PREDICTION MODEL DEVELOPMENT OF TOLERANCE/ SURVIVAL TIMES FOR SEMI-IMMERSED COLD/WET WALK

Peter Tikuisis and Andrew J. Young
Defence and Civil Institute of Environmental Medicine
North York, Ontario, Canada
U.S. Army Research Institute of Environmental Medicine
Natick, Massachusetts, U.S.A.

INTRODUCTION

Four soldiers died from hypothermia while participating in a vigorous training exercise during a swamp crossing. These soldiers (Ranger trainees) were malnourished and sleep-deprived, having lost about 16% of their body mass and 60% of their body fatness. Immersed in about 14°C water occasionally up to the neck level, casualities were reported after **2-3** h of entry. This incident led to a reassessment of training guidelines on cold weather submersion limits, in part through a modelling effort, Modifications to a previously-developed survival prediction model (1) were made to specifically include i) partial immersion, ii) wetness of the non-immersed body portion, iii) walking activity, and iv) fatigue. The resultant model contains two cylinders representing the non-immersed and immersed regions of the trunk, and one representing the thigh. Wetness may be due to rain and/or previous immersion, The suppression of shivering due to walking is taken into account and fatigue is simulated by reducing the individual's metabolic capacity. The following is a brief descriptive account of the modifications designed to predict tolerance/survival times for challenging cold/wet training exercises under exhaustive conditions.

MODEL DEVELOPMENT

The present model originated from the development of a steady state cylindrical heat conduction model initially derived for the prediction of survival times for cold **air** exposure. Many of its features including the correspondence between body size and model geometry, and the process of heat transfer between the body and the environment are outlined in Tikuisis (1).

Metabolic heat production from exercise and shivering is a key component of the model. Heat production from walking is predicted using the formula presented by Pandolf et al. (2) taking into account load, walking speed, and terrain. The additional effort involved in displacing water is also taken into account. Heat production from shivering is predicted using a formula regressed from decreases in rectal (Tre) and mean skin (Tsk) temperatures due to cold exposure **(3).** It is not known how shivering may be affected by fatigue; however, a check on the model's prediction against heat production due to shivering of Ranger trainees during a cold air test conducted at the end of their swamp phase without rest or nourishment indicates reasonably good agreement (see figure below). Suppression of shivering is assumed to decrease exponentially by 50 and 75% with increases in relative exercise intensities of 25 and 50%, respectively **(4).** The cessation of exercise and shivering is predicted using the glycogen-depletion algorithm of Wissler (5) [see (1) for implementation].

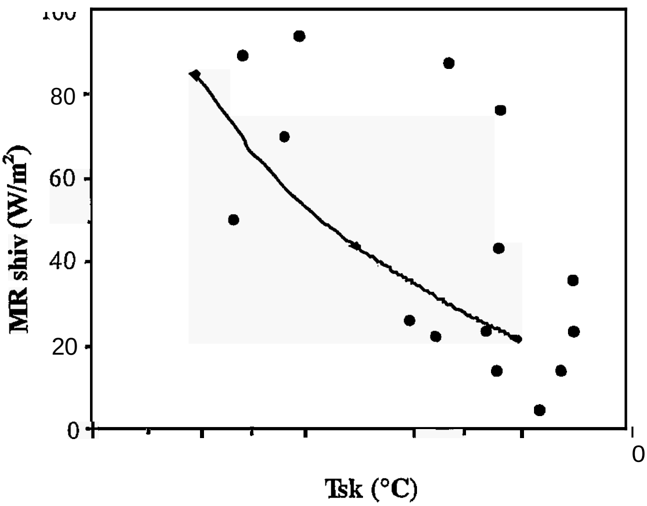

Figure: Measured (circles) and predicted (line) metabolic shivering response to cold mean skin temperatures for a rectal temperature range between 35.5 and 36.0°C. Data are from a preliminary analysis of a recent unpublished study on the impact of Ranger training on thermoregulatory response to a sedentary cold air (10°C) test.

Partial immersion is simulated by introducing a second cylindrical compartment having the same characteristics as the first, but immersed in water instead of exposed to air. Heat losses are calculated for each compartment as described in Tikuisis (1) and these are combined according to the level of immersion to determine the body's overall heat debt. It is assumed that the compartments are sufficiently well-stirred in the deep core so that their temperatures can be equated. The calculation of the resultant core and surface temperatures is outlined in Tikuisis and Keefe (6).

To account for the heat loss of the leg, only the upper portion (i.e., thigh) is considered. Its heat loss is determined using the same procedure as applied to the main body compartments but scaled accordingly, and it is added to the body's heat debt. Its surface temperature contributes to the body's mean skin temperature using a weighted average and a partial immersion of the thigh can be stipulated. When the main body is partially or fully immersed in water and at rest, the thigh's contribution to total heat loss diminishes with increasing level of immersion using an *ad hoc* formulation to preserve the calibration of the original model for water immersion (1).

