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Defence and Civil
INSTITUTE OF ENVIRONMENTAL MEDICINE

INSTITUT DE MEDECINE ENVIRONNEMENTALE
pour la défense

1133 Sheppard Avenue West, PO Box 2000, North York, Ontario, Canada M3M 3B9
Tel. (416) 635-2000 Fax. (416) 635-2104

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PREDICTION OF SURVIVAL TIME IN COLD AIR

Peter Tikuisis
John Frim

Defence and Civil Institute of Environmental Medicine
1133 Sheppard Avenue West, P.O. Box 2000
North York, Ontario
Canada M3M 3B9

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EXECUTIVE SUMMARY

The prediction of survival time (*ST*) for cold exposure is somewhat hypothetical since controlled data of deep hypothermia are unavailable. To use existing information for individuals far from deep hypothermia, extrapolations are necessary. Accidental exposures are insufficiently documented for detailed analysis, but can serve as checks on model predictions.

This report describes the development of a mathematical model for predicting *ST* in the cold. The model is based on steady-state heat conduction in a single cylinder comprised of a core and two annular concentric shells representing the fat plus skin and the clothing plus still boundary layer, respectively. The ambient condition can be either air or water; the distinction is made by assigning different values of insulation to the still boundary layer. Where the cold exposure is too severe for metabolic heat production to balance heat loss, *ST* is largely determined by the heat conduction characteristics of the model. Where a balance occurs, *ST* is governed by the depletion time of the energy reserve for shivering. End of survival is marked by the core temperature reaching a value of 30°C (based on loss of conciousness) although the model is capable of predicting lower body temperatures.

Published survival curves for cold water immersion are used to calibrate the model. The model is then tested against three very diverse air exposures: thermoneutrality to check the model's steady-state predictions, an experimental 3 h nude exposure at 5°C to check the model's initial predictions of body temperatures and metabolic heat production, and an accidental exposure at -20°C to check the model's prediction of *ST*. In each, predictions concurred well with the observation.

Model predictions are subsequently made for various combinations of clothing protection and wind conditions in air ranging from -50 to 10°C. These predictions are intended for guidance in planning and preparedness for intended or accidental exposure to cold. Due to the inherent uncertainties in these predictions, their usefulness may be greater with relative comparisons than in absolute terms. It is important to note that the predictions in this report are based on the uninjured individual in a sedentary condition. Further research, especially on long-term endurance to generate heat through shivering, is required to improve the predictive capability of the model.

ABSTRACT

The prediction of survival time (*ST*) for cold exposure is somewhat hypothetical since controlled data of deep hypothermia are unavailable. At best, case histories of accidental exposure can be used for guidance. This study describes the development of a simple heat conduction model for the prediction of *ST* under sedentary conditions in the cold. Predictions are not made for cold injury nor for the injured individual. The model is based on steady-state heat conduction in a single cylinder comprised of a core and two annular concentric shells representing the fat plus skin and the clothing plus still boundary layer, respectively. The ambient condition can be either air or water; the distinction is made by assigning different values of insulation to the still boundary layer. Metabolic heat production (*M*) is predicted by temperature signals from the core and skin, but is not allowed to exceed heat loss. Where the cold exposure is too severe for *M* to balance heat loss, *ST* is largely determined by the heat conduction characteristics of the model. Where a balance occurs, *ST* is governed by the depletion time of the energy reserve for shivering. End of survival is marked by the core temperature reaching a value of 30°C, although the model is capable of predicting lower body temperatures. Model predictions for cold water (0 to 20°C) immersion agree with the values reported by Molnar (1946) and Veghte (1972). A sampling of *ST* predictions for nude exposure in relatively calm (1 km/h wind) cold air of an average healthy male are the following: 3, 5, 10, and > 24 h for -20, -10, 0, and 10°C, respectively. With 2 clo of insulation in a 10 km/h wind, *ST*s are 7, 10, 17, and > 24 h for -50, -40, -30, and -20°C. The predicted *ST*s must be weighted against the extrapolative nature of the model. At present, it would be prudent to use the predictions in a relative sense, that is, to estimate the benefit of increasing one's insulation in terms of percentage increase in *ST*. Clearly, model predictions are subject to fine adjustments as more information becomes available for calibration.

INTRODUCTION

Exposure to cold can be life-threatening to the ill-equipped or unprotected individual. While appropriate levels of protection can usually be planned for in most situations, circumstances can lead to extreme or lengthy exposures. This is especially true where storage of protective equipment is limited or the equipment is damaged. To help facilitate planning and to be better prepared for contingencies, prediction of survival time (*ST*) in the cold is essential. Predictions are usually based on experience; however, observations of controlled exposures are limited to mild levels of hypothermia (on the order of 2-3°C drop in central core temperature) far from any risk of death. Published data on cold survival are usually limited to accidental cases and thus can provide guidance only for specific situations.

An alternative option for predicting *ST* is through the use of mathematical models. One such model used at DCIEM was developed through heat loss equations outlined in NATO ACCP-1 (1992) taking into account body tissue insulation, clothing, ambient temperature, wind speed, and metabolic heat production (see APPENDIX on development and application). However, the latter value must be specified by the user and is assumed to remain constant. If metabolic heat production balances heat loss, then the model predicts an infinite *ST*. On the other hand, if heat production is less, then *ST* is determined proportionally by the net heat imbalance. This arbitrary assignment of metabolic heat production makes the model very impractical to use, as demonstrated in the APPENDIX. It could be used to establish the time-averaged metabolic heat production given the *ST*, but without expert knowledge of heat production, the prediction of *ST* is very speculative.

A more desirable modelling approach is one that simulates the physical and physiological processes underlying human response to cold. Unfortunately, the lack of information on such processes, especially the latter, make this task very difficult. At best, models can be constructed to reflect the present state of knowledge and calibrated with well-documented cases of survival in the cold. Greater certainty can be attached to predictions involving interpolation amongst known cases than those involving extrapolation.

As will be seen, the major influence on how *ST* is predicted is the severity of the cold exposure. Under extreme conditions where heat loss exceeds the individual's ability to produce heat, time to a low deep body temperature is largely a heat conduction problem, whereas if heat production can balance heat loss, then *ST* essentially depends on how long such heat production can be maintained. Information on the

latter is almost non-existent, consequently, certainty in the prediction of *ST* will diminish with increasing value of *ST*.

The aim of this study is to construct and calibrate a mathematical model for the purpose of predicting *ST* in cold air. Despite the inherent uncertainties in such a development, there is sufficient information to begin. The need for predictions through a rationally-derived model outweighs the present reliance on scattered data or recursive estimations using simple models (see APPENDIX). Further, a rational model will help to identify the physical and physiological processes that are poorly understood and require further research, ultimately leading to more reliable model predictions.

MODEL DEVELOPMENT

1. Configuration

The model is based on steady state heat conduction in a cylindrical core-shell configuration (see Fig. 1). Emphasis is placed on the prediction of central body temperature and not of the extremities. Thus, the model developed herein will not be applicable for predicting cold injury. It is further assumed that protection against the cold is uniformly applied to the surface of the body. The steady state condition excludes the initial transient response to cold which is characterized by vasoconstriction usually resulting in a delay in the fall of deep body temperature for up to 1 h. Thus, *ST* predictions arising from the steady state condition may be conservative. Finally, a core temperature of 30°C is taken as the endpoint for *ST* in this study. Although death usually occurs when deep body temperature is colder than 30°C, unconciousness develops at this value (Golden 1973) and the individual is incapable of reversing further cooling without intervention.

Steady state heat loss (Q) is predicted by

$$Q = \frac{T_0 - T_3}{R_{eff}} \tag{1}$$

where T_0 and T_3 refer to core and ambient temperatures, respectively, and R_{eff} (in units of $°C \cdot m^2 \cdot W^{-1}$) is the effective thermal resistance for bodies having internal heat production given by

$$R_{eff} = \frac{r_3}{2 \cdot k_{co}} + \frac{r_3}{k_{sf}} \cdot \ln\frac{r_2}{r_1} + \frac{r_3}{k_{cl}} \cdot \ln\frac{r_3}{r_2} \tag{2}$$

where r_i is the compartment radius, k is the thermal conductivity, and co, sf, and cl refer to core, skin plus subcutaneous fat, and clothing plus "still" air boundary layer, respectively. Equation 2 assumes that heat is produced only in the core compartment. The three consecutive terms of Eq. 2 will be designated as a_1, a_2, and a_3.

