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HUMAN THERMOREGULATORY MODEL FOR WHOLE BODY IMMERSION IN WATER AT 20 AND 28°C

U S ARMY RESEARCH INSTITUTE
OF
ENVIRONMENTAL MEDICINE
Natick, Massachusetts

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MEDICAL RESEARCH & DEVELOPMENT COMMAND

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ABSTRACT

The mathematical models of thermoregulation of Stolwijk and Hardy and Montgomery were used to develop a model suitable for the simulation of human physiological responses to cold-water immersion. Data were obtained from experiments where thirteen healthy male volunteers were totally immersed under resting and nude conditions for 1 h in water temperatures of 20 and 28°C. Mean measured rectal temperature (T_{re}) fell by about 0.9 and 0.5°C in 20 and 28°C water for all subjects, yet mean measured metabolic rate (M) rose by about 275 and 90 W for the low body fat group (n=7) and 195 and 45 W for the moderate body fat group (n=6). To predict the observed T_{re} and M values, the present model a) included thermal inputs for shivering from the skin independent of their inclusion with the central temperature to account for the observed initial rapid rise in M, b) determined a thermally neutral body temperature profile such that the measured and predicted initial values of T_{re} and M were matched, c) confined the initial shivering to the trunk region to avoid an overly large predicted initial rate of rectal cooling, and d) calculated the steady-state convective heat loss by assuming a zero heat storage in the skin compartment to circumvent the acute sensitivity to the small skin-water temperature difference when using conventional methods. The last three modifications are unique to thermoregulatory modelling. A BASIC computer listing of the model and a sample simulation are provided.

INTRODUCTION

Nude immersion in water colder than the deep body body temperature represents an acute exposure to cold since convective heat loss is many times greater than in air. Temperature gradients become large and physiological responses are dramatic. These factors contribute to the complexity of mathematically modelling the human thermoregulatory response. Since the inception of mathematical models of human thermoregulation (see reviews by Hardy (15) and Hwang and Konz (18)), data to test these models for cold-water immersion have been available yet have been only recently applied. Mathematical models of thermoregulation can be steady-state or dynamic. Steady-state models apply where a heat balance exists, and therefore, are limited to the prediction of physiological responses that do not change with time. Most studies of cold-water immersion are, however, concerned with the transient responses upon immersion. Dynamic models can be applied to predict these responses.

Dynamic models of thermoregulation use physical representations of the human body, principles of heat conduction, and control theory to simulate physiological responses to a change in the environment. Such models provide a useful theoretical device to evaluate and interpret experimental data, and potentially can be applied to a wide range of subject classifications and environmental conditions. The dynamic models assessed by Hardy in 1972 (15) were found inadequate for predicting human responses to cold environments. Among these was the Stolwijk-Hardy model (25) originally developed to predict the physiological responses of nude man in an air environment. In 1976, Gordon et al. (13) extended the concepts of Stolwijk and Hardy (25) and Wissler (29) to model the physiological responses to a transient cold air exposure. In 1989, Wissler (30) evaluated this model's predictive capability for cold-water immersion and found it unsuitable. Other models that Wissler evaluated included

his own and Stolwijk-Hardy, yet, the agreement between measured and predicted values of temperature, metabolic rate, and net sensible heat loss was found to be less than satisfactory. Although a more recent application of the Wissler model to other cold water immersion studies has provided improved predictions (3 ;, a difficulty with this model is its inability to match measured and predicted initial core temperatures and metabolic rates. Strong and Goldman (28) developed a linearized model for predicting skin and rectal temperatures specitically for cold water immersion. However, their model did not include conductive heat exchange between tissue and blood which is known to critically affect the heat storage of the body, nor did they model for a muscle compartment where shivering activity increases the body's metabolic rate (the model requires the experimentally determined metabolic rate as an input).

An alternative model is a version of the Stolwijk-Hardy model developed by Montgomery (21) also for cold water immersion, but not tested by Wissler (30). In our study using data of resting nude subjects totally immersed in cold water, we found the Montgomery model not wholly satisfactory for predicting transient changes in rectal temperature and metabolic rate, yet with certain modifications of the model, good agreement was obtained. These modifications include adding a shivering component responsive to skin temperature only, matching the measured and predicted initial core temperatures and metabolic rates, confining the initial shivering to the trunk region, and determining the steady-state convective heat loss to the water through use of the heat storage equation. Various forms of the first modification have appeared elsewhere in other models whereas the last three modifications are unique to thermoregulatory modelling and may be generally applicable.

This report describes these modifications and presents a comparison between the measured and predicted thermoregulatory responses for whole body

immersion in cold water. Data from experiments of nude whole body immersion were used since skin temperatures quickly reach steady-state values and the heat losses to the water are limited to convective heat transfer which, as will be seen, can easily be determined once a steady-state skin temperature is reached. A BASIC computer listing of the model and a sample simulation are given in APPENDIX 3.

METHODS

Data

Data presently used were available from a series of whole body water immersion studies (5,12). Thirteen healthy male volunteers were totally immersed under resting and nude conditions for 1 h in water temperatures of 20 and 28°C. Since a subject's thermal and metabolic response depends largely on his body composition (8,17,19,20,24,28), this study classified the subjects into two groups, those of low body fat (LBF) and those of moderate body fat (MBF).

Mean (± SD) anthropometric values of the LBF group (n=7) were: height = 174.9 (4.5) cm, weight = 69.0 (7.5) kg, skinfold = 5.83 (0.75) mm, body fat = 9.67 (1.57)%, and surface area = 1.83 (0.11) m^2. Values for the MBF group (n=6) were: height = 175.7 (6.4) cm, weight = 79.2 (13.1) kg, skinfold = 11.82 (4.26) mm, body fat = 17.62 (4.11)%, and surface area = 1.94 (0.17) m^2.

Model

The model used in the present study is based largely on the Montgomery version (21) of the Stolwijk-Hardy model (25). The human body is treated as a passive heat transfer system and is divided into six distinct segments, the head modelled as a sphere and the trunk, arms, hands, legs, and feet modelled as cylinders. The model is shown schematically in Fig. 1. Heat flows radially in the model segments and heat transfer between segments is through conduction via

the central blood. Each segment is composed of four concentric annular compartments, the core, muscle, fat, and skin, as proposed by Stolwijk and Hardy (25). In addition, the central blood is a single compartment located within the trunk segment. The Montgomery version of expanding the number of core and muscle compartments by four each is not used. Instead, the relative weight distribution, thermal-capacitance values, basal metabolic rates, and basal blood-flow rates of all compartments proposed by Montgomery are used. The reader is referred to Ref. 21 for these values.

The thermoregulatory controlling system integrates the thermoreceptor output signals of certain compartments and determines the response through efferent commands. For example, cold signals may induce shivering. The thermoreceptor output signal of each compartment is determined by the difference between the compartment's current temperature and its set-point value. Set-point values are established before immersion and remain constant throughout the immersion. The efferent commands involve sweating, vasomotor response, and shivering. Unless otherwise indicated, the thermoreceptor and efferent output simulations follow the method of Montgomery (21).

Thermal conductances between compartments were determined according to the method outlined by Stolwijk and Hardy (25). Thermal resistances for spherical and cylindrical geometries were obtained from Sekins and Emery (23). Thermal conductivity values for the core and muscle compartments were taken from Stolwijk (26), and those for the fat and skin compartments were taken from Sekins and Emery (23).

Since the subjects were totally immersed in water, both radiative and evaporative heat transfer from the body were considered negligible. Total respiratory heat loss was determined by the combined respired evaporative and respired convective heat losses of the trunk core (11) and by the basal

respiratory heat loss of head core (26). The subjects breathed through a snorkel and therefore the respiratory heat loss was determined by assuming that the air breathed was fully saturated and at a temperature equal to the water temperature.

Initial and Set-Point Temperatures

Initial conditions assume thermal neutrality. By simulating an exposure to an arbitrary environment in the zone of thermal neutrality, the original Stolwijk-Hardy model will generate steady-state temperatures for all compartments including the central blood (26,27). The resultant initial temperatures are thus assigned as the set-point temperatures for thermoregulation. One drawback with this method is that the model's temperature profile, which is based on "standard" man, does not necessarily match the subject's profile in his pre-immersion state, and therefore, thermoregulation may be arbitrarily imposed. Furthermore, initial offsets between measured and predicted core temperatures may affect the level of agreement during the subsequent immersion phase.

Ideally, the initial temperature profile of the model should match the subject's. At present, it is not possible to measure the subject's temperature profile, so certain assumptions must be made. First, in accordance with Stolwijk (26), it was assumed that the subject was thermally neutral in his pre-immersion state (this is reasonable considering that the subjects in our study were resting in an air environment within the zone of thermal neutrality before immersion). Second, it was assumed that the subject's measured pre-immersion metabolic rate represented his basal value (BMR) and that the model's trunk core temperature represented his rectal temperature (T_{re}).

A thermal neutral temperature profile can thus be determined for any subject by setting the heat storage of each model compartment equal to zero and solving the resulting linear equations using matrix methods. By specifying values

of the trunk core (rectal) and central blood temperatures, an iterative solution is sought such that the heat storage of the central blood is also zero. The temperature distribution obtained for "standard" man by this procedure agrees exactly to that obtained using the convention procedure, but for conditions other than "standard", this procedure has the advantage of matching model and subject values of T_{re} and BMR. The predicted neutral temperature profile obtained using this procedure for the MBF group is shown in Fig. 2.

Convective Heat Loss

A major theoretical obstacle for any thermoregulatory model is the determination of convective heat loss, especially in water immersion where heat transfer is many times greater than in air (4,24). Heat transfer is sensitive to the skin-water temperature difference, especially as the skin temperature (T_{sk}) nears the temperature of the water. Because of this sensitivity, small changes in T_{sk} can cause large changes in the predicted convective heat transfer (C), as demonstrated in the DISCUSSION. These large changes in C critically affect the heat storage of the skin compartment (S_{sk}), and consequently the heat loss of the body. This problem is exacerbated by the assumptions of body shape and water motion that determine the heat transfer coefficient (see APPENDIX A).

It has been shown experimentally that the mean weighted skin temperature ($\bar{T}_{sk}$) of nude subjects falls exponentially during immersion in cold water (28), and that the asymptotic limit is a temperature slightly higher than the water temperature, although the skin-water temperature difference increases with lowered water temperature (20,22,28). These experimental observations can be coupled with the theoretical determination of the convective heat transfer coefficient to arrive at a model prediction of convective heat loss that avoids the uncertainties discussed above.

First, the rate of change of skin temperature ($\dot{T}_{sk}$) must equal S_{sk}/C_{sk} where C_{sk} is the heat capacity of the skin. Second, $\dot{T}_{sk}$ should be proportional to the difference between the skin compartment's steady-state temperature ($T_{sk_{ss}}$) and its current temperature to approximate the exponential fall in T_{sk} and to allow T_{sk} to approach $T_{sk_{ss}}$ asymptotically. Through numerical integration, the incremental change in T_{sk} can thus be approximated by:

$$\Delta T_{sk} = (T_{sk_{ss}} - T_{sk_o}) \{1 - \exp (-S_{sk} \cdot \Delta t / C_{sk} (T_{sk_{ss}} - T_{sk_o}))\}, \quad (1)$$

where T_{sk_o} is the skin temperature before the incremental change and Δt is the time increment chosen sufficiently small so that the above constraints are satisfied.

In the present study, $T_{sk_{ss}}$ was assigned the experimentally measured value, yet an arbitrary value close to the temperature of the water could have been assigned without incurring a large error in determining the convective heat loss (see DISCUSSION). The heat storage of the skin was determined through a thermal balance of the skin compartment:

$$S_{sk} = M_{sk} - C - K_{skbl} + K_{fsk}, \quad (2)$$

where M_{sk} is the metabolic rate of the skin, K_{skbl} is the conductive heat transfer rate from the skin to the blood, and K_{fsk} is the conductive heat transfer rate from the fat to the skin. The convective heat transfer was determined through fluid dynamic considerations (see Eq. 6 and APPENDIX A). This calculation was carried out by assuming a water velocity of 0.005 m/s which represents the motion produced in "still" water by respiration and mild shivering (32). Although shivering intensity can be expected to increase with increased immersion time, a steady-state skin temperature was attained well before the water motion was seriously underestimated.

