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

U.S. ARMY RESEARCH INSTITUTE OF
ENVIRONMENTAL MEDICINE
Natick, Massachusetts

JUNE 1987
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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_r) 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_r 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_r 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
19. Abstract (cont'd)

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

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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<sub>re</sub>) 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<sub>re</sub> 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<sub>re</sub> 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 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 1984, 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 specifically 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 (4.9) cm, weight = 69.0 (7.5) kg, skinfold = 5.63 (0.73) mm, body fat = 9.67 (1.57)%, and surface area = 1.83 (0.11) m². Values for the MBF group (n=6) were: height = 175.7 (6.9) cm, weight = 79.2 (13.1) kg, skinfold = 11.82 (4.26) mm, body fat = 17.62 (4.11)%, and surface area = 1.96 (0.17) m².

Model

The model used in the present study is based largely on the Montgomery version (21) of the Stolwijk-Hardy model (23). 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 $T_e$ 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 \(T_{sk}\) 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 ($T_{skss}$) and its current temperature to approximate the exponential fall in $T_{sk}$ and to allow $T_{sk}$ to approach $T_{skss}$ asymptotically. Through numerical integration, the incremental change in $T_{sk}$ can thus be approximated by:

$$\Delta T_{sk} = (T_{skss} - T_{sk0}) (1 - \exp (-S_{sk} \Delta t / C_{sk} (T_{skss} - T_{sk0}))),$$

where $T_{sk0}$ is the skin temperature before the incremental change and $\Delta t$ is the time increment chosen sufficiently small so that the above constraints are satisfied.

In the present study, $T_{skss}$ 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:

$$S_{sk} = M_{sk} - C_{sk} \cdot K_{skbl} + K_{fsk},$$

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 $T_{skss}$ 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

$$T_{BL}(i) = T(i) + (T_{b1} - T(i)) \cdot \exp(-\lambda \cdot \text{COLDS})$$

where $T_{BL}(i)$ is the effective blood temperature in the $i$th compartment, $T(i)$ is the compartment temperature, $T_{b1}$ is the central blood temperature, $\lambda$ 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 ($T_{air-neutral}$) 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:

\[
\text{CHILL} = AD \times [5 \times \text{COLD}(1) \times \text{COLD} + 65 \times \left(\frac{\text{COLD}}{\text{PBF}}\right)^{1.5}],
\]

(4)

where \( \text{CHILL} \) is the metabolic response (W) to the cold stress, \( AD \) is the subject's surface area (m\(^2\)), \( \text{COLD}(1) \) 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 \( \text{PBF} \) 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 \( \lambda \) 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 \( AD \) 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:

\[
\begin{align*}
\text{CHILM (trunk)} &= 0.85 + 0.12 \exp(-0.5 \times t/\text{PBF}) \\
\text{CHILM (arm)} &= 0.05 (1-\exp(-0.5 \times t/\text{PBF})) \\
\text{CHILM (leg)} &= 0.07 (1-\exp(-0.5 \times t/\text{PBF}))
\end{align*}
\]

(5)

where \( \text{CHILM} \) 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 \( \text{CHILM} \) 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 ($T_b$), 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 ($T_{sk}$) 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 \( C_{CLH} \cdot C_{OLS} \) (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.
The 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 (6):

\[ k = C/(T_{te} - \bar{T}_{sh}), \]  

and

\[ h_c = C/(\bar{T}_{sh} - T_w), \]
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 Bouteliers et al. (2). The potential for such a disparity has already been noted by Bouteliers 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 $T_{skss}$ 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 $T_{skss}$ 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/m². 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 Boutejier 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):

$$T_b = x \cdot T_{sk} + (1 - x) \cdot T_{re}, \quad (8)$$

where $x$ varies depending on the environment, then the rate of change of mean
body temperature ($\dot{T}_b$) 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 $\dot{T}_b$ and $\dot{T}_{re}$ listed in Table 2.