Wetness must be considered for the upper air-exposed compartment in the event of prior immersion or rain. Boutelier (7) has provided data indicating the loss of clothing insulation against various degrees of wetness. These data can be mathematically expressed by the following biphasic relationship: reduction in insulation (%) = 0.0554•wetness if wetness < 316 $gm \cdot m^{-2}$ and 9.17 + 0.0264•wetness if greater, Wetness not only reduces insulation, but it also promotes further heat loss ***via*** evaporation. which is estimated using the formulae outlined by Nishi *(8).*

RESULTS/DISCUSSION

It is not possible to present the variety of predictions that the model has been designed to simulate. Instead, attention will be focused on conditions that are relevant to the Ranger training program. The table shown below lists predicted times to various values of Tre for two types of trainees: lean and severely fatigued ***vs*** average and moderately fatigued. The former represents the leanest of those individuals recently engaged in the cold air test and the severely fatigued condition is representative of earlier Ranger training sessions when rations were less than presently administered. The present training conditions, however, continue to impose significant sleep deprivation and malnourishment.

Table: Predicted times to decreases in rectal temperature. Assumed characteristics are *63.9* kg, *1.77* m, *5.1%* body fat for the lean individual, and *70.0* kg, *1.77* m, *11.9%* body fat for the average individual. The respective metabolic capacities are assumed to be *20* and 50% of normal representing severe and moderate states of fatigue. Common assumed conditions are an air temperature equal to the water temperature, clothing with a "dry" insulation value of 1.0 clo, walking speed of *0.8* $km \cdot h^{-1}$, a *35* kg carrying load, terrain factor of *1.8* (2), water current at 0.5 $m \cdot s^{-1}$, wind at 5 $km \cdot h^{-1}$, and rain (with ensuing wetness of 1000 $gm \cdot m^{-2}$).

Tw (°C)	Immersion Level	Time (h) to Tre = 35.5/ 34.0/ 30.0°C lean	average
5	neck	0.31 0.51 1.0	0.41 0.91 1.6
	mid-chest	0.41 0.7/ 1.4	0.61 1.21 2.1
	thigh	0.71 1.01 1.9	1.01 2.01 3.3
10	neck	0.41 0.71 1.3	0.51 1.31 2.2
	mid-chest	0.61 0.91 1.8	0.81 2.01 3.2
	thigh	1.11 1.51 2.7	1.11 3.41 5.2
15	neck	0.7/ 1.11 2.0	0.71 2.81 4.2
	mid-chest	1.21 1.61 2.8	1.01 4.21 6.2
	thigh	2.01 2.71 4.4	1.51 6.91 9.9
20	neck	2.01 2.11 4.2	1.31 8.61 12.0
	mid-chest	3.01 4.01 6.1	1.91 12.11 16.8
	thigh	4.71 6.21 9.4	4.01 17.61 24.3

An overview of the predictions suggests that the current recommended submersion limits (9) are conservative for very cold water and liberal for moderately cold water especially for mid-chest immersions without rain (not shown). An important consideration is that the present model does not take into account respiratory distress from sudden immersion in very cold water nor the possible loss of mobility and dexterity, which might explain the rationale behind the cold water submersion limits.

The prediction of a longer time to Tre = 35.5°C for the lean *vs* average individual for moderately cold water immersion is a consequence of a higher heat production due to lower body fatness (3); however, note that the average individual has much longer predicted times to Tre = 34 and 30°C since their metabolic capacity is not as quickly exhausted. The results presented above are subject to change following a more rigorous analysis of the recent Ranger cold air test. In the interim, the model should suffice as a reasonable decision aid considering that subject conditions and model parameters were purposely chosen to yield conservative estimates.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of their respective institutes in this collaborative study. Special thanks are due to staff members at USARIEM for their valued advice, to staff members at the Naval Aerospace Medical Research Laboratory, Pensacola, FL, for assistance in carrying out the Ranger cold air test, and finally to the U.S. Army Ranger Training Brigrade, Fort Benning, GA, for tasking this study.

REFERENCES

1. Tikuisis, P. 1995. Predicting survival time for cold exposure. *International Journal of Biometeorology,* **39,** 94-102.
2. Pandolf, K.B., Stroscheim, L.A., Drolet, L.L., Gonzalez, R.R. and Sawka, M.N. 1986. Prediction modeling of physiological responses and human performance in the heat. *Computing in Biology and Medicine*, **16,** 319-329,
3. Tikuisis, P., Gonzalez, R.R., Oster, R.A. and Pandolf, K.A. 1988. Role of body fat in the prediction of the metabolic response for immersion in cold water. *Undersea Biomedical Research,* **15**, 123-134.
4. Hong, S.-I. and Nadel, E.R. 1979. Thermogenic control during exercise in a cold environment. *Journal of Applied Physiology,* **47(5)**, 1084-1089.
5. Wissler, E.H. 1985. Mathematical simulation of human thermal behavior using whole-body models, in A. Shitzer and R.C. Eberhart (eds.), *Heat transfer in medicine and biology* (Plenum Press, New York), 347-355.
6. Tikuisis, P. and Keefe, A.A. 1996. Prediction of sea survival time, DCIEM Report No. 96-R12, North York, Ontario, Canada.
7. Boutelier, C. 1979. Survival and protection of aircrew in the event of accidental immersion in cold water, NATO Advisory Group for Aerospace Research and Development Report No. AGARD-AG-211, Neuilly Sur Seine, France.
8. Nishi, **Y.** 1981. Measurement of thermal balance of man, in K. Cena and J.A. Clark (eds.), *Bioengineering thermal physiology and comfort* (Elsevier Press, New York), 30-38.
9. Cold Weather Training Standard Operating Procedure, Table 1 *Cold weather submersion limits*, 4th Ranger Training Battalion, U.S. Infantry School, Ft. Benning, GA, U.S.A.