Once the skin temperature was close to its assigned steady-state value (assumed by the model when the difference between T_{sk} and $T_{sk_{ss}}$ was less than

0.00°C), no further change in skin temperature occurred. The convective heat transfer from skin to water was then determined assuming zero heat storage of the skin compartment (i.e. setting $S_{sk} = 0$ in Eq. 2).

Efferent Shivering Command

Central to any thermoregulatory model for cold exposure is the efferent command for shivering. Montgomery (21) specified the shivering command as a product of a control coefficient, a central (head core) thermoreceptor output signal and the appropriate skin (peripheral) thermoreceptor output signal. As will be seen, such an expression is incapable of predicting the initial rapid rise in metabolic rate that has been repeatedly observed for cold-water immersion (1,10,16). There is sufficient evidence to support the view that to some extent, shivering is independently controlled by skin thermoreceptors (1,3,6,8,14,28). In fact, the original Stolwijk-Hardy model allowed for this. Since the initial rapid increase in metabolic rate correlates well with the observed initial rapid decrease in skin temperature, the controller equation for shivering in the present model included a shivering component responsive to skin temperature only.

An increase in the metabolic rate due to shivering entails a corresponding increase in muscular blood flow which can indirectly affect the core temperature. If the arm and leg muscle temperatures are lower than that of the central blood as indicated in Fig 2, then any sudden increase in blood flow to these muscles will lower the central blood temperature. Given that the observed metabolic rate initially rises rapidly, a model prediction of a corresponding increased blood flow to the limb muscles would indirectly cause an initial fall in trunk core temperature (through conductive heat exchange with the central blood) much more rapidly than observed. To avoid this, the present model confined initial shivering to the trunk (since its temperature was close to that of the central blood) and delayed the onset of shivering of the limb muscles exponentially.

Counter-Current Heat Exchange

To conserve body heat, counter-current heat exchange of the limbs (i.e. arms, hands, legs, and feet) may occur. A simple yet effective means of modelling this is to assume an effective temperature of the blood in the limb which is used to determine the conductive heat exchange in that compartment temperature (in which case the counter-current heat exchange is 100% effective). The expression used to determine this value is

$$TBL(i) = T(i) + (T_{bl} - T(i)) \cdot \exp(-\lambda \cdot COLDS) \quad (3)$$

where TBL(i) is the effective blood temperature in the ith compartment, T(i) is the compartment temperature, T_{bl} is the central blood temperature, λ is a proportional control coefficient, and COLDS is the weighted skin thermoreceptor output signal. The dependence on COLDS allows for an increase in the counter-current heat exchange with increasing severity of exposure.

Simulation Procedure

The anthropometric characteristics of the model subject assumed the average values for the group it was simulating. The neutral (and set-point) temperature profile was determined separately for each body fat group and exposure based on the group's mean measured pre-immersion T_{re} and M. Values of air temperature ($T_{air\text{-}neutral}$) and central blood temperature determined for a condition of thermal neutrality are listed in Table 1. During the immersion, the compartments' heat storage were determined using the finite difference procedure outlined by Stolwijk (26). The incremental change in temperature of any compartment could not exceed 0.1°C.

RESULTS

Figures 3 to 6 illustrate the measured (±SE) and predicted values of the rectal (modelled as the trunk core) temperature and metabolic rate. To obtain

these predicted values, the following controller expression for shivering was used:

$$CHILL = A_D*(5\cdot COLD(1)\cdot COLDS + 65\cdot(COLDS/PBF)^{1.5}), \quad (4)$$

where CHILL is the metabolic response (W) to the cold stress, A_D is the subject's surface area (m^2), COLD(1) is the head core thermoreceptor output (equal to the difference between the current temperature of the head core and its set-point value only when the head core temperature is less than its set-point value, otherwise the output value is zero), and PBF is the subject's percent body fat. For the MBF group immersed in 28°C water, a value of 2 instead of 5 was used for the proportional control coefficient of the first term. In all cases, the value of λ was zero indicating that it was not necessary to use the counter-current heat exchange mechanism, although it remains in the model as an option. In the Montgomery model (21), only the first term of Eq. 4 is present, and the product of A_D times the control coefficient was assigned a value of 24.4 W (21 kcal/h).

To avoid the excessive initial decrease in trunk core temperature discussed earlier, initial shivering was confined to the trunk and a portion of this shivering was shifted to the arm and leg muscles exponentially according to:

$$\begin{aligned} CHILM\ (trunk) &= 0.85 + 0.12 \exp(-0.5\cdot t/PBF) \\ CHILM\ (arm) &= 0.05\ (1-\exp(-0.5\cdot t/PBF)) \\ CHILM\ (leg) &= 0.07\ (1-\exp(-0.5\cdot t/PBF)), \end{aligned} \quad (5)$$

where CHILM is the weighing factor of the corresponding muscle's contribution to the overall shivering, t is the elapsed time (min) since immersion, and the control coefficients 0.85, 0.05 and 0.07 were taken from Stolwijk and Hardy (27). Note that as t increases, the CHILM factors revert to the values given by Stolwijk and Hardy (27) which were also used by Montgomery (21). The attenuation by the group's PBF of both the shivering command in Eq. 4 and the exponent in Eq. 5 was a necessary modelling construct to obtain the results

shown in Figs 3 to 6. Also shown in these figures are the predicted values using the present model but without the independent shivering command from the skin and without the delayed onset of shivering of the limb muscles.

The predicted temperature profile for the MBF group after 1 h of immersion in 20°C water is illustrated in Fig. 2. Every compartment except the trunk muscle shows a decrease in temperature; the increase in temperature in the trunk muscle is slight, from 37.10 to 37.33°C. Decreases in temperature in the other compartments range from small changes in the core and muscle of active compartments to large changes in the inactive compartments and the fat and skin compartments of all segments. Figure 2 is representative of the model prediction (in a qualitative sense) of the LBF group and for immersion in 28°C water of both groups.

Figure 7 shows the model prediction of mean body temperature ($\bar{T}_b$), trunk core temperature, mean skin temperature, metabolic rate, and convective heat loss for the MBF group immersed in 20°C water. The mean body temperature was determined by weighting each compartment's temperature according to its heat capacity (26). The mean skin temperature ($\bar{T}_{sk}$) was similarly determined from all skin compartments. The overall convective heat loss was determined by summing the convective heat loss of each segment.

DISCUSSION

Efferent Shivering Command

To obtain agreement with the measured metabolic and thermal response to cold-water immersion, an efferent shivering command based, in part, independently on the skin temperature, and a delayed onset of limb shivering was required. The possibility of an independent skin temperature effect on shivering was not excluded in the Stolwijk-Hardy and Montgomery models (although it was

not used by Montgomery (21)), and as pointed out by Cabanac (6), the debate over additive versus multiplicative combinations of thermoreceptor output signals has not been resolved. In the present model, the shivering command from the skin appears to be dependent on the skin thermoreceptor output signal raised to the power 1.5. Furthermore, this signal is attenuated by the subject's percent body fat, also raised to the same power. Differences in the shivering response to the same core and skin temperatures between low and moderate body fat groups has been previously reported for the data used in this study (28).

The independent efferent command from the skin was necessary to predict the observed initial rapid rise in metabolic rate. This is demonstrated by the dashed lines in Figs. 3 through 6 where only the first term of Eq. 4 was used and its coefficient was adjusted to correspond to the value used by Montgomery (21). One reason that the rapid initial rise in metabolic rate cannot be predicted with the shivering command based on the product COLD(1) · COLDS (see Eq. 4) alone is that the head core temperature is very slow to change initially (1,3), and therefore, despite the rapid initial change in skin temperature, the product of cold signals from the head core and skin has a depressed value in the initial stage of immersion. In fact, the central temperature may initially increase (10) in which case the product has a zero value.

An alternative shivering command could have been based on the time derivative of the skin temperature (30). Such a command would produce a transient increase in shivering intensity. Considering the rapidly falling T_{sk} upon immersion, this transient would decay well before any appreciable decrease in T_{re}. Instead, our data indicated that initial values of M peaked between 6 and 18 minutes after immersion, much longer than the few minutes it took for a steady-state skin temperature to be reached. Because of the high variability in individual responses, no attempts were made to model this behavior.

T' delayed onset of limb shivering was necessary to avoid a model prediction of a large initial decrease in trunk core temperature. Such a decrease would stem from increased blood flow from the cooler muscles of the arms and legs thereby lowering the central blood temperature which in turn would lower the trunk core temperature (27). The exponential factor governing the delayed onset (see Eq. 5) suggests that limb shivering of the LBF group began sooner than that of the MBF group. At present, direct experimental evidence to test this dependence on body fat is lacking.

Set-Point Temperatures

The thermal neutral temperature profile and hence the set-point values for thermoregulation were determined according to the pre-immersion data of the subjects and not on the expected values for the standard man as used in the Stolwijk-Hardy model (26,27). The possibility of adjustable set-point temperatures, which our method inherently assumes, has been reported previously (14). The advantage that the present method provides over the Stolwijk method is to assure that the model subject is thermally neutral at the outset of an exposure and that the measured and predicted initial values of core temperature and metabolic rate are matched. This procedure is not limited to cold water immersion and may be potentially useful for all environmental conditions.

Tissue Conductance and Heat Transfer Coefficient

An important test and useful application of the present model is its prediction of average tissue conductance, k, and the convective heat transfer coefficient, h_c. These values can be calculated from the model predictions as (4):

$$k = C/(T_{re} - \bar{T}_{sk}), \quad (6)$$

and

$$h_c = C/(\bar{T}_{sk} - T_w), \quad (7)$$

where T_{re} is represented by the trunk core temperature and T_w is the water temperature. Table 2 lists these values for both body fat groups and exposures after 1 h of immersion. Steady-state conditions can be assumed at this time (2), as demonstrated in Fig. 7. The values of average tissue conductance shown in Table 2 are in good agreement with other reported values (4,10,20,24). In fact, the predicted increase of average tissue conductance with lowered water temperature is consistent with the decreasing insulative value of increasingly active muscle (19). Such a decrease was noted by both Craig and Drovak (10) and McArdle et al. (20) where T_w was lowered from 28 to 24°C. Further support of the model stems from its prediction of higher average tissue conductance for the LBF group compared to the MBF group.

The model-predicted values of the convective heat transfer coefficient (see Table 2) are in agreement with the values reported by Witherspoon et al. (32), Nadel et al. (22), and Strong et al. (28), but are much higher than those reported by Boutelier et al. (2). The potential for such a disparity has already been noted by Boutelier et al. (2) and reasons given stem from differences in the measurement and theoretical determination of convective heat loss. It should be noted that the heat transfer coefficient is highly sensitive to the skin-water temperature difference. For instance, complete agreement between the h_c values for the 20 and 28°C exposures of either body fat group can be obtained by increasing the steady-state skin temperature by less than 0.1°C for the exposure to 28°C water.

The procedure by which the present model determined the convective heat loss to the water avoided this sensitivity once steady-state of the skin temperature was reached. Recall that the experimentally-measured values of the steady-state skin temperature were used, however, the choice of $T_{sk_{ss}}$ could have been made arbitrarily without significantly affecting the final result since

the convective heat loss during steady-state of the skin temperature is largely determined by the conductive heat transfer from the fat to the skin. This heat transfer is only slightly affected by small changes in the steady-state value of the skin temperature. For example, if $T_{sk_{ss}}$ was raised from 21.0 to 21.5°C for the MBF group immersed in 20°C water, the predicted convective heat loss to the water would change by less than 4% from 166.0 to 160.2 W/m^2. Note, however, that changing the skin temperature from 21.0 to 21.5°C would decrease the convective heat transfer coefficient (See Eq. 7) by 67% which further demonstrates the potential disparity among reported values of h_c as pointed out by Bouteiier et al. (2).

