for the Vapor Pressure of Liquids as a Function of Temperature," *J. Chem. Phys.*, **21**, 264 (1953).
Grieves, R. B., and G. Thodos, "The Critical Temperatures of Multicomponent Hydrocarbon Systems," *AIChE J.*, **8**, 550 (1962).
———., "The Critical Pressures of Multicomponent Hydrocarbon Mixtures and the Critical Densities of Binary Hydrocarbon Mixtures," *ibid.*, **9**, 25 (1963).
Kay, W. G., A. Kreglewski, and S. Pak, "Critical Properties of Hydrocarbon Mixtures," Ohio State Univ. Research Foundation, Rep. [4] API Project No. PPC 15.8 (1969).
Kreglewski, A., and W. B. Kay, "The Critical Constants of Conformal Mixtures," *J. Phys. Chem.*, **73**, 3359 (1969).
Li, C. C., "Critical Temperature Estimation for Simple Mixtures," *Can. J. Chem. Eng.*, **19**, 709 (1971).
Partington, E. J., J. S. Rowlininson, and J. F. Weston, "The Gas-Liquid Critical Temperatures of Binary Mixtures. Part I," *Trans. Faraday Soc.*, **56**, 479 (1960).
Redlich, O., and J. N. S. Kwong, "On the Thermodynamics of Solutions. V. An Equation of State. Fugacities of Gaseous Solutions," *Chem. Rev.*, **44**, 233 (1949).
Schick, L. M., and J. M. Prausnitz, "On the Correlation of Critical Properties of Mixtures," *AIChE J.*, **14**, 673 (1968).
Smith, R. L., and K. M. Watson, "Boiling Points and Critical Properties of Hydrocarbon Mixtures," *Ind. Eng. Chem.*, **29**, 1408 (1937).
Spear, R. R., R. L. Robinson, Jr., and K-C Chao, "Critical States of Ternary Mixtures and Equations of State," *Ind. Eng. Chem. Fundamentals*, **10**, 588 (1971).
Sutton, J. R., *Advances in Thermophysical Properties at Extreme Temperatures and Pressures*, p. 76, Am. Soc. Mech. Engrs., New York (1965).
Thodos, G., and T. Akijama, "Interaction Model for the Critical Pressures of Aliphatic Hydrocarbon Mixtures," *Can. J. Chem. Eng.*, **48**, 311 (1970).

Manuscript received August 28, 1972; revision received and accepted December 15, 1972.

Calculation of Temperature Distribution in the Human Body

An improved procedure is presented for the calculation of detailed steady-state temperature distributions throughout the human body. The efficacy of the proposed computation procedure is demonstrated by comparison of calculated and experimental results for seven studies conducted on four subjects. Core temperatures were predicted within ±0.2°C and deviations for individual skin temperatures generally were within ±0.5°C.

CHARLES E. HUCKABA
LYNN W. HANSEN
JOHN A. DOWNEY and
ROBERT C. DARLING

Department of Rehabilitation Medicine
College of Physicians and Surgeons
Columbia University, New York, N.Y. 10032

SCOPE

The ability to calculate temperature distributions throughout the human body at resting conditions in a neutral thermal environment is a prerequisite for studying quantitatively the manner in which the body responds to various types of heat and exercise stresses. Proposed control mechanisms for human thermoregulation can be evaluated only by means of an acceptable model of the controlled body system.

This information can be of value to both engineering and medical practitioners. Computer simulation of the human thermal system would greatly facilitate the specification of optimum work-rest cycles for production workers who must perform their tasks in hostile thermal environments as compared with schedules based solely on traditional, subjective trial and error observations. Likewise, this approach can be a boon to clinicians under both acute and long-term care situations. On the one hand, there is a chance that computer analysis will lead to improved management of fevers, and on the other it could perhaps lead to the more effective use of heating as a physical therapeutic modality in the rehabilitation medicine field.

In addition, the techniques developed in this study demonstrate generally applicable methods for treating distributed parameter systems having both internal heat generation and partial internal regulation of heat dissipation. In view of the fact that the operation of large packed-bed reactors bears many analogies to such a system, the the techniques developed for the physiologic system may well be used to advantage in the analysis of such corresponding technological situations.

