Cold Exposure Survival Model

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Model Demonstration

This presentation will begin with a demonstration of the model that we have developed for predicting survival times during cold exposure (Tikuisis 1995, 1997). Hereafter, we will refer to this model as CESM (Cold Exposure Survival Model), and following the demonstration, we'll discus the challenges of making such predictions.

The user interface (see Fig. 1) of the model accepts inputs according to three separate categories. The first category pertains to the characteristics of the subject such as age, gender, weight, height, body fatness, and fatigue, plus the level of water immersion. The second category consists of environmental factors (the air exposure factors of temperature, humidity, and wind speed are not shown in Fig. 1 because of the example chosen below) and the last category concerns the clothing protection on the individual.

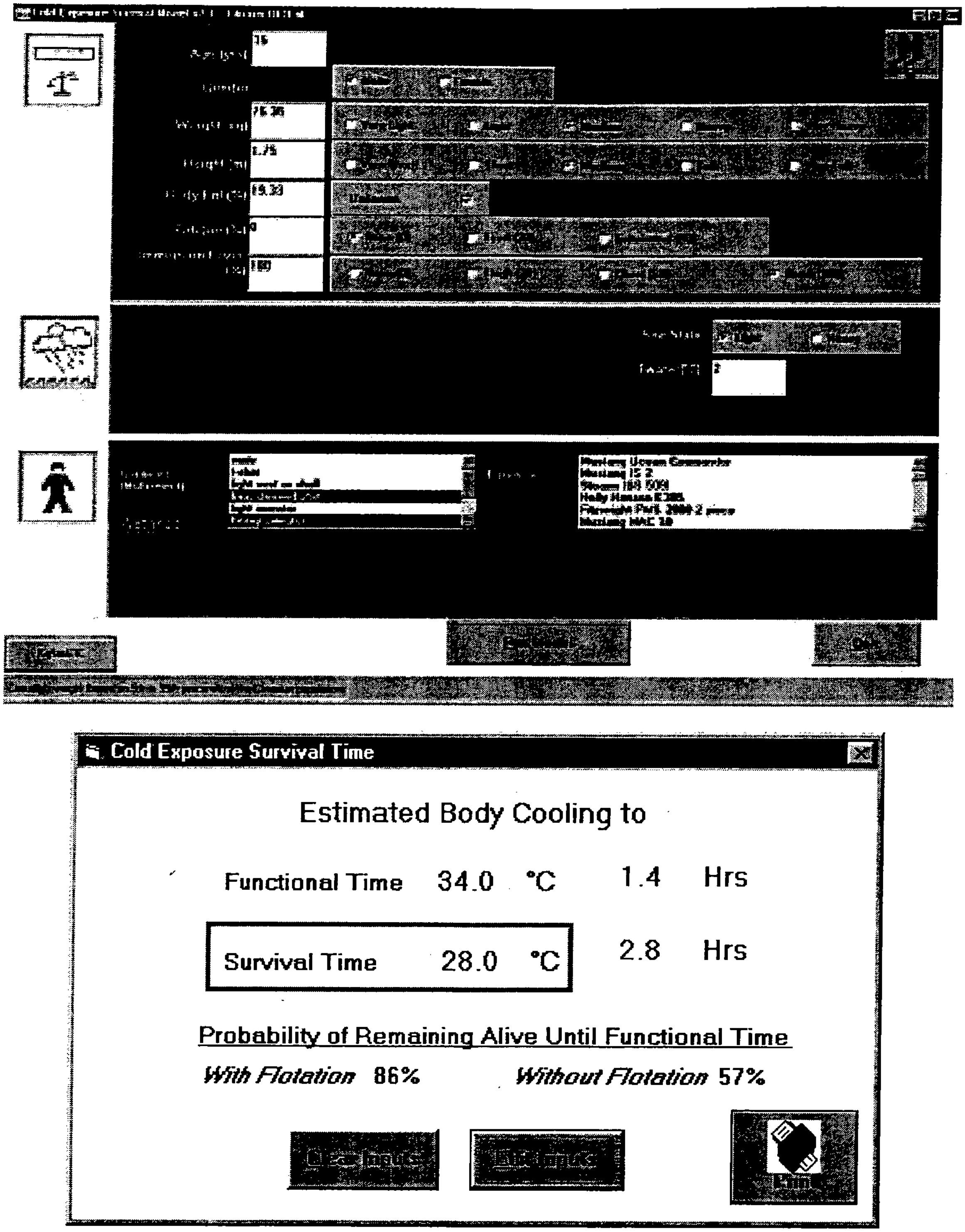
For example, let us choose a 35 yr old male, as shown in Fig. 1. The weight of the individual can be entered directly if known, otherwise it must be estimated. To accommodate the latter, CESM provides a menu from which the individual's weight can be selected. The 'very light' category refers to the 5th percentile of the population, 'light' refers to the 25th percentile, etc. up to 95th percentile for the 'very heavy' category. Height is similarly selected. Body fat (BF) is an important determinate of survival time, however, its value is rarely known. In this case, CESM determines the %BF according to a regression formula based on age, gender, weight and height. In the present example, we have chosen the 50th percentile for weight, and height leading to a BF of 19.3%.

