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TITLE

PREDICTION OF SURVIVAL TIME AT SEA BASED ON OBSERVED BODY COOLING RATES

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TECHNICAL NOTE

Prediction of Survival Time at Sea Based on Observed Body Cooling Rates

PETER TIKUISIS, Ph.D.

TIKUISIS P. *Prediction of survival time at sea based on observed body cooling rates.* **Aviat Space Environ Med 1997; 68:441–8.**

The prediction of survival time (ST) of individuals stranded at sea is particularly difficult since reliable controlled data are unavailable. An individual's rate of body cooling is governed by the difference between heat loss and heat production. It has been suggested that the rate of deep body cooling can be extrapolated to estimate ST. The observed linearity of this cooling rate against water temperature is consistent with the predictions of an independently-developed mathematical model of ST. This model has been extended to simulate conditions of partial immersion and wet clothing, and subsequently calibrated against observed human cooling rates. The resultant modification allows a much broader range of ST predictions involving calm and rough seas, and non-immersion wet conditions. Predictions are presented for lean vs. fat individuals, a "worst" case scenario where shivering is absent, and partial immersion. While these predictions must be considered speculative and subject to change as better information becomes available, the model can be useful as a decision aid. It would be prudent, however, to consider the predictions in a relative vs. absolute sense; i.e., for comparative purposes.

INDIVIDUALS STRANDED at sea have been greatly aided through advances in personal protective equipment and locator technologies. Yet, despite these advances, successful rescue is often contingent on how quickly a search and rescue (SAR) operation can respond. Unfortunately, rescuers are often faced with a compromising decision due to weather constraints; that is, whether to proceed immediately at some risk or to wait for more favorable conditions with less risk. Such a decision is more easily made if the well-being of the individual(s) is known. However, failing this possibility, a prediction of survival status and outcome is required. Years of experience improve the professional's predictive capability; yet, faced with many confounding variables, most rescue operations present a unique challenge. Out of humanitarian concerns, SAR operations are sometimes conducted longer than is necessary, resulting not only in additional expense but at the compromise of valuable resources that might be better allocated elsewhere. Guidelines for SAR continuation are not precisely quantified, hence the requirement for a rationally-derived predictive model of survival time. Such a model can potentially become a valuable resource and decision aid.

Several attempts have been made to predict tolerance/survival times for cold water immersion. These include the nomogram of Smith and Hames (19) and the relatively simple mathematical models of Hall (9) and Timbal et al. (23) that were critically examined by Tikuisis (26). Nunneley et al. (17) applied a highly complex whole-body thermoregulatory model (27) to predict the time of deep body cooling to a temperature of 34°C, considered the threshold for incapacitation. No predictions were given for the lower body temperature of 30°C considered as the threshold for unconsciousness (22). In the present study, survival time (ST) will refer to the lower deep body temperature which can be viewed as a liberal endpoint. This definition of ST is based on severe hypothermia and excludes the risk of death from injury or drowning.

Predictions of survival outcome or ST would be relatively straightforward if reliable data were available. Unfortunately, our most direct source of information is primarily limited to case histories which are often insufficiently documented. This caveat and its consequences have been discussed in previous studies that outlined the development of a mathematical model for the prediction of ST for cold air exposure (25,26). This model was derived using known biophysical and physiological characteristics, and calibrated with selected survival cases; yet its predictive capability largely remains untested. As in most model developments of this nature, calibration and validation are ongoing processes subject to the availability of new information.

An examination of other literature on survival estimates reveals that ST might be extrapolated from the observed body cooling rates in humans exposed to wet/cold conditions (11,22). These cooling rates have been shown by the same authors to be linearly related to water temperature. Coincidently, while the model (26) prediction of ST is curvilinear with water temperature (**Fig. 1**), the corresponding mean deep body cooling rate (calculated from the change in rectal temperature over ST) is seen to also be nearly linearly dependent on water temperature for both nude and clothed immersions. Therefore, the proposed strategy in this study is to apply the observed deep body cooling rates under various wet/cold immersion and non-immersion conditions towards

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From the Defence and Civil Institute of Environmental Medicine, North York, Ont. Canada.

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Address reprint requests to: Peter Tikuisis, Ph.D., DCIEM, 1133 Sheppard Ave. West, P.O. Box 2000, North York, Ont., Canada M3M 3B9.