Most of the previous work in this field was conducted by physiologists who were concerned primarily with making experimental measurements of body heat balance under

limited conditions of specific clinical interest. Only in recent years has there been any attempt to formulate a comprehensive mathematical model of the human thermal system. The work done by both a chemical engineer (Wissler, 1970) and a biophysicist (Stolwijk, 1970, 1971) has formed the background of the work reported in this paper. 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 provided in this study.

In addition to leading to useful results for steady state situations, the computation procedure provides a method of estimating initial conditions in sufficient detail to form the starting point for predicting variations in body temperature distribution under changing thermal forcings induced by various environmental and physiologic transients. Work directed toward the extension of the model to cover these circumstances in currently underway.

CONCLUSIONS AND SIGNIFICANCE

The present paper demonstrates the adequacy of the proposed model for predicting temperature distributions throughout the human body for steady state conditions. Direct comparison of calculated and observed values for seven studies on four subjects show deviations of about 0.2°C for core temperatures (ear drum and rectal) and about 0.5°C for six skin temperatures. In view of the inherent variability of the physiologic system and the fact that its thermal state is affected by psychologic as well as physiologic factors, it is believed that further refinements in the model are not justified at this time.

The major contribution of this work compared to that of previous investigators lies in the refinements developed in the basic physiologic and thermal parameters involved in the body heat balance equations shown in Table 1. Although alterations described in the text of the paper were made in connection with anatomical parameters, thermal conductances, and metabolic heat distribution, it is believed that the most significant improvements were achieved with respect to blood flow distribution and in allowing 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 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. Although the long-range objective of our study is to devise such predictive techniques, consideration of methods available in the literature indicated that models proposed for the passive system alone were in need of further refinement. Our efforts in this direction are reported in this paper.

Two basic approaches to the modeling of the passive system 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. Moreover, calculated steady state temperature distributions produced some results that do not conform to usual physiological expectations (Aschoff and Wever, 1958). For instance, in some cases calculated hand skin temperature was greater than that for the arm and likewise for the foot as compared to the leg. Since steady state profiles serve as the initial conditions for the calculation of temperature variations under transient conditions, it is imperative that the model for the passive system not only be free of such inconsistencies but be carefully confirmed by means of precise data observed on human subjects.

MODEL FORMULATION

The model follows the same basic format as that outlined by Stolwijk (1970) except that we represent the head as a cylindrical rather than as a spherical element. Our model, then, consists of six cylindrical anatomical segments: head, trunk, arms, hands, legs, and feet. In the case of the extremities, single cylinders are used to represent both arms together, and similarly for the hands, legs, and feet respectively. Each of these segments is subdivided into four concentric layers: core, muscle, fat, and skin. In addition, a central blood compartment is included, resulting in a total of 25 lumps or nodes.

The mathematical model for use in predicting steady state temperature distributions consists of steady state

TABLE 1. STEADY STATE HEAT BALANCE EQUATIONS APPLYING TO EACH ANATOMICAL SEGMENT
(Head, Trunk, Arms, Hands, Legs, Feet)

	INPUT			=	OUTPUT			
	Metabolic Heat Production	+	Heat Transfer Through Inner Surface	=	Heat Transfer Through Outer Surface	+	Heat Exchange with Blood	
Core	M_c	+	0	=	$(TC)_c\,(T_c - T_m) + E_R{}^{*}$	+	$CBF(c_B)\,(T_c - T_e)$	(1)
Muscle	$M_m + H_B{}^{**}$	+	$(TC)_c\,(T_c - T_m)$	=	$(TC)_m\,(T_m - T_f)$	+	$MBF(c_B)\,(T_m - T_e)$	(2)
Fat	M_f	+	$(TC)_m\,(T_m - T_f)$	=	$(TC)_f\,(T_f - T_s)$	+	$FBF(c_B)\,(T_f - T_e)$	(3)
Skin	M_s	+	$(TC)_f\,(T_f - T_s)$	=	$E_s + H_sA_s\,(T_s - T_A)$	+	$SBF(c_B)\,(T_s - T_e)$	(4)

For six anatomical segments we have 24 equations.
Also,

$$T_{CB} = \frac{\Sigma[(BF_i)\,(T_i)]}{\Sigma(BF_i)} = \frac{\Sigma[(BF_i)\,(T_i)]}{C.O.} \qquad (25)$$