Mean Body Temperature

The present model can provide insight into the thermal response of the whole body from its prediction of the rate of change of mean body temperature. Assuming that the mean body temperature can be approximated by (9):

$$\bar{T}_b = x\,\bar{T}_{sk} + (1 - x)\,T_{re}, \tag{8}$$

where x varies depending on the environment, then the rate of change of mean body temperature ($\dot{\bar{T}}_b$) should be less than the rate of change of rectal temperature ($\dot{T}_{re}$) after the skin temperature has reached its steady-state value. Since the rectal temperature can be represented by the trunk core temperature, this prediction holds true, as can be seen from the estimated (based on the slope of temperature against time) values of $\dot{\bar{T}}_b$ and $\dot{T}_{re}$ listed in Table 4.

To check on the internal consistency of the model, the rate of change of mean body temperature can alternatively be determined through the thermal balance equation for a body totally immersed in water by (21):

$$\dot{\bar{T}}_b = (M\text{-}C\text{-}H_R)/C_b, \tag{9}$$

where H_R is the rate of total respiratory heat loss (from head and trunk core compartments) and C_b is the heat capacity of the whole body. The values of $\dot{\bar{T}}_b$

determined by Eq. 9 and shown in Table 2 are in close agreement with those estimated from the slope of temperature change with time. This confirms that the model is self-consistent with the prediction of changing body temperature during cold-water immersion.

Conclusion

Nude immersion in cold water summons dramatic physiological responses not fully considered in the early development of thermoregulatory models. To model this response mathematically requires refinement of certain mechanisms that are otherwise adequate for less acute exposures. This was the rationale for the modifications of the Stolwijk-Hardy and Montgomery models from which the present model evolved. Although these modifications were derived explicitly for cold water immersion, they may be generally applicable to other conditions.

The inclusion of an independent shivering command from the skin was optional in the Stolwijk-Hardy and Montgomery models although it was not used by Montgomery (21). Without this independent shivering command, it is not possible to predict the initial rapid increase in metabolic rate for nude immersion in cold water using only the product of signals from the head core and the skin.

The remaining modifications are unique to thermoregulatory modelling. The present method of determining a thermally neutral temperature profile allows matching of the predicted and measured initial core temperatures and metabolic rates. The delayed onset of limb shivering eases the transition of increased blood flow to the limb muscles thereby avoiding too rapid a decrease in central blood temperature. The use of the heat storage equation of the skin compartment to predict the convective heat loss during steady-state of the skin temperature circumvents the high sensitivity to the skin-water temperature difference when using conventional methods.

Table 1: Measured* and model values for thermal neutrality in air and for response to cold water immersion

T_w (°C)	20		28	
Group Classification	LBF	MBF	LBF	MBF
BMR (W/m^2)*	49.4	47.2	50.5	42.5
T_{re} (°C)*	37.48	37.48	37.32	37.52
$T_{air\text{-}neutral}$ (°C)	28.60	28.85	28.25	29.80
T_{bl} (°C)	37.26	37.25	37.10	37.32
$T_{sk_{ss}}$ (°C)*	21.0	21.0	28.4	28.4

Table 2: Model prediction after 1 h of water immersion

T_w (°C)	20		28	
Group Classification	LBF	MBF	LBF	MBF
M (W/m^2)	221.1	154.0	94.8	64.4
C (W/m^2)	214.9	166.0	99.7	82.3
H_R (W/m^2)	17.6	12.9	6.4	5.1
T_{re} (°C)	36.54	36.61	36.93	37.00
k ($W/m^2/°C$)	13.83	10.63	11.69	9.57
h_c ($W/m^2/°C$)	214.9	166.0	249.3	205.8
$\dot{T}_{re}$* (°C/h)	-0.87	-1.13	-0.36	-0.64
$\dot{T}_b$* (°C/h)	-0.36	-0.72	-0.32	-0.62
$\dot{T}_b$** (°C/h)	-0.32	-0.67	-0.32	-0.62

*slope of temperature against time

**calculated using Eq. 9.

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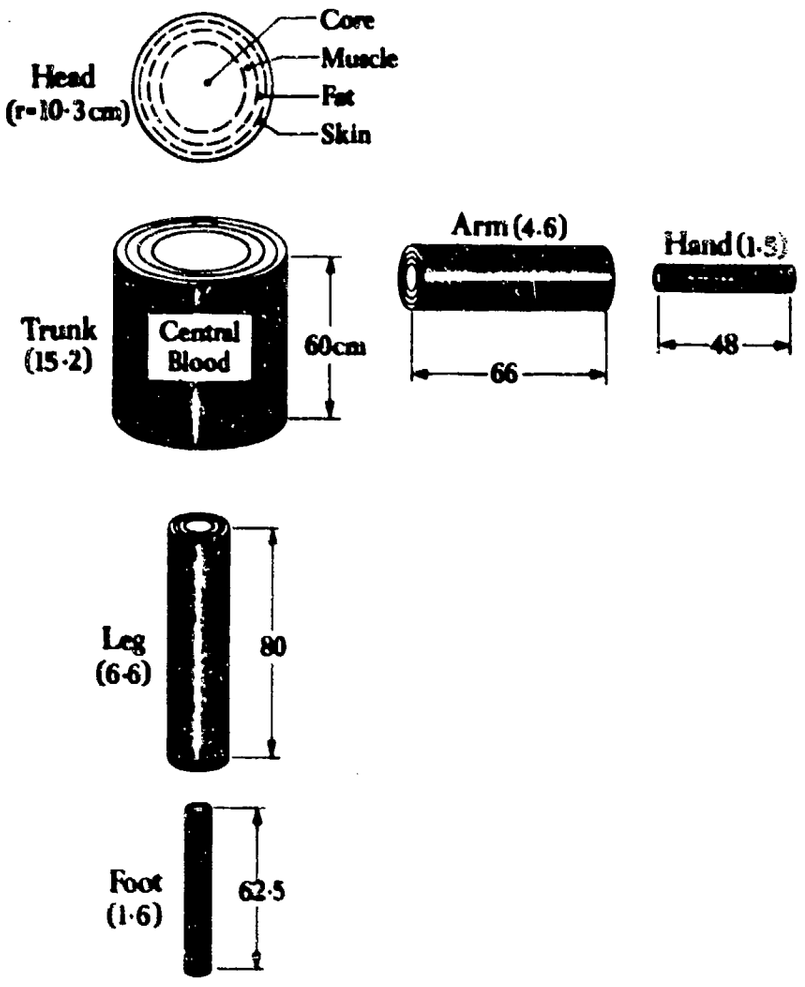

Fig. 1. Schematic (not drawn to scale) of the human body (only one side shown) used in the thermoregulatory model. Each body segment is composed of four concentric annular compartments, the head modelled as a sphere and the others as cylinders. Length of the cylinders are given in cm (26). The central blood compartment is located within the trunk segment. The numbers in parenthesis represents the outer radii (cm) of the model segments for the MRF group used in this study.

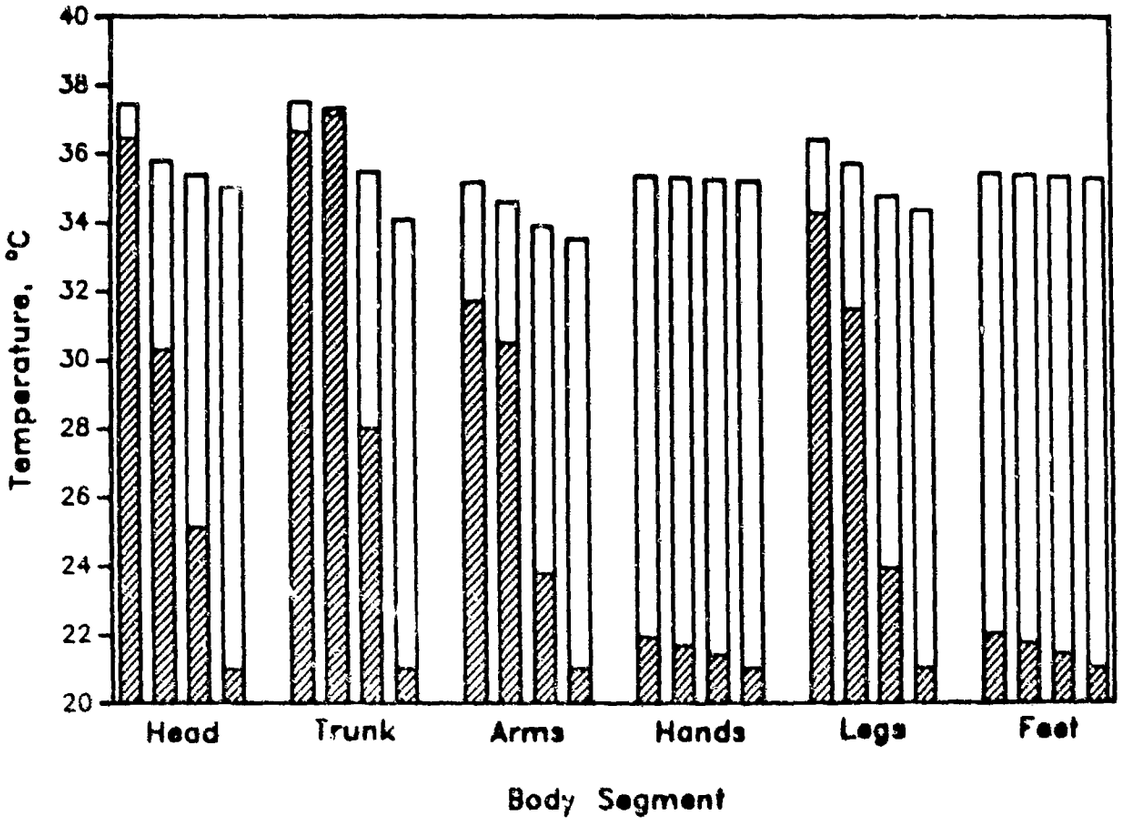

Fig. 2. Predicted temperature profiles for the MBF group in the neutral air environment prior to immersion (open bar) and after 1 h of nude whole body immersion at rest (dashed bar). Compartments for each segment are ordered core, muscle, fat, and skin from left to right. The measured mean pre-immersion rectal temperature of 37.88°C and metabolic rate of 47.2 W/m^2 were inputed as the model subject's thermally neutral trunk core temperature and basal metabolic rate. An air temperature of 28.85°C and an initial central blood temperature of 37.25°C were predicted for a condition of thermal neutrality. The final skin temperature was experimentally-determined (see text).