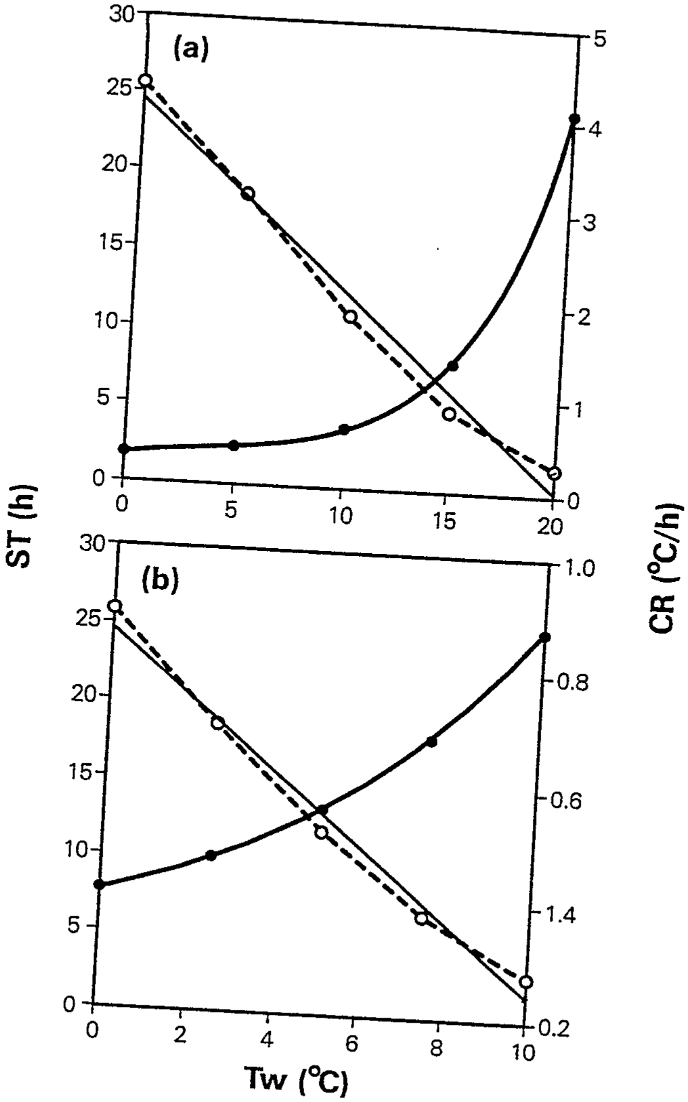

Fig. 1. Model prediction (26) of survival time (ST; solid circles) and mean deep body cooling rate (CR; open circles) against water temperature for an average individual (73.9 kg, 1.77 m, 17.7% body fat) for (a) nude immersion in calm water and (b) clothed immersion (0.5 clo immersed value) in rough water. The straight solid lines are linear regressions of the CR values and have r^2 values of (a) 0.983 and (b) 0.984.

the calibration of the mathematical model and then to apply the model for predictions under much broader conditions. In addition, the model is expanded to simulate partial immersion and to include wetness/leakage of insulative garments.

METHODS

Model Development

Deep Body Temperature

The basic model assumes steady state heat conduction in a cylindrical core-shell configuration. Heat is generated uniformly within the core region and its central axis represents the deep body core temperature. Two outer concentric shells represent the fat plus skin and the clothing plus still-boundary layer, respectively. Basic anthropometric measures such as mass, height, and body fatness are taken into account; however, no distinction is made for gender differences with respect to exposure survivability. A schematic of the basic model is represented by one of the cylinders shown in **Fig. 2** and the relevant heat transfer equations are outlined in Tikuisis (26).

The individual is assumed to be sedentary and, therefore, reliant on shivering as the only source of heat beyond normal resting values [assumed equal to $BSA^{-1} \cdot \{3.22 + 0.67 \cdot wt + 24.2 \cdot ht - 0.33 \cdot age\}$ from Harris and Bennedict (10) where BSA is the body surface area (7), wt is weight in kilograms, ht is height in meters, and age is in years]. The metabolic rate due to shivering is predicted according to the decreases in skin and deep core temperatures (24), but its maximum value is limited to 4.5 times the individual's resting metabolism (12). If the cold stress overwhelms the individual's heat production, then ST is largely determined by the rate of heat loss from the body. If, on the other hand, the individual's heat production can balance heat loss, then ST is governed by the endurance time of shivering. The endurance time is predicted according to the glycogen depletion model of Wissler (27); its implementation is described in Tikuisis (26). End of survival or ST is defined as the time when the body's deep core temperature reaches 30°C.

Steady state heat loss (Q; in $W \cdot m^2$) from the model cylinder is predicted by (26):

$$Q = \frac{(T_0 - T_3)}{R_{eff}} \qquad \text{Eq. 1}$$

where T_0 and T_3 refer to the cylindrical centre (deep 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 uniform internal heat production in the core region only and expressed as (26):

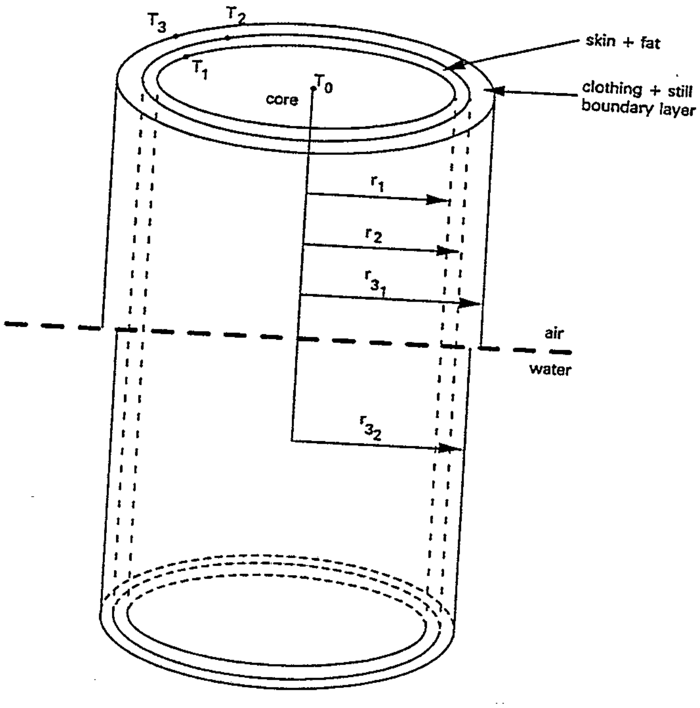

Fig. 2. Schematic representation of the two-cylinder core-multishell model. The dashed line separates the upper and lower portions of the body assumed to be air-exposed and water-immersed, respectively.

$$R_{eff} = \frac{r3}{2\cdot k_{co}} + \frac{r3}{k_{sf}}\cdot \ln\frac{r2}{r1} + \frac{r3}{k_{el}}\cdot \ln\frac{r3}{r2} \qquad \text{Eq. 2}$$

where r_i is the compartment radius, k is the thermal conductivity, and co, sf, and el refer to the core, skin plus subcutaneous fat, and external insulation layer (clothing plus an unstirred ambient boundary layer), respectively. For brevity, the three consecutive terms of Eq. 2 are designated as a_1, a_2, and a_3. Eq. 2 is applicable for either air or water environments; the distinction is governed by the radius and thermal conductivity of the external layer (26).

