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Prediction of Dynamic Temperature Distributions in the Human Body

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A detailed procedure is presented for the calculation of unsteady state temperature distributions throughout the human body. The adequacy of the proposed computation procedure is demonstrated by comparison of calculated and experimental results for studies conducted on subjects exposed to decreasing ambient temperatures. Core temperatures were predicted within ±0.2°C, and average deviations for individual skin temperatures generally were within ±0.5°C.

SCOPE

Proposed control mechanisms for use in predicting human thermoregulatory responses to various types of heat and exercise transients can be evaluated only through the use of an acceptable model of the controlled body system.

Computer simulation of the human thermal system would be of value to both engineers and clinicians. The availability of such techniques could provide a rational basis for improving the efficiency of human performance, especially in stressful thermal environments, of production workers, miners, and even be useful in the conditioning of athletes. In the medical field one can envisage a variety of potential applications including the improved management of fevers, better maintenance of body heat balance during surgery, as well as more effective application of heat and exercise modalities in physical therapy regimens prescribed for paralytic patients.

On the other hand, the procedures described in this paper demonstrate generally applicable methods for treating the dynamics of distributed parameter systems having both internal heat generation and partial internal regulation of heat dissipation. Since the operation of large packed bed reactors bears many analogies to such a system, the techniques developed for the physiologic system may well be used to advantage in the analysis of such corresponding technological situations.

The present paper constitutes an extension of our previous work (Huckaba et al., 1973), concerned with steady state temperature distributions, to the dynamic case. Prior developments reported by both a chemical engineer (Wissler, 1970) and a biophysicist (Stolwisk, 1970) also constituted valuable background resources. In neither instance, however, was a comparison provided of computed and experimental values of individual skin temperatures. Comparison of mean skin temperatures constitutes a less critical test of the efficacy of a proposed model than the direct comparison of individual values as provided in this study.

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CONCLUSIONS AND SIGNIFICANCE

The present paper demonstrates the adequacy of the proposed model for predicting temperature distributions throughout the human body for unsteady state conditions. Direct comparison of calculated and observed values for studies on subjects exposed to decreasing ambient temperatures show deviations of about 0.2°C for core temperatures (ear drum and oral) and average deviations of about 0.5°C for eleven skin temperatures. In view of the inherent variability of the physiologic system and the fact that its thermal state is affected by emotional as well as physiologic stimuli, it is believed that major efforts to effect further refinements in the model are not indicated at this time.

The major contributions of this work compared to that of previous investigators lies in the use of forty-five lumped nodes to approximate the distributed parameter system and in various refinements effected in the basic physiologic and thermal parameters involved in the body heat balance equations shown in Table 1. The most significant improvements were achieved with respect to allowing for the time variations of metabolic heat distribution, blood flow distribution, and for the heat given up by the blood to surrounding tissues in flowing along the arms and legs.

Since obvious constraints apply to making invasive measurements in human subjects except under therapeutically justifiable circumstances, direct observations of body temperatures generally can be made only on the surface of the skin and in the natural body orifices such as the ear, mouth, and rectum. However, in many instances subcutaneous and other relatively inaccessible internal temperatures may be more pertinent to the guidance of therapy or to the assessment of work or exercise stresses. Only by predictive methods, such as outlined in this paper, can such information be obtained.

Temperature distribution in the body is a complex function of many interacting physiologic, emotional, and environmental variables. Although the various elements comprising the human thermal system are very closely intertwined, it has been customary to consider it as consisting of a controlled (passive) system and a controlling (active) system. Although such an artifice subdivides the problem into more manageable proportions for purposes of analysis, the prediction of responses to various thermal stresses must involve the simultaneous solution of mathematical models for each of these subsystems.

Two basic approaches to the thermal modeling of the human body are described in the literature. Wissler (1970) attempted to deal realistically with the distributed properties of the system, allowing for both geometric and time variations in body temperatures. His basic model is in the form of a series of partial differential equations, but solution on a digital computer requires their transformation to a corresponding set of approximate finite difference equations.