CESM can be applied to situations involving cold air exposure and/or cold water immersion. For this demonstration, we will assume conditions that an individual might have faced in the water after the sinking of the Titanic. We'll assume that the individual is not fatigued and is immersed to the neck-level, thus only the water parameters apply. In this example, we select a light sea state and a water temperature of 2°C. Clothing can be selected in any combination of different garments by making appropriate selections from the clothing menu shown on the lower left of the input screen in Fig.1. Alternatively, actual clothing ensembles can be selected from the adjacent menu on the right. Among these are coveralls, survival suits, etc. Let us suppose that our unfortunate individual is wearing a long-sleeved shirt and a heavy sweater. Clothing is specified for the torso only since the other regions of the body are assumed to be clothed to the same level of protection.

To recap, we have selected a 50th percentile male of 35 years of age, neck-immersed in light seas at 2°C, and wearing medium-weight clothing. The model predicts times to two different stages of body cooling on the basis of these inputs; a functional time of 1.4 h and a survival time of 2.8 h (see output screen of Fig. 1). The functional time is the predicted time for the individual's deep body temperature (T_{db}) to decrease to 34°C at which point the individual would suffer motor and cognitive impairments. The survival time is the predicted time for T_{db} to reach 28°C at which point unconsciousness is likely to occur. If we change the value of one of the input factors, say the weight, then CESM predicts shorter times for a lighter individual and vice-versa. In this case, %BF changes automatically to correspond to the changes in the weight, or any of the other individual characteristics.

This brief demonstration covered only the body cooling portion of the model. An additional calculation pertaining only to neck-level immersion in water provides the probability of finding the individual alive at the predicted functional time. That is, if CESM predicts that 1.4 h elapses before the individual's T_{db} reaches 34°C, then what is the chance of finding that person alive at that time? Causes of death other than hypothermia are considered here. This calculation will be explained later, but suffice it for now that in the present example, there is a 86% chance of finding the individual alive at 1.4 h if flotation is worn and 57% if not (see output screen of Fig. 1).

In summary, CESM predicts times to specific body temperatures corresponding to functional and survival times, and secondly, it provides a prediction of finding an immersed individual alive at the predicted functional time.



Cold Exposure Survival Time

Estimated Body Cooling to

Functional Time 34.0 °C 1.4 Hrs

Survival Time 28.0 °C 2.8 Hrs

Probability of Remaining Alive Until Functional Time

With Flotation 86% *Without Flotation* 57%

Figure 1. Displays of the input and output screens of CESM (see text for explanation).

Model Calibration/Validation

To calibrate and check CESM predictions, we require information on the characteristics of the individual, exposure conditions, and the level of clothing protection. We also need to know the individual's T_{db} at the end of the exposure, and the individual's state of cognition or consciousness associated with their deep body temperature.