* E_R applies only to head core and represents respiratory evaporative heat loss.
** H_B applies only to arms and legs and represents heat lost by blood flowing through these segments (assumed transferred to muscle layers).
N.B.: T_e, the entering blood temperature, is assumed equal to T_{CB} except for hands and feet, for which T_e is assumed to be 0.5°C below T_{CB}.

heat balance equations for each of these anatomical sections. For any given anatomical segment such as the head, trunk, etc., the equations follow the format shown in Table 1. The metabolic heat production consists of that fraction of the total body metabolism assigned to each node. The term for the heat transferred through the inner surface of a cylindrical section by conduction involves mean thermal conductances evaluated as described below. The core section, having no inner surface, has no term corresponding to this category. Heat transfer through the outer surface occurs also by means of conduction except for the skin, which loses heat by evaporation, convection, and radiation. The latter two items are accounted for together by means of the environmental heat transfer coefficient H_s. Heat exchange with the blood is proportional to the change in temperature in the blood as it flows through a given section.

Although the basic equations outlined in Table 1 apply to each of the 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 the heat loss to the surrounding tissues from the blood flowing along the arms and legs on the way to the hands and feet. An assumption that all of this heat is absorbed by the arm and leg muscles proved adequate, and this input is represented by the term H_B in the muscle layer equation of Table 1. The inlet blood temperature T_e is equal to the central blood temperature except in the case of the hand and foot since the blood in flowing through the arm and leg segments experiences a fall in temperature.

In addition to the resulting 24 steady 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 steady state temperature distributions it is necessary to solve simultaneously the 25 equations comprising the model using a digital computer.

SPECIFICATION OF MODEL PARAMETERS

Before temperatures can be calculated, however, it is necessary to supply values for all of the other variables contained in this set of 25 equations. Even though our

TABLE 2. PHYSICAL CHARACTERISTICS OF SUBJECTS

Subject	Height, cm	Weight, Kg	Body surface area, m^2	Physical condition
JD	191	77	2.06	Normal
CH	186	77	2.02	Normal
SC	183	89	2.14	Paraplegic Level T-6
JW	168	58	1.64	Paraplegic Level T-11

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

Rather than using a so-called "standard man," we have specified the model in detail for each of the four subjects listed in Table 2. Direct anatomical measurements were used to obtain the total volume of each of the six anatomical segments, as illustrated for subject SC in Table 3. The total volume for each segment was distributed in turn among the four layers in a manner similar to that used by Stolwijk (1970). The surface area for each of the anatomical segments except for the hands was evaluated as that corresponding to a cylinder having the volume and length of each segment. In the case of the hand, in view of the fact that it is not well approximated by a cylindrical shape, a direct evaluation of surface area was made. In this instance, therefore, the length of the cylindrical segment was obtained from the observed values of volume and area.

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. It was estimated that for the subjects studied an average cardiac output of approximately 6 liters per minute could be used, and this was distributed among the 24 nodes as shown in Table

4. 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 our subjects. On the basis of general information summarized by Abramson (1967), it was assumed that 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 could be neglected.

The final subdivision of total cardiac output shown in Table 4 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.

Metabolic Heat Production

The total metabolic heat production was obtained by laboratory measurement of oxygen consumption, using methods to be described later. An average value of 4.82 Kcal/liter O_2 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, as shown in Table 5.

TABLE 3. ANATOMICAL PARAMETERS FOR SUBJECT SC

A. Volume, Area and Length of Segments

	Volume		Area		Length
	Liters	%	m^2	%	cm
Head	6.5	7.6	0.157	8.3	30.0
Trunk	51.9	60.4	0.685	36.0	72.0
Arms	8.1	9.4	0.330	17.4	107.0
Hands	0.9	1.0	0.073	3.8	47.2
Legs	16.6	19.3	0.546	28.7	143.0
Feet	2.0	2.3	0.110	5.8	48.0
Total	86.0	100.0	1.901	100.0	

B. Percentage Distribution of Volume Among the Layers of Each Segment

	Skin	Fat	Muscle	Core	Total
Head	0.51	0.70	0.70	5.69	7.60
Trunk	1.98	10.40	26.40	21.57	60.35
Arms	0.64	1.29	4.48	2.99	9.40
Hands	0.29	0.23	0.12	0.41	1.04
Legs	1.12	2.22	9.50	6.47	19.31
Feet	0.57	0.53	0.18	1.02	2.30
Total	5.11	15.37	41.38	38.14	100.00