The change in mean body temperature (T_b) is found by taking the difference between the heat produced metabolically (M) and the amount of heat lost to the environment, i.e.,

$$\Delta T_b = \frac{(M - Q)\cdot \Delta t}{cb} \qquad \text{Eq. 3}$$

where Δt is the time step and cb is the mean heat capacity of the body. The algorithm to calculate the resultant change in deep core temperature (taking into account the geometrical correspondence between the body and model cylinder, and avenues of heat loss other than conduction) is outlined in Ref. 26.

To simulate partial immersion, the present model consists of two cylinders aligned end-to-end (Fig. 2). The convention adopted herein is to air-expose the upper cylinder (i = 1) and water-immerse the lower cylinder (i = 2). Each cylinder will usually have a different rate of heat loss (separately predicted by Eq. 1) and consequently will have a different change in mean temperature (Eq. 3).

Assuming that the deep core regions of the cylinders are sufficiently well-stirred so that their temperatures can be equated, we have (26):

$$\frac{c11 + (r3_1/r2)\cdot(2\cdot Tb_1\cdot Reff_1 - c21)}{c31} = \frac{c12 + (r3_2/r2)\cdot(2\cdot Tb_2\cdot Reff_2 - c22)}{c32} \qquad \text{Eq. 4}$$

where the left and right hand sides represent the deep core temperatures of the upper and lower cylinders, respectively, and:

$$c1_i = a2_i\cdot T3_i \qquad \text{Eq. 5}$$

$$c2_i = (2 - f_{co})\cdot(Reff_i - a3_i)\cdot T3_i \qquad \text{Eq. 6}$$

$$c3_i = a2_i + ra_i\cdot[f_{co}\cdot Reff_i + (2 - f_{co})\cdot a3_i] \qquad \text{Eq. 7}$$

$$ra_i = r3_i/r2 \qquad \text{Eq. 8}$$

and where f_{co} represents the fraction by body volume of the core compartment. Note that r_1 and r_2 represent the cylindrical radii to the outer core boundary and skin surface, respectively, which are common to both cylinders whereas r_3 represents the radius to the outer surface of the still boundary layer which varies with the ambient condition (i.e., air vs. water; Fig. 2) at temperatures T_{3_1} and T_{3_2}.

Isolating T_{b_2} (mean temperature of the water-immersed cylinder) from Eq. 4:

$$Tb_2 = \frac{1}{2\cdot Reff_2} \times \left\{c22 + \frac{(c32/c31)\cdot[c11 + ra1\cdot(2\cdot Tb_1\cdot Reff_1 - c21)] - c12}{ra2}\right\} \qquad \text{Eq. 9}$$

and equating to $T_b - (1 - f_{im})\cdot T_{b_1}/f_{im}$, where T_b is the new overall mean body temperature based on the weighted contribution of each cylinder and f_{im} is the fraction of the overall body immersed in water, leads to:

$$Tb_1 = \frac{Tb - \dfrac{f_{im}}{2\cdot Reff_2}\cdot\left\{c22 + \dfrac{(c32/c31)\cdot(c11 - ra1\cdot c21) - c12}{ra2}\right\}}{(1 - f_{im}) + f_{im}\cdot\left(\dfrac{c32}{c31}\right)\cdot\left(\dfrac{ra1}{ra2}\right)\cdot\left(\dfrac{Reff_1}{Reff_2}\right)} \qquad \text{Eq. 10}$$

Finally, the common deep core temperature is calculated by evaluating either side of Eq. 4. For example, rewriting the left hand side of Eq. 4 with appropriate substitutions from Eqs. 5 to 7 leads to:

$$To = \frac{a21\cdot T3_1 + \left(\dfrac{r3_1}{r2}\right)\cdot[2\cdot Tb_1\cdot Reff_1 - (2 - f_{co})\cdot T3_1\cdot(Reff_1 - a3_1)]}{a21 + \left(\dfrac{r3_1}{r3}\right)\cdot[f_{co}\cdot Reff_1 + (2 - f_{co})\cdot a3_1]} \qquad \text{Eq. 11}$$

Clothing

Clothing provides an important protective layer of insulation to the body's surface. Its effectiveness is maximized with increased trapped air [clothing air layers have an insulative value of about 24.4 $m\cdot{}^\circ C\cdot W^{-1}$ or 1.57 $clo\cdot cm^{-1}$ in more conventional terms (4) where 1 clo (0.155 $m^2\cdot{}^\circ C\cdot W^{-1}$) of insulation provides thermal comfort for a sedentary individual in air at approximately 23°C (8)]. Wetness through rain, spray, or previous immersion, however, will degrade the insulative quality of clothing by replacing the trapped air with water which is considerably more heat conductive. Dry suits retain the insulative advantage of air, but their effectiveness is reduced by compression upon immersion. Further, dry suits are subject to leakage through poor fitting or tearing. The above variances make it very difficult to predict the insulation of immersed or wet clothing. Consequently, we rely on experimental values of body cooling rates to provide the insulative estimates of wet clothing.

A direct correspondence between ST and deep body cooling rates in wet/cold exposed humans was proposed by Hayward et al. (11). Further, the linear relationship between the cooling rate and water temperature illustrated by Steinman and Hayward (22) is consistent with the model prediction shown in Fig. 1. By adjusting the model's insulation values to obtain agreement between its predicted ST values and those extrapolated from the mean observed body cooling rates, we can estimate the clothing's in situ insulation. Body cooling rates have been measured in humans for both immersion and non-immersion conditions (20,21). Although out of the water, the latter condition involved wetness through prior immersion and subsequent spraying from occasional breaking waves.