This represents the desirable data. Data with this level of detail are usually only available from controlled studies and are limited to conditions that do not exceed a mild hypothermic state. Typically, the deep body temperature is not allowed to go decrease below 35°C in laboratory experiments, and thus much of the controlled T_{db} data reside between 35 and 37°C. There are many accidental cases involving severe hypothermia, but of these, only very few are documented to the level of detail required to calibrate or validate CESM. As a result, predicting the time course of body core cooling to 28°C is extremely extrapolative.

On the other hand, data are available for the statistics of survival during cold water immersion and the probability of finding someone alive as a function of time during such exposures. We will now consider in more detail the deterministic prediction of the rate of body cooling and the probabilistic prediction of survival outcome for water immersion.

Body Cooling Prediction

An important assumption in CESM is that the individual is considered sedentary. That is, the only source of body heat in addition to the resting metabolism is shivering. Any activity beyond this would contribute to internal heat production, which cannot be predicted unless the actual activity is known. The sedentary assumption is a reasonable one for accidental exposures to cold and it represents a worst case scenario. We also assume a normal physiological response to cold. Relevant information that can be obtained from laboratory experiments on individual responses to cold is coded into the model. The possibility of death due to causes other than hypothermia are not considered, at least in the model prediction of the rate of body cooling.

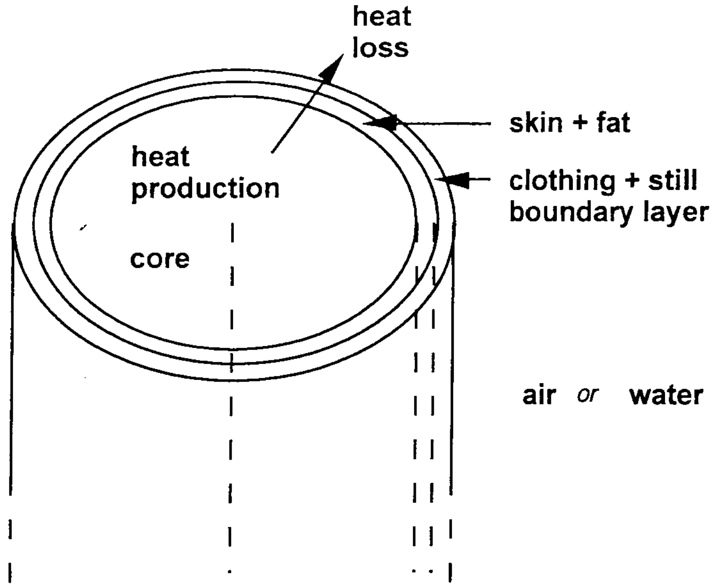


Figure 2. Schematic of the body cooling portion of the model.

The model is schematized in Fig. 2 and is essentially based on a core-shell configuration. If heat is produced within the core of the cylinder, that heat passes through two layers of insulation. The internal layer of insulation is represented by the skin and fat of the individual, and the external insulation layer is represented by clothing and the still boundary layer. As indicated earlier, CESM can be applied to problems involving cold exposure in both air and water environments.

An important feature of the model is its discrimination of different body types. During the model demonstration, the impact of different body size conditions was discussed. Typical model predictions for three body fat conditions are shown in Fig. 3 with survival time plotted against water temperature. Lean individuals have the fastest body cooling rates and hence the shortest predicted survival times while fat individuals should last longer, with other factors being the same. Similar survival curves can be constructed with variations in other factors, such as sea state, level of clothing protection, etc.

We conclude our consideration of the body cooling portion of the model by reiterating that this prediction is deterministic. It predicts not "if", but "when" lethal hypothermia will occur. Although this portion of the model is based on physical principles of heat conduction and physiological responses to cold stress, its predictions of body cooling to temperatures below 34°C are extrapolative. Little is known about what happens to the body's response to cold when its deep body temperature drops below this level. This is particularly challenging for model development since we are unable to acquire controlled data for these situations. Instead, we must rely on case histories, yet the documentation is rarely as good as required, and there are simply too few detailed cases to support a statistical approach at this time.