All of the other workers including Smith and James (1964) and Stolwijk and Hardy (1966) approximated the distributed parameter system in terms of lumped parameter configurations composed of various numbers and types of simple geometric elements. They divided the body into gross anatomical segments (for example, head, trunk, extremities), each of which in turn was considered to consist of a series of concentric cylindrical layers (for example, core, muscle, skin), although in a later paper Stolwijk (1970) represented the head as a sphere. Although temperature curves predicted on the basis of these representations showed reasonable contours, comparison of computed and observed values was generally limited to values of mean skin temperature, and it is possible that even greater deviations than those shown occurred for individual skin temperatures.

The present paper represents an extension of our previously reported work (Huckaba et al., 1973) on the calculation of steady state temperature distributions. Adequate representation of the body thermal system under unsteady state circumstances has required an increase in lumped nodes from twenty-five to forty-five as well as taking into account the time variations of metabolic heat distribution, blood flow distribution, heat losses from blood in flowing along the extremities, and heat exchange between the body surface and the environment.

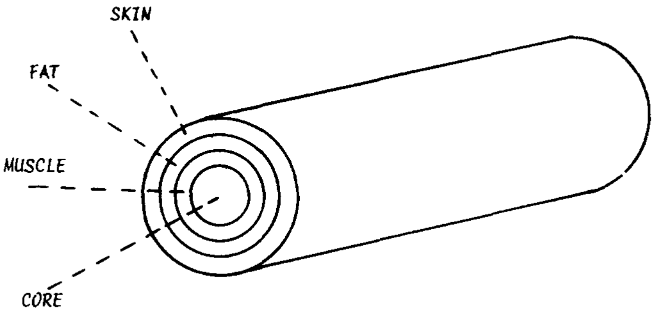

Fig. 1. Four-layer model.

MODEL FORMULATION

The model follows the same basic format as that outlined by Stolwijk (1970) and in our previous paper (Huckaba et al., 1973). The dynamic model consists of eleven cylindrical anatomical segments: head, neck, upper trunk, lower trunk, upper arms, forearms, hands, fingers, thighs, legs, and feet. In the case of extremity segments, single cylinders are used to represent corresponding pairs of elements together; that is, one cylinder for the two forearms, etc.

Each of the eleven cylindrical subsections is, in turn, subdivided into four concentric layers: core, muscle, fat, and skin, as shown in Figure 1. In addition, a central blood compartment is included, so that the lumped parameter representation consists of a total of forty-five nodes.

The mathematical model for use in predicting dynamic temperature distributions consists of unsteady state heat balance equations for each of these anatomical sections. For any given anatomical segment such as the head, neck, etc., the equations follow the format shown in Table 1.

In each equation the metabolic heat production and the blood flow rate consists of that fraction of each of the total body quantities assigned to the individual node. The term for the heat transferred through the inner surface of a cylindrical section by conduction involves the use of mean thermal conductances as described by Huckaba et al. (1973). The core section, having no inner surface, has no term corresponding to this category. Conductive heat transfer also occurs through the outer surface of each subele-

TABLE 1. UNSTEADY STATE HEAT BALANCE EQUATIONS APPLYING TO EACH ANATOMICAL SEGMENT

	Metabolic heat production		Heat transfer through inner surface		Heat transfer through outer surface		Heat exchange with blood		Change in storage	
Core	M_c	+	0	−	$(TC)_c\,(T_c - T_m) + E_R^*$	−	$CBF\,(c_B)\,(T_c - T_e)$	=	$m_c c_c \frac{dT_c}{dt}$	(1-1)
Muscle	$M_m + H_B^\dagger$	+	$(TC)_c\,(T_c - T_m)$	−	$(TC)_m\,(T_m - T_f)$	−	$MBF\,(c_B)\,(T_m - T_e)$	=	$m_m c_m \frac{dT_m}{dt}$	(1-2)
Fat	M_f	+	$(TC)_m\,(T_m - T_f)$	−	$(TC)_f\,(T_f - T_s)$	−	$FBF\,(c_B)\,(T_f - T_e)$	=	$m_f c_f \frac{dT_f}{dt}$	(1-3)
Skin	M_s	+	$(TC)_f\,(T_f - T_s)$	−	$(E_s + C + R)$	−	$SBF\,(c_B)\,(T_s - T_e)$	=	$m_s c_s \frac{dT_s}{dt}$	(1-4)