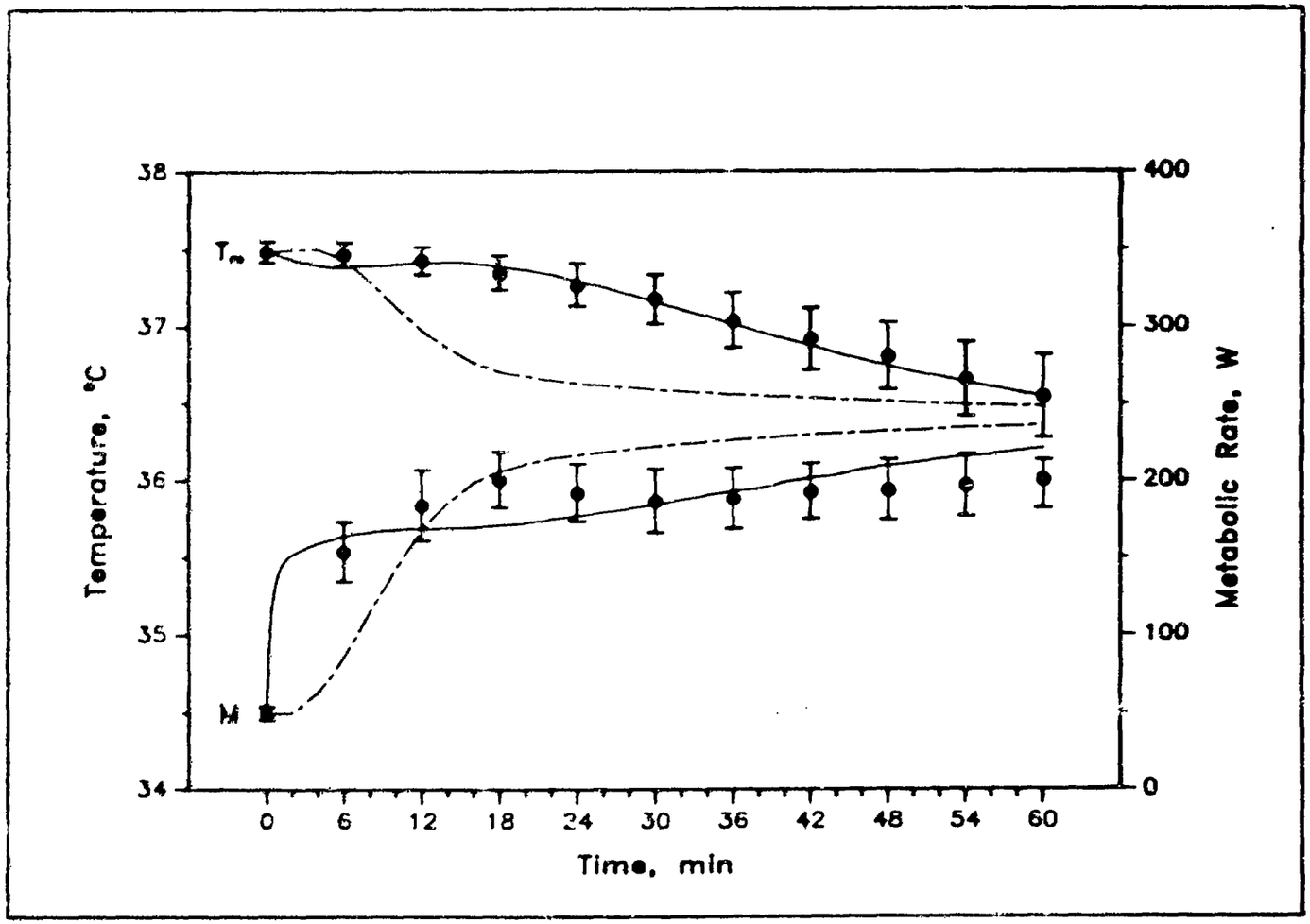

Fig. 3. Measured (•) ± SE and predicted (solid line) rectal temperature (T_{re}) and metabolic rate (M) plotted against time for the LBF group (n=7) immersed in 20°C water. The dashed line shows the prediction according to the Montgomery controller for shivering (21).

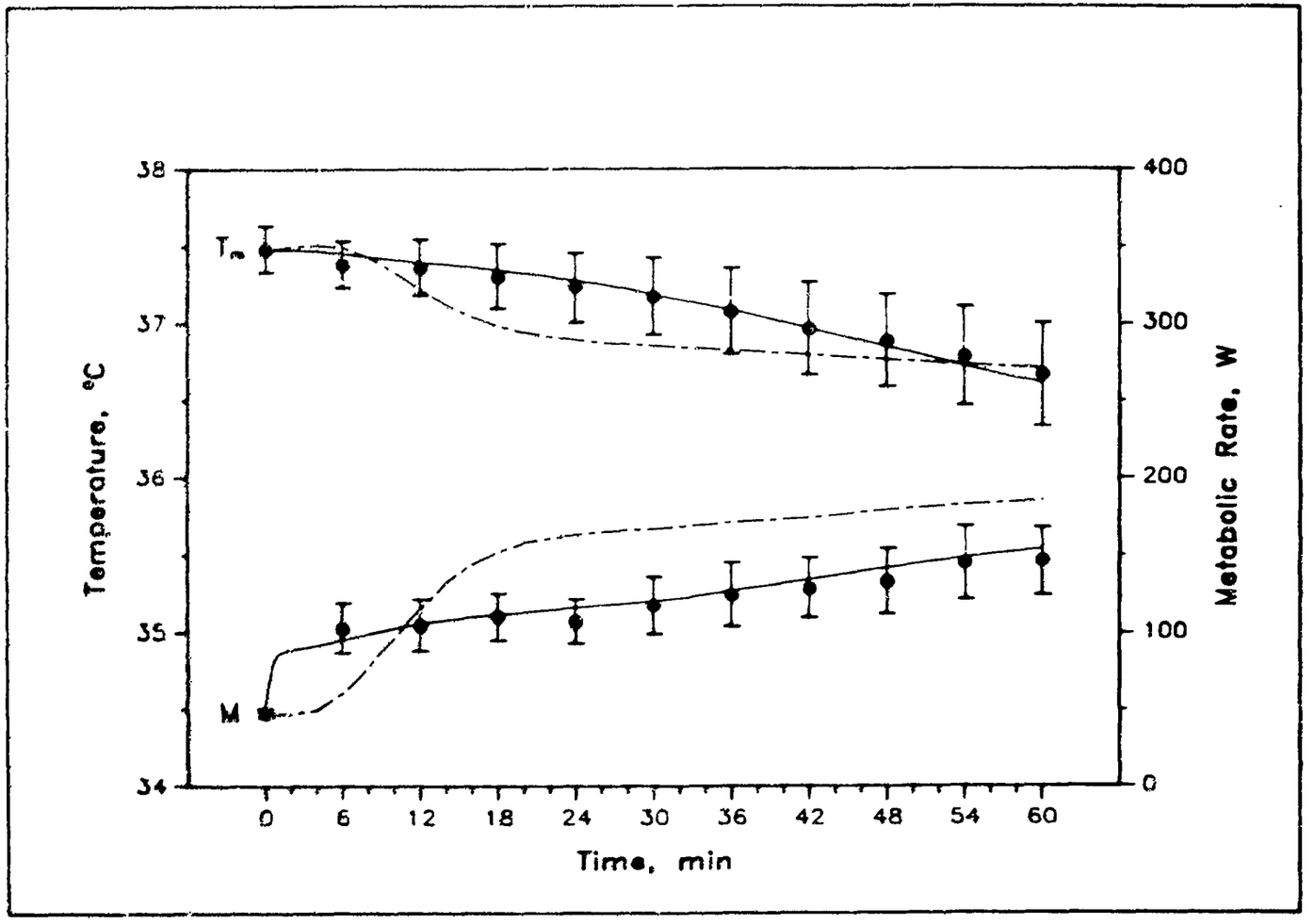

Fig. 4. Measured (•) ± SE and predicted (solid line) rectal temperature (T_{re}) and metabolic rate (M) plotted against time for the MBP group (n=6) immersed in 20° water. The dashed line shows the prediction according to the Montgomery controller for shivering (21).

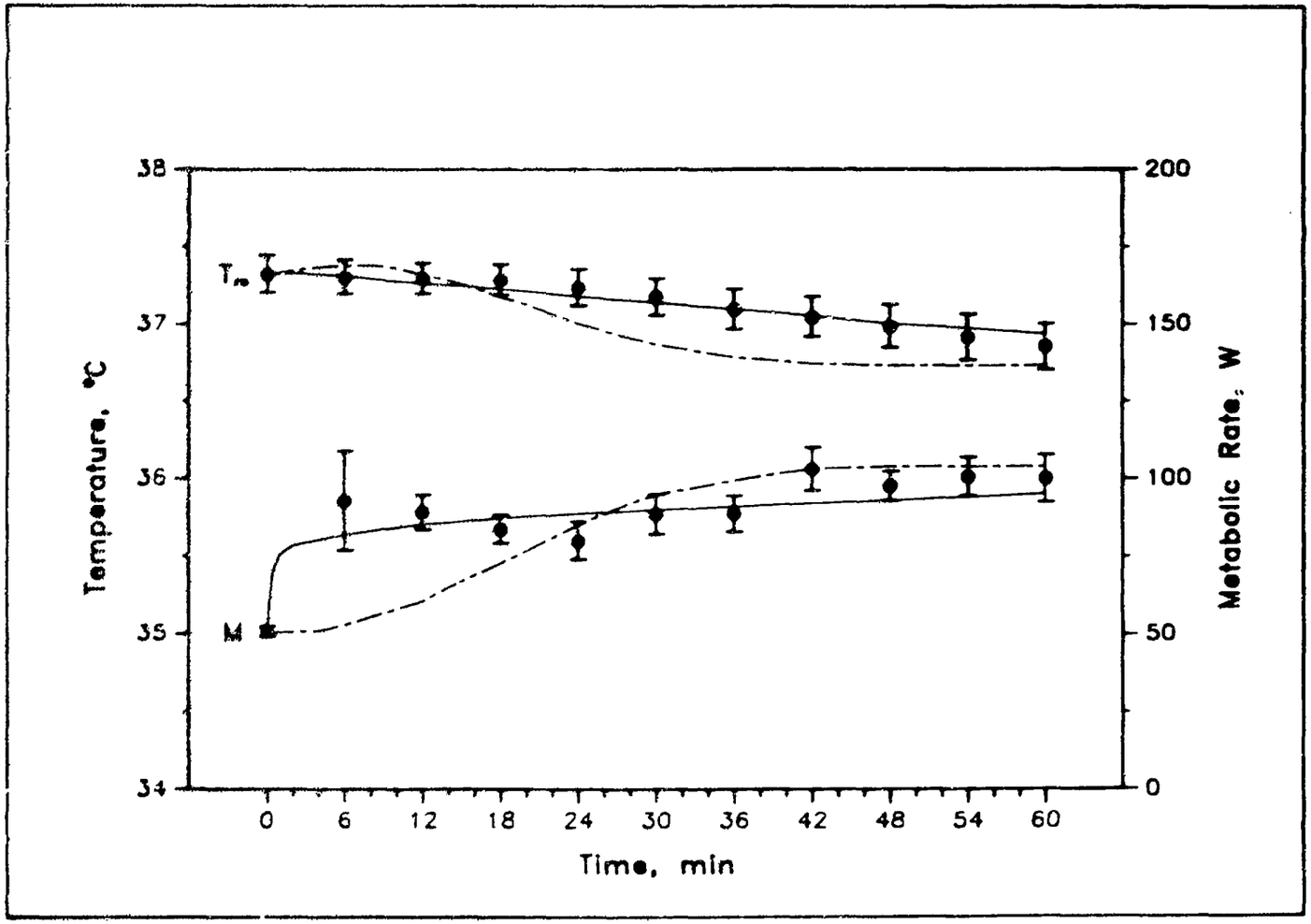

Fig. 5. Measured (•) ± SE and predicted (solid line) rectal temperature (T_{re}) and metabolic rate (M) plotted against time for the LBF group (n=7) immersed in 28°C water. The dashed line shows the prediction according to the Montgomery controller for shivering (21).