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):

$$\dot{T}_b = (M - C \cdot HR)/C_b, \quad (9)$$

where $HR$ 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 $\dot{T}_b$
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

<table>
<thead>
<tr>
<th>$T_w$ (°C)</th>
<th>20</th>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LBF</td>
<td>MBF</td>
</tr>
<tr>
<td>Group Classification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMR (W/m²)*</td>
<td>49.4</td>
<td>47.2</td>
</tr>
<tr>
<td>$T_{re}$ (°C)*</td>
<td>37.48</td>
<td>37.48</td>
</tr>
<tr>
<td>$T_{air-neutral}$ (°C)</td>
<td>28.60</td>
<td>28.38</td>
</tr>
<tr>
<td>$T_{bl}$ (°C)</td>
<td>37.26</td>
<td>37.25</td>
</tr>
<tr>
<td>$T_{sk_{SS}}$ (°C)*</td>
<td>21.0</td>
<td>21.0</td>
</tr>
</tbody>
</table>
Table 2: Model prediction after 1 h of water immersion

<table>
<thead>
<tr>
<th>$T_w$ (°C)</th>
<th>20</th>
<th>23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group Classification</td>
<td>LBF</td>
<td>MBF</td>
</tr>
<tr>
<td>$M$ (W/m²)</td>
<td>221.1</td>
<td>154.0</td>
</tr>
<tr>
<td>$C$ (W/m²)</td>
<td>214.9</td>
<td>166.0</td>
</tr>
<tr>
<td>$HR$ (W/m²)</td>
<td>17.6</td>
<td>12.9</td>
</tr>
<tr>
<td>$T_{re}$ (°C)</td>
<td>36.54</td>
<td>36.61</td>
</tr>
<tr>
<td>$k$ (W/m²/°C)</td>
<td>13.83</td>
<td>10.63</td>
</tr>
<tr>
<td>$h_c$ (W/m²/°C)</td>
<td>214.9</td>
<td>166.0</td>
</tr>
<tr>
<td>$\frac{\Delta T_{re}}{\Delta t}$ (°C/h)</td>
<td>-0.87</td>
<td>-1.13</td>
</tr>
<tr>
<td>$\frac{\Delta T_d}{\Delta t}$ (°C/h)</td>
<td>-0.36</td>
<td>-0.72</td>
</tr>
<tr>
<td>$\frac{\Delta T_{d}'}{\Delta t}$ (°C/h)</td>
<td>-0.32</td>
<td>-0.67</td>
</tr>
</tbody>
</table>

* 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. Lengths of the cylinders are given in cm (26). The central blood compartment is located within the trunk segment. The numbers in parentheses represent the outer radii (cm) of the model segments for the MUF 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 37.48°C and metabolic rate of 67.2 W/m² were inputed as the model subject's thermally neutral trunk core temperature and basal metabolic rate. An air temperature of 28.35°C and an initial central blood temperature of 37.23°C were predicted for a condition of thermal neutrality. The final skin temperature was experimentally-determined (see text).
Fig. 3. Measured (•) ± 2SE and predicted (solid line) rectal temperature ($T_r$) and metabolic rate (M) plotted against time for the LBP 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 MBF group (n=6) immersed in 20°C water. The dashed line shows the prediction according to the Montgomery controller for shivering (21).
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 28°C water. The dashed line shows the prediction
according to the Montgomery controller for shivering (21).
Fig. 6. Measured (●) ± SE and predicted (solid line) rectal temperature ($T_{rb}$) and metabolic rate (M) plotted against time for the MBP group (n=6) immersed in 23°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 ($T_r$), mean skin temperature ($T_{sk}$), metabolic rate ($M$), and convective heat transfer ($C$), for the MBF 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)

\[ h_C = \frac{K_w \, \text{Nu}}{d} \quad \text{(A1)} \]

where \( K_w \) is the thermal conductivity of water, \( \text{Nu} \) 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)

\[ \text{Nu}_f = 0.66 \, \text{Re}^{1/2} \, \text{Pr}^{1/3}, \quad \text{(A2)} \]

where \( \text{Re} \) is the Reynolds number and \( \text{Pr} \) is the Prandtl number. The Reynolds number is determined by

\[ \text{Re} = \frac{V_w \, d}{\nu}, \quad \text{(A3)} \]

where \( V_w \) is the water velocity and \( \nu \) is the kinematic viscosity of water. The Prandtl number is determined by

\[ \text{Pr} = \frac{\nu}{D}, \quad \text{(A4)} \]

where \( D \) is the molecular diffusivity of water.