For eleven anatomical segments we have forty-four equations. Also

$$T_{CB} = \frac{\Sigma[(BF_i)\,(T_i)]}{\Sigma(BF_i)} = \frac{\Sigma[(BF_i)\,(T_i)]}{\text{C.O.}} \quad (1\text{-}5)$$

* E_R Applies only to head core and represents respiratory evaporative heat loss.
† H_B Represents the fraction of heat lost by blood flowing through specified segments which is transferred to muscle layers.
N.B.: T_e, the entering blood temperature, is assumed equal to T_{CB} except in those cases where blood cooling occurs and T_e is below T_{CB} as indicated in Table 5.

ment except for the skin, which loses heat by evaporation E_S, convection C, and radiation R. Heat exchange with the blood is proportional to the change in temperature in the blood as it flows through a given section. The net change of all of these heat transfer rates constitutes the change of heat storage in each node.

Although the basic set of equations outlined in Table 1 applies to each of the eleven anatomical segments, in the case of the head core an additional term must be added to the output side to account for respiratory evaporative heat loss E_R. Furthermore, it was found necessary to account for heat loss to the surrounding muscle tissues and venous blood vessels from the arterial blood flowing along the extremities. Consequently, the inlet blood temperature T_e is equal to the central blood temperature, except in the case of the extremities.

In addition to the resulting forty-four unsteady state heat balance equations written in this format, there is another equation used to calculate the mixed blood temperature as it flows back into the central blood compartment from the various anatomical segments. In order to predict unsteady state temperature distribution curves, it is necessary to solve simultaneously the forty-five equations comprising the model by using a digital computer.

SPECIFICATION OF MODEL PARAMETERS

Before temperatures can be calculated, it is necessary to supply values for all the other variables contained in this set of forty-five equations. Even though our basic model is similar in broad outline to that used by Stolwijk (1970), substantial adjustments have been made in the detailed specification of most of the supplementary relationships and parameters.

Anatomical parameters for use in evaluating the masses of each of the forty-four tissue segments and the areas of the eleven skin sections were evaluated individually for for each of the subjects, listed in Table 2, by using procedures outlined in our prior paper (Huckaba et al., 1973).

Blood Flow

One of the significant features of the proposed model is the use of a more realistic blood flow distribution based upon both information found in the literature and our direct measurements on the subjects. Cardiac output under conditions of rest was estimated from the oxygen consumption as directly measured in each study. A linear relationship between cardiac output and oxygen consumption was given by Ekelund and Holmgren (1967) as follows:

$$\text{C.O.} = 6.17 + 0.0063\,\dot{V}_{O_2} \quad (1)$$

Total cardiac output for the resting condition was distributed among the forty-four nodes as shown in Table 3.

TABLE 2. PHYSICAL CHARACTERISTICS OF SUBJECTS

Subject	Height (cm)	Weight (Kg)	Body surface area (m^2)
JD	191	77	2.06
CH	186	77	2.02

TABLE 3. BLOOD FLOW DISTRIBUTION AT REST (%)
@ $T_a = 30°C$

	Core	Muscle	Fat	Skin	Total
Head	11.36	0.15	0.00	1.30	12.81
Neck	6.82	4.70	0.00	0.80	12.32
Upper trunk	18.94	6.62	0.00	1.45	27.01
Lower trunk	28.33	9.92	0.00	2.18	40.43
Upper arm	0.00	0.97	0.00	0.11	1.08
Forearms	0.00	0.97	0.00	0.11	1.08
Hands	0.00	0.05	0.00	0.43	0.48
Fingers	0.00	0.05	0.00	0.43	0.48
Thighs	0.00	1.50	0.00	0.15	1.65
Legs	0.00	1.50	0.00	0.15	1.65
Feet	0.00	0.11	0.00	0.90	1.01
Total	65.45	26.54	0.00	8.01	100.00