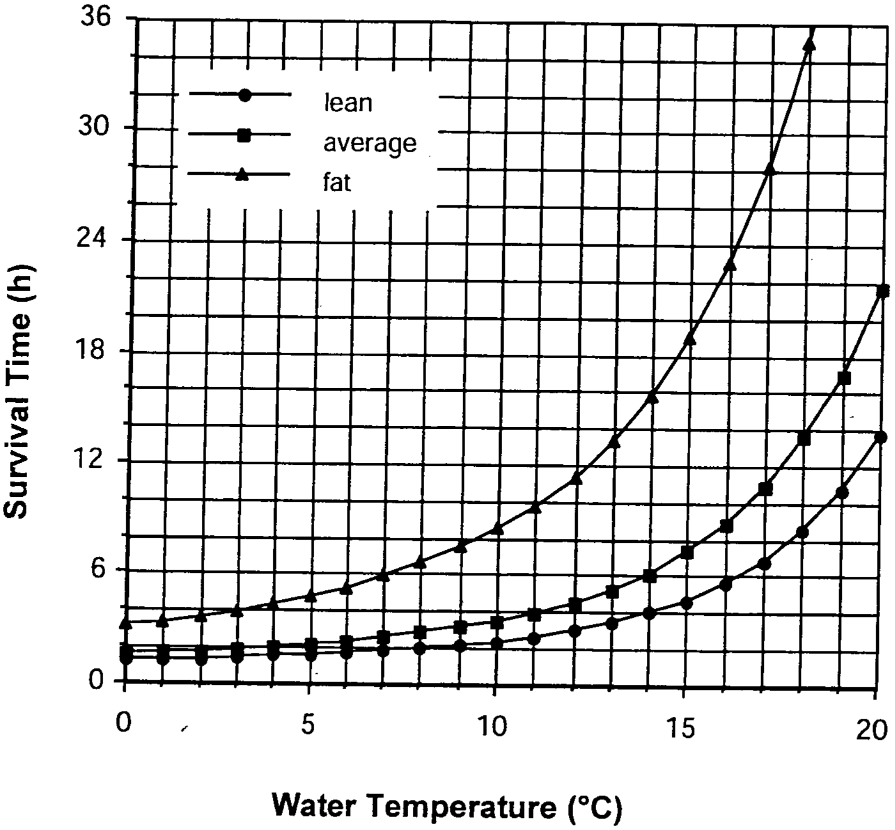


Figure 3. Model predictions of body cooling times to a core temperature to 28°C for water-immersed individuals of different body fatnesses.

Immersion Survival Outcome Prediction

The model prediction of finding someone alive during immersion is based on data from the U.K. National Immersion Incidence Survey. These data were analyzed and modelled by Oakley and Pethybridge (1997). The U.K. survey covered 930 incidents in which there were 66 deaths. The factors that were considered in the model included immersion time, water temperature, and whether or not the individual wore a buoyancy device. The model was based on the following logistic form:

$$\mathrm{Pr} = \frac{\theta}{1+\theta} \qquad (1)$$

where Pr is the probability of finding the immersed individual alive and the quantity θ is defined in terms of three parameters; α, β and γ; and two independent variables; time of immersion (t_{imm}) and water temperature (T_w):

$$\theta = \exp[\alpha + \beta \cdot \ln(t_{imm}) + \gamma \cdot T_w] \qquad (2)$$

The data were segregated into three groups according to whether a buoyancy device was worn, not worn, or if unknown. The model was then fitted to each group using maximum likelihood. Resultant parameter values for each of the groups are given in Table 1 and the percent survival rate is shown in Fig. 4.

Table 1. Immersion survival outcome model parameter values (see Eq. 2).

Buoyancy Device	*Parameters*		
	α	β	γ
Yes	5.55	- 0.888	0.121
No	3.99	- 0.888	0.120
?	2.52	- 0.888	0.291