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

\[ \text{Nu}_f = 0.54 \, (\text{Pr} \cdot \text{Gr})^{1/4}, \quad \text{(A5)} \]

where \( \text{Gr} \) is the Grashof number determined by

\[ \text{Gr} = \beta g D^3 \left( T_{sk} - T_w \right)/\nu^2, \quad \text{(A6)} \]

and where \( \beta \) is the coefficient of thermal expansion of water and \( g \) is the acceleration due to gravity.

If the ratio \( \text{Gr}/\text{Re}^2 \) 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 A: 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 satisfied (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 3710. 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 ($T_{eq}$) and heat storage of the central blood ($P_{blood}$) is displayed. If $T_{eq}$ does not match the initial measured rectal temperature or if $|P_{blood}|$ exceeds 0.1°C/min, then enter new estimates of $T_{neutral}$ and $T_{blood}$. Otherwise, the program calculates a 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, 6 and 7). Following the description of the CONTROLLED SYSTEM, the neutral temperature distribution is given in the compartmental order described earlier where $T_1$, $T_2$, $T_3$ and $T_6$ 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 (hypothalamus) temperature in °C, and **HFSK** is the convective heat loss in W/m² (values greater than 999 are indicated as 999).
REM BASIC listing of RWBC (Thermoreulatory 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, Rapo GM. Aerospace Med v41 1970 p1269-1277
16 REM Ref 5 Garge RP, 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.  
Soringt-Verlag, 1977
20 REM Ref 9 Sekins KM, Emery AF. Thermal Science for Physical Medicine. In :  
21 REM Ref 10 Ruch TC, Patton HD. Physiology and Biophysics. W.B.Saunders. 1965
28 REM
29 REM Identification of body segments and compartments
30 REM
31 REM I refers to body segments as follows
32 REM  1 = head  2 = trunk  3 = arms  4 = hands  5 = legs  6 = feet
33 REM N refers to segment compartments as follows
34 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 heat  
storage of blood = 0 and T(11) = initial measured rectal temperature
66 REM SSSTK = 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 TPR = 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/m²)
79 REM DIFF = difference between compartment temperature and its set-point
80 REM WARM (COLD) = warm (cold) signal
81 REM O = 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.
89 REM
90 LPRINT "RESTING WHOLE BODY COOLING" : LPRINT " " : LPRINT " "
91 REM
92 REM Description of the CONTROLLED SYSTEM
93 REM
94 REM Calculate Body Weight Distribution from Pierson and Eagle (1915).
95 REM
96 REM INPUT "Subject height (cm), weight (kg), and body fat (%)"; HT, WT, PBF
97 REM
98 REM FBF = PBF/100
99 SG = 5.548001/(FBF + 5.044)
100 IF FBF < 0 THEN PRINT "ERROR LINE 140" : END
101 AT = FBF*WT
102 NAT = WT - AT
103 REM
104 REM Calculate Surface Area (SA) from DuBois and DuBois (1915), see Ref 1 p24
105 REM
106 DIM L(7)
107 SA = .007184*WT^0.425*HT^0.725
108 L(2) = .6
109 L(3) = 1.12
110 L(4) = .96
111 L(5) = 1.6
112 L(6) = 1.25
113 REM
114 REM Table of Relative Weight Distribution for Model Compartments (CSWT), see Ref 1 p25
115 REM
116 DIM CSWT(7,1,3)
117 CSWT(1,1,1) = .028232
118 CSWT(1,1,2) = .02518
119 CSWT(1,2,1) = .00588
120 CSWT(2,1,1) = .028232
121 CSWT(2,1,2) = .02518
122 CSWT(2,2,1) = .00588
123 CSWT(3,1,1) = .01764
124 CSWT(3,1,2) = .023756
125 CSWT(3,2,1) = .05328