Following this 'calibration' procedure, **Table I** lists the estimated clothing insulation values for immersions in calm and rough seas by matching as closely as possible the data-extrapolated and model-predicted STs. The "still" water boundary insulation is assumed to be 0.05 and 0.01 clo for the calm and rough sea conditions, respectively, which correspond to relative water velocities of 0.13 and 1.5 $m\cdot s^{-1}$ (2). Most of the fitted insulation

TABLE I. MODEL-FITTED INSULATION VALUES (ICL IN CLO UNITS) FOR VARIOUS CLOTHING ENSEMBLES FOR IMMERSIONS IN CALM AND ROUGH SEAS. MODEL AND DATA VALUES ARE SURVIVAL TIMES (IN HOURS); THE LATTER ARE EXTRAPOLATED FROM MEAN OBSERVED DEEP BODY COOLING RATES IN YOUNG LEAN MALES.

	Calm Sea at 10.7 °C			Rough Sea				
					6.1°C		11.1°C	
Clothing Ensemble*	Icl	Model	Data†	Icl	Model	Data‡	Model	Data†
Nude	0	3.2	na	0	1.7	na	2.7	na
Flight Suit + 1	0.04	3.9	2.4	0.02	1.8	1.3	3.0	2.1
Float Coat + 1 + 2	0.08	4.7	4.7	0.03	1.9	na	3.2	3.1
Aviation Coverall + 1	0.18	7.4	7.5	0.09	2.4	2.7	4.3	4.2
Boatcrew Coverall + 1 + 2	0.19	7.8	7.7	0.10	2.5	2.6	4.5	3.8
Short Wetsuit (3.2 mm) + 1	0.14	6.2	6.2	0.14	3.0	na	5.5	5.6
Full Wetsuit (4.8 mm) + 1	0.28	11.3	11.4	0.23	4.2	4.4	8.3	8.2
Dry Coverall + 3	0.63	>36	na	0.42	8.6	8.8	17.4	na
Torn Dry Coverall + 3	0.63	4.0**	na	0.42	2.3**	2.3	4.0**	na
Dry Suit (4.8 mm) + 2	0.66	>36	15.0	0.44	9.2	na	18.6	18.3

* Additional clothing are 1 = cotton underwear, 2 = cotton uniform, and 3 = thick underwear.
† 72.2 kg, 1.74 m, 12.0% body fat, 24.3 yrs (21).
‡ 71.7 kg, 1.75 m, 11.1% body fat, 23.5 yrs (20).
** See Wetness/Leakage section.

values shown in Table I appear reasonable [eg., the values for the dry coverall ensemble concur with the value of 0.6 clo estimated by Steinman and Kubilis (20)]. Disparities in ST occur for the flight suit and the dry suit (calm sea). No insulative value could be fitted for the flight suit to achieve the low data-extrapolated STs of 2.4 h (calm sea) and 1.3 to 2.1 h (rough sea); note the higher predicted ST for the nude condition [originally calibrated using sea survival curves (15, 25, 28)]. It is conceivable that the data-extrapolated STs for the flight suit are underestimated. The flight suit clo values were, therefore, arbitrarily selected to fall between the nude and more insulative float coat conditions. The final values including the "still" water boundary layer range from 0.03 to 0.09 clo which compares well with the value of 0.06 estimated by Steinman and Kubilis (20).

The cooling rate observed for the dry suit was reported higher under calm vs. rough sea conditions at similar water temperatures (10.7 and 11.1°C). The lower cooling rate for rough seas was reportedly (21) attributed to a higher metabolic rate due to the colder stress experienced by the subjects. However, this leads to an unreasonably low extrapolated ST for the calm sea condition. It is known that ST diminishes considerably under rough vs. calm seas (13) as predicted for all the other clothing ensembles. The dry suit insulation under calm seas is, therefore, assumed to be higher than under rough seas (the 50% increase is estimated from comparisons with other clothing ensembles). The impact of varying metabolic rates on the relationship between ST and body cooling rates is examined in the Discussion section.

Wetness/Leakage

The reduction in clothing insulation due to wetness has been characterized differently depending on whether the individual is water-immersed (via leakage) or air-exposed but wetted through prior immersion, spray, or precipitation. If water-immersed, the loss of insulation can be approximated by:

$$\text{loss of insulation (\%)} = 100 \cdot (1 - e^{-0.022 \cdot \sqrt{\text{wetness}}}) \qquad \text{Eq. 12}$$

based on the fit of data of immersion-protection clothing presented by Allan et al. (1) and where wetness is the water ingress in $g \cdot m^{-2}$. A value of 6200 $g \cdot m^{-2}$ (representing an 82% loss of insulation) was applied to the torn dry coverall to attain a ST of 2.3 h in rough seas at 6.1°C, fitted against the extrapolated ST of 2.3 h from the measured deep body cooling rate (Table I).

If air-exposed, we begin by calculating the non-immersion insulative values of the clothing ensembles listed in Table I using the guidelines of McCullough et al. (14). The intrinsic dry insulation values of a combination of individual garments such as the flight suit + underwear is obtained from the following summation formula:

$$\text{dry ensemble } I_{cl} = 0.676 \cdot \sum I_{cl} + 0.117 \qquad \text{Eq. 13}$$

where I_{cl} within the summation refers to the intrinsic dry insulation value of the garment (in clo units); values of all the ensembles are presented in **Table II.** The total dry insulation of the ensemble must include the external air layer insulation which is determined with the algorithm developed by Danielsson (6). The degradation of the external air layer insulation with increased wind is taken into account. Further degradation due to wetness and its impact on thermoregulation is calculated as follows.