The radius of a cylinder is twice its volume divided by the surface area along its circumference. If the volume and surface area of the model cylinder are matched to the corresponding values of a human body, then the model radius would be much smaller than the radius of the human trunk. In addition, the surface area of the body that actually exchanges heat with the environment ranges from 50 to 80% of the total body surface area (Fourt and Hollies 1970). Therefore, to reflect this and to obtain a closer correspondence between the model and trunk dimensions, the model radius is increased by a factor of 1.5, i.e.,

$$r_2 = 1.5 \cdot \left(\frac{2 \cdot wt}{\rho \cdot A_D} \right) \tag{3}$$

where wt, ρ, and A_D are the weight, density, and surface area of the body, respectively. The skin plus fat thickness $(r_2 - r_1)$ is based on a regression equation for young males (Durnin and Womersley 1974) and a body density determined from the percentage of body fat (Siri 1961). The "standard" anthropometric values used in this study are a body fatness (bf) of 14.8%, and height and weight of 1.74 m and 74.5 kg, respectively, based on males from 17 to 39 yrs old (Bell and Cox 1984). The latter values yield a body surface area (A_D) of 1.89 m^2 (DuBois and DuBois 1916). In this instance, $r_1 = 0.107$ m and $r_2 = 0.111$ m.

Thermal conductivities of tissue are 0.60 and 0.35 $W \cdot m^{-1} \cdot {}^\circ C^{-1}$ for core and skin plus fat, respectively (Sekins 1982). The latter value pertains to cold tissue. The thermal conductivity for clothing and the overlapping still air boundary layer is assumed to be 0.041 $W \cdot m^{-1} \cdot {}^\circ C^{-1}$ based on 4 clo per inch (Burton and Edholm 1969); hence 1 clo (0.155 ${}^\circ C \cdot m^2 \cdot W^{-1}$) is represented by a thickness of 0.00635 m. The thickness of the still air boundary layer is governed by windspeed (see Wind Effect further below).

2. Temperatures

The core temperature is assumed to begin at 37.0°C. At steady state, the skin temperature is

$$T_2 = T_3 + a_3 \cdot Q \tag{4}$$

and the core-subcutaneous fat boundary temperature is

$$T_1 = T_2 + \frac{r_2}{r_3} \cdot a_2 \cdot Q \tag{5}$$

Note that the combined radiative and convective heat transfer coefficient is given by a_3^{-1}. Mean core temperature is given by (Sekins 1982)

$$\overline{T}_{co} = \frac{T_0 + T_1}{2} \tag{6}$$

and mean skin plus fat temperature is approximated by

$$\overline{T}_{sk} = \frac{T_1 + T_2}{2} \tag{7}$$

Finally, mean body temperature is given by

$$\overline{T}_b = f_{co} \cdot \overline{T}_{co} + (1 - f_{co}) \cdot \overline{T}_{sk} \tag{8}$$

where f_{co} is the fraction by volume of the core compartment.

Once heat production (M) is known (see Heat Production below), the change in the body's mean temperature is determined by

$$\Delta\overline{T}_b = \frac{(M - Q) \cdot \Delta t}{cb} \tag{9}$$

where cb is the heat capacity and Δt is the time step in the numerical calculation. Then, using the relationships of Eqs. 1 and 4 to 8, the resultant core temperature is

$$T_0 = \frac{a_2 \cdot T_3 + (r_3/r_2) \cdot [2 \cdot \overline{T}_b \cdot R_{eff} - (2 - f_{co}) \cdot T_3 \cdot (R_{eff} - a_3)]}{a_2 + (r_3/r_2) \cdot [f_{co} \cdot R_{eff} + (2 - f_{co}) \cdot a_3]} \tag{10}$$

The numerical calculation assumes a quasi-steady state, that is, while model temperature and heat variables are calculated assuming steady state at each time step, any heat imbalance resulting in a non-zero value of $\Delta\overline{T}_b$ (Eq. 9) will lead to changes in the model variables for the next time step.

The value of M used in Eq. 9 relates to the body's surface area (A_D) which is larger than the model's surface area (see Eq. 3). Thus, the metabolic rate applied to

the model underestimates the body's total heat production. For example, if M is 100 $W{\cdot}m^{-2}$, then assuming the standard anthropometric values, total heat production ($M{\cdot}A_D$) is 189 W. However, 100 $W{\cdot}m^{-2}$ applied to the model cylinder yields a total heat production ($M{\cdot}2\pi r_2 l$ where $l = (wt/\rho)/(\pi r_2^2)$) of 126 W. The difference or amount of heat production not accounted for by the model (63 W in the example) can represent other avenues of body heat loss such as through respiration and the convective heat transfer by the blood from the core to the extremities. The latter's contribution is supported by the finding that while the trunk produces most of the body's heat during shivering (Bell et al. 1992), the limbs are responsible for most of the body's heat loss (Tikuisis 1989).

3. Heat Production and Endurance

Heat production by shivering only in a healthy uninjured individual (in $W{\cdot}m^{-2}$) is predicted according to (Tikuisis 1988)

$$M_{shiv} = \frac{6.4{\cdot}(32 - T_{2s})^2 + 75.8{\cdot}(32 - T_{2s}){\cdot}(37 - T_0)}{A_D{\cdot}bf} \qquad (11)$$

where T_{2s} is the temperature signal of the skin. Its value is equal to T_2 if above 5°C, otherwise it is fixed at 5°C to avoid an unrealistically high efferent shivering command. In addition, as the core temperature decreases below 32°C, it is assumed that the overall shivering command weakens (Giesbrecht - private communication). This attentuation is modelled by a hyperbolic cosine function that reduces the shivering heat production by a factor of 100 as core temperature decreases from 32 to 30°C; i.e.,

$$M_{shiv} \div \cosh\left[\frac{T_0 - 32}{0.378}\right] \qquad (12)$$

The predicted value of M_{shiv} is not allowed to exceed 200 $W{\cdot}m^{-2}$ ($M_{shiv\,(max)}$); coupled with the resting rate of metabolism (M_{rest}) fixed at 50 $W{\cdot}m^{-2}$, the resultant M represents five times the resting value (Iampietro et al. 1960)). If the shivering reserve (MR_{shiv}; see below) is exhausted, then shivering continues but its intensity is attenuated by the following factor

$$M_{shiv} \div \cosh\left[\frac{\sum M_{shiv}{\cdot}\Delta t/\beta - MR_{shiv}}{0.38{\cdot}MR_{shiv}}\right] \qquad (13)$$

where β is the shivering reserve consumption factor (see Eq. 16) and the value of 0.38 was chosen following model calibration so that shivering intensity is halved when $\sum M_{shiv} \cdot \Delta t / \beta$ exceeds 150% of MR_{shiv}. The resultant shivering metabolic rate is then added to M_{rest} for total heat production (M). However, M_{rest} is first modified by the Q_{10} effect (Werner and Buse 1988) which states that metabolism decreases with decreasing tissue temperature. In the present model,

$$M_{rest} \div 2^{-(\overline{T}_{co} - 28)/10} \qquad (14)$$

if mean core temperature $\overline{T}_{co}$ < 28°C, otherwise no reduction is assumed. Finally, M is not allowed to exceed heat loss, Q, otherwise mean body temperature would rise contrary to observation.

An important determinate of survival time is the length of time that metabolites are available for utilization (Sowood 1984; Maidment 1993). Two factors must be considered, the metabolic "reserve" for shivering and the rate of its depletion. The shivering reserve (MR_{shiv}) is based on the storage of muscle glycogen, which is assumed to be 6000 kJ per 65 kg of body mass (Newsholme and Leech 1983) or 25.64 $W \cdot h \cdot kg^{-1}$. For the standard body dimensions of 1.74 m and 74.5 kg introduced earlier, MR_{shiv} becomes 1013 $W \cdot h \cdot m^{-2}$.