35
430 CSWT(4,1,1) = .0004704
440 CSWT(4,1,2) = .003648
450 CSWT(4,2,1) = .001188
460 CSWT(5,1,1) = .030362
470 CSWT(5,1,2) = .079168
480 CSWT(5,2,1) = .161
490 CSWT(6,1,1) = .009418
500 CSWT(6,1,2) = .005694
510 CSWT(6,2,1) = .001183
520 CSWT(1,3,1) = .0333
530 CSWT(1,4,1) = .00423
540 CSWT(2,3,1) = .6333
550 CSWT(2,4,1) = .0213
560 CSWT(3,3,1) = .0867
570 CSWT(3,4,1) = .00754
580 CSWT(4,3,1) = .01333
590 CSWT(4,4,1) = .00294
600 CSWT(5,3,1) = .2133
610 CSWT(5,4,1) = .01854
620 CSWT(6,3,1) = .02
630 CSWT(6,4,1) = .00376
650 REM
660 REM Calculate Compartement Weights, SWT(kg), and Thermal Capacitance Values, C(kcal/C), see Ref 1 p26
670 REM
680 DIM SWT(70), C(70)
690 CB = 0
700 FOR I = 1 TO 6
710 FOR N = 1 TO 4
720 SWT(10*I+N-10) = (CSWT(I,N,1) + CSWT(I,N,2))*NAT
730 NEXT N
740 NEXT I
750 CB = CB + C(10*I-7) + C(11) + C(11) + C(10*I-6)
760 NEXT I
770 REM to account for the thermal capacitance of blood in trunk core, see Ref 2 p708
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(I0*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 DM = .18*MR - QSF
890 WC = 0 ; WM = 0 ; WSF = 0
910 FOR I = 1 TO 6
915 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
1080  QB(1) = QB(1) + .164*MR
1090  QB(11) = QB(11) + .56*MR
1100  QC = .82*MR
1120  QB = .29
1130  REM Calculate Basal Blood Flow, BFB(1/n), 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
1220  BFB(4) = 5.34*SWT(4)
1240  BFB(14) = 1.56*SWT(14)
1250  BFB(24) = 1.04*SWT(24)
1260  BFB(34) = 1.05*SWT(34)
1270  BFB(44) = 2.38*SWT(44)
1280  BFB(54) = 1.29*SWT(54)
1300  REM
1310  REM Calculate Compartamental 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

