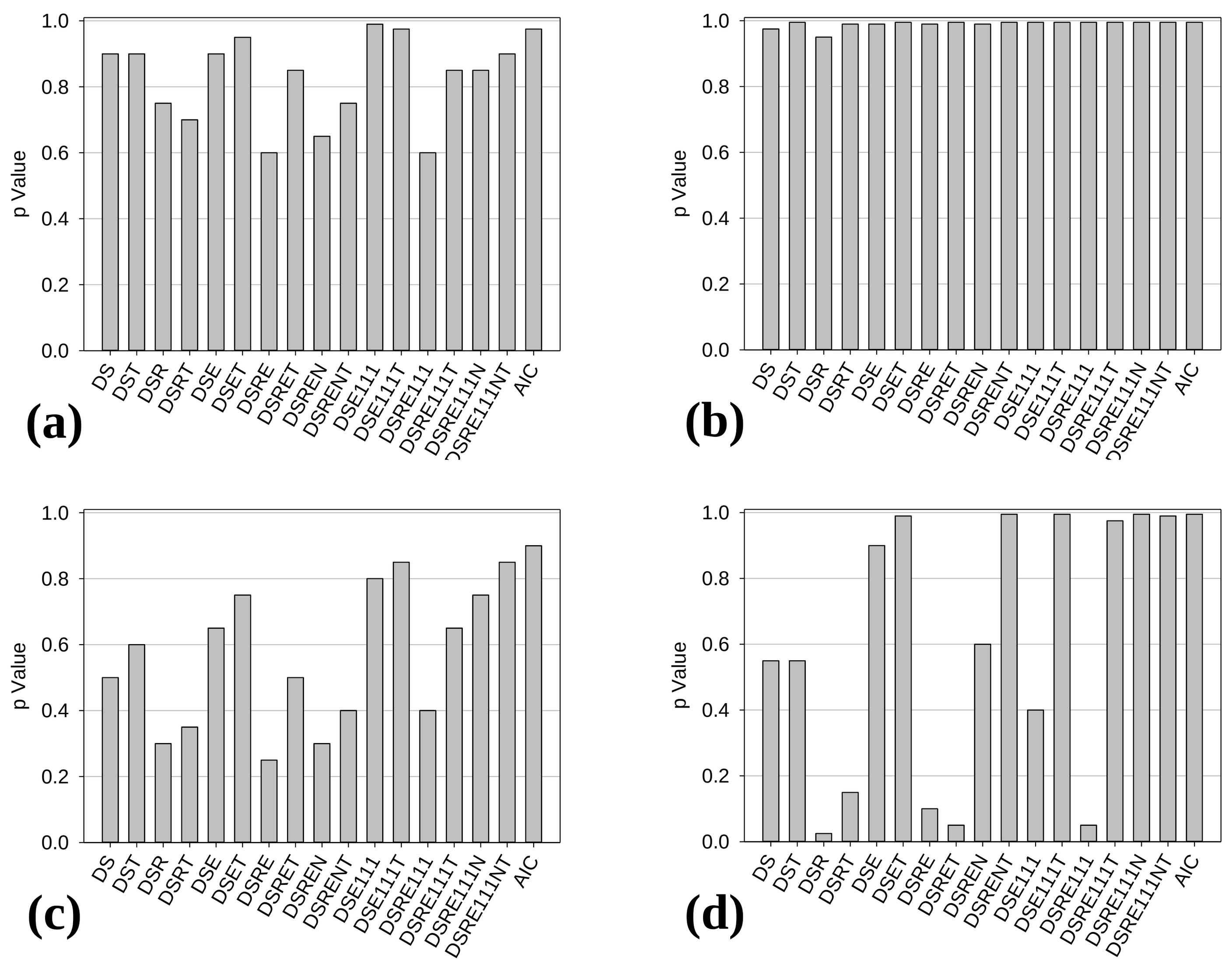

Figure 2. Models performance compared by profile depth. Depth groupings were selected after examination of depth distribution of BIG292 data set. (a) 0-50 fsw (b) 50-100 fsw (c) 100-300 fsw (d) 300+ fsw.

DISCUSSION

Model performance based on Pearson's group χ2 indicates that, while no model outperformed the AICc multi-model, the DSR model performed the least well compared to observed DCS incidence in the data **(Figure 1)**. Results from the AICc evidence ratio test show that the DSRE111N and DSRE111NT hazard function models were the best of the models tested. Multi-model averaging resulted in a blended model that was best able to predict DCS incidence based on the number of degrees of freedom of the model. Only two models, which were nested, were needed to exceed the 90% evidence ratio suggested for model selection [5]. Model performance by Pearson's group χ2 was inconsistent by depth groups **(Figure 2)**. The largest differences were in the 300+ fsw group, where only a few models performed well.

This work shows that selection of the hazard function, independent of the gas kinetics model, can improve the model fit and predictive capabilities.

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