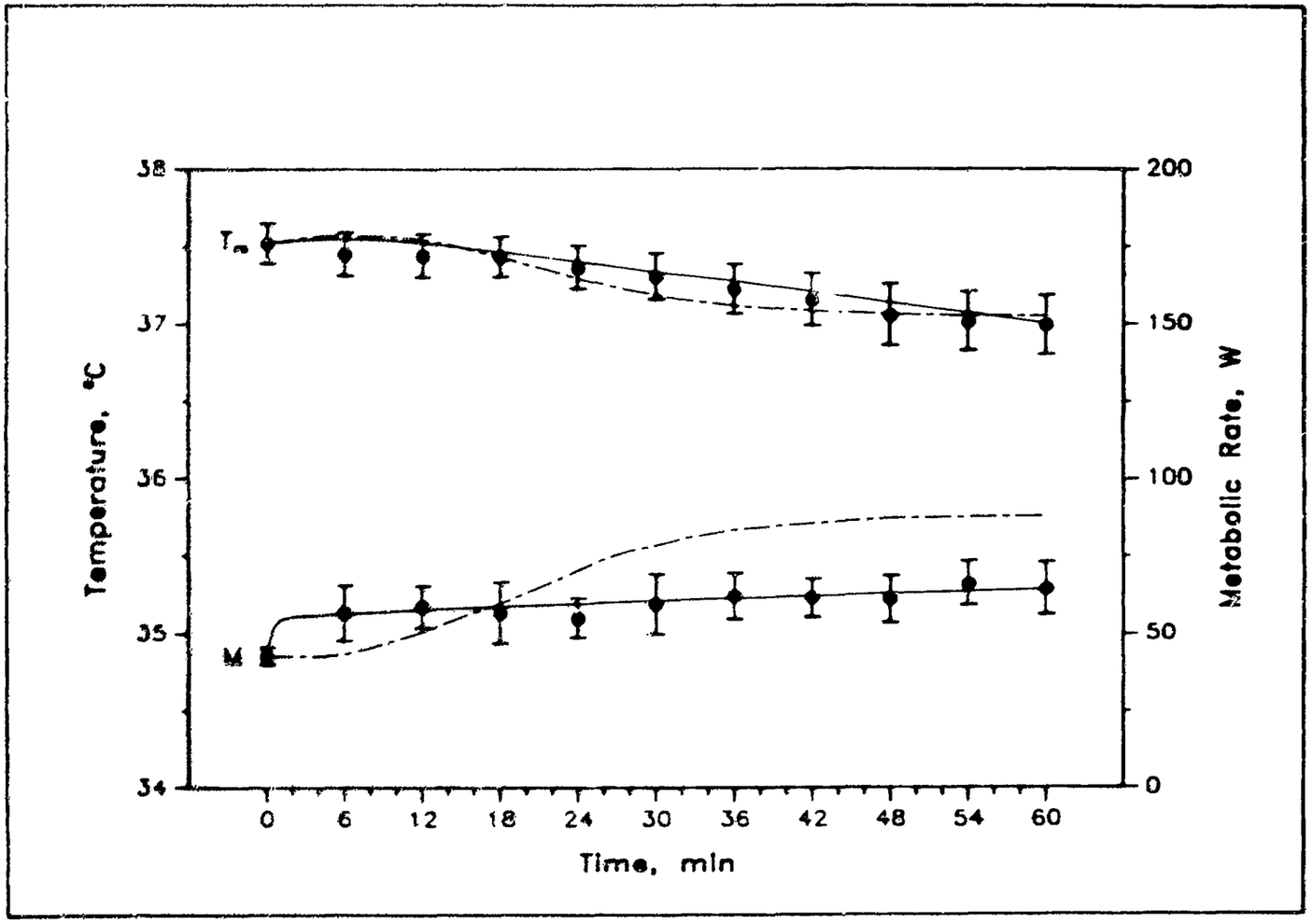

Fig. 4. Measured (●) ± SE and predicted (solid line) rectal temperature (T_{re}) and metabolic rate (M) plotted against time for the MBF group (n=6) immersed in 28°C water. The dashed line shows the prediction according to the Montgomery controller for shivering (21).

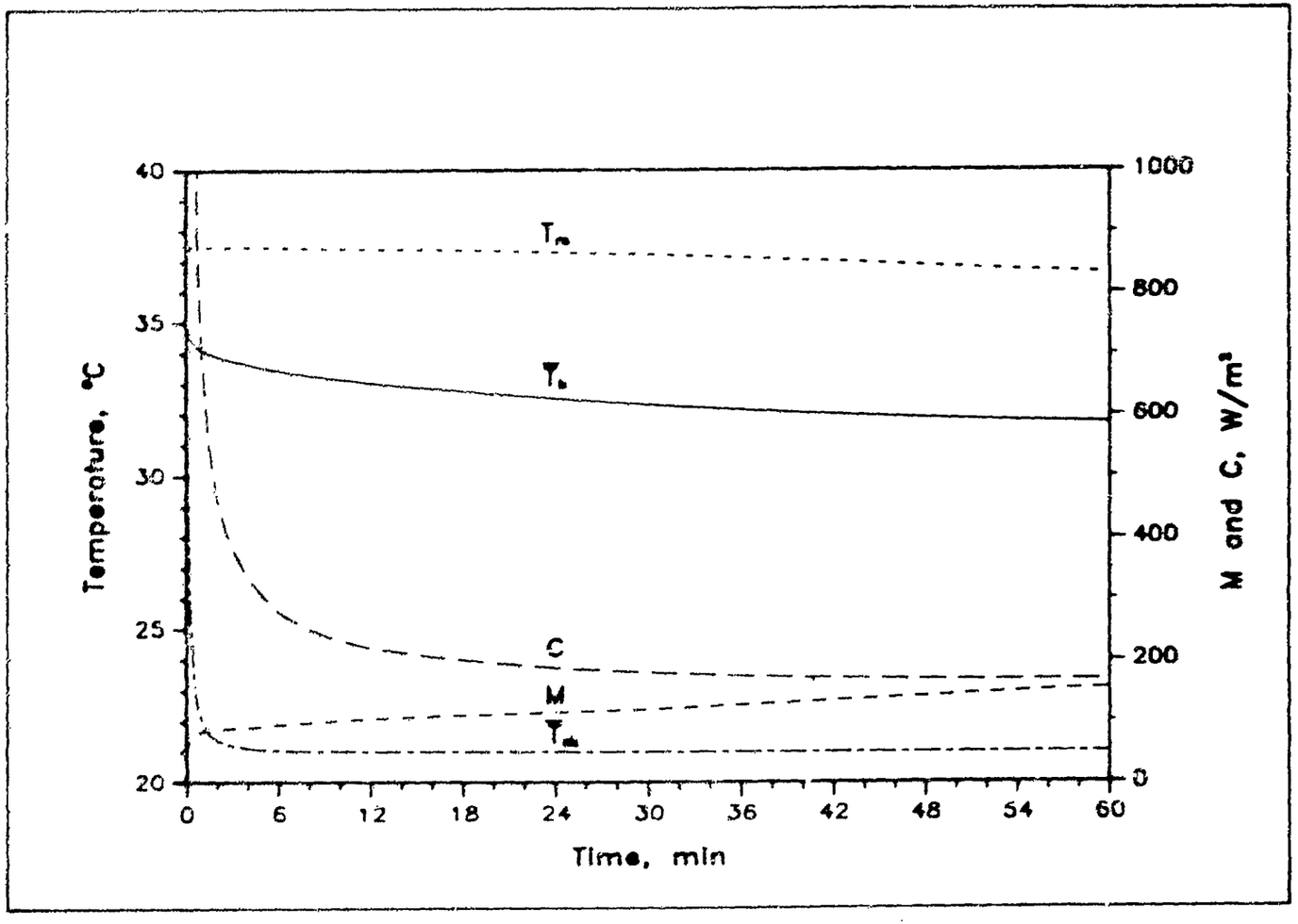

Fig. 7. Predicted mean body temperature (T_b), rectal temperature (T_{re}), mean skin temperature (T_{sk}), metabolic rate (M), and convective heat transfer (C), for the MBP group immersed in 20°C water.

APPENDIX A: Convective Heat Transfer Coefficient

The convective heat transfer coefficient for flow across spherical and cylindrical segments is determined by (21)

$$h_c = Kw\ Nu/d \tag{A1}$$

where Kw is the thermal conductivity of water, Nu is the Nusselt number, and d is the segment diameter. Convective heat transfer involves both forced and free convection.

The Nusselt number for forced convection is determined by (7)

$$Nu_{fo} = 0.66\ Re^{1/2}\ Pr^{1/3}, \tag{A2}$$

where Re is the Reynolds number and Pr is the Prandtl number. The Reynolds number is determined by

$$Re = V_w\ d/\ \nu, \tag{A3}$$

where V_w is the water velocity and ν is the kinematic viscosity of water. The Prandtl number is determined by

$$Pr = \nu/D, \tag{A4}$$

where D is the molecular diffusivity of water.

The Nusselt number for free convection is determined by (7)

$$Nu_{fr} = 0.54\ (Pr \cdot Gr)^{1/4}, \tag{A5}$$

where Gr is the Grashof number determined by

$$Gr = \beta g D^3\ (T_{sk} - T_w)/\nu^2, \tag{A6}$$

and where β is the coefficient of thermal expansion of water and g is the acceleration due to gravity.

If the ratio G_r/R_e^2 is small, then forced convection dominates, otherwise free convection dominates (7). When the ratio is near unity, it is assumed that the two terms are additive.

APPENDIX B: BASIC Statements Implementing Thermoregulatory Model and A Sample Simulation

The source program typed out by the computer is listed below. The first section (lines 10 to 21) lists all the references used to develop the program. This is followed by the identification of body segments and compartments (lines 29 to 38) and a glossary of terms not identified elsewhere in the program (lines 50 to 88).

Next begins the description of the CONTROLLED SYSTEM (lines 100 to 1760). Here given inputs of subject height, weight, percent body fat, and basal metabolic rate, an extensive physical and physiological description of the model compartments is computed. Compartment weight, dimension, thermal capacitance, basal heat production, basal blood flow, and thermal conductance are given in order of head, trunk, arms, hands, legs, and feet from top to bottom, and core, muscle, fat, and skin from left to right. An example follows the source listing.

The next section describes the CONTROLLING SYSTEM (lines 2090 to 2720). Estimates of the air temperature and central blood temperature for condition of thermal neutrality are entered; if this condition is not satisified (to be determined by the user later), then the program is re-run with new estimates. The water temperature, steady state skin temperature, net amount of internal power produced to exercise, time step for printout of results, and the total simulation time are entered. Finally, the values of the control coefficients, C0 through C7, are entered. C0 specifies the half-time for the onset of limb shivering; C1 through C6 are the parameters that define the shivering response (see Eq. 9 in text); and C7 determines the extent of counter-current heat exchange. In addition to calculating the neutral temperature distribution from which the model's set-point values are assigned (a printout is optional), this

section specifies the skin thermoreceptor inputs and effector outputs and the distribution factors of heat production for muscle due to exercise and shivering.

Simulation of the exposure begins on line 2730. Warm and cold signals are established by comparing a compartment's set-point value to its current temperature. Initial signals upon immersion in cold water arise predominantly from the skin compartments and to a much lesser extent from core temperatures affected by the respired heat loss. The efferent outflow or amount of shivering and vasoconstriction are determined in lines 2930 and 2980. The efferent output or metabolic rate, blood flow, and respired evaporative and convective heat loss are determined in lines 3010 to 3270. Convective heat transfer coefficients for the initial transient cooling of the skin are determined in lines 3310 to 3580. Heat flow values for all compartments including the central blood are determined in lines 3610 to 3790. The optional counter-current heat exchange is declared by specifying C7 as non-zero. The integration step is then determined in lines 3810 to 3871 under the constraint that the change in temperature of any compartment cannot exceed 0.1°C during that step. Before the simulation continues, a screen printout of the predicted initial trunk core temperature (T_{re}) and heat storage of the central blood (Fblood) is displayed. If T_{re} does not match the initial measured rectal temperature or if |Fblood| exceeds 0.1°C/min, then enter new estimates of Tneutral and Tblood. Otherwise, the program calculates the new compartment temperatures and the simulation continues until the exposure is over. A printout of the model temperature distribution is optional.