37
1460  \( R(4-N) = (0.75*VOL/\pi)^{1/3} \)
1465  \( RCM(4-N) = (R(4-N)^{3/2} - 0.00375*SWT(4-N)/\pi)^{1/3} \)
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  RCM(10*I-6) = (VOL/(\pi*L(I)))^0.5
1600  R(10*I-6) = (R(10*I-6)^{2} - 0.0035*SWT(10*I-6)/\pi*L(I))^{0.5}
1610  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)))^0.5
1640  RCM(10*I-N-6) = (R(10*I-N-6)^{2} - 0.0035*SWT(10*I-N-6)/\pi*L(I))^{0.5}
1650  A(10*I-N-6) = 2*\pi*R(10*I-N-6)*L(I)
1660  NEXT N
1700  FOR N = 1 TO 3
1785  J = 10*I+N-10
1790  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))
1795  TC(J) = 1/TR(J)
1800  NEXT N
1840  NEXT I
1850  REM
1860  REM End of Description
1870  REM
1880  INPUT "Enter 1 for model description, else 0"; CODE
1890  IF CODE = 0 THEN GOTO 2100
1970  LPRINT " 
1980  LPRINT "HT =" HT " WT =" WT " SG =" SG " FBF =" FBF " SA =" SA 
1990  LPRINT "QC =" QC " QM =" QM " QSF =" QSF 
2010  LPRINT "WC =" WC " WM =" WM " WSF =" WSF 
2020  LPRINT " 
2030  LPRINT "Core Muscle Fat Skin" 
2040  LPRINT " Weight SWT (kg)" : LPRINT " " 
2050  FOR I = 1 TO 6
2060  LPRINT USING "###.### "; SWT(10*I-9),SWT(10*I-8),SWT(10*I-7),SWT(10*I-6)
2070  NEXT I
2080  LPRINT " 
2090  LPRINT "Radius R (cm)" ; LPRINT " " 
2100  FOR I = 1 TO 6
2110  LPRINT USING "###.### "; 100*R(10*I-9),100*R(10*I-8),100*R(10*I-7),100*R(10*I-6)
2120  NEXT I
2130  LPRINT " 
2140  LPRINT "Thermal Capacitance C (kcal/C)" ; LPRINT " " 
2150  FOR I = 1 TO 6
2160  LPRINT USING "###.### "; C(10*I-9),C(10*I-8),C(10*I-7),C(10*I-6)
2170  NEXT I
2180  LPRINT " 
2190  LPRINT "Basal Heat Production OB (kcal/h)" ; LPRINT " " 
2200  FOR I = 1 TO 6
2210  LPRINT " 
38
1970 LPRINT USING "##.##" ; QB(10*I9), QB(10*I8), QB(10*I7), QB(10*I6)
1980 NEXT I
1990 LPRINT "" ; LPRINT "Basal Blood Flow BFB (1/h)" ; LPRINT ""
2000 FOR I = 1 TO 6
2010 LPRINT USING "##.##" ; BFB(10*I9), BFB(10*I8), BFB(10*I7), BFB(10*I6)
2020 NEXT I
2030 LPRINT "" ; LPRINT "Thermal Conductance TC (kcal/C/h)" ; LPRINT ""
2040 FOR I = 1 TO 6
2050 LPRINT USING "##.##" ; TC(10*I9), TC(10*I8), TC(10*I7), TC(10*I6)
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), T(70)
2130 INPUT "Tneutral*rblood Twater ssTSK WORK'I DPRINT TMAX" ; TA, TB, TWAT, SE
2135 DPRINT = DPRINT/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 = 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/(TAIR + 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(11) = 4.5 ; EB(11) = ERES + CRES
2250 REM
2252 REM Table of heat transfer coefficients from skin to air, see Ref 3 p 59
2254 REM
2256 HSS(1) = 6.71*A(4) ; HSS(2) = 5.93*A(14)
REM Calculate compartmental temperature and matrix coefficients for the 4x4 representation of the non-homogeneous system of equations for determining the neutral temperature distribution.

REM Begin Gauss Elimination method by initializing first terms to unity and normalizing accordingly.

REM Begin elimination procedure and normalize.

REM Begin substitutions.

REM Assign set-point temperatures, TSET(C)
REM
T(61) = TB
FOR N = 1 TO 61 : TSET(N) = T(N) : NEXT N
INPUT "Enter 1 for neutral temperature distribution, else 0"; CODE
IF CODE = 0 THEN GOTO 2530
LPRINT "": LPRINT " T1 T2 T3 T4" : LPRINT "" FOR I = 1 TO 6
LPRINT USING "##.##"; T(10*I-9),T(10*I-8),T(10*I-7),T(10*I-6)
RENT Table of skin thermoreceptor inputs and effector outputs, see Ref 1 p32
SKINR(1) = .0695 : SKINR(2) = .4935 : SKINR(3) = .0686
SKINR(4) = .1845 : SKINR(5) = .1505 : SKINR(6) = .0334
SKINS(1) = .081 : SKINS(2) = .481 : SKINS(3) = .154
SKINS(4) = .031 : SKINS(5) = .218 : SKINS(6) = .035
SKINV(1) = .132 : SKINV(2) = .322 : SKINV(3) = 9.500001E-02
SKINV(4) = .121 : SKINV(5) = .23 : SKINV(6) = .1
SKINS(1) = .05 : SKINS(2) = .15 : SKINS(3) = .05
SKINC(4) = .35 : SKINC(5) = .05 : SKINC(6) = .35
REM
REM Start of simulation
TSET(1) = T(1) : TSET(2) = T(2) : TSET(3) = T(3)
TSET(4) = T(4) : TSET(5) = T(5) : TSET(6) = T(6)
LPRINT "TIME TB MR EV TBL TCR TMD TSK HFSK" : LPRINT ""
REM Establish thermoreceptor output and integrate peripheral efferents, see Ref 1 p31-32
REM
REM Determine efferent outflow, see Ref 1 p33
REM
REM Table of distribution factors of heat production for muscle due to exercise (WORKM) and to shivering (CHILM), see Ref 1 p33
WORKM(1) = 0 : WORKM(2) = .3 : WORKM(3) = .08
WORKM(4) = .01 : WORKM(5) = .6 : WORKM(6) = .01
CHILM(1) = .02 : CHILM(2) = .0499999 : CHILM(3) = .05
CHILM(4) = 0 : CHILM(5) = .07 : CHILM(6) = 0
INPUT "Enter 1 for temperature distribution, else 0"; CODE
RENT Start of simulation
REM
LPRINT "": LPRINT " TIME TB MR EV TBL TCR TMD TSK HFSK" : LPRINT ""
REM
REM Determine efferent outflow, see Ref 1 p33
REM
REM Determine efferent outflow, see Ref 1 p33
REM
REM Table of distribution factors of heat production for muscle due to exercise (WORKM) and to shivering (CHILM), see Ref 1 p33
WORKM(1) = 0 : WORKM(2) = .3 : WORKM(3) = .08
WORKM(4) = .01 : WORKM(5) = .6 : WORKM(6) = .01
CHILM(1) = .02 : CHILM(2) = .0499999 : CHILM(3) = .05
CHILM(4) = 0 : CHILM(5) = .07 : CHILM(6) = 0
INPUT "Enter 1 for temperature distribution, else 0"; CODE
RENT Start of simulation
REM
LPRINT "": LPRINT " TIME TB MR EV TBL TCR TMD TSK HFSK" : LPRINT ""
REM
REM Determine efferent outflow, see Ref 1 p33
REM
REM Determine efferent outflow, see Ref 1 p33
CHILM(2) = .6493993 + .12*X ; CHILM(3) = .05*(1 - X) ; CHILM(5) = .07*(1 - X)

