Development of a quasi-physiological model for the prediction of signs/symptoms of decompression sickness following submarine tower escape

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Introduction

All UK Royal Navy submarines are equipped with escape towers designed to allow submariners egress in the case of a distressed submarine (DISSUB) incident. If tower escape is attempted, submariners, who may have spent over 24 hours at a raised pressure within the DISSUB compartment, are rapidly pressurised to ambient sea pressure and then ascend to the surface. Pressure exposures such as these come with a risk of decompression sickness (DCS) which, within the context of tower escape, has the potential to be deadly at the surface.

Robust mathematical models for the prediction of rates of DCS are desirable in order to better inform protocol in DISSUB situations. Due to the difference in severity of possible DCS symptoms, a model capable of making predictions which distinguish between symptoms is of more value than one which predicts overall rates of DCS when it comes to estimating probability of survival.

To our knowledge, there are no published models for the prediction of rates of DCS categorised by symptom.

We have developed new models to make predictions of rates of different symptoms of DCS.

For the purposes of this work, four categories of DCS were identified and investigated:

- neurological or central nervous system (CNS) DCS
- limb pain DCS
- respiratory DCS
- cutaneous (skin) DCS

At the core of the quasi-physiological model is the instantaneous risk function:

$$r_c = M^{\gamma_c} G_c \left(\frac{Ptiss_c - Pamb - Thr_c}{Pamb} \right)^{\beta_c}$$

r	is the instantaneous risk
M	is body mass
γ	is an exponent determining how risk varies with M
G	is a weighting factor, usually termed the gain
$Ptiss$	is the total tissue gas burden
$Pamb$	is the ambient sea pressure
Thr	is the threshold pressure
β	allows the risk to vary non-linearly

Each of these parameters, apart from body mass and ambient pressure, is individually defined for each of c tissue compartments within the model.

Development

The Quasi-physiological Model

The models developed here are based on the structure of the models created by Thalmann *et al*. They consider the uptake and elimination of inert gas from tissue compartments, described by a set of parameters, within the body.

- τ is a time constant parameter which determines the inert gas uptake and elimination. In this case just nitrogen was considered.
- ***Pxo*** is a crossover pressure, allowing gas elimination to follow either linear or exponential kinetics. Setting Pxo very high prevents linear kinetics from being invoked.

Model Calibration

Each model was calibrated independently for each symptom category against particular subsets of the available data. The Levenberg-Marquardt algorithm was used to optimise model parameter values to achieve the best fit of the model to the data by maximum likelihood. Large numbers of initial models were used to avoid the routine ending up in local maxima. The best model for each of the symptoms was selected based on the Akaike Information Criteria (AIC) which is a numerical value taking into account the number of parameters a model has.

Original Data

The original data come from trials carried out at research centres in the UK (QinetiQ), the US (NMRC, NEDU, UWISC) and Canada (Canadian Forces). These are grouped into datasets which contain a number of pressure exposures of man, goat, sheep or pig subjects. Only certain datasets were included for the calibration of particular symptoms. Only those highlighted in the table were included in the calibration data for the relevant symptom models (alternating colours for legibility).

These data only include pressure exposures which are relevant to submarine tower escape. No exposures with staged decompression were included.

QinetiQ's Hyperbaric Trials Unit

Data

Dataset	Species	Exposures (n)	Cases of DCS			
			CNS (n)	Limb pain (n)	Respiratory (n)	Cutaneous (n)
6HRGOAT	GOAT	60	0	14	0	0
ASATAREQ	MAN	30	0	2	0	0
ASATDC	MAN	23	3	7	0	1
ASATNMRQ	MAN	18	0	1	0	0
ASATNSMQ	MAN	20	0	4	0	0
BESCHLC	MAN	112	0	0	0	0
DC4DQQ	MAN	321	0	1	0	0
DC4WQQ	MAN	74	1	2	0	0
EDU557QQ	MAN	110	0	0	0	0
EDU849LT	MAN	141	2	20	0	0
EDU849S2	MAN	60	0	13	0	0
EDU885AQQ	MAN	112	0	4	0	0
EDUAS45Q	MAN	12	0	2	0	0
HISTGOAT	GOAT	387	16	45	0	0
NMR8697Q	MAN	477	2	8	0	2
NMR9209	MAN	48	0	2	0	0
NMR97NOD	MAN	103	2	1	0	1
NMRNSW2Q	MAN	49	2	3	0	0
NSM6HR	MAN	57	0	3	0	0
PASAQQ	MAN	5	0	1	0	0
USSATPIG110fsw	PIG	44	27	7	16	37
PSATESCG	GOAT	270	12	32	2	0
PSESESCG	GOAT	272	16	1	0	0
SATESCM	MAN	90	1	0	0	1
SATFR85Q	MAN	13	0	0	0	0
TSATSESG	GOAT	142	1	27	1	0
SATSESM	MAN	38	0	0	0	0
SESESCM	MAN	254	0	0	0	0
SUBX87QQ	MAN	115	2	0	0	0
UPS290QQ	MAN	274	3	0	0	0
USSATPIG	PIG	55	27	6	17	43
UWSATSPa	SHEEP	70	35	62	52	0
Total	-	**3856**	**152**	**268**	**88**	**85**