It is known from exercise physiology studies that endurance time falls off exponentially as exercise intensity increases. Wissler (1985) has modelled the endurance time of shivering (in h) on this basis assuming that the relative effort of shivering can be measured by the ratio $L_r = M_{shiv}/M_{shiv\,(max)}$, i.e.,

$$endurance\ time = \frac{18}{L_r} \cdot e^{-4.0 \cdot L_r} \qquad (15)$$

Although it is known that fat is also metabolized during shivering (Vallerand and Jacobs 1989), glycogen storage in this development serves as a reference point and the value of 18 h in Eq. 15 is a calibration factor that corresponds to observed fatigue during shivering. For example, shivering at 36 and 100% of maximum shivering intensity have estimated endurance times of about 12 and 0.33 h, respectively.

The following empirical factor, adopted from above, is therefore used to attenuate the consumption of the shivering reserve (see Eq. 13):

$$\beta = \frac{18}{1000} \cdot M_{shiv\,(max)} \cdot e^{-4.0 \cdot L_r} \qquad (16)$$

where the value of 1000 is arbitrarily chosen to represent the reference shivering reserve in $W \cdot h \cdot m^{-2}$. If, for example, the initial shivering reserve is 1013 $W \cdot h \cdot m^{-2}$, then at 25, 50, and 75% of maximum shivering intensity (i.e., M_{shiv} = 50, 100, and 150 $W \cdot m^{-2}$, respectively), the shivering reserve is exhausted at 26.8, 4.9, and 1.2 h (determined by $MR_{shiv} \cdot \beta \cdot M_{shiv}{}^{-1}$), respectively. Note that endurance time is increased or decreased if MR_{shiv} is either increased or decreased, respectively.

4. **Wind Effect**

Under all conditions, the model assumes the existence of a still air boundary layer on the outermost surface. The effect of wind is to reduce the thickness of this boundary layer. If clothing is worn, there are the additional factors of compression and/or penetration leading to further reductions in insulation.

First, the effect of wind on nude conditions is addressed. According to Burton and Edholm (1969), the insulation (in clo) of the still air boundary layer (taking radiative and convective heat transfer into account) is predicted by

$$I_{air}{}^{-1} = 0.61 \cdot \tau^3 + 0.19 \cdot \sqrt{v/\tau} \qquad (17)$$

where τ is $(T_3 + 273)/298$ and v is windspeed in $cm \cdot s^{-1}$. It is important to note that v varies with distance above ground level. For example, I_{air} is approximately 0.5 clo with a windspeed of 2 $km \cdot h^{-1}$ and 0.1 clo when wind is increased to 90 $km \cdot h^{-1}$.

The effect of wind on the insulation of clothing has been examined primarily through empirical methods. Factors such as compression and penetration are difficult to isolate. Usually, measurements of the heat transfer coefficient are regressed against various wind conditions. Adopting the approach of Steadman (1984), the following *ad hoc* heat transfer equation is applicable to military winter clothing (CORD 1992) subjected to winds of up to 15 $km \cdot h^{-1}$:

$$h = a + 1.4 \cdot v^{0.6} \qquad (18)$$

where h is the total heat transfer coefficient from the skin to the environment and a is the calm air intercept value which depends on the level of insulation worn. Its value and the resultant surface insulation are obtained through the following procedure.

A reference heat transfer coefficient ($h_{ref\,(2)}$) is determined from an arbitrary condition of 1 clo (intrinsic value) of insulation applied to the model and exposed to a 2 $km \cdot h^{-1}$ wind (leading to a total insulation of 1.5 clo). Equation 18 is then used to

determine the intercept value of a, and subsequently used to determine the reference heat transfer coefficient at the required wind condition ($h_{ref(v)}$). The resultant ratio of $h_{ref(v)}/h_{ref(2)}$, therefore, establishes the relative change in heat transfer for windspeeds different from 2 km·h^{-1}. This ratio is then applied to predict the heat transfer coefficient of the actual clothing condition through

$$h = h_{cl(2)} \cdot \left[\frac{h_{ref(v)}}{h_{ref(2)}} \right]^{2/(1 + I_{cl})} \tag{19}$$

where the exponent is an empirical fit to reduce the relative effect of the wind with increasing level of the intrinsic insulation (I_{cl}) and $h_{cl(2)}$ is the heat transfer coefficient of I_{cl} for a 2 km·h^{-1} wind condition (assumed total insulation of I_{cl} + 0.5 clo). No restrictions are placed on the values of v and I_{cl} used in Eqs. 18 and 19 except to note that an extrapolation is involved when windspeed exceeds 15 km·h^{-1}. Once the value of h is calculated, the final insulation value is determined through iteration using Newton's method.

As an example, for total insulation (clothing plus still air boundary layer) values of 1.5 and 3.5 clo at a 2 km·h^{-1} wind condition, the resultant total insulations are 1.28 and 3.25 for a 5 km·h^{-1} wind, and 0.89 and 2.73 for a 20 km·h^{-1} wind. These reductions are consistent with those reported by CORD (1992) for various cold weather military ensembles. If the windspeed is less than 2 km·h^{-1}, then the total insulation is increased, as expected. For example, the resultant total insulations of the two examples above are 1.79 and 3.81 for a 0.25 km·h^{-1} wind.

CALIBRATION

Since heat transfer has been modelled by conduction only, the actual medium that the model is exposed to is inconsequential. In essence, the thermal insulation of the still boundary layer, whether it is air or water, is the determinant of heat loss to the environment. Assuming a still water boundary layer thickness of about 4 mm (Burton and Edholm 1969) and a thermal conductivity of 0.6 W·m^{-1}·°C^{-1} (Sekins 1982), the boundary layer provides an insulation of 0.04 clo.

Exposure to water was chosen for calibration of the model since survival times have been more clearly delineated from accidental immersions than from cold air exposure. Figure 2 shows the survival curves based on the reports of Molnar (1946) and Veghte (1972), and the model values for nude and clothed conditions. The latter

was included to simulate clothing that may have been worn but assumed to be thoroughly soaked. The additional insulation of such wet clothing is assumed to be 0.07 clo per intrinsic dry clo value based on the ratio of thermal conductivities of air to water (i.e., 0.041:0.60). To obtain *ST* curves that fell reasonably between those of Molnar (1946) and Veghte (1972), it was necessary to adjust a component of the shivering attenuation factor to 0.38 (see Eq. 13).

The model tends to slightly overpredict *ST* for water temperatures (T_w) < 5°C. This is likely due to other factors not accounted for in the model when skin temperatures are exceedingly low which occurs with contact at low T_w. However, considering that such temperatures are not expected to be reached in most applications of cold air exposure, a correction is not presently applied to the model.

RESULTS

The model was tested against three very different conditions of air exposure: i) thermoneutrality, ii) nude exposure at 5°C, and iii) an accidental exposure at -20°C. These conditions and the corresponding model predictions are listed in Table 1. The first exposure represents no thermal stress and tests the model's steady-state prediction. The second represents an experimental condition that is well-documented and tests the model's initial predictions during cold stress. The third represents an accidental situation that tests the model's long-term predictions during severe cold exposure. All conditions assume sedentary activity superimposed by any shivering that may occur.

Two thermoneutral conditions were tested assuming a calm wind condition [1 km·h^{-1} (< 0.3 m·s^{-1})], nude at 28°C and 1 clo of clothing at 21°C. The predicted steady-state metabolic rates and skin temperatures (central core temperature remains fixed at 37°C) are 44 and 42 W·m^{-2}, and 32.2 and 32.1°C, respectively. These values agree reasonably well with observation (Parsons 1993).

The experimental condition involved a 3 h nude exposure at 5°C and a wind of 3.6 km·h^{-1}, although a value of 2 km·h^{-1} was assumed since the subjects were seated and exposed to wind from the back (Vallerand et al. 1993). The model predicts values of 160 W·m^{-2}, 35.3°C, and 17.8°C after 3 h of exposure for M, T_0, and T_2, respectively. These values, except for T_0, compare closely to the measured values of heat production and skin temperature at the end of the experiment. The predicted central core temperature is about 1°C lower than the measured rectal temperature probably due to the assumption of uniform heat production in the model; if the intensity of heat production is actually higher towards the core, then core temperature should be

correspondingly higher. Figure 3 shows the evolution of the model-predicted temperatures and metabolic rate. In this case, *ST* is predicted to be 11.4 h. Note the pronounced decreases in M, first when the metabolic reserve for shivering is depleted after about 6.5 h of exposure and then when core temperature drops below 32°C after 10 h of exposure.