An example run follows. This simulation was for the MBF group immersed in 20°C water (see Figs. 2, 4 and 7). Following the description of the CONTROLLED SYSTEM, the neutral temperature distribution is given in the compartmental order described earlier where T1, T2, T3 and T4 refer to the

core, muscle, fat and skin, respectively. Following this are the results for the simulated immersion given every 6 min up to 1 h. TIME is the time in min, TB is the mean body temperature in °C, MR is the metabolic rate in W, EV is the total evaporative heat loss in W, TBL is the central blood temperature in °C, TCR is the trunk core (rectal) temperature in °C, THD is the head core (hypothalmus) temperature in °C, and HFSK is the convective heat loss in W/m^2 (values greater than 999 are indicated as 999).

```
1  REM BASIC listing of RWBC (Thermoregulatory model for Whole Body Cooling of
nude subject immersed in cold water)
9  REM
10 REM References used in the listing
11 REM
12 REM Ref 1 Montgomery LD. Annals Biomed Eng v2 1974 p19-46
13 REM Ref 2 Stolwijk JAJ. Mathematical Model of Thermoregulation. In:
       Physiological and Behavioral Temperature Regulation 1970, p703-721
14 REM Ref 3 Stolwijk JAJ, Hardy JD. Control of Body Temperature. In: Handbook
       of Physiology 1977, p45-68
15 REM Ref 4 Bullard RW, Rapp GM. Aerospace Med v41 1970 p 1269-1277
16 REM Ref 5 Gagge AP, Nishi Y, Gonzalez RR. Standard Effective Temperature -
       A Single Temperature Sensation and Thermal Discomfort
17 REM Ref 6 Witherspoon JM, Goldman RF, Breckenridge JR. J de Physiologie v63
       1971 p459-462
18 REM Ref 7 Stolwijk JAJ, Hardy JD. Pflugers Archiv v291 1966 p129-162
19 REM Ref 8 Campbell GS. An Introduction to Environmental Biophysics.
       Springt-Verlag, 1977
20 REM Ref 9 Sekins KM, Emery AF. Thermal Science for Physical Medicine. In :
       Therapeutic Heat and Cold. Baltimore. Williams and Wilkins 1982
21 REM Ref 10 Ruch TC, Patton HD. Physiology and Biophysics. W.B.Saunders. 196
28 REM
29 REM Identification of body segments and compartments
30 REM
32 REM I refers to body segments as follows
34 REM  1 = head  2 = trunk  3 = arms  4 = hands  5 = legs  6 = feet
36 REM N refers to segment compartments as follows
38 REM  1 = core  2 = muscle  3 = fat  4 = skin
40 REM
50 REM Glossary of terms
51 REM
52 REM FBF = fractional body fat
53 REM SG = body specific gravity
54 REM AT = weight (kg) of adipose tissue
55 REM NAT = weight (kg) of non-adipose tissue
56 REM CB = body heat capacity (kcal/C)
57 REM MR = metabolic rate (kcal/h)
58 REM QSF (WSF) = basal metabolism (weight) of the skin and fat
59 REM QM (WM) = basal metabolism (weight) of the muscle
60 REM QC (WC) = basal metabolism (weight) of the skeleton & connective tissue
61 REM TR = thermal resistance (C*h/kcal)
62 REM K = tissue thermal conductivity (kcal/h/m/C)
63 REM Tneutral = air temperature required for thermal neutrality
64 REM Tblood = central blood temperature required to obtain correct Tre
65 REM Note that Tneutral and Tblood are estimated by trial and error until hea
       storage of blood = 0 and T(11) = initial measured rectal temperature
66 REM SSTSK = steady state skin temperature
67 REM WORKI = net amount of internal power produced by exercise (kcal/h)
68 REM DPRT = time increment (min) for printout of prediction
69 REM TMAX = total simulation time (min)
70 REM TIM = time (h); TIME = time (min)
71 REM TPRT = time of printout (h)
72 REM PAIR = vapour pressure (mmHg)
73 REM TB = mean weighted body temperature (C)
```

```
74 REM EV = evaporative heat loss (kcal/h)
75 REM TBL = central blood temperature (C)
76 REM TCR = trunk core temperature (C)
77 REM THD = head core temperature (C)
78 REM HFSK = convective heat loss to water (kcal/h/m^2)
79 REM DIFF = difference between compartment temperature and its set-point
80 REM WARM (COLD) = warm (cold) signal
81 REM Q = metabolic rate (kcal/h)
82 REM BF = blood flow (l/h)
83 REM E = evaporative heat loss (kcal/h)
84 REM BC = conductive heat exchange between compartment and central blood
85 REM TD = conductive heat exchange between compartments
86 REM HF = heat storage of compartment
87 REM F = rate of change of compartment temperature
88 REM X = factor to introduce limb shivering exponentially with half-time CC
90 REM
91 LPRINT "RESTING WHOLE BODY COOLING" : LPRINT " " : LPRINT " "
92 REM
100 REM Description of the CONTROLLED SYSTEM
110 REM
120 REM Calculate Body Weight Distribution from Pierson and Eagle (1915),
        see Ref 1 p24
130 REM
140 INPUT "Subject height (cm), weight (kg), and body fat (%)"; HT,WT,PBF
150 FBF = PBF/100
160 SG = 5.548001/(FBF + 5.044)
170 IF FBF < 0 THEN PRINT "ERROR LINE 140": END
180 AT = FBF*WT
190 NAT = WT - AT
200 REM
210 REM Calculate Surface Area (SA) from DuBois and DuBois (1915), see Ref 1 p2
        and Assign Segment Lengths (L), see Ref 2 p708
220 REM
225 DIM L(7)
230 SA = .007184*WT^.425*HT^.725
240 L(2) = .6
250 L(3) = 1.12
260 L(4) = .96
270 L(5) = 1.6
280 L(6) = 1.25
290 REM
300 REM Table of Relative Weight Distribution for Model Compartments (CSWT),
        see Ref 1 p25
310 REM
320 DIM CSWT(7,(1,3)
340 CSWT(1,1,1) = .028232
350 CSWT(1,1,2) = .02518
360 CSWT(1,2,1) = .00588
370 CSWT(2,1,1) = .18704
380 CSWT(2,1,2) = .038832
390 CSWT(2,2,1) = .2834
400 CSWT(3,1,1) = .011764
410 CSWT(3,1,2) = .023756
420 CSWT(3,2,1) = .05328
```

```
430 CSWT(4,1,1) = .0004704
440 CSWT(4,1,2) = .003648
450 CSWT(4,2,1) = .001188
460 CSWT(5,1,1) = .030352
470 CSWT(5,1,2) = .079168
480 CSWT(5,2,1) = .161
490 CSWT(6,1,1) = .0009412
500 CSWT(6,1,2) = .005684
510 CSWT(6,2,1) = .001188
530 CSWT(1,3,1) = .0333
540 CSWT(1,4,1) = .00423
550 CSWT(2,3,1) = .6333
560 CSWT(2,4,1) = .0213
570 CSWT(3,3,1) = .0867
580 CSWT(3,4,1) = .00754
590 CSWT(4,3,1) = .01333
600 CSWT(4,4,1) = .00294
610 CSWT(5,3,1) = .2133
620 CSWT(5,4,1) = .01894
630 CSWT(6,3,1) = .02
640 CSWT(6,4,1) = .00376
650 REM
660 REM Calculate Compartment Weights, SWT(kg), and Thermal Capacitance Values,
      C(kcal/C), see Ref 1 p26
670 REM
680 DIM SWT(70),C(70)
685 CB = 0
690 FOR I = 1 TO 6
700  FOR N = 1 TO 4
710   SWT(10*I+N-10) = (CSWT(I,N,1) + CSWT(I,N,2))*NAT
720   C(10*I+N-10) = (.9*CSWT(I,N,1) + .5*CSWT(I,N,2))*NAT
730  NEXT N
740  SWT(10*I-7) = CSWT(I,3,1)*AT
750  C(10*I-7) = .6*SWT(10*I-7)
755  CB = CB + C(10*I-9) + C(10*I-8) + C(10*I-7) + C(10*I-6)
760 NEXT I
770 REM to account for the thermal capacitance of blood in trunk core,
      see Ref 2 o708
780 C(11) = C(11) - 2.25
790 C(61) = 2.25
800 REM Calculate thermal capacitance of immersed skin (CS)
810 CS = 0
820 FOR I = 1 TO 6 : CS = CS + C(10*I-6) : NEXT I
825 REM
830 REM Calculate Basal Heat Production, QB(kcal/h), see Ref 1 p27
840 REM
850 INPUT "Resting metabolic rate (kcal/h/m^2)"; BMR
860 MR = BMR*SA
870 QSF = .3*(.05882*NAT + AT)
880 QM = .18*MR - QSF
890 QC = .1*MR
900 WC = 0 : WM = 0 : WSF = 0
910 FOR I = 1 TO 6
930  WC = WC + SWT(10*I-9)
```

```
940  WM = WM + SWT(10*I-8)
960  WSF = WSF + SWT(10*I-7) + SWT(10*I-6)
970 NEXT I
980 DIM QB(70)
1000 FOR I = 1 TO 6
1010  QB(10*I-9) = SWT(10*I-9)*QC/WC
1020  QB(10*I-8) = SWT(10*I-8)*QM/WM
1040  QB(10*I-7) = SWT(10*I-7)*QSF/WSF
1050  QB(10*I-6) = SWT(10*I-6)*QSF/WSF
1060 NEXT I
1070 REM to account for extra values for head and trunk cores, see Ref 1 p27
1090  QB(1) = QB(1) + .16*MR
1100  QB(11) = QB(11) + .56*MR
1115  QC = .82*MR
1120 REM
1130 REM Calculate Basal Blood Flow, BFB(1/h), see Ref 1 p28
1140 REM
1150 DIM BFB(70)
1160 FOR I = 1 TO 6 : FOR N = 1 TO 4
1170  BFB(10*I+N-10) = 1.2*QB(10*I+N-10)
1180 NEXT N : NEXT I
1200 BFB(1) = 45
1210 BFB(11) = 210
1230 BFB(4) = 5.34*SWT(4)
1240 BFB(14) = 1.56*SWT(14)
1250 BFB(24) = 1.04*SWT(24)
1260 BFB(34) = 10.5*SWT(34)
1270 BFB(44) = 2.38*SWT(44)
1280 BFB(54) = 12.5*SWT(54)
1300 REM
1310 REM Calculate Compartmental Volume, V(m^3), Radii, R(m), Interfacial Areas,
       A(m^2), and Thermal Conductances, TC(kcal/C/h), see Ref 2 p707 and
       Ref 9 p84&94
1315 REM Assumes volume (m^3) = weight (kg)/1000
1320 REM
1330 DIM V(7),R(70),A(70),RCM(70),TC(70),TR(70),K(70)
1332 FOR I = 1 TO 6
1334  K(10*I-9) = .36 : K(10*I-8) = .2394
1336  K(10*I-7) = .1634 : K(10*I-6) = .288
1338 NEXT I
1340 K(12) = .2988 : K(22) = .2988 : K(42) = .2988
1345 PI = 3.14159
1350 FOR I = 1 TO 6
1360  FOR N = 1 TO 4
1370   V(I) = V(I) + SWT(10*I+N-10)/1000
1380  NEXT N
1390 NEXT I
1400 REM head segment as sphere
1410 VOL = V(1)
1420 R(4) = (.75*VOL/PI)^(1/3)
1425 RCM(4) = (R(4)^3 - .000375*SWT(4)/PI)^(1/3)
1430 A(4) = 4*PI*R(4)^2
1440 FOR N = 1 TO 3
1450  VOL = VOL - SWT(5-N)/1000
```

```
1460  R(4-N) = (.75*VOL/PI)^(1/3)
1465  RCM(4-N) = (R(4-N)^3 - .000375*SWT(4-N)/PI)^(1/3)
1470  A(4-N) = 4*PI*R(4-N)^2
1480 NEXT N
1520 FOR N = 1 TO 3
1530  TR(N) = (1/RCM(N) - 1/R(N))/(4*PI*K(N)) + (1/R(N) - 1/RCM(N+1))/(4*PI*K(N+
1))
1540  TC(N) = 1/TR(N)
1550 NEXT N
1560 REM remaining segments as cylinders
1570 FOR I = 2 TO 6
1580  VOL = V(I)
1590  R(10*I-6) = (VOL/(PI*L(I)))^.5
1595  RCM(10*I-6) = (R(10*I-6)^2 - .0005*SWT(10*I-6)/(PI*L(I)))^.5
1600  A(10*I-6) = 2*PI*R(10*I-6)*L(I)
1610  FOR N = 1 TO 3
1620   VOL = VOL - SWT(10*I-N-5)/1000
1630   R(10*I-N-6) = (VOL/(PI*L(I)))^.5
1635   RCM(10*I-N-6) = (R(10*I-N-6)^2 - .0005*SWT(10*I-N-6)/(PI*L(I)))^.5
1640   A(10*I-N-6) = 2*PI*R(10*I-N-6)*L(I)
1650  NEXT N
1700  FOR N = 1 TO 3
1705  J = 10*I+N-10
1710  TR(J) = LOG(R(J)/RCM(J))/(2*PI*K(J)*L(I)) + LOG(RCM(J+1)/R(J))/(2*PI*K(J+1
)*L(I))
1720  TC(J) = 1/TR(J)
1730  NEXT N
1740 NEXT I
1750 REM
1760 REM End of Description
1770 REM
1780 INPUT "Enter 1 for model description, else 0"; CODE
1790 IF CODE = 0 THEN GOTO 2100
1795 LPRINT " "
1800 LPRINT "HT =" HT "  WT =" WT "  SG =" SG "  FBF =" FBF "  SA =" SA
1810 LPRINT "QC =" QC "  QM =" QM "  QSF =" QSF
1815 LPRINT "WC =" WC "  WM =" WM "  WSF =" WSF
1820 LPRINT " "
1825 LPRINT " Core    Muscle    Fat    Skin"
1830 LPRINT " " : LPRINT "Weight SWT (kg)" : LPRINT " "
1840 FOR I = 1 TO 6
1850  LPRINT USING "##.###  "; SWT(10*I-9),SWT(10*I-8),SWT(10*I-7),SWT(10*I-6)
1860 NEXT I
1870 LPRINT " " : LPRINT "Radius R (cm)" : LPRINT " "
1880 FOR I = 1 TO 6
1890  LPRINT USING "##.##   "; 100*R(10*I-9),100*R(10*I-8),100*R(10*I-7),100*R(1
0*I-6)
1900 NEXT I
1910 LPRINT " " : LPRINT "Thermal Capacitance C (kcal/C)" : LPRINT " "
1920 FOR I = 1 TO 6
1930  LPRINT USING "##.###  "; C(10*I-9),C(10*I-8),C(10*I-7),C(10*I-6)
1940 NEXT I
1950 LPRINT " " : LPRINT "Basal Heat Production QB (kcal/h)" : LPRINT " "
1960 FOR I = 1 TO 6
```

```
1970  LPRINT USING "##.###   "; QB(10*I-9),QB(10*I-8),QB(10*I-7),QB(10*I-6)
1980 NEXT I
1990 LPRINT " " : LPRINT "Basal Blood Flow BFB (1/h)" : LPRINT " "
2000 FOR I = 1 TO 6
2010  LPRINT USING "###.##   "; BFB(10*I-9),BFB(10*I-8),BFB(10*I-7),BFB(10*I-6)
2020 NEXT I
2030 LPRINT " " : LPRINT "Thermal Conductance TC (kcal/C/h)" : LPRINT " "
2040 FOR I = 1 TO 6
2050  LPRINT USING "##.##    "; TC(10*I-9),TC(10*I-8),TC(10*I-7),TC(10*I-6)
2060 NEXT I
2065 AB = A(4) + A(14) + A(24) + A(34) + A(44) + A(54)
2070 LPRINT " " : LPRINT "Segment Surface Area A (m*m)" : LPRINT " "
2080 LPRINT "A1 =" A(4) "  A2 =" A(14) "  A3 =" A(24) "  A4 =" A(34)
2081 LPRINT "A5 =" A(44) "  A6 =" A(54) "  AB =" AB : LPRINT " "
2090 REM
2100 REM Description of the CONTROLLING SYSTEM
2105 REM
2110 REM Initial conditions, assumes relative humidity (RH) = 1, and air
       temperature (TAIR) = water temperature (TWAT)
2120 REM
2125 DIM EB(70),HSS(7),T(70),TSET(70),TF(11,11),EF(11),WORKM(7),CHILM(7)