The loss of insulation due to wetness is linearly approximated by:

$$\text{loss of insulation (\%)} = \begin{cases} 0.0554 \cdot \text{wetness} & \text{if wetness} \leq 316.2\ g \cdot m^{-2} \\ 9.17 + 0.0264 \cdot \text{wetness} & \text{if wetness} \geq 316.2\ g \cdot m^{-2} \end{cases} \qquad \text{Eq. 14}$$

based on the fit of data presented by Boutelier (3). Wetness during air exposure introduces an evaporative component (Ev) to body heat loss, expressed as (16):

$$E_v = f_w \cdot E_{max} \qquad \text{Eq. 15}$$

where f_w is the fraction of maximum skin wetness assumed to be linearly related to wetness and E_{max} is the maximum evaporative heat loss (in $W \cdot m^{-2}$) given by:

$$E_{max} = \frac{16.5 \cdot h_{air} \cdot (P_s - P_a)}{1 + 0.92 \cdot h_{air} \cdot R_{cl}} \qquad \text{Eq. 16}$$

TABLE II. MODEL-FITTED WETNESS VALUES (IN $g \cdot cm^{-2}$) FOR VARIOUS CLOTHING ENSEMBLES FOR WET/COLD NON-IMMERSION IN AIR AT 7.7°C AND 28 $k \cdot h^{-1}$ WITH OCCASIONAL BREAKING WAVES. A MINIMUM VALUE OF 500 $g \cdot cm^{-2}$ WAS ASSIGNED TO THE NUDE AND DRY GARMENTS TO SIMULATE SURFACE WETNESS. DRY INTRINSIC INSULATION VALUES (ICL IN CLO) WERE DETERMINED USING THE GUIDELINES OF McCULLOUGH (14). MODEL AND DATA VALUES ARE SURVIVAL TIMES (IN HOURS).

Clothing Ensemble*	Icl	Wetness	Model	Data†
Nude	0	500	2.1	na
Flight Suit + 1	0.56	2800	2.2	2.2
Float Coat + 1 + 2	1.54	1550	8.5	na
Aviation Coverall + 1	0.73	1550	4.1	9.3
Boatcrew Coverall + 1 + 2	1.76	1750	8.0	7.9‡
Short Wetsuit (3.2 mm) + 1	0.73	650	9.4	na
Full Wetsuit (4.8 mm) + 1	0.87	650	11.8	11.9
Dry Coverall + 3	0.72	500	11.3	12.3
Torn Dry Coverall + 3	0.72	950	6.5	6.6
Dry Suit (4.8 mm) + 2	1.10	500	21.4	na

* Additional clothing are 1 = cotton underwear, 2 = cotton uniform, and 3 = thick underwear.

† Extrapolated from mean observed deep body cooling rates in young lean males [71.7 kg, 1.75 m, 11.1% body fat, 23.5 yr (20)].

‡ Pertains to sitting atop a capsized boat under similar conditions but with continuous spray.

and where h_{air} is the external heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$), R_{cl} is the internal clothing insulation including intermediate air layers ($m^2 \cdot K \cdot W^{-1}$), and P is the vapour pressure (kPa). The values of h_{air} and R_{cl} are determined using the algorithm of Danielsson (6).

It can be expected that shivering increases in response to Ev but that this increase is limited so that the cooling effect of evaporative heat loss does not lead to increases in metabolism when the body temperature is relatively high (i.e., beyond the shivering threshold). As an ad hoc approximation, the increase in shivering metabolism is assumed proportional to Ev but factored by $1 - \exp(-M_{shiv}/M_{shiv_{max}})$ where M_{shiv} is the predicted shivering metabolic rate based solely on body temperatures (24) and $M_{shiv_{max}}$ is the maximum shivering intensity. Under thermoneutral conditions, M_{shiv} is zero and, therefore, no increase in metabolism due to evaporative heat loss is predicted, as expected.

Table II lists the fitted wetness values (corresponding to losses of insulation from 22 to 83%; see Eq. 14) and STs for a wetted non-immersion condition due to prior immersion and occassional spray simulating open wet/cold life-raft conditions at sea (7.7°C air temperature and 28 $k \cdot h^{-1}$ wind). The low cooling rate reported for the aviation coverall ensemble leading to an unrealistically high extrapolated ST (9.3 h) is reportedly a consequence of a relatively high metabolic rate caused by the cold stress (21); this circumstance was encountered previously with the dry suit listed in Table I and is examined in the Discussion section. The lower model-predicted ST (4.1 h) was attained by assuming the same wetness factor as fitted for the float coat suit.

RESULTS

Several examples will be given to illustrate the predictive range of the model. Of course, the reliability of the model predictions is reduced as conditions deviate from the domain of the referenced studies used to calibrate the model. Examples will include differences in ST between lean and fat individuals, a "worst" case scenario where the shivering capacity is absent, and partial immersion conditions. It is implicitly assumed that I_{cl} and the wetness factors do not change with body size. For purposes of illustration, the following mean anthropometric characteristics are used (5): height = 1.77 m; weight = 66.3, 73.9, and 88.2 kg; and body fat = 11.2, 17.7, and 28.6% for lean, average, and fat individuals, respectively. The example clothing ensemble is the boatcrew coverall + cotton underwear + cotton uniform (Tables I and II). Hereafter, the clothing ensembles will be understood to include the undergarments as listed in the Tables.

Fig. 3 shows the predicted ST for lean to fat individuals (a) immersed in rough seas and (b) air-exposed under moderately wet conditions (1550 $g \cdot m^{-2}$ representing 50% loss of clothing insulation). The marked increase in ST for fatter individuals (by more than a factor of 2) is attributed to the additional insulation of the individual's thicker subcutaneous tissue layer. This difference is consistent with the predicted cooling times of the Wissler model (18) and it may partly explain the relatively wide range of reported survival times in accidental immersions (15,28).

Fig. 4 shows the predicted ST for an average individual under the same conditions as presented in Fig. 3, but extended over the entire range of clothing ensembles outlined in Tables I and II. These ensembles are grouped according to their degree of protection (low, medium, and high) as ascertained by the predicted ST. The spread in ST values can be expected to widen, and in some instances overlap, if lean to fat individuals are considered.

Loss of shivering capacity through fatigue or injury can severely reduce ST. This is especially evident where shivering is critical for defence against heat loss. Without shivering, the individual's resting metabolism may be insufficient to prevent rapid body cooling. Predicting changes in an individual's shivering capacity due to fatigue or injury is beyond the scope of this investigation; however, for purposes of model demonstration, the "worst" case will assume no shivering capacity. **Fig. 5** compares the predicted ST for an individual immersed in a calm sea condition with and without shivering. Not surprisingly, the predicted ST for a shivering individual is markedly higher than for an individual incapable of shivering.