The accidental case involves the crash of a CF Hercules 130 near Alert, NWT, Canada (Canadian Forces 1991). During the approximately 36 h before rescue arrived, the average air temperature was -20°C and the wind changed from calm to blizzard conditions, however, in the shelter of the damaged fuselage (mats on floor and entrance draped with a tarpaulin), low wind speeds can be assumed. The clothing varied from flight suit to parka, however, most victims huddled or were snow-covered, and their clothing was partially wet. For purposes of simulation, two different insulation/wind conditions were assumed: 1.3/0.5 and 1.7/1.0 clo/km·h^{-1}. The predicted *ST*s (see Table 1) of 30.2 and 46.3 h, respectively, appear reasonable on the basis that the victims were considered near the end of their endurance (one victim succumbed to hypothermic death but this individual was less insulated and suffered greater exposure than those who survived).

APPLICATIONS

Predictions of the model will be given for air temperatures from -50 to 10°C in two figures and six tables for various combinations of insulation and wind speed. Figure 4 shows *ST* plotted against air temperature (T_{air}) for a clothing insulation of 1.5 clo and wind conditions from 1 (calm) to 50 km·h^{-1}. Similarily, Fig. 5 shows *ST* for a 2 km·h^{-1} wind condition and insulative conditions from nude to 3 clo. In each, *ST* increases hyperbolically with T_{air} and with either decreasing wind speed or increasing insulation.

Tables 2 to 7 list *ST* for insulative conditions from nude to 3 clo and for wind conditions from 1 to 50 km·h^{-1}. *ST* values greater than 36 h are not specified since the certainty in their values is greatly diminished due to uncertainty in the long-term endurance to generate heat.

Considering the speculative nature of the model predictions, care should be exercised in their use. The values may be more meaningful in relative comparisons than in absolute terms. That is, in the case of exposure to -35°C under calm conditions, as an example, the predicted *ST* (see Table 2) is approximately quadrupled by doubling the clothing insulation from 1 to 2 clo.

DISCUSSION

The model was calibrated for the standard body configuration and not tested for other anthropometric values. One should expect a decrease in *ST* for thin and less fat individuals since both a decreased body radius and decreased fatness impose less thermal resistance to heat loss, and vice-versa. To test this, predictions were made for two body types representing the lean and moderately fat individuals of the CF (Bell and Cox 1984) using the following approximate respective anthropometric values of 1.68 m, 65 kg, and 7.6% body fat, and 1.78 m, 81 kg, and 25.9% body fat. Predicted *ST*s for nude exposure at 5°C and 2 km·h^{-1} wind are 8.3 and 19.0 h, respectively, which are 27% lower and 67% higher than that predicted for the standard body. Although data are not available to test these predictions, they concur with general observation (Burton and Edholm 1969, Hayward and Keatinge 1981).

The above illustrates one area where further research is required. Among several others that emerge from this study, the primary unknown is the individual's level of endurance to generate heat through shivering. While experiments may never be conducted to completely exhaust an individual's shivering capacity, long-term exposures to cold can yield important information regarding metabolite utilization and endurance. Also of prime concern is how the pathophysiology of injury affects the body's thermoregulatory defence mechanisms against cold in terms of vasomotor response and thermogenesis.

Another area lacking information is the effect of wind on various clothing ensembles. This study adopted a highly empirical formulation based on very specific clothing. Whether such a formulation is generally applicable is not known and requires further attention.

Although the model was developed for cold air exposure, its calibration with cold water immersion survival data makes it entirely valid for cold water application. Using the same body anthropometric values as above representing lean and moderately fat individuals, predicted *ST*s for nude immersion in 10°C water are 2.3 and 6.7 h, respectively. These values are close to the limits reported by Molnar (1946) and Veghte (1972). If clothing is worn and kept dry (eg. survival suit), no adjustment of the clothing insulation value beyond compression is required. Note that in this case, the *ST* curves shown in Fig. 2 are not applicable.

As mentioned earlier, the prediction of *ST* in cold air is based on theory and observation of individuals far from hypothermia. Essentially, the model predictions are extrapolative, however, their concurrence with various diverse examples of air

exposure is supportive. The model also represents a substantive improvement over the simplistic approach outlined in the APPENDIX which requires expert knowledge of the metabolic rate for reasonable predictions.

LIMITATIONS/RECOMMENDATIONS

The following summarizies the limitations of the model:

i) assumes a healthy, uninjured, and sedentary individual,

ii) assumes full exposure (i.e., standing or immersion),

iii) does not take solar radiation into account,

iv) assumes the energy reserve for shivering is based on glycogen depletion, and

v) *ST* predictions for cold air exposure are based on theory and cannot be verified experimentally.

The following are recommendations for future work:

i) conduct experimental work to characterize long-term heat production via shivering,

ii) incorporate factors such as exercise, solar radiation, posture, contact with surfaces, and variablity in energy reserves into the model,

iii) take injury into account by considering the pathophysiological changes that affect thermoregulation,

iv) revise model for cold water immersion predictions involving dry/survival suits, and

v) issue the model in a simplified PC format and/or *ST* guidelines in pamphlet form for practical use.

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APPENDIX: Simple Model for Estimating Survival Time

The foregoing report describes a fairly complex model of human thermoregulation that was developed to predict survival time during cold exposure. The model is based upon concentric cylinders representing body and clothing compartments, and it uses complex relationships between insulation, heat transfer, heat production, heat loss, and energy reserves to predict the thermal state of the body over time.

Is this complexity really necessary? Can simpler expressions for body cooling suffice to predict survival time? The intent of this APPENDIX is to demonstrate that although simpler expressions are available, their application is very limited and they require expert input to obtain reasonable predictions.

1. Model

NATO document ACCP-1 (1992) Appendix B contains the following standard equation for calculating the rate of heat loss from the human body

$$H_{(R+C)} = 6.45 \cdot \frac{(T_s - T_a) \cdot A_D}{I} \qquad \text{(A1)}$$

where $H_{(R+C)}$ is the heat loss by radiation and convection (in $W \cdot m^{-2}$; heat loss by evaporation and conduction are assumed to be negligible), A_D is the body surface area, and I is the total insulation (in clo) between the skin at temperature T_s and the air environment at temperature T_a. This equation has been used to develop a simple model for predicting survival time during cold exposure as follows.

The basis of the model is a calculation of the time required for a body to cool at a constant rate from thermoneutrality to a thermal state considered to be a lower limit of survival, such as a deep core temperature (T_c) of 30°C. Survival time is thus obtained from

$$ST = \frac{\Delta BHC}{H_{net}} \qquad \text{(A2)}$$

where ΔBHC is the change in body heat content between the two thermal states and H_{net} is the difference between $H_{(R+C)}$ and the rate of metabolic heat production, i.e.,

$$H_{net} = H_{(R+C)} - M \qquad \text{(A3)}$$

Several of the parameters in the above equations, such as T_a, A_D, and I, are fairly straightforward to obtain. The others are more difficult to estimate with certainty, particularly the value of T_s in Eq. A1. Clearly, a value of 33°C associated with comfort at thermoneutrality is inappropriate, since not allowing for vasoconstriction and cooling of the skin results in a high heat loss rate and an unreasonably short estimate of ST. At the other extreme is a skin temperature equal or close to T_a, the lowest possible skin temperature under any circumstances, but using that value would result in zero heat loss and an infinite ST. A reasonable estimate for T_s at any point in time can be obtained by allowing it to partition itself between T_c and T_a according to the relative magnitudes of I_{air}, I_{clo}, and I_{tis} representing the insulations of the still air boundary layer, the clothing, and the tissues, respectively, under steady state heat flow conditions, i.e.,

$$T_s = \frac{T_a \cdot I_{tis} + T_c \cdot (I_{clo} + I_{air})}{I_{tis} + I_{clo} + I_{air}} \qquad \text{(A4)}$$

although this expression assumes no internal heat production.