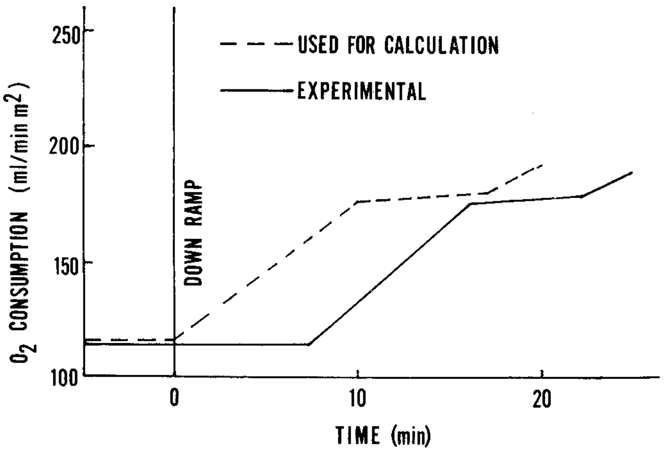

Fig. 2. Metabolic response, study CH.

TABLE 4. METABOLIC DISTRIBUTION AT REST (%)

@ $T_a = 30°C$

	Core	Muscle	Fat	Skin	Total
Head	20.00	0.13	0.08	0.09	20.30
Neck	3.00	0.13	0.08	0.09	3.30
Upper truck	22.57	4.05	0.98	0.38	27.98
Lower trunk	33.70	6.10	1.48	0.42	41.70
Upper arms	0.25	0.55	0.10	0.11	1.01
Forearms	0.25	0.55	0.10	0.17	1.07
Hands	0.05	0.02	0.03	0.05	0.15
Fingers	0.05	0.02	0.02	0.05	0.14
Thighs	0.44	1.24	0.20	0.20	2.08
Legs	0.35	0.93	0.15	0.20	1.63
Feet	0.24	0.07	0.13	0.20	0.64
Total	80.90	13.79	3.35	1.96	100.00

The distribution of cardiac output among the total body skin, muscle, and visceral tissues was based on values given by Wade and Bishop (1962) and Chien (1971). Venous occlusion plethysmography (Greenfield et al., 1963) was used to measure hand and forearm blood flow in the subjects studied. On the basis of general information summarized by Abramson (1967), it was assumed that approximately 90% of the hand blood flow occurs in the skin and 10% in the muscle; in the arm the distribution was taken as 90% to the muscle and 10% to the skin. The blood flow values listed in the table for the foot skin and muscle were obtained by using the same total blood flow rate per unit mass and the same layer distribution as in the hand. A similar procedure was employed to obtain the values for the leg relative to the arm. In estimating the blood flow distribution, it was further assumed that there was minimal flow to fat and bone, and that it could be neglected. The final distribution of blood flow as shown in Table 3 resulted from a meticulous, evolutionary trial-and-error procedure involving repeated calculations and blood flow adjustments until each segment showed good agreement between calculated and observed physiologic temperatures.

It was also necessary to allow for blood flow variations as a function of time during the dynamic response period. Based on both experimental observations and information in the literature on vasoconstriction, all skin areas were assumed to be constricted along a linear pathway to 9% of the steady state value at 20 min. of the unsteady state period. Muscle blood flow, on the other hand, because of shivering, was assumed to have increased by 100% in a linear manner at this 20 min. time.

Metabolic Heat Production

The total metabolic heat production was obtained by laboratory measurement of oxygen consumption, by using methods to be described later. An average value of 4.82 Kcal/l oxygen was used for the caloric equivalent of oxygen (Gemmill and Brobeck, 1968). The distribution of the total heat of metabolism among skin, muscle, and visceral tissues follows the percentages listed by Aschoff and Wever (1958). An unassigned 10.5% was proportioned according to mass to the remaining tissues not accounted for in their compilation: additional trunk viscera, fat, bone, and connective tissue. The percentage metabolic distribution at rest is shown in Table 4, and a typical time variation of total metabolic heat production is shown in Figure 2. The increase of metabolic heat during the down ramp period is distributed among the muscle layers of the eleven segments as follows: head 0.35%, neck 0.35%, upper trunk 34.0%, lower trunk 51.0%, thigh 4.8%, leg 4.8%, foot 0.1%, upper arm 2.3%, forearm 2.3%, hand 0.0%, finger 0.0%.