SWEAT = 32*DIFF(1) + 29*(WARM - COLDS)

DILAT = 117*DIFF(1) + 7.5*(WARM - COLDS)

CHILL = SA/1.163*(C1*COLDS^C3/PBF^C4 + C2*COLD(1)*COLDS^C5/PBF^C6)

STRIC = -5*DIFF(1) + 5*(COLDS - WARM)

IF SWEAT ( 0 THEN SWEAT = 0

IF DILAT ( 0 THEN DILAT = 0

IF CHILL ( 0 THEN CHILL = 0

IF STRIC ( 0 THEN STRIC = 0

REM

REM Assign efferent output, see Ref 1 p 34-35

REM

FOR I = I TO 6

Q(10*I-9) = QB(10*I-9)

Q(10*I-8) = QB(10*I-8) + WORKM(I)*WORKI + CHILM(I)*CHILL

BF(10*I-9) = BFB(10*I-9)

BF(10*I-8) = BFB(10*I-8) - Q(10*I-8) - QB(10*I-8)

G(10*I-7) = QB(10*I-7)

G(10*I-6) = QB(10*I-6)

BF(10*I-7) = BFB(10*I-7) - Q(10*I-7)

BF(10*I-6) = (BFB(10*I-6) + SKIN(1)*DILAT)/(1 + SKINC(I)*STRIC)) * 2^(DIFF(10*I-6)/6)

NEXT I

REM evaporative heat loss from the head, see Ref 2 p 708 & 712

E(1) = EB(1)

REM resired evaporative and convective heat loss, see Ref 5 p 246

ERES = .001978*MR*(44 - PAIR)

CRES = .001032*MR*(34 - TAIR)

E(11) = ERES + CRES

REM Calculate total metabolic rate

MR = 0

FOR I = 1 TO 6 : FOR N = 1 TO 4

MR = MR + Q(10*I+N-10)

NEXT N : NEXT I

REM

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

REM

FOR I = I TO 6

DELT = T(10*I-6) - TWAT

REM Initial heat flow is approximated by assuming minimal forced convection - after steady state is attained, heat flow is determined by assuming zero heat storage for the immersed skin

VEL = 18

REM linear aor of kinematic viscosity (cm*cm/s) from CRC

VU = .0148 - .000224*TWAT

REM Reynolds No. where factor .36 converts VU to m*m/h

RE = 2*R(10*I-6)*VEL/(.36*VU)