Using this approach, the upper limit of T_s would be the steady state value obtained with T_c at 37°C, while the lower limit would be that when T_c had reached the survival limit of 30°C. It could be argued that perhaps the most reasonable choice should be the average of the upper and lower limits. However, given the simplicity of this model, the variations between individuals, and knowing that estimated survival times might be used to determine the duration of search and rescue efforts, choosing the lower value (and hence, a lower rate of heat loss and a longer ST estimate) may be prudent.

ΔBHC in Eq. A2 is the product of body mass, the change in mean body temperature between thermoneutrality and the survival limit, and the specific heat of 3.47 $J \cdot kg^{-1}$ for the human body, i.e.,

$$\Delta BHC = 3.47 \cdot wt \, \Delta \overline{T}_b \qquad \text{(A5)}$$

Assuming that mean body temperature is the weighted mean of T_c and T_s according to (Burton and Edholm 1969)

$$\overline{T}_b = 0.67 \cdot T_c + 0.33 \cdot T_s \qquad \text{(A6)}$$

then ΔBHC, and hence ST, are influenced by the initial and final values selected for T_c and T_s. Typical inital values would be T_c = 37°C and T_s = 33°C, while a reasonable final value for T_s would be the value from Eq. A4 when final T_c is 30°C.

Another parameter of considerable uncertainty is the metabolic heat production, as discussed in the main report. Body cooling normally elicits shivering to elevate heat production and defend the core against hypothermia. Heat production is also elevated by any exercise or physical activity being performed. In this simple model, M is estimated using a somewhat recursive approach: if expected STs are long (eg. > 24 h), then a relatively low average metabolic rate (near 150 W) may be appropriate, whereas if expected STs are shorter, a higher metabolic rate (between 200 and 400 W) may be sustainable for a significant portion of the exposure time. In any case, selection of a fixed metabolic rate over the entire surivival duration is quite arbitrary and imposes a major limitation to this simple model of ST, as demonstrated below.

2. Example Calculations

Consider cold exposure of a man having a height of 170 cm and weight of 70 kg (A_D = 1.81 m^2). Assume the man is in a -40°C environment wearing 3 clo of insulation, there is a strong wind blowing so that I_{air} is only 0.2 clo, and he is maximally vasoconstricted so that I_{tis} is 0.8 clo (Burton and Edholm 1969). Under these conditions, a final steady state T_s from Eq. A4 would be 16°C when T_c reaches the survival end-point of 30°C, and the ΔBHC to reach this state would be 2.5 MJ from Eq. A5. Conservatively using 16°C for T_s in Eq. A1 yields a heat loss rate $H_{(R+C)}$ of 204.3 W. Assuming an average metabolic heat production M of only 150 W over the exposure time, H_{net} is 54.3 W, and 2.5 MJ of heat would be lost in 12.8 h.

Knowing that a constant heat production of 150 W is not really correct, one can examine how ST depends on M. Increasing M to 200 W (due to a longer period of intense shivering or exercise) decreases H_{net} to only 4.27 W and raises ST to 162.7 h. Of course, it is clear that this metabolic rate could not be sustained continuously for almost 1 week, so one would tend not to use this value. However, the sensitivity of the model to M is quite clear. In fact, any condition in which heat loss is nearly balanced by heat production will yield a very long and unrealistic ST. Graphically, the plot of ST against some other parameter becomes very "steep" under certain conditions. To illustrate further, changing T_a in the above example to -25°C (M still at 150 W) yields a ST of 59.8 h, while simply raising T_a to -22°C extends ST to over 350 h. This is almost a 6-fold predicted increase in ST for a 3°C change in the environment (although ST is also dependent on T_s, as long as the gradient between skin and the

environment is large, small changes in T_s will have only a small effect on *ST*).

3. Summary

This APPENDIX has presented a simple model for predicting *ST* in the cold. The model is based upon fundamental relationships describing heat transfer between a body and its environment, and upon accepted methods of calculating or estimating some of the physiological responses to cold. The model may provide reasonable estimates of *ST* under conditions where the sensitivity of *ST* to changes in a particular parameter is low, such as when there is little insulation on the body and the rate of heat loss to the environment is large. Under these conditions, the analysis mimics a simple heat conduction problem. However, when conditions are such that the body may be able to maintain thermal homeostasis for a considerable portion of the exposure period, the reliability of the *ST* prediction is quite low. Further, the model depends heavily on the expertise of the user in providing reasonable estimates for *M* based on recursive analysis of the problem. The model could be improved to rectify these limitations. However, the necessary refinements would take the model out of the realm of a "simple" construct, and it would inevitably evolve to resemble the model described in the main body of this report.

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Table 1: Model predictions for various air exposures. I refers to the intrinsic value of clothing insulation and the prefix "ss" indicates the variable value when thermal balance is attained.

T_{air} (°C)	I (clo)	v ($km \cdot h^{-1}$)	ss$M$ ($W \cdot m^{-2}$)	ssT_0 (°C)	ssT_2 (°C)	ST (h)
28	0.0	1.0	44	37.0	32.2	-----
21	1.0	1.0	42	37.0	32.1	-----
5	0.0	2.0	160	35.3	17.8	11.4
-20	1.3	0.5	128	35.5	20.4	30.2
-20	1.7	1.0	106	35.5	22.7	46.3

Table 2: Predicted *ST* in h for a 1 km·h^{-1} wind condition.

T_{air}	nude	0.5 clo	1.0 clo	1.5 clo	2.0 clo	2.5 clo	3.0 clo
-50	1.4	2.3	4.1	7.5	13.6	23.9	
-45	1.5	2.5	4.8	9.1	17.1	29.8	
-40	1.7	2.9	5.8	11.3	21.6		
-35	1.9	3.4	7.1	14.5	27.7		
-30	2.1	4.1	8.9	19.1			
-25	2.4	5.0	11.8	25.4			
-20	2.9	6.5	16.2	35.0			
-15	3.7	8.8	22.8				
-10	4.8	12.7	33.6				
-5	6.7	19.5					
0	10.3	32.0					
5	17.7						
10	34.3						

Table 3: Predicted *ST* in h for a 2 km·h^{-1} wind condition.

T_{air}	nude	0.5 clo	1.0 clo	1.5 clo	2.0 clo	2.5 clo	3.0 clo
-50	1.1	2.0	3.5	6.4	11.6	20.7	34.3
-45	1.2	2.2	4.1	7.7	14.4	25.7	
-40	1.3	2.5	4.9	9.5	18.4	32.6	
-35	1.5	2.9	5.9	12.0	23.5		
-30	1.6	3.4	7.4	15.8	30.8		
-25	1.9	4.2	9.5	21.1			
-20	2.2	5.3	13.0	28.9			
-15	2.6	7.0	18.4				
-10	3.3	9.9	26.9				
-5	4.5	15.2					
0	6.7	24.6					
5	11.4						
10	22.1						

Table 4: Predicted *ST* in h for a 5 $km \cdot h^{-1}$ wind condition.

T_{air}	nude	0.5 clo	1.0 clo	1.5 clo	2.0 clo	2.5 clo	3.0 clo
-50	0.8	1.6	2.7	4.9	8.7	15.6	26.7
-45	0.9	1.7	3.1	5.8	10.6	19.6	33.4
-40	1.0	1.9	3.7	6.9	13.4	24.7	
-35	1.1	2.2	4.3	8.6	17.3	31.8	
-30	1.2	2.5	5.3	11.1	22.6		
-25	1.4	3.0	6.7	14.9	30.2		
-20	1.6	3.7	8.8	20.4			
-15	1.9	4.8	12.3	28.8			
-10	2.3	6.5	18.0				
-5	3.0	9.6	27.6				
0	4.2	15.6					
5	6.7	27.4					
10	13.0						

Table 5: Predicted *ST* in h for a 10 $km \cdot h^{-1}$ wind condition.