Heat Loss Data

Total evaporative heat loss was evaluated by direct measurement on the subject, by using a sensitive bed scale capable of detecting weight changes to within ±0.5 g. The convective heat loss was calculated from the experimental ambient and mean skin temperatures as follows:

$$C = h_c A_s (T_a - \overline{T}_s) \qquad (2)$$

Free convection was assumed, and the heat transfer coefficient was adapted from the data given by Hardy and DuBois (1938). Heat loss due to radiation was computed from the measured wall and mean skin temperatures as follows:

$$R = h_r A_r (T_w - \overline{T}_s) \qquad (3)$$

$$h_r = \sigma \epsilon_s \epsilon_w (T_w^2 + \overline{T}_s^2)(T_w + \overline{T}_s) \qquad (4)$$

where

σ = Stefan-Boltzmann constant
= 4.88×10^{-8} Kcal/m²-hr.-°K⁴
ϵ_s = emissivity of the skin
ϵ_w = emissivity of the surrounding walls

Thus, the radiative heat transfer coefficient is a function of the radiation area, the view factor, the emissivities of the body and surrounding surfaces, and the temperatures of the surfaces. In this computation, the observed skin temperatures were weighted in proportion to the surface areas of the eleven anatomical segments. Radiative view factors representing the fraction of each section of the anatomy exchanging radiation with the surroundings rather than with another part of the body were estimated as follows: 0.6 for the head and neck, 0.9 for the trunk, and 0.8 for the extremities.

Respiratory heat loss assigned to the head core in the model was estimated by the methods described by Fanger (1970). The balance of the evaporative loss was distributed to the various skin layers in proportion to both their relative surface area and weighting factors to allow for the variation in rate of insensible water loss in different body areas. Based on data given by Kuno (1956), the factors used were as follows: hands and feet = 4, head = 2, remainder of body = 1.

Table 5. Blood Cooling in the Extremities

@ Steady state

Segment	$T_{CB} - T_e$ (°C)
Thigh	0.10
Leg	0.25
Foot	0.33
Upper arm	0.15
Forearm	0.48
Hand	0.85
Finger	1.20

Loss of Heat from Arterial Blood in Extremities

For all anatomical segments except for the extremities, the entering blood temperature is assumed to be equal to the central blood temperature. However, because of the fact that as blood proceeds along the extremities away from the trunk there is loss of heat, it was estimated that the blood entering the various extremities segments had cooled below the central blood temperature by the amounts shown in Table 5. This heat loss by the blood in passing through the arms and legs was assumed to be transferred to the muscle layers (60%) and venous blood vessels (40%) of these segments.

EXPERIMENTAL METHODS

A series of unsteady state studies was performed on two subjects (Table 2) not only to provide improved values of some of the basic parameters involved in the model, but also to serve as a means of checking the ability of the model to predict unsteady state temperature distributions. In these cases the subject, lying on a nylon mesh trampoline, was exposed first to a constant temperature, close to 30°C, constant humidity environment, and allowed to achieve thermal equilibrium as indicated by constancy of the various physiologic temperatures being monitored. Then followed a down ramp in room temperature to around 15°C in order to induce a metabolic thermoregulatory response. The air movement in the room was kept at a minimum during the whole period.

The same experimental techniques as described in our previous paper (Huckaba et al., 1973) were employed to monitor physiologic and environmental temperatures, relative humidity of the room, evaporative weight loss from the body, change in oxygen consumption (metabolic activity), and changes in blood flow to hand and forearm areas. Nineteen thermocouples were assigned to the following body locations: mouth (under the tongue) or ear drum, forehead, cheek, neck, chest, anterior shoulder, abdomen, lower left trunk, mid-back, right thigh, left thigh, left calf, left foot, left upper arm, right upper arm, left forearm, left palm, right palm, and left index finger. Four thermocouples were used at the following environmental locations: ambient air space above subject, and wall, floor, and ceiling of room.

All data were recorded as a function of elapsed time throughout the course of the unsteady state response period.