2126 DIM SKINR(7),SKINS(7),SKINV(7),SKINC(7)
2127 DIM WARM(70),COLD(70),DIFF(70)
2128 DIM Q(70),BF(70),E(70),TBL(70)
2129 DIM BC(70),TD(70),HF(70),F(70)
2130 INPUT "Tneutral  Tblood  Twater  ssTSK  WORKI  DPRINT  TMAX"; TA,TB,TWAT,SS
TSK,WORKI,DPRT,TMAX
2135 DPRT = DPRT/60 : TMAX = TMAX/60
2140 TAIR = TWAT
2150 PAIR = EXP(18.6686 - 4030.183/(TAIR + 235))
2160 TIM = 0 : TPRT = 0
2165 LPRINT " " : LPRINT "Tneutral-air ="TA"C   Tblood ="TB"C   Twater ="TWAT"C"
 : LPRINT " "
2170 REM Input control constants; C0 see 2905;; C1 to C6 see 2930; C7 see 3637
2180 INPUT "Enter control constants C0 to C7"; C0,C1,C2,C3,C4,C5,C6,C7
2185 REM
2190 LPRINT " " : LPRINT "C0 ="C0"  C1 ="C1"  C2 ="C2"  C3 ="C3"  C4 ="C4"  C5 =
"C5"  C6 ="C6"  C7 ="C7 : LPRINT " "
2200 REM
2230 REM Calculate initial temperature distribution, T(N), assuming subject is
       thermally neutral for given Tneutral-air (RH = .5) and Tblood
2232 REM
2234 REM Table of basal evaporative rates, EB(kcal/h), see lines 3160-3230 and
       Ref 2 p 708  and Ref 5 p 246
2238 PA = .5*EXP(18.6686 - 4030.183/(TA + 235))
2240 ERES = .001978*MR*(44 - PA)
2242 CRES = .001032*MR*(34 - TA)
2244 EB(4) = .6120001 : EB(14) = 3.27 : EB(24) = 1.185
2245 EB(34) = .432 : EB(44) = 2.98 : EB(54) = .6
2246 EB(1) = 4.5 : EB(11) = ERES + CRES
2250 REM
2252 REM Table of heat transfer coefficients from skin to air, see Ref 3 p 50
2254 REM
2256 HSS(1) = 6.71*A(4) : HSS(2) = 5.93*A(14)
```

```
2258 HSS(3) = 5.42*A(24) : HSS(4) = 6.53*A(34)
2260 HSS(5) = 5.42*A(44) : HSS(6) = 6.88*A(54)
2290 REM
2292 REM Calculate compartmental temperature and matrix coefficients for the
       4x4 representation of the non-homogeneous system of equations for
       determining the neutral temperature distribution
2293 REM
2300 FOR I = 1 TO 6
2302  TF(1,1) = .9*BFB(10*I-9) + TC(10*I-9)
2304  TF(1,2) = -TC(10*I-9)
2306  EF(1) = QB(10*I-9) - EB(10*I-9) + .9*BFB(10*I-9)*TB
2308  TF(4,3) = -TC(10*I-7)
2310  TF(4,4) = .9*BFB(10*I-6) + TC(10*I-7) + HSS(I)
2312  EF(4) = QB(10*I-6) - EB(10*I-6) + .9*BFB(10*I-6)*TB + HSS(I)*TA
2314  FOR N = 2 TO 3
2316   TF(N,N-1) = -TC(10*I+N-11)
2318   TF(N,N) = .9*BFB(10*I+N-10) + TC(10*I+N-11) + TC(10*I+N-10)
2320   TF(N,N+1) = -TC(10*I+N-10)
2322   EF(N) = QB(10*I+N-10) - EB(10*I+N-10) + .9*BFB(10*I+N-10)*TB
2324  NEXT N
2330 REM
2332 REM Begin Gauss Elimination method by initializing first terms to unity and
       normalizing accordingly
2333 REM
2334  EF(1) = EF(1)/TF(1,1)
2336  TF(1,2) = TF(1,2)/TF(1,1)
2338  EF(4) = EF(4)/TF(4,3)
2340  TF(4,4) = TF(4,4)/TF(4,3)
2342  FOR N = 2 TO 3
2344   EF(N) = EF(N)/TF(N,N-1)
2346   TF(N,N+1) = TF(N,N+1)/TF(N,N-1)
2348   TF(N,N) = TF(N,N)/TF(N,N-1)
2350  NEXT N
2355 REM
2360 REM Begin elimination procedure and normalize
2361 REM
2362  FOR N = 2 TO 3
2364   TF(N,N) = TF(N,N) - TF(N-1,N)
2366   EF(N) = EF(N) - EF(N-1)
2368   EF(N) = EF(N)/TF(N,N)
2370   TF(N,N+1) = TF(N,N+1)/TF(N,N)
2372  NEXT N
2374  TF(4,4) = TF(4,4) - TF(3,4)
2376  EF(4) = (EF(4) - EF(3))/TF(4,4)
2378 REM
2380 REM Begin substitutions
2381 REM
2382  T(10*I-6) = EF(4)
2384  FOR N = 1 TO 3
2386   T(10*I-N-6) = EF(4-N) - TF(4-N,5-N)*T(10*I-N-5)
2388  NEXT N
2390 NEXT I
2400 REM
2402 REM Assign set-point temperatures, TSET(C)
```

```
2403 REM
2404 T(61) = TB
2406 FOR N = 1 TO 61 : TSET(N) = T(N) : NEXT N
2410 INPUT "Enter 1 for neutral temperature distribution, else 0"; CODE
2412 IF CODE = 0 THEN GOTO 2530
2414 LPRINT " " : LPRINT " T1      T2      T3      T4" : LPRINT " "
2416 FOR I = 1 TO 6
2418  LPRINT USING "##.##  "; T(10*I-9),T(10*I-8),T(10*I-7),T(10*I-6)
2420 NEXT I
2520 REM
2530 REM Table of skin thermoreceptor inputs and effector outputs,
       see Ref 1 p32
2540 REM
2560 SKINR(1) = .0695 : SKINR(2) = .4935 : SKINR(3) = .0686
2570 SKINR(4) = .1845 : SKINR(5) = .1505 : SKINR(6) = .0334
2580 SKINS(1) = .081 : SKINS(2) = .481 : SKINS(3) = .154
2590 SKINS(4) = .031 : SKINS(5) = .218 : SKINS(6) = .035
2600 SKINV(1) = .132 : SKINV(2) = .322 : SKINV(3) = 9.500001E-02
2610 SKINV(4) = .121 : SKINV(5) = .23  : SKINV(6) = .1
2620 SKINC(1) = .05 : SKINC(2) = .15 : SKINC(3) = .05
2630 SKINC(4) = .35 : SKINC(5) = .05 : SKINC(6) = .35
2640 REM
2650 REM Table of distribution factors of heat production for muscle due to
       exercise (WORKM) and to shivering (CHILM), see Ref 1 p33
2660 REM
2680 WORKM(1) = 0      : WORKM(2) = .3  : WORKM(3) = .08
2690 WORKM(4) = .01 : WORKM(5) = .6    : WORKM(6) = .01
2700 CHILM(1) = .02  : CHILM(2) = .8499999 : CHILM(3) = .05
2710 CHILM(4) = 0      : CHILM(5) = .07 : CHILM(6) = 0
2715 REM
2720 INPUT "Enter 1 for temperature distribution, else 0"; CODE
2725 REM
2730 REM Start of simulation
2740 REM
2745 LPRINT " " : LPRINT "  TIME      TB       MR       EV      TBL      TCR      THD
    TSK      HFSK" : LPRINT " "
2750 REM Establish thermoreceptor output and intergrate peripheral efferents,
       see Ref 1 p 31-32
2760 REM
2775 INIT = 1
2780 FOR N = 1 TO 60
2790  WARM(N) = 0 : COLD(N) = 0
2800  DIFF(N) = T(N) - TSET(N)
2810  IF DIFF(N) > 0 THEN WARM(N) = DIFF(N) ELSE COLD(N) = -DIFF(N)
2820 NEXT N
2830 WARMS = 0 : COLDS = 0
2840 FOR I = 1 TO 6
2850  WARMS = WARMS + WARM(10*I-6)*SKINR(I)
2860  COLDS = COLDS + COLD(10*I-6)*SKINR(I)
2870 NEXT I
2880 REM
2890 REM Determine efferent outflow, see Ref 1 p 33
2900 REM
2905 X = EXP(-.693*60*TIM/C0)
```

```
2907 CHILM(2) = .0499999 + .12*X : CHILM(3) = .05*(1 - X) : CHILM(5) = .07*(1 -
X)
2910 SWEAT = 32*DIFF(1) + 29*(WARMS - COLDS)
2920 DILAT = 117*DIFF(1) + 7.5*(WARMS - COLDS)
2930 CHILL = SA/1.163*(C1*COLDS^C3/PBF^C4 + C2*COLD(1)*COLDS^C5/PBF^C6)
2940 STRIC = -5*DIFF(1) + 5*(COLDS - WARMS)
2950 IF SWEAT < 0 THEN SWEAT = 0
2960 IF DILAT < 0 THEN DILAT = 0
2970 IF CHILL < 0 THEN CHILL = 0
2980 IF STRIC < 0 THEN STRIC = 0
3000 REM
3010 REM Assign efferent output, see Ref 1 p 34-35
3020 REM
3040 FOR I = 1 TO 6
3060  Q(10*I-9) = QB(10*I-9)
3070  Q(10*I-8) = QB(10*I-8) + WORKM(I)*WORKI + CHILM(I)*CHILL
3080  BF(10*I-9) = BFB(10*I-9)
3090  BF(10*I-8) = BFB(10*I-8) + Q(10*I-8) - QB(10*I-8)
3110  Q(10*I-7) = QB(10*I-7)
3120  Q(10*I-6) = QB(10*I-6)
3130  BF(10*I-7) = BFB(10*I-7)
3140  BF(10*I-6) = ((BFB(10*I-6) + SKINV(I)*DILAT)/(1 + SKINC(I)*STRIC))*2^(DIF
(10*I-6)/6)
3150 NEXT I
3160 REM evaporative heat loss from the head, see Ref 2 p 708 & 712
3165 E(1) = EB(1)
3180 REM respired evaporative and convective heat loss, see Ref 5 p 246
3190 ERES = .001978*MR*(44 - PAIR)
3200 CRES = .001032*MR*(34 - TAIR)
3220 E(11) = ERES + CRES
3230 REM Calculate total metabolic rate
3240 MR = 0
3250 FOR I = 1 TO 6 : FOR N = 1 TO 4
3260  MR = MR + Q(10*I+N-10)
3270 NEXT N : NEXT I
3300 REM
3310 REM Determine heat transfer coefficients from skin to water HSS (kcal/h/C)
        for initial non-steady state cooling, see Ref 6 and Ref 8 p 65-70
3320 REM
3370 FOR I = 1 TO 6
3380  DELT = T(10*I-6) - TWAT
3400 REM Initial heat flow is approximated by assuming minimal forced convectior
        - after steady state is attained, heat flow is determined by assuming
        zero heatstorage for the immersed skin
3410  VEL = 18
3420 REM linear appr of kinematic viscosity (cm*cm/s) from CRC
3430  VU = .0148 - .000224*TWAT
3440 REM Reynolds No. where factor .36 converts VU to m*m/h
3450  RE = 2*R(10*I-6)*VEL/(.36*VU)
3460 REM linear appr of Prandtl No. based on 9.5 at 10C and 7.3 at 22C
3470  PR = 11.3 - .18*TWAT
3480 REM Nusselt No. for forced convection, see Ref 8 p 66
3490  NUFO = .66*RE^.5*PR^(1/3)
3500 REM linear appr of thermal expansion of water (1/C) from CRC
```

```
3510  TE = 9.999999E-06*TWAT
3520 REM Grashof No. where factor 10^6 to convert R(m) to R(cm) is imbedded in
       coefficient of NUFR, see Ref 8 p 65
3530  GR = 980*TE*(2*R(10*I-6))^3*(T(10*I-6) - TWAT)/VU^2
3540 REM Nusselt No. for free convection, see Ref 8 p 69
3550  NUFR = 17.1*(GR*PR)^.25
3560 REM heat transfer coefficient assuming Kw = 0.52 kcal/m/h/C from CRC
3570  HSS(I) = .52*(NUFD + NUFR)*A(10*I-6)/(2*R(10*I-6))
3580 NEXT I
3600 REM
3610 REM Calculate heat flows HF (kcal/h), see Ref 1 p 36
3620 REM
3625 REM Calculate blood temperatures for optional counter-current heat exchang
       (set C7 = 0 for no effect)
3630 FOR I = 1 TO 6 : FOR N = 1 TO 4
3632  TBL(10*I+N-10) = T(61)
3634 NEXT N : NEXT I
3635 FOR I = 3 TO 6 : FOR N = 1 TO 3 : J = 10*I+N-10
3637  TBL(J) = T(J) + (T(61) - T(J))*EXP(-C7*COLDS)
3639 NEXT N : NEXT I
3650 FOR I = 1 TO 6
3655  FOR N = 1 TO 3 : J = 10*I+N-10
3660   BC(J) = .9*BF(J)*(T(J) - TBL(J))
3670   TD(J) = TC(J)*(T(J) - T(J+1))
3680  NEXT N
3690  BC(10*I-6) = .9*BF(10*I-6)*(T(10*I-6) - TBL(10*I-6))
3700  TD(10*I-6) = HSS(I)*(T(10*I-6) - TWAT)
3710  HF(10*I-9) = Q(10*I-9) - E(10*I-9) - BC(10*I-9) - TD(10*I-9)
3720  FOR N = 2 TO 4
3730   HF(10*I+N-10) = Q(10*I+N-10) - E(10*I+N-10) - BC(10*I+N-10) + TD(10*I+N-
1) - TD(10*I+N-10)
3740  NEXT N
3750 NEXT I
3760 HF(61) = 0
3770 FOR I = 1 TO 6 : FOR N = 1 TO 4
3780  HF(61) = HF(61) + BC(10*I+N-10)
3790 NEXT N : NEXT I
3800 REM
3810 REM Determine optimum integration step, DT (change in T cannot > 0.1 C)
3820 REM
3830 DT = TPRT - TIM
3840 FOR I = 1 TO 6 : FOR N = 1 TO 3
3850  F(10*I+N-10) = HF(10*I+N-10)/C(10*I+N-10)
3860  IF .1/ABS(F(10*I+N-10)) < DT THEN DT = .1/ABS(F(10*I+N-10))
3862 NEXT N
3864 F(10*I-6) = HF(10*I-6)/C(10*I-6)
3866 IF (T(10*I-6) - TWAT) < 2 THEN GOTO 3870
3868 IF .1/ABS(F(10*I-6)) < DT THEN DT = .1/ABS(F(10*I-6))
3870 NEXT I
3871 F(61) = HF(61)/C(61)
3872 REM
3874 REM Check that initial conditions are satisfied; if not, then start over
       with new estimates of Tneutral and Tblood
```

```
3880 IF INIT ) 0 THEN PRINT "Tr ="T(11)   "Fblood ="F(61) : INPUT "Enter 1 to re
start, else 0"; INIT
3890 IF INIT ) 0 THEN GOTO 2130
3900 REM
3910 REM Calculate new temperatures
3920 REM
3930 TIM = TIM + DT
3940 FOR I = 1 TO 6 : FOR N = 1 TO 3
3950  T(10*I+N-10) = T(10*I+N-10) + F(10*I+N-10)*DT
3955  IF T(10*I+N-10) ( TWAT THEN PRINT "TEMP"10*I+N-10"="T(10*I+N-10) : END
3960 NEXT N
3964 REM Force skin temperature to approach its assigned steady-state value
       exponentially; when Tskin is within 0.005C of this value, zero heat
       storage assumed
3965 TDIFF = T(10*I-6) - SSTSK : IF TDIFF ( 5.000001E-03 THEN TD(10*I-6) = 0(10*
I-6) - E(10*I-6) - BC(10*I-6) + TD(10*I-7) : GOTO 3967
3966 T(10*I-6) = SSTSK + TDIFF*EXP(F(10*I-6)*DT/TDIFF)
3967 NEXT I
3970 T(61) = T(61) + F(61)*DT
3980 IF TPRT ) TIM THEN GOTO 4300
3985 REM
3990 REM Print results
4000 REM
4010 REM Calculate cardiac output (l/min) and body temperature (C)
4020 CO = 0 : TB = 0
4030 FOR I = 1 TO 6 : FOR N = 1 TO 4
4040  CO = CO + BF(10*I+N-10)/60
4045  TB = TB + T(10*I+N-10)*C(10*I+N-10)/CB
4050 NEXT N : NEXT I
4070 REM Calculate total evaporative heat loss (kcal/h)
4125 EV = E(1) + E(4) + E(11)
4130 REM Calculate skin temperature and skin heat flow (kcal/h)
4135 REM Note that when calculating TDskin, transition occurs when Tskin is
       within 0.005C of its steady-state value
4140 TSK = 0 : HFSK = 0
4150 FOR I = 1 TO 6
4160  TSK = TSK + T(10*I-6)*C(10*I-6)/CS
4170  HFSK = HFSK + TD(10*I-6)
4180 NEXT I
4185 REM Note conversion from kcal/h to W
4188 IF 1.163*HFSK/SA ) 999 THEN HFSK = 999*SA/1.163
4190 LPRINT USING "###.##  "; 60*TIM,TB,1.163*MR/SA,1.163*EV/SA,T(61),T(11),T(1)
,TSK,1.163*HFSK/SA
4192 IF CODE = 0 THEN GOTO 4200
4195 FOR I = 1 TO 6 : LPRINT USING "###.##  "; T(10*I-9),T(10*I-8),T(10*I-7),T(1
0*I-6) : NEXT I
4200 TPRT = TPRT + DPRT
4300 IF TMAX ( TPRT THEN END ELSE GOTO 2780
```