T_{air}	nude	0.5 clo	1.0 clo	1.5 clo	2.0 clo	2.5 clo	3.0 clo
-50	0.7	1.3	2.2	3.8	6.6	11.8	20.8
-45	0.8	1.4	2.4	4.4	8.0	14.7	25.9
-40	0.8	1.6	2.8	5.2	9.9	18.8	32.8
-35	0.9	1.8	3.3	6.4	12.6	24.0	
-30	1.0	2.0	3.9	8.0	16.6	31.4	
-25	1.2	2.3	4.9	10.5	22.1		
-20	1.3	2.8	6.2	14.4	30.3		
-15	1.5	3.5	8.4	20.3			
-10	1.8	4.5	12.1	29.7			
-5	2.3	6.4	18.6				
0	3.2	10.1	30.4				
5	4.9	17.7					
10	9.0	35.1					

Table 6: Predicted *ST* in h for a 20 km·h^{-1} wind condition.

T_{air}	nude	0.5 clo	1.0 clo	1.5 clo	2.0 clo	2.5 clo	3.0 clo
-50	0.6	1.0	1.7	2.9	4.9	8.6	15.1
-45	0.7	1.1	1.9	3.3	5.8	10.5	19.0
-40	0.7	1.3	2.2	3.9	7.1	13.2	23.9
-35	0.8	1.4	2.4	4.6	8.8	17.1	30.8
-30	0.9	1.6	2.9	5.6	11.3	22.3	
-25	1.0	1.8	3.5	7.1	15.1	29.8	
-20	1.1	2.1	4.3	9.5	20.7		
-15	1.3	2.5	5.6	13.3	29.3		
-10	1.5	3.2	7.8	19.5			
-5	1.9	4.3	11.7	30.0			
0	2.5	6.4	19.0				
5	3.8	10.9	33.7				
10	6.7	21.4					

Table 7: Predicted *ST* in h for a 50 km·h^{-1} wind condition.

T_{air}	nude	0.5 clo	1.0 clo	1.5 clo	2.0 clo	2.5 clo	3.0 clo
-50	0.5	0.8	1.3	2.0	3.3	5.5	9.4
-45	0.6	0.8	1.4	2.2	3.8	6.5	11.5
-40	0.6	0.9	1.5	2.5	4.4	7.9	14.5
-35	0.7	1.0	1.7	2.9	5.3	10.0	18.8
-30	0.8	1.1	1.9	3.5	6.6	12.9	24.5
-25	0.8	1.3	2.2	4.3	8.5	17.4	32.9
-20	1.0	1.5	2.7	5.4	11.5	23.7	
-15	1.1	1.7	3.4	7.2	16.3	33.7	
-10	1.3	2.1	4.4	10.3	23.7		
-5	1.6	2.7	6.2	15.8			
0	2.0	3.7	9.7	25.6			
5	2.9	5.9	17.0				
10	5.0	11.1	33.6				

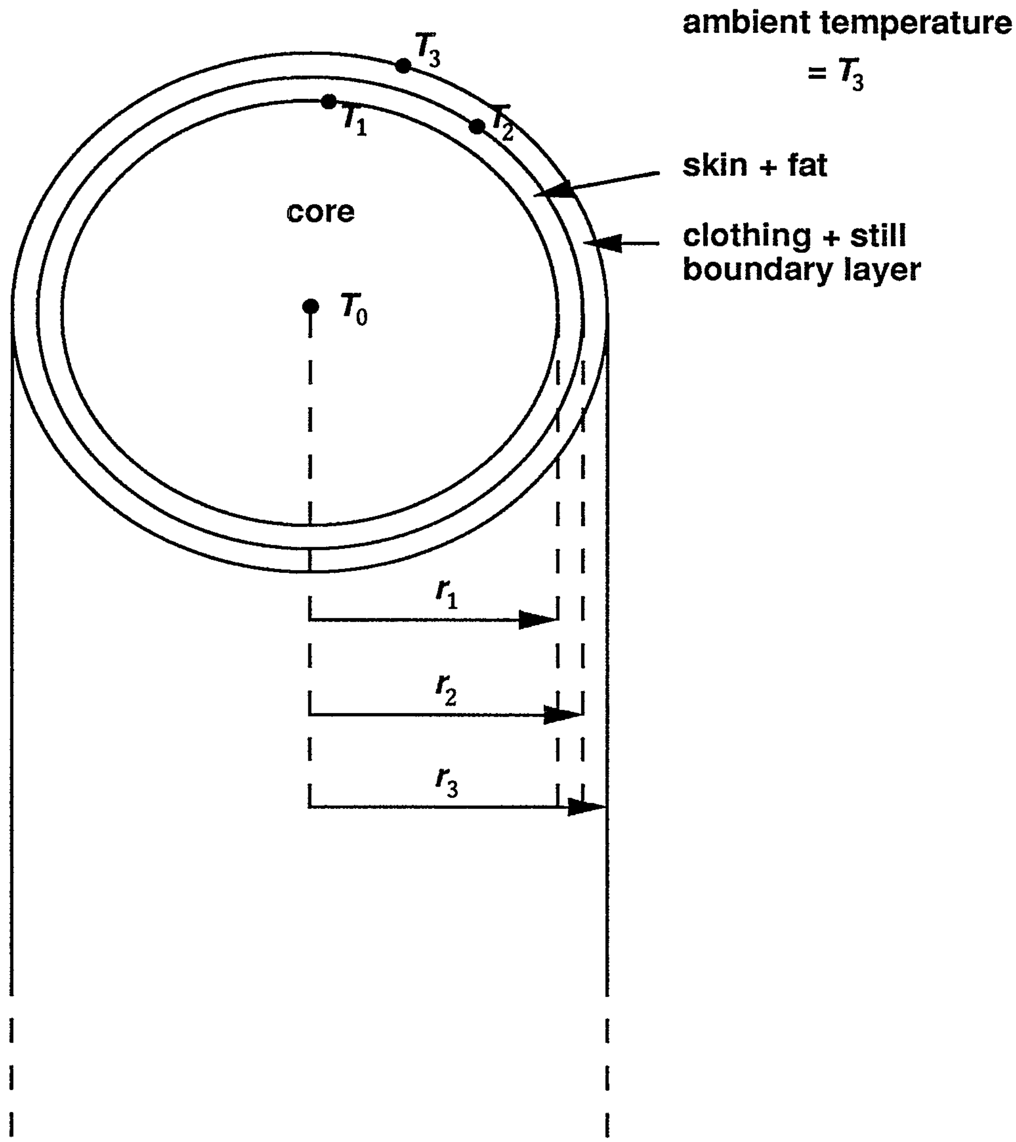

Fig 1. Schematic of the core-shell model.