COMPARISON OF CALCULATED AND OBSERVED TEMPERATURE PROFILES

In order to subject the model and the associated parameter evaluation procedures to a definitive test, it was desired to see how well various physiologic temperatures observed during unsteady state studies could be predicted by computation. The calculations involved solving a set of forty-five simultaneous first-order ordinary differential equations. In the basic computation of temperature distributions, the Runge-Kutta method was employed. Calculations were repeated at a time interval of 0.01 min. during the transient period. The matrices of model parameters as described previously were allowed to vary with time. Such variations

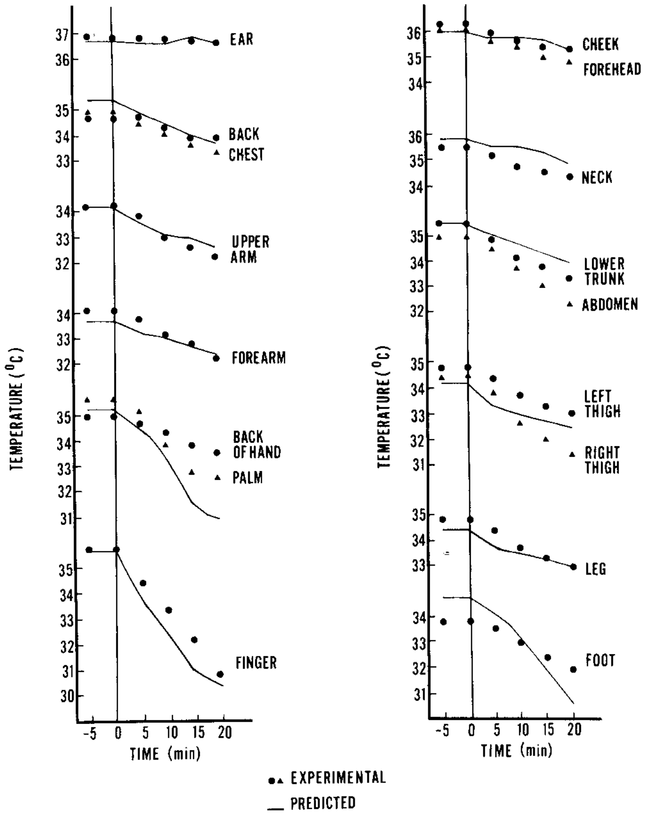

Fig. 3. Calculated vs. experimental results, subject JD.

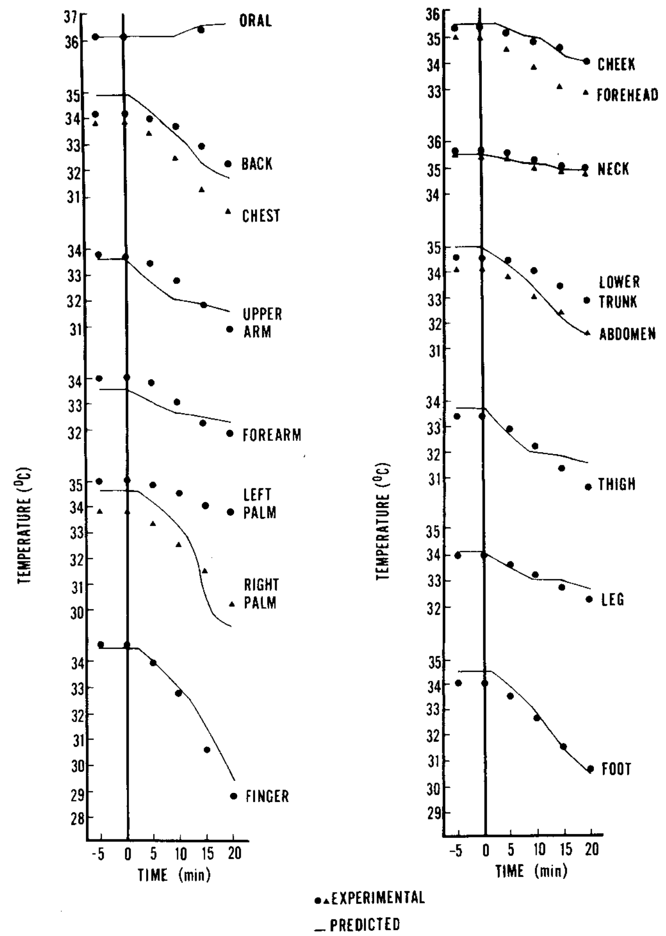

Fig. 4. Calculated vs. experimental results, subject CH.