The original model was configured to represent the torso of the body (26). Partial immersion in the present version is simulated with two cylinders, the upper assigned to air exposure and the lower to water immersion (see model development under "Deep Body Temperature" section). Immersion at or below the thigh level can be approximated by adjusting f_{im} (fraction of overall body immersed in water). To arrive at reasonable predictions, the values of 0.6 and 0.2 are arbitrarily used to simulate mid-chest and thigh level immersions. **Fig. 6** shows the predicted ST for an individual immersed at these levels for a fixed wet/cold air exposure condition (5°C, 20 $km \cdot h^{-1}$, 50% loss of clothing insulation due to

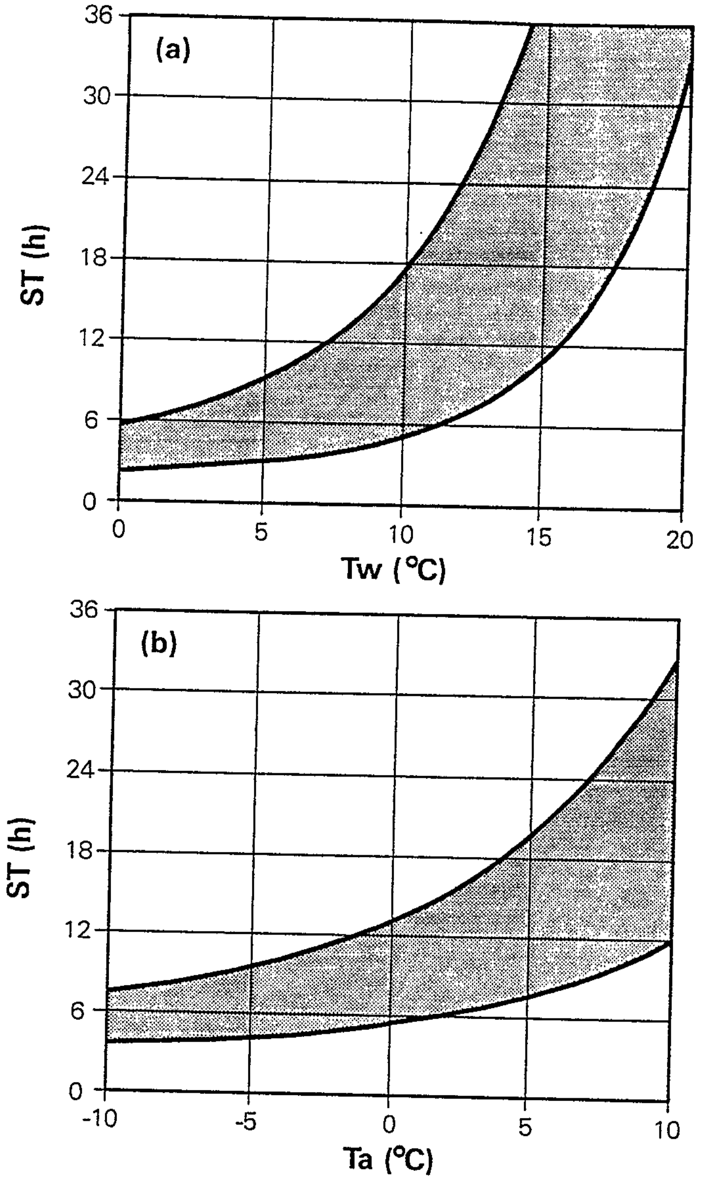

Fig. 3. Model prediction of survival time for individuals wearing the boatcrew ensemble (Tables I and II) for (a) immersion in rough seas vs. water temperature and (b) exposure to air at 20 km·h^{-1} under wet conditions (clothing wetness of 1550 g·m^{-2}) vs. air temperature. The lower and upper boundaries of the shaded regions represent predictions for lean and fat individuals, respectively.

wetness). Note the higher predicted ST values for mid-chest vs. thigh level immersion for water temperatures exceeding 10°C. The lower values for thigh level immersion are attributed to a higher cold stress from a wet-clothed condition under the influence of a moderate wind at 5°C.

DISCUSSION

Model predictions of ST are extrapolative by the fact that the underlying physiological basis is largely derived from experimental conditions involving mild hypothermia (where deep body temperature rarely drops below 35°C). Calibration of the present model relied on the extrapolation of reported rates of deep body cooling (20,21). This coupling is supported by the concurrence between the model prediction (Fig. 1) and the observations of Hayward et al. (11) and Steinman and Hayward (22) on the linear relationship between body cooling rates and water temperature. This coupling does not necessarily validate the extrapolation to a deep body temperature of 30°C, but it does represent a consistent approach to predicting ST. Validation will ultimately rest upon well-documented case histories which are too few at present.

The approach adopted for partial immersion conditions involved a complex combination of deep core temperatures from each model cylinder (through Eqs. 4 to