REM linear aor of Pranotl No. based on 9.5 at 10C and 7.3 at 22C

PR = 11.3 - .18*TWAT

REM Nusselt No. for forced convection, see Ref 8 p 66

NUFO = .66*RE^(.5)*PR^(-1/3)

REM linear aor of thermal expansion of water (1/C) from CRC
REM Grashof No. where factor $10^{-6}$ to convert $R(m)$ to $R(cm)$ is imbedded in coefficient of NUF, see Ref 8 & 65

$$GR = 980 \times TE \times (2 \times R(10 \times I-6))^{3/2} \times (T(10 \times I-6) - TWAT) / VU^{2}$$

REM Nusselt No. for free convection, see Ref 8 & 69

$$NUFR = 17.1 \times (GR \times PR)^{0.25}$$

REM heat transfer coefficient assuming $Kw = 0.52$ kcal/m/h/°C from CRC

$$HSS(I) = 0.52 \times (NUF0 + NUFR) \times A(10 \times I-6) / (2 \times R(10 \times I-6))$$

NEXT I

REM Calculate heat flows HF (kcal/h), see Ref 1 & 36

FOR I = 1 TO 6 : FOR N = I TO 4

TBL(I10*I+N-10) = T(61)

NEXT N : NEXT I

FOR I = 1 TO 6

BC(J) = 0.9 BF(J) * (T(J) - TBL(J))

TD(J) = TC(J) * (T(J) - T(J+1))

NEXT N

BC(10*I-6) = 0.9 BF(10*I-6) * (T(10*I-6) - TBL(10*I-6))

TD(10*I-6) = HSS(I) * (T(10*I-6) - TWAT)

HF(10*I-9) = Q(10*I-9) - E(10*I-9) - BC(10*I-9) - TD(10*I-9)

FOR N = 2 TO 4

HF(10*I+N-10) = Q(10*I+N-10) - E(10*I+N-10) - BC(10*I+N-10) + TD(10*I+N-10)

NEXT N

HF(61) = 0

FOR I = 1 TO 6 : FOR N = 1 TO 4

HF(61) = HF(61) + BC(10*I+N-10)

NEXT N : NEXT I

WRITE HEAT FLOWS

REM Determine optimum integration step, DT (change in T cannot ) 0.1 C

DT = TPR - TIM

FOR I = 1 TO 6 : FOR N = 1 TO 3

F(10*I+N-10) = HF(10*I+N-10) / C(10*I+N-10)

IF .1 / ABS(F(10*I+N-10)) < DT THEN DT = .1 / ABS(F(10*I+N-10))

NEXT N

IF .1 / ABS(F(10*I-6)) < DT THEN DT = .1 / ABS(F(10*I-6))

NEXT I

F(61) = HF(61) / C(61)

REM Check that initial conditions are satisfied; if not, then start over

with new estimates of $T_{neutral}$ and $T_{blood}$
3880 IF INIT = 0 THEN PRINT "Tr ="T(11) "Fblood ="F(61) : INPUT "Enter 1 to restart, else 0" : INIT
3890 IF INIT = 0 THEN GOTO 2130
3900 REM
3910 REM Calculate new temperatures
3920 REM
3930 FOR I = 1 TO 6 : FOR N = 1 TO 3
3940 T(10*I+N-10) = T(10*I+N-10) + F(10*I+N-10)*DT
3950 IF T(10*I+N-10) < TAT THEN PRINT "TEMP"10*I+N-10"="T(10*I+N-10) : END
3960 NEXT N
3970 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
3980 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 3960
3990 T(10*I-6) = SSTSK + TDIFF*EXP(F(10*I-6)*DT/TDIFF)
4000 NEXT I
4010 T(61) = T(61) + F(61)*DT
4020 IF TPRT = 0 THEN GOTO 4300
4030 REM Print results
4040 FOR I = 1 TO 6 : FOR N = 1 TO 4
4050 CO = CO + BP(10*I+N-10)/60
4060 TB = TB + T(10*I+N-10)*C(10*I+N-10)/CB
4070 NEXT N : NEXT I
4080 REM Calculate total evaporative heat loss (kcal/h)
4090 EV = E(1) + E(4) + E(11)
4100 REM Calculate skin temperature and skin heat flow (kcal/h)
4110 REM Note that when calculating TDskin, transition occurs when Tskin is within 0.005C of its steady-state value
4120 TSK = 0 : HFSK = 0
4130 FOR I = 1 TO 6
4140 TSK = TSK + T(10*I-6)*C(10*I-6)/CS
4150 HFSK = HFSK + TD(10*I-6)
4160 NEXT I
4170 REM Note conversion from kcal/h to W
4180 IF 1.163*HFSK/SA 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
4200 IF CODE = 0 THEN GOTO 4200
4210 FOR I = 1 TO 6 : LPRINT USING "###.##", T(10*I-9), T(10*I-8), T(10*I-7), T(10*I-6)
4220 NEXT I
4230 TPRT = TPRT + DPRT
4300 IF TMAX < TPRT THEN END ELSE GOTO 2780
RESTING WHOLE BODY COOLING