Table 6. Calculated Temperature Profiles (°C) for Study *JD*

Segment / Layer	Upper trunk	Neck	Head	Lower trunk	Thigh	Leg	Foot	Upper arm	Forearm	Hand	Finger
(a) $t = 0$ (Initial steady state) Ambient temp. = 29.2°C											
Core	36.7	36.6	36.7	36.7	36.1	35.7	35.1	35.9	35.2	35.5	35.8
Muscle	36.6	36.5	36.5	36.6	36.0	35.6	35.1	35.8	35.2	35.4	35.7
Fat	36.0	36.5	36.5	35.8	35.1	34.7	34.9	34.9	34.1	35.2	35.6
Skin	35.4	35.8	36.0	35.4	34.2	34.4	34.8	34.2	33.6	35.0	35.5
(Mean skin temp. = 34.8°C; Central blood temp. = 36.6°C)											
(b) $t = 10$ min. Ambient temp. = 24.2°C											
Core	36.8	36.7	36.7	36.8	36.0	35.5	34.1	35.6	35.0	33.7	32.6
Muscle	36.9	36.6	36.5	36.8	35.9	35.5	34.0	35.5	34.9	33.6	32.5
Fat	35.6	36.5	36.5	35.3	34.5	33.9	33.6	34.1	33.5	33.4	32.4
Skin	34.5	35.5	35.8	34.6	32.9	33.5	33.1	33.1	33.0	33.1	32.2
(Mean skin temp. = 33.9°C; Central blood temp. = 36.6°C)											
(c) $t = 20$ min. Ambient temp. = 22.9°C											
Core	36.7	36.6	36.6	36.7	35.9	35.4	32.2	35.4	34.8	31.6	30.7
Muscle	36.8	36.5	36.3	36.7	35.8	35.3	32.1	35.3	34.6	31.5	30.6
Fat	35.2	36.4	36.2	34.7	34.2	33.5	31.4	33.8	33.0	31.2	30.3
Skin	33.7	34.8	35.3	33.9	32.4	33.0	30.6	32.7	32.4	30.7	30.2
(Mean skin temp. = 33.1°C; Central blood temp. = 36.6°C)											

Table 7. Thermal and Flow Quantities for Study *JD*

	Time (min.) 0	10	20
Metabolism, Kcal/h	61.4	82.7	84.8
Evaporation, Kcal/h	31.3	21.8	21.8
Radiation, Kcal/h	27.8	41.7	47.6
Convection, Kcal/h	14.0	29.4	31.1
Cardiac output, l/min.	7.50	7.97	8.02
Total muscle blood flow, l/min.	1.99	2.52	2.58
Total skin blood flow, l/min.	0.61	0.33	0.22

were formulated either from measured data (for example, the metabolic heat production and heat loss data) or from postulations derived after numerous trial-and-error procedures (for example, the blood flow distribution and the arterial blood cooling in extremities). The calculations were carried out to 20 min. after the room temperature down ramp, during which time the major dynamic skin temperature responses occur and thus constitute the greatest challenge to the predictive capability of the model.

Four studies, two on each subject, were conducted, and corresponding calculations were performed for each case. Figure 3 shows a comparison of calculated vs. observed temperatures for one of the studies on subject JD, and Figure 4 shows the same for subject CH. Similar results were obtained as well in the other two studies.

Examination of the calculated and observed temperature values shown in these figures indicates that head core temperatures agree with ±0.2°C, and, except for a few cases, average skin temperature deviations generally are within ±0.5°C. In some cases where there is only single thermocouple readings for a given anatomical segment, for example, neck of study JD (Figure 3), it is possible that the experimental data is in error because of faulty attachment of thermocouple to the skin.

In order to achieve the agreement shown in Figures 3 and 4 between computed and experimental results, it was necessary to incorporate a time lag in the observed metabolic response data, such as that shown in Figure 2 for study JD. Physiologic considerations supporting this procedure are discussed in the next section.

Further evidence relative to the validity of the calculation procedure is shown in Table 6, in which the calculated temperatures at three selected times for all of the forty-five nodes in the model are summarized for a typical study (JD). Table 7 lists corresponding thermal and flow quantities. These results show several interesting features relative to the response induced as the ambient temperature drops from 29.2° to 22.9°C over a period of 20 min.