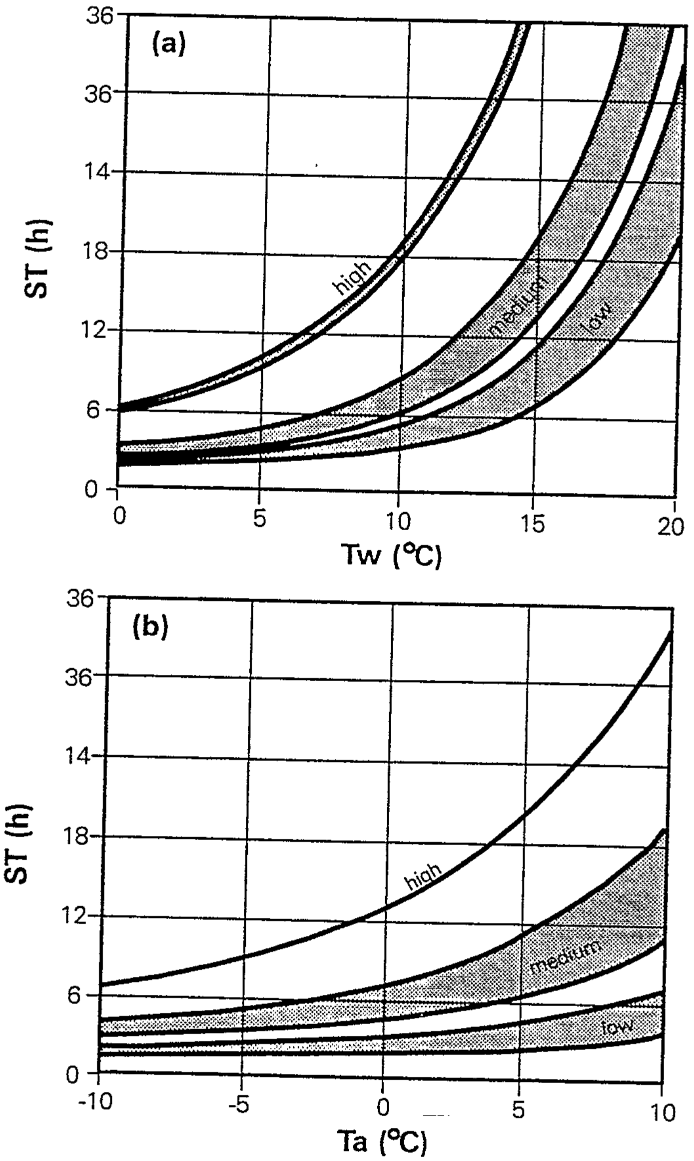

Fig. 4. Model prediction of survival time for an average individual under various degrees of clothing protection. For (a) immersion in rough seas vs. water temperature, low = {nude, flight suit, float coat, aviation coverall, boatcrew coverall, torn coverall}, medium = {short wetsuit, full wetsuit}, and high = {dry coverall, dry suit} (see Table I for undergarment additions). For (b) exposure to air at 20 km·h^{-1} under wet conditions vs. air temperature, low = {nude, flight suit, aviation coverall}, medium = {float coat, boatcrew coverall, short wetsuit, full wetsuit, dry coverall, torn coverall}, and high = {dry suit} (see Table II for undergarment additions and wetness values).

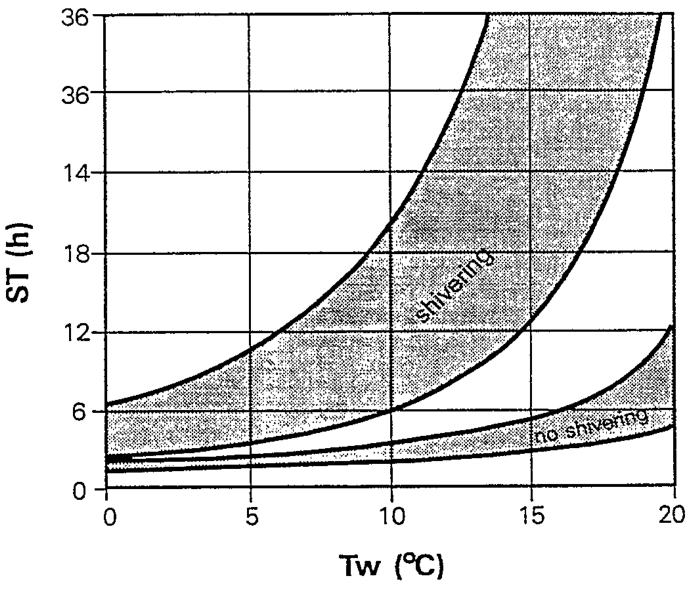

Fig. 5. Model prediction of survival time vs. water temperature for individuals wearing the boatcrew ensemble (Table I) for immersion in calm seas. The upper and lower shaded regions represent predictions for shivering and no shivering conditions, and their lower and upper boundaries represent lean and fat individuals, respectively.

11). A much simpler alternative is to take a weighted average of the ST predicted for each cylinder. Consider, for example, the wet/cold condition used for Fig. 6 (boatcrew coverall) but at fixed air and water temperatures of 5°C. Model-predicted STs are 10.2 and 4.8 h for non-immersion and full immersion, respectively. Simple weighted averages of these values yield STs of 7.0 and 9.1 h for mid-chest ($f_{im} = 0.6$) and thigh level ($f_{im} = 0.2$) immersions. However, these values are higher than the respective partial immersion model predictions of 6.3 and 8.6 h. Other examples have consistently demonstrated an overprediction using the simple weighted average approach.

For some of the calibration data, a higher ST was reported with increased cold stress. This occurred for the dry suit where STs of 15.0 and 18.3 h were extrapolated from measured body cooling rates for immersions in calm and rough seas at essentially the same temperature, 10.7 and 11.1°C, respectively (Table I). It also occurred for the non-immersed wet condition where the data-extrapolated ST of 9.3 h for the aviation coverall appears unrealistically high when compared to the STs of other more insulative ensembles (Table II). The authors (21) attributed the increased ST to a relatively higher metabolic rate due to an increased cold stress. Indeed, a higher heat production will lessen the rate of deep body cooling; however, it can be argued that this is a temporary condition since increased metabolic activity will also hasten fatigue (18,26). When the capacity to shiver is compromised, ST diminishes accordingly (acutely demonstrated in Fig. 5). This aspect is not represented by the observed cooling rates, and therefore, readjustment of the affected Icl values was necessary to retain consistency with the cooling rates reported for the other clothing ensembles.

Of course, this adjustment raises an uncertainty regarding the extrapolation of all the measured deep body cooling rates since precise information on metabolic activity is unknown. Steinman and Kubilis (20) reported that the 95% confidence interval of estimated STs varied approximately by a factor of three. Consequently, the model-predicted values (calibrated against the mean observed deep body cooling rates) must be gauged accordingly.