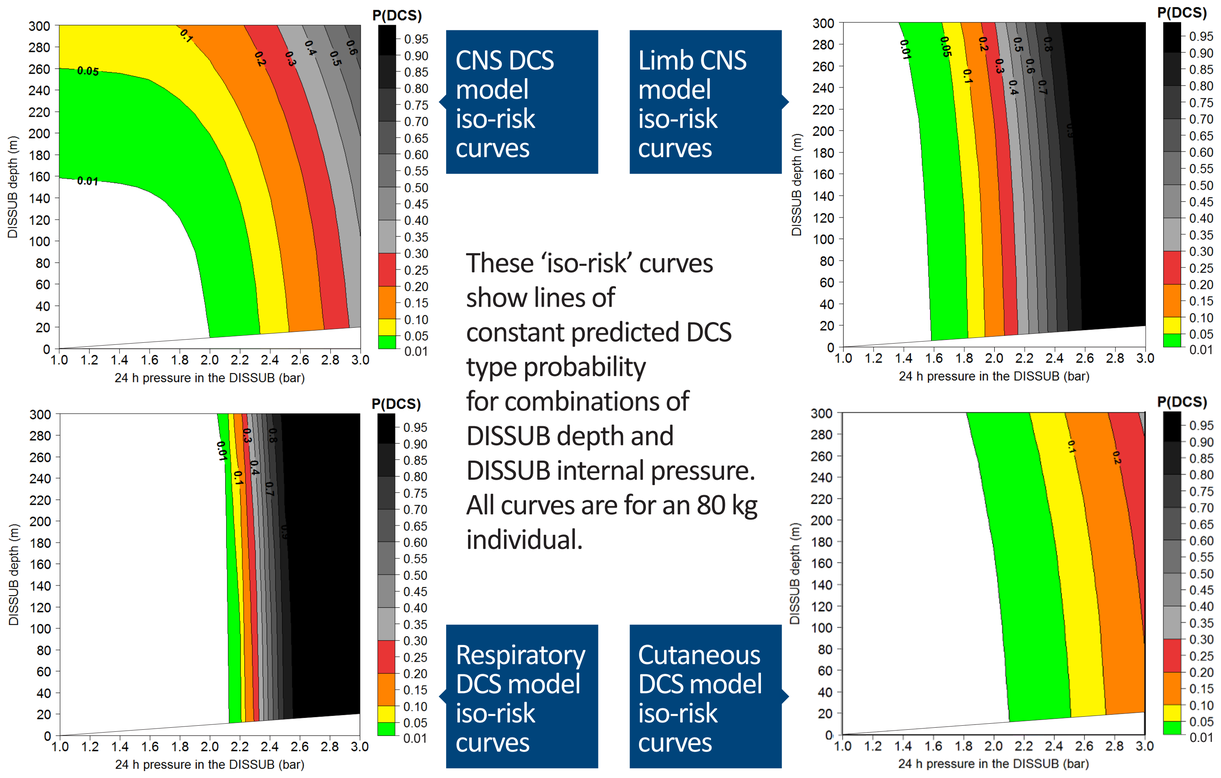
Results

c	CNS Model Parameters					
	τ (s)	γ	G (s^{-1})	*Pxo* (Pa)	β	*Thr* (Pa)
1	28.3 [20-52]	1.36e -03 [9.8 -04 – 1.9e -03]	3.14e -06 [2.8e -06 – 6.1e -06]	6.15e+04 [5.3e+03 – 1.2e+05]	2.29 [1.9 – 2.9]	3126 [1340 – 5400]
2	4388.8 [3859 – 5027]	9.59e -01 [8.6e -01 – 1.4e -00]	1.39e -06 [6.0e -07 – 1.7e -06]	Inf	4.71 [4.4 – 5.3]	4374 [622 – 27100]

c	Limb Pain Model Parameters					
	τ (s)	γ	G (s^{-1})	*Pxo* (Pa)	β	*Thr* (Pa)
1	1614 [1169 – 2523]	0	9.4e -06 [7.9e -06 – 2.2e -05]	Inf	6.32 [5.2 – 7.8]	0
2	9236 [6279 – 11858]	0.0310 [0.021 – 0.051]	3.6e -06 [6.9e -07 – 3.9e -06	Inf	1.27 [0.39 – 1.3]	0
3	12757 [10968 – 16310]	0.140 [0.064 – 0.17]	2.6e -04 {2.3e -04 – 5.5e -04]	Inf	5.66 [5.5 – 6.9]	0

c	Respiratory Model Parameters					
	τ (s)	γ	G (s^{-1})	*Pxo* (Pa)	β	*Thr* (Pa)
1	22266 [20770 – 28260]	1.904 [1.91 – 2.87]	2.707e -06 [1.75e -07 – 4.11e -06	Inf	2.319 [2.29 – 6.10]	75251 [50470 – 76880]

c	Cutaneous Model Parameters					
	τ (s)	γ	G (s^{-1})	*Pxo* (Pa)	β	*Thr* (Pa)
1	6131 [4460 – 8280]	8.960e -02 [2.52e -03 – 8.98e -01]	1.800e -05 [1.28e -06 – 3.59e -05]	Inf	4.685 [3.78 – 6.21]	0



Discussion

- The new models are capable of making predictions for sub-saturated tissue states and for changing internal DISSUB pressure.
- CNS DCS is greatly affected by the escape depth while limb pain, respiratory and cutaneous DCS are only mildly affected.
- Optimised parameter values suggest body mass is more important in the prediction of CNS and respiratory DCS than in limb pain or cutaneous DCS.
- It would be inappropriate to use these models for making predictions for pressure exposures with dives deeper than 300 m or in which there is significant staged decompression.
- These models will be used to generate probability of survival estimations.

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