1. The temperature gradient from the core to outer skin surface increases with time in each segment.
2. Although temperatures in the extremities generally decrease in the distal direction, there are a number of exceptions in the finger, hand, and foot values. As indicated by Abramson (1967), these anomalies are probably due to blood flow effects in these segments.
3. The core temperatures of the head, neck, and trunk remain almost constant, even though the skin segments are cooled significantly.
4. The central blood temperature remains always at 36.6°C.
5. Cardiac output increases as the ambient temperature decreases.
6. Total muscle blood flow increases at the colder temperatures.
7. Total skin blood flow decreases with the mean skin temperature.

These results generally are in agreement with currently accepted concepts of thermoregulatory physiology and thereby add credence to the viability of the proposed calculation procedure to that supplied directly in Figures 3 and 4.

DISCUSSION OF RESULTS

In view of the good agreement between calculated and observed values, it is concluded that the procedure described above is adequate for calculating unsteady state temperature distributions in the human body under conditions of decreasing ambient temperature. Although there are several areas, especially with respect to the evaluation of the basic parameters, in which significant improvements have been achieved, much empiricism remains. Allowing for the temperature gradient of the blood as it passes through the extremities is supported by physiological evidence (Aschoff and Wever, 1958), which means that a proper representation would require allowance for geometric as well as temporal variations, that is, a distributed parameter model. The measures adopted in our calculation method, although approximate, permitted us to preserve the calculational convenience of the lumped parameter format.

In view of the closeness of agreement between calculated and experimental temperatures at the initial steady state condition ($t = 0$, Figures 3 and 4), it is believed that the percentage blood flow distribution given in Table 3 constitutes a fairly adequate representation for resting subjects at 30°C. There is little segmental blood flow data available in the literature except for the hand and forearm. This fact, along with the sensitivity of this parameter to emotional stimuli, combine to make the blood distribution the most difficult of all of the parameters in the heat balance equations to specify accurately.

As shown in Figure 2, it was necessary to incorporate a time lag into observed metabolic data in order to achieve an adequate agreement between calculated and observed temperatures. This procedure would appear to be supported by physiologic considerations in view of the fact that the actual exothermic metabolic reactions occur at the cells, and the resulting carbon dioxide must traverse a tortuous pathway involving many resistances as well as several intervening control systems before appearing in the exhaled breath, where it is detected by the experimental gas exchange methods.

Although there still remain opportunities for effecting further refinements in the computation procedure, in view of the inherent variability of physiologic systems, the indeterminate role of nonthermal stimuli including emotional, discomfort, gastrointestinal, and endocrine factors and the precision with which physiologic variables can be monitored, further refinements in the basic model do not appear warranted at this time. However, the model remains to be confirmed for increasing ambient temperatures. Also, continuing efforts should be made to devise improved representations for the time variations of extremity blood cooling, blood flow distribution, metabolic distribution, and time lag under the influence of various environmental thermal stresses. Moreover, extension of these methods to exercise conditions should be considered in view of the many practical situations of interest to both engineers and clinicians.

NOTATION

A_r = effective skin area for radiation, m^2
A_s = skin area, m^2
BF = blood flow to any given node, g/hr.
C = convective heat loss, Kcal/hr.
c = specific heat of a node, Kcal/g °C
c_B = specific heat of blood, Kcal/g °C
CBF = core blood flow rate, g/hr.
C.O. = cardiac output, l/min.
E_R = respiratory evaporative heat loss, Kcal/hr.
E_s = evaporative heat loss from skin, Kcal/hr.
FBF = fat blood flow rate, g/hr.
h_c = convective heat transfer coefficient
h_r = radiative heat transfer coefficient
H_B = heat lost by blood to arms and legs (see Table 1), Kcal/hr.
M = metabolic heat production, Kcal/hr.
m = mass of a node, g
MBF = muscle blood flow rate, g/hr.
R = radiative heat loss, Kcal/hr.
SBF = skin blood flow rate, g/hr.
T = temperature, °C
$\overline{T}_s$ = mean skin temperature, °C
t = time, hr.
TC = thermal conductance, Kcal/(hr.)(°C)
$\dot{V}_{O_2}$ = oxygen consumption, ml/min.

Subscripts

a = ambient air
c = core
CB = central blood
e = entering value
f = fat
i = individual value
m = muscle
s = skin
w = wall

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