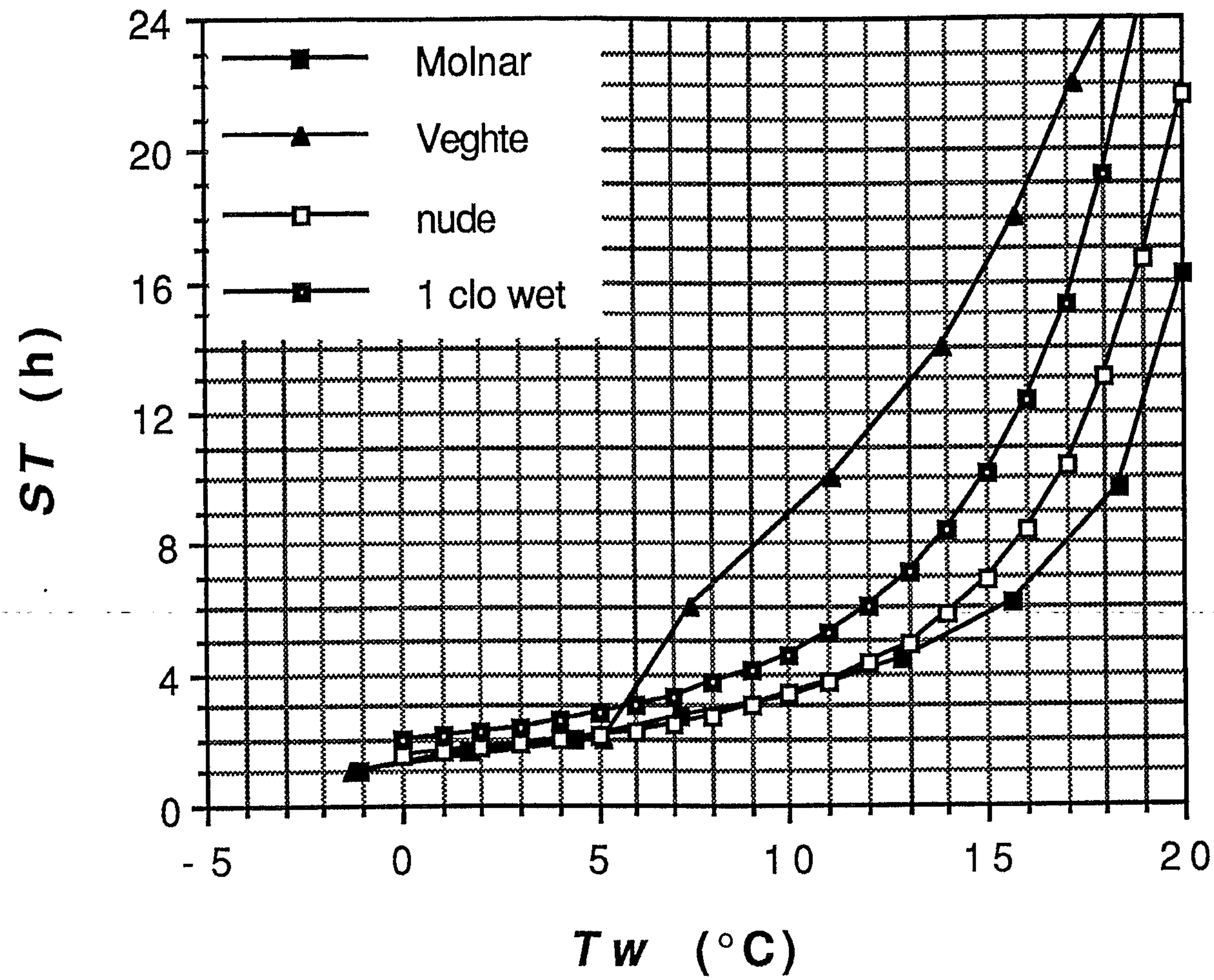

Fig 2. Survival times plotted against water temperature based on the reports of Molnar (1946) and Veghte (1972), and from the model following calibration. 1 clo wet implies clothing having an intrinsic insulation of 1 clo but in a completely wet condition.

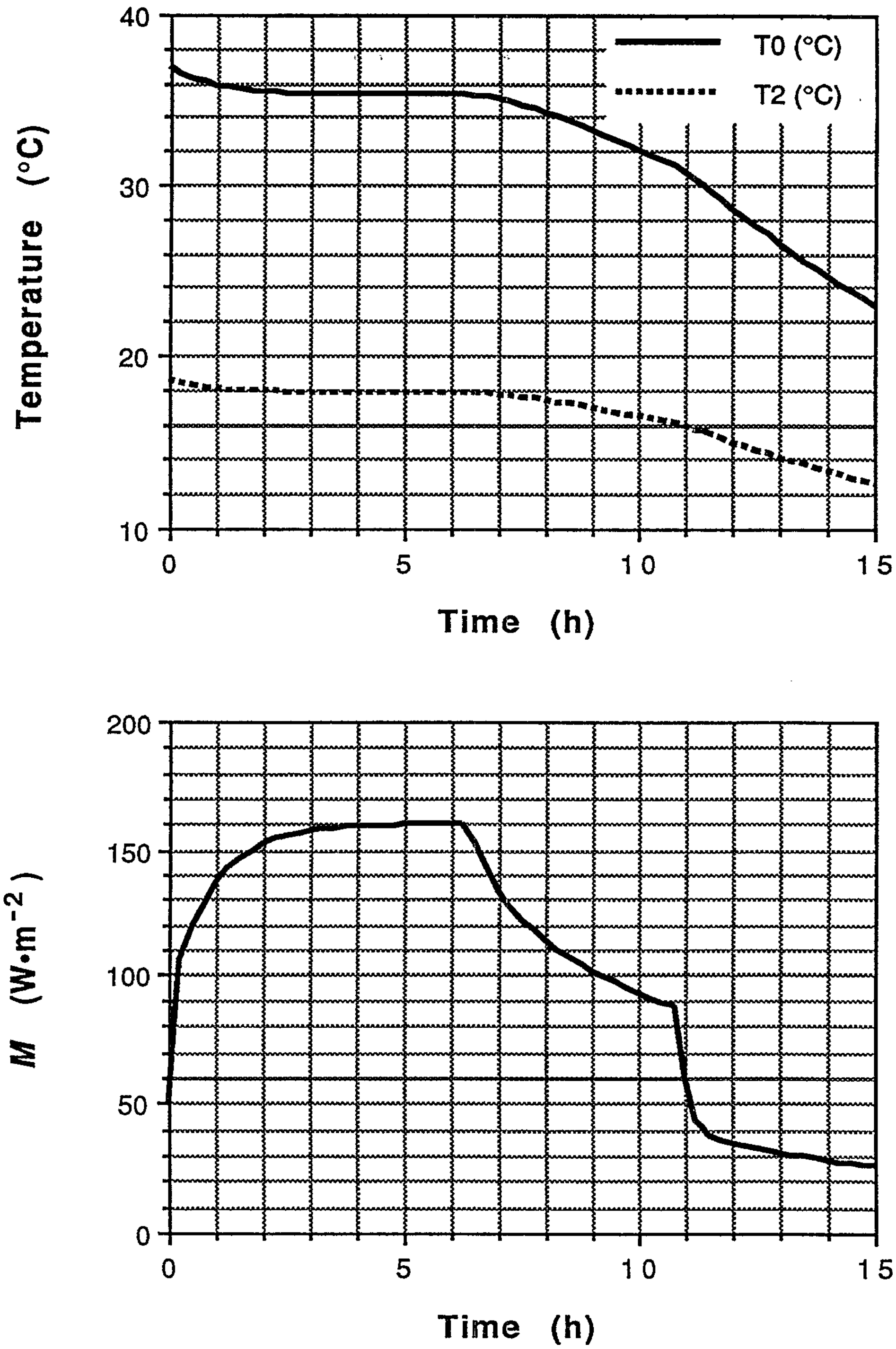

Fig 3. Model-predicted temperatures and metabolic rate against time for a nude exposure to 5°C at 2 km·h^{-1} under sedentary conditions.