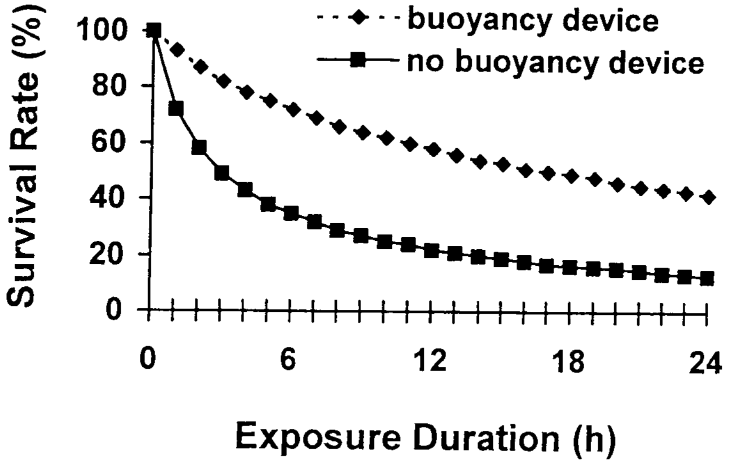


Figure 4. Model-predicted influence of personal flotation on survival outcome of individuals immersed in 5°C water.

The survival outcome does not take into account any of the factors used in the body cooling portion of the model; that is to say, it doesn't consider individual characteristics, sea state, or clothing protection. Figure 5 illustrates how well the U.K. model of survival outcomes compare to the observed data used to calibrate the model. The data were categorized according to immersion times beginning with consecutive 15-min periods, and ending with time periods that cover 1 to 2 h, 2 to 4 h, and > 4 h, respectively. Although the agreement between predicted and observed rates appears good, the chi square is significant only at the 0.5 level.

The prediction of the immersion survival outcome is a probabilistic approach in which the factors are immersion time, water temperature, and whether or not a buoyancy device is worn. Model parameters, however, are biased since the statistics neglect immersions of very short duration. Accidents in which individuals are rescued within a few minutes are usually not reported, nor are incidents in which bodies are not found.

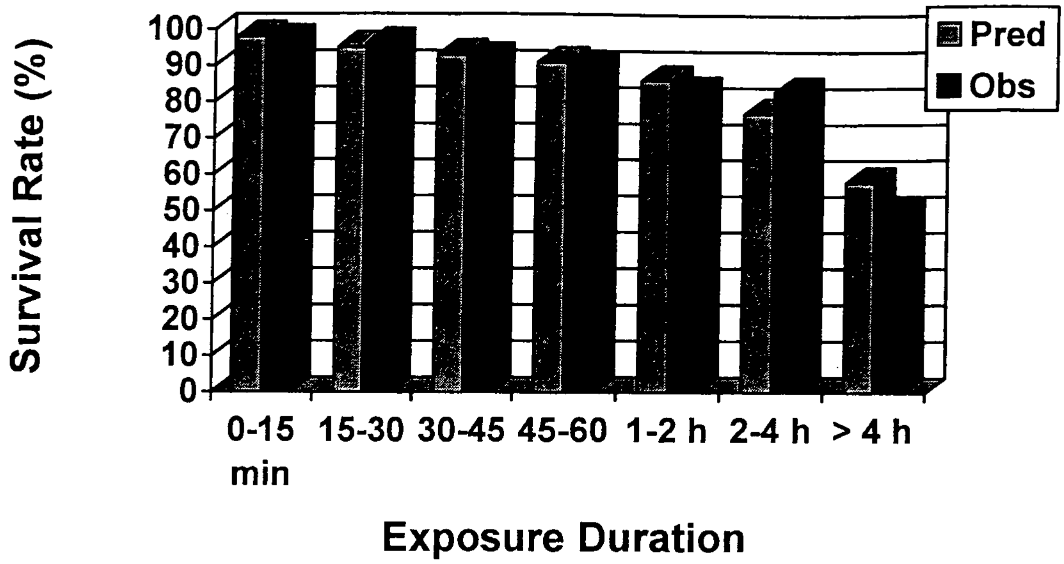


Figure 5. Comparison of predicted and observed survival outcomes for immersion in water ($\chi^2 = 4.46$; df = 5; $p > 0.5$).

Clearly, much work remains to be done with respect to both the prediction of survival times due to hypothermia and the survival outcomes during immersion. Continued laboratory experiments and better documentation of the status of accidentally cold-exposed individuals will facilitate the improvement of CESM. Additional surveys of accidental immersions with particular attention to the immersion time will strengthen the statistical assessment of immersion survival outcome.

References

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