\[ \begin{align*}
HT &= 175.7 \quad WT = 79.2 \quad SG = 1.062795 \quad FBF = 0.1762 \quad SA = 1.953368 \\
QC &= 64.9995 \quad QM = 8.930359 \quad QSF = 5.337824 \\
WC &= 28.39902 \quad WM = 33.00977 \quad WBF = 17.79112
\end{align*} \]

<table>
<thead>
<tr>
<th>Core</th>
<th>Muscle</th>
<th>Fat</th>
<th>Skin</th>
</tr>
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<tbody>
<tr>
<td>Weight SWT (kg)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3.485</td>
<td>0.384</td>
<td>0.465</td>
<td>0.276</td>
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<tr>
<td>14.737</td>
<td>18.490</td>
<td>8.838</td>
<td>1.390</td>
</tr>
<tr>
<td>2.318</td>
<td>3.476</td>
<td>1.210</td>
<td>0.498</td>
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<tr>
<td>0.269</td>
<td>0.078</td>
<td>0.186</td>
<td>0.192</td>
</tr>
<tr>
<td>7.146</td>
<td>10.304</td>
<td>2.977</td>
<td>1.236</td>
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<tr>
<td>0.445</td>
<td>0.078</td>
<td>0.279</td>
<td>0.245</td>
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</tbody>
</table>

| 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)

<p>| | | | | |</p>
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<tr>
<td>6.91</td>
<td>8.88</td>
<td>9.44</td>
<td>0.00</td>
<td></td>
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</tbody>
</table>

### Segment Surface Area A (m²/m)

\[
A_1 = 0.133937 \\
A_2 = 0.5724 \\
A_3 = 0.324942 \\
A_4 = 9.346019E-02 \\
A_5 = 0.6630005 \\
A_6 = 0.1282577 \\
A_B = 1.915998
\]

### Neutral-air = 28.85 C  Tblood = 37.25 C  Twater = 20 C

\[
C_0 = 24.43 \\
C_1 = 65 \\
C_2 = 5 \\
C_3 = 1.5 \\
C_4 = 1.5 \\
C_5 = 1 \\
C_6 = 0 \\
C_7 = 0
\]

### Time (min) | T1 | T2 | T3 | T4
---|---|---|---|---
0.00 | 37.42 | 35.79 | 35.38 | 35.01
6.00 | 37.41 | 35.78 | 35.38 | 35.00
12.00 | 37.39 | 35.77 | 35.38 | 35.00
18.00 | 37.38 | 35.76 | 35.38 | 35.00
24.00 | 37.37 | 35.75 | 35.38 | 35.00
30.00 | 37.36 | 35.74 | 35.38 | 35.00
36.00 | 37.35 | 35.73 | 35.38 | 35.00
42.00 | 37.34 | 35.72 | 35.38 | 35.00
48.00 | 37.33 | 35.71 | 35.38 | 35.00
54.00 | 37.32 | 35.70 | 35.38 | 35.00
60.00 | 37.31 | 35.69 | 35.38 | 35.00

### 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 | 36.95 | 36.95 | 21.00 | 186.16
36.00 | 32.13 | 126.75 | 11.10 | 36.83 | 36.85 | 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 | 31.73 | 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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