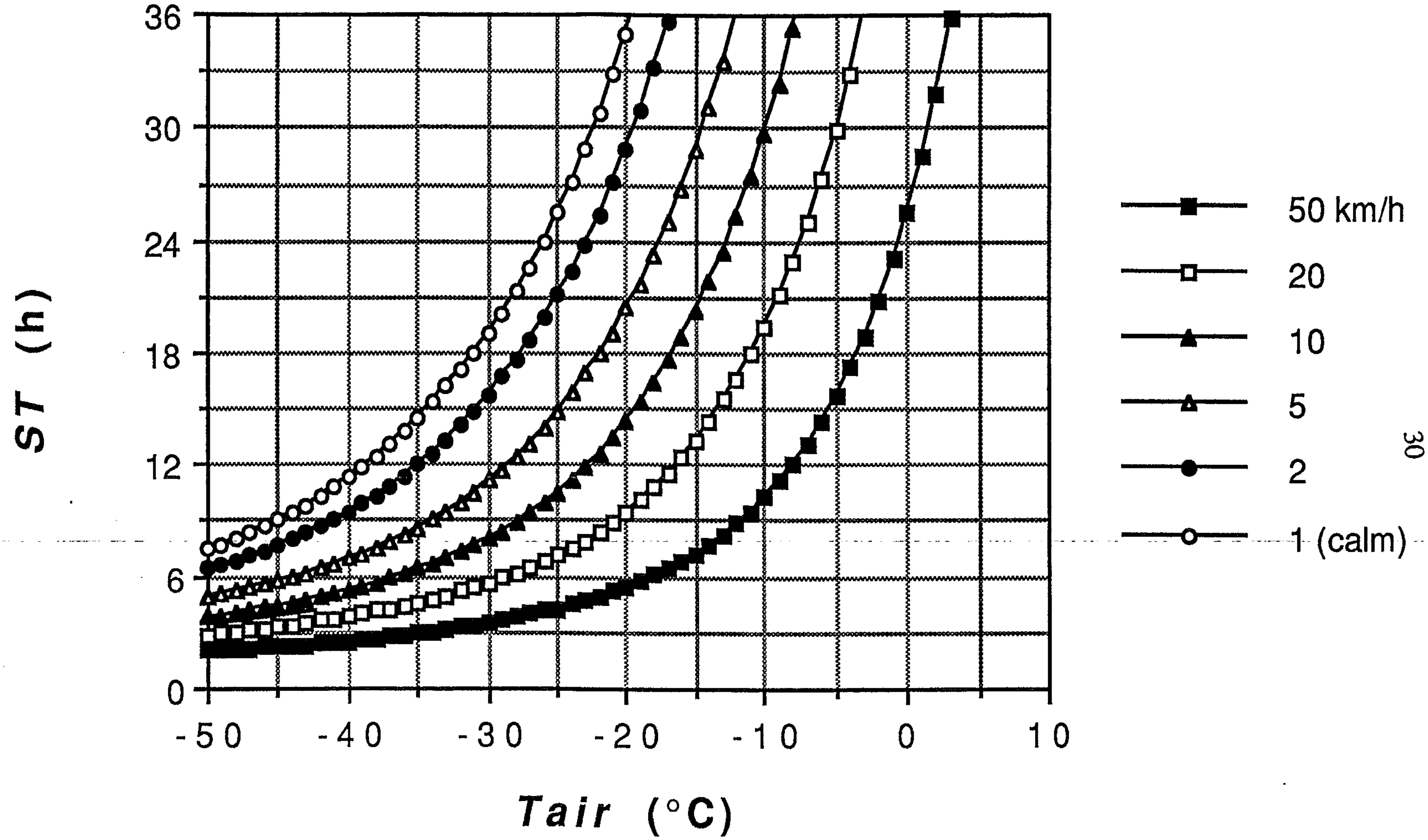

Fig 4. Model-predicted survival times against air temperature for a clothing insulation of 1.5 clo and various wind conditions.

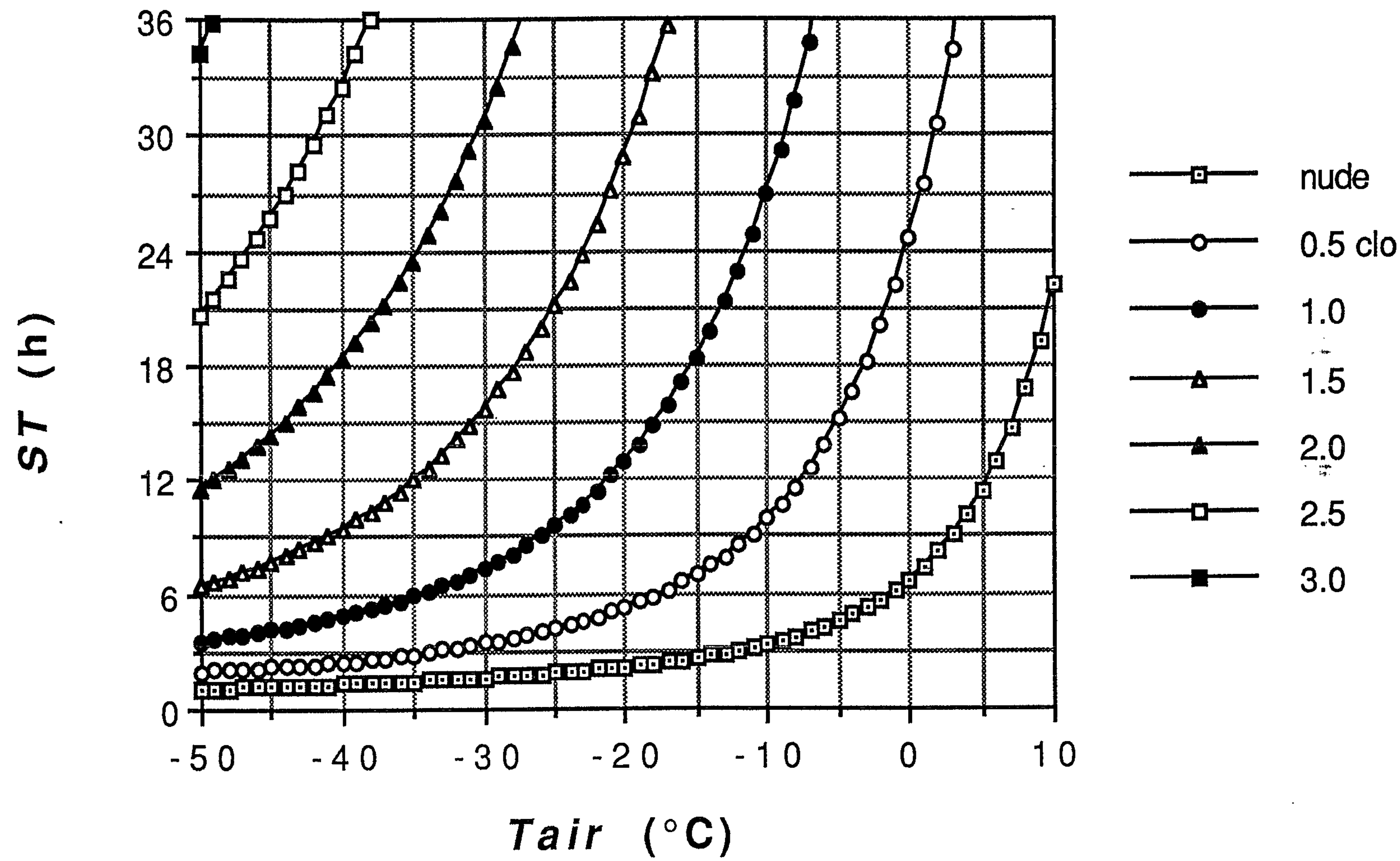

Fig 5. Model-predicted survival times against air temperature for a wind at 2 km·h^{-1} and various insulative conditions.

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The prediction of survival time (ST) for cold exposure is inexact since controlled data of deep hypothermia are unavailable. At best, case histories of accidental exposure can be used for guidance. This study describes the development of a simple heat conduction model for the prediction of ST under sedentary conditions in the cold. Predictions are not made for cold injury. The model is based on steady-state heat conduction in a single cylinder comprised of a core and two annular concentric shells representing the fat plus skin and the clothing plus still boundary layer, respectively. The ambient condition can be either air or water; the distinction is made by assigning different values of insulation to the still boundary layer. Metabolic heat production (M) is predicted by temperature signals from the core and skin, but is not allowed to exceed heat loss. Where the cold exposure is too severe for M to balance heat loss, ST is largely determined by the heat conduction characteristics of the model. Where a balance occurs, ST is governed by the depletion time of the energy reserve for shivering. End of survival is marked by the core temperature reaching a value of 30°C, although the model is capable of predicting lower body temperatures. The model dimensions were first scaled according to body dimensions. Then, to obtain reasonable agreement with available information, the model radius was expanded. Model predictions for cold water (0 to 20°C) immersion agree with the values reported by Molnar (1946) and Veghte (1972). A sampling of ST predictions for nude exposure in relatively calm (1 km/h wind) cold air of an average healthy male are the following: 3, 5, 10, and > 24 h for -20, -10, 0, and 10°C, respectively. With 2 clo of insulation in a 10 km/h wind, STs are 7, 10, 17, and > 24 h for -50, -40, -30, and -20°C. The predicted STs must be weighted against the extrapolative nature of the model. At present, it would be prudent to use the predictions in a relative sense, that is, to estimate the benefit of increasing one's insulation in terms of percentage increase in ST. Clearly, model predictions are subject to change as more information becomes available for calibration.

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