RESTING WHOLE BODY COOLING

HT = 175.7 WT = 79.2 SG = 1.062795 FBF = .1762 SA = 1.953368
QC = 64.9995 QM = 8.930359 QSF = 5.337824
WC = 28.39902 WM = 33.00977 WSF = 17.79112

Core	Muscle	Fat	Skin
Weight SWT (kg)			
3.485	0.384	0.465	0.276
14.737	18.490	8.838	1.390
2.318	3.476	1.210	0.498
0.269	0.078	0.186	0.192
7.146	10.504	2.977	1.236
0.445	0.078	0.279	0.245
Radius R (cm)			
9.41	9.74	10.11	10.32
8.84	13.28	14.94	15.18
2.57	4.06	4.46	4.62
0.94	1.07	1.33	1.55
3.77	5.93	6.41	6.59
1.06	1.15	1.43	1.63
Thermal Capacitance C (kcal/C)			
2.479	0.345	0.279	0.248
10.000	16.641	5.303	1.251
1.466	3.129	0.726	0.449
0.147	0.070	0.112	0.173
4.365	9.454	1.786	1.112
0.247	0.070	0.167	0.221
Basal Heat Production QB (kcal/h)			
13.656	0.104	0.139	0.083
48.503	5.002	2.652	0.417
0.647	0.940	0.363	0.150
0.075	0.021	0.056	0.058
1.994	2.842	0.893	0.371
0.124	0.021	0.084	0.074
Basal Blood Flow BFB (l/h)			
45.00	0.12	0.17	1.47
210.00	6.00	3.18	2.17
0.78	1.13	0.44	0.52
0.09	0.03	0.07	2.01
2.39	3.41	1.07	2.94
0.15	0.03	0.10	3.07

Thermal Conductance TC (kcal/C/h)

1.48	6.47	8.50	0.00
2.12	4.06	10.24	0.00
3.71	7.81	20.87	0.00
4.85	6.18	6.89	0.00
5.33	11.99	35.85	0.00
6.91	8.88	9.44	0.00

Segment Surface Area A (m*m)

A1 = .133937 A2 = .5724 A3 = .324942 A4 = 9.346019E-02
A5 = .6630005 A6 = .1282577 A8 = 1.915998

Tneutral-air = 28.85 C Tblood = 37.25 C Twater = 20 C

C0 = 24.43 C1 = 65 C2 = 5 C3 = 1.5 C4 = 1.5 C5 = 1 C6 = 0 C7 = 0

T1	T2	T3	T4
37.42	35.79	35.38	35.01
37.48	37.10	35.47	34.07
35.15	34.58	33.85	33.49
35.34	35.29	35.24	35.17
36.42	35.70	34.76	34.35
35.43	35.38	35.33	35.26

TIME	TB	MR	EV	TBL	TCR	THD	TSK	HFSK
0.00	34.97	47.19	5.83	37.25	37.48	37.42	34.28	999.00
6.00	33.42	95.44	9.04	37.22	37.45	37.33	21.03	276.28
12.00	33.02	105.34	9.70	37.17	37.39	37.18	21.00	220.06
18.00	32.73	110.91	10.06	37.11	37.34	37.09	21.00	198.72
24.00	32.49	115.36	10.34	37.04	37.27	37.03	21.00	186.16
30.00	32.29	120.64	10.72	36.94	37.19	36.95	21.00	177.91
36.00	32.13	126.75	11.10	36.83	37.08	36.85	21.00	172.79
42.00	31.99	133.59	11.53	36.71	36.96	36.75	21.00	169.65
48.00	31.88	141.00	12.02	36.59	36.84	36.64	21.00	167.59
54.00	31.79	147.74	12.52	36.48	36.72	36.54	21.00	166.43
60.00	31.71	154.09	12.95	36.38	36.61	36.43	21.00	166.17

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