TABLE 4. BLOOD FLOW DISTRIBUTION AT 30°C (ml/min)

	Skin	Fat	Muscle	Core	Total
Head	62	0	20	900	982
Trunk	240	0	1092	3120	4452
Arms	14	0	128	0	142
Hands	57	0	6	0	63
Legs	29	0	262	0	291
Feet	63	0	7	0	70
Total	465	0	1515	4020	6000

TABLE 5. PERCENTAGE DISTRIBUTION OF METABOLISM

	Skin	Fat	Muscle	Core	Total
Head	0.18	0.17	0.27	16.52	17.14
Trunk	0.70	2.46	10.15	59.55	72.86
Arms	0.23	0.30	1.72	0.70	2.95
Hands	0.10	0.05	0.05	0.10	0.30
Legs	0.40	0.52	3.66	1.53	6.11
Feet	0.20	0.13	0.07	0.24	0.64
Total	1.81	3.63	15.92	78.64	100.00

Heat Loss Data

Total evaporative heat loss was evaluated by direct measurement on the subject, using a sensitive bed scale capable of detecting weight changes to within ± 0.5 g. Using this value along with that of total metabolic heat production, it was possible to calculate the environmental heat transfer coefficient (for convection and radiation) from the overall steady state heat balance. In this computation, the observed skin temperatures were weighted in proportion to the surface areas of the six 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, 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, rest of body = 1.

Other Parameters

Integrated mean thermal conductances calculated for adjacent layers in each cylindrical segment are used in our model.

For all anatomical segments except for the hands and feet, 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 hands and feet had cooled 0.5°C below the central blood temperature. This heat lost by the blood in passing through the arms and legs was assumed to be transferred to the muscle layers of these segments.

EXPERIMENTAL METHODS

A series of steady state studies was performed on four subjects 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 steady state temperature distribution. In these cases the subject, lying on a nylon mesh trampoline, was exposed to a constant temperature,

TABLE 6. COMPARISON OF CALCULATED AND OBSERVED TEMPERATURES, °C

Study	JD			CH			SC XVII			SC XVIII			JW I			JW II			JW III		
	Obs.	Calc.	Δ	Obs.	Calc.	Δ	Obs.	Calc.	Δ	Obs.	Calc.	Δ	Obs.	Calc.	Δ	Obs.	Calc.	Δ	Obs.	Calc.	Δ
Head core	36.6	36.4	−0.2	36.8	37.0	+0.2	36.7	36.7	0.0	36.9	36.9	0.0	36.9	36.7	−0.2	36.9	36.7	−0.2	36.8	36.8	0.0
Trunk core	—	36.5	—	—	37.2	—	—	36.9	—	—	37.0	—	37.2	36.8	−0.4	37.0	36.8	−0.2	36.9	36.9	0.0
Head skin	35.9	35.3	−0.6	36.0	35.7	−0.3	36.0	35.5	−0.5	36.0	35.6	−0.4	36.2	35.6	−0.6	36.1	35.6	−0.5	36.0	35.9	−0.1
Trunk skin	35.2	35.2	0.0	35.2	35.5	+0.3	35.1	35.3	+0.2	35.0	35.3	+0.3	35.6	35.5	−0.1	35.1	35.3	+0.2	35.6	35.7	+0.1
Arm skin	34.3	34.7	+0.4	35.1	34.9	−0.2	35.1	34.8	−0.3	34.3	34.7	+0.4	35.4	34.9	−0.5	35.3	34.8	−0.5	34.8	35.2	+0.4
Hand skin	34.4	34.6	+0.2	35.4	35.1	−0.3	35.3	34.9	−0.4	34.1	35.0	+0.9	36.2	35.0	−1.2	36.0	35.1	−0.9	35.7	35.3	−0.4
Leg skin	34.6	34.7	+0.1	34.9	34.9	0.0	34.7	34.8	+0.1	35.2	34.7	−0.5	34.5	35.1	+0.6	34.7	34.9	+0.2	35.5	35.3	−0.2
Foot skin	34.7	34.2	−0.5	35.2	34.8	−0.4	34.8	34.6	−0.2	35.1	34.6	−0.5	34.4	34.8	+0.4	34.3	34.9	+0.6	35.9	35.1	−0.8
Total metabolism, Q		65.7			80.7			74.5			83.8			64.2			69.0			61.9	
Evaporative loss, E		31.3			27.9			27.5			29.0			21.5			16.0			18.5	
Environmental coefficient, H_s		5.1			7.4			7.8			7.8			6.6			8.6			6.7	
Mean skin temper-		34.9			35.2			35.1			35.0			35.3			35.1			35.5	
ature, $\overline{T_s}$		30.6			30.6			31.2			30.5			30.4			30.5			30.6	
Ambient temperature, T_A																					

constant humidity environment. He was allowed to achieve thermal equilibrium as indicated by constancy of the various physiologic temperatures being monitored.