It is instructive to compare the present model predictions with other approaches. Models developed by Hall (9) and Timbal et al. (23) have been previously examined and found to predict unrealistic STs due to fixed metabolic constraints (26). Although not explicitly stated, the present model is capable of predicting the temporal evolution of body temperatures. Therefore, a comparison of predicted times to a deep core temperature of 34°C can

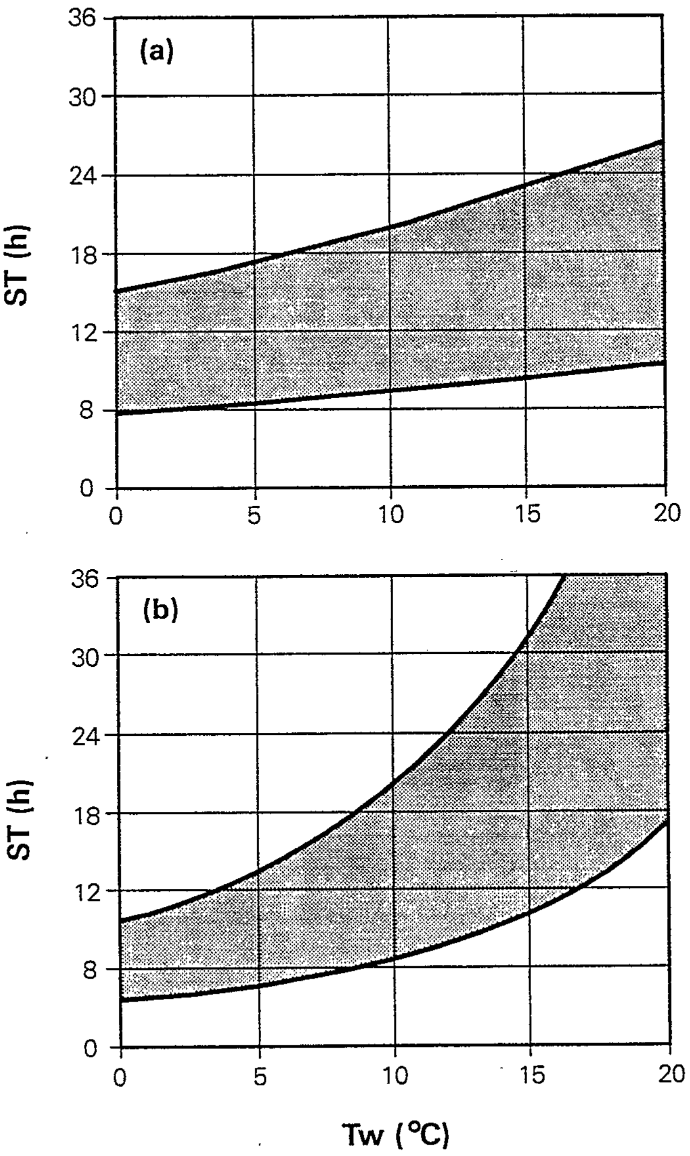

Fig. 6. Model prediction of survival time vs. water temperature for individuals wearing the boatcrew ensemble (Tables I and II) for partial immersion in calm seas and air-exposure under continuous wet/cold conditions (5°C, 20 km·h^{-1}, and 1550 g·m^{-2} clothing wetness). (a) and (b) represent predictions for thigh and mid-chest level immersions, respectively, and the lower and upper boundaries of the shaded regions represent lean and fat individuals.

be made with the Wissler model (17). Predicted times will be given for three levels of immersion insulation {0.06, 0.33, 0.70 clo}. For the 10th percentile individual [66.7 kg, 1.69 m, 6.7 mm skinfold, 23.3 yr old reported by Nunneley et al. (17)] immersed in 5°C water, the present and Wissler model predictions are {1.0, 3.4, 12.3 h} and {0.5, 1.5, 10.6 h}, respectively. For the 90th percentile individual [91.5 kg, 1.85 m, 21.7 mm skinfold, 39.0 yr old (17)], the respective predictions are {2.4, 6.1, 18.1 h} and {3.4, 6.5, > 14 h}. In general, the present vs. Wissler model predictions are higher for the lean individual and lower for the fat individual, but there is a general convergence as the level of insulation increases. Similar differences would also be found between the Wissler model predictions and the observed deep body cooling rates (20,21) used in the calibration of the present model.

Model predictions may be better appreciated in relative terms. For example, the benefit of increased fatness is seen to more than double the ST when compared to the predicted values of lean individuals (Fig. 3, 5, and 6). Another individual trait of interest is stature. Consider the effect of changing only the height of the otherwise average individual by 10% so that the body surface area changes from 1.90 to 1.76 and 2.04 m^2 corresponding to heights of 1.59 and 1.95 m, respectively (7). For immersion in calm water at 10°C with the boatcrew coverall ensemble (Table I), the respective predicted STs are 10.9 and 7.3 h. Consequently, tall vs. short individuals have a lower predicted ST explained by the fact that net heat loss increases as the ratio of body surface area to volume increases.

The prediction of ST entails considerable extrapolation due to the uncertainty and limitations of information regarding severe hypothermia. Greater certainty can be ascribed to conditions that approximate the experimental ones used in the calibration of the model; however, STs obtained from the measured deep body cooling rates are also extrapolative. Further, the metabolic activity under the experimental conditions is not known and this has lead to some ambiguity regarding the cooling rates for various degrees of cold stress. At present, the model predictions are contingent on the validity of the extrapolation of cooling rates from mild/moderate cold stress conditions which represent the vast majority of the measured values. Until our knowledge of shivering endurance and human thermoregulatory response over a wide hypothermic range is improved, predictions of ST will continue to rely on extrapolative techniques. Under this caveat, the model described herein can nevertheless be applied as an auxiliary decision aid when survival time estimates are required.

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