Temperatures were measured with copper-constantan thermocouples, which had been calibrated to within ±0.1°C against a Bureau of Standards certified thermometer. Twenty-four temperatures were monitored continuously in order to reflect in detail the thermal conditions of both the subject and the surrounding environment. Nineteen probes were assigned to the following body locations: ear drum, mouth (under the tongue), rectum, index finger, hand, left forearm, right forearm, upper arm, anterior shoulder, cheek, forehead, chest, abdomen, shoulder blades, middle of back, lower trunk, thigh, calf, and foot. Thermocouples were attached to the skin by means of a drop of collodion. Environmental conditions were monitored by means of thermocouples suspended at two points in the ambient space over the subject, and by probes attached to the wall, floor, and ceiling. Previous evaluation of the thermal stability of the room indicated a temperature uniformity of approximately ±0.5°C. Relative humidity was measured by both a sling psychrometer and a recording hygrometer.

Oxygen consumption was measured using an open circuit method (Downey et al., 1971). Gas analyses were obtained by means of a paramagnetic O_2 analyzer and an infra-red CO_2 analyzer, with independent checks carried out on additional samples using the Scholander method as described by Consolazio et al. (1951). Flow rates were measured by means of a dry gas meter with independent checks being obtained by accumulating gases in a water-filled gasometer over a measured period of time.

Evaporative weight losses were determined by means of a Potter (Model #33) metabolic bed scale. Calibration of this scale under both static and dynamic conditions indicated that weight changes of approximately ±0.5 grams could be detected.

Right hand blood flow and left forearm blood flow were measured simultaneously using venous occlusion plethysmography (Greenfield et al., 1963). The blood flow to the left hand was occluded by a high pressure cuff during forearm flow measurements.

COMPARISON OF CALCULATED AND OBSERVED TEMPERATURE PROFILES

In order to subject the model and the various procedures described in previous sections for evaluating basic parameters to a definitive test, it was desired to see how well various physiological temperatures observed during steady state studies of the four subjects listed in Table 1 could be predicted. The experimental values listed in Table 6 were obtained by allowing each subject to achieve a thermal steady state at an ambient temperature of 30 to 31°C and relative humidity of 50%. Also listed for each study are the values observed for the total metabolism, evaporative weight loss, and environmental coefficient, as well as the ambient temperature and mean skin temperature.

TABLE 7. CALCULATED TEMPERATURE PROFILE FOR STUDY SC XVII, °C

	Core	Muscle	Fat	Skin
Head	36.7	35.9	35.7	35.5
Trunk	36.9	36.6	35.7	35.3
Arms	36.1	35.9	35.0	34.8
Hands	35.1	35.1	35.0	34.9
Legs	36.3	36.1	35.1	34.8
Feet	35.0	34.9	34.8	34.6

Mixed blood temperature: 36.6

Examination of the calculated and observed temperature values for the seven studies listed in Table 6 indicates that head core temperatures agree within ± 0.2°C. In the three instances in which rectal temperatures were also measured, only in one case (JW I) does the deviation exceed this amount, and this could have resulted from improper placement of the rectal probe. Except for a few values, skin temperature deviations generally are within ± 0.5°C, and for any given study the average of the absolute magnitudes of the deviations is well within 0.5°C.

Further evidence relative to the validity of the calculation procedure is shown in Table 7, in which the calculated temperatures of all of the 25 nodes in the model are summarized for one study (SC XVII). All of these temperatures appear to bear an appropriate relationship to one another. For instance, for corresponding layers the hand temperature is lower than the arm temperature, and likewise for the foot as compared to the leg. Furthermore, the trunk core temperature is 0.2°C higher than the head core temperature.

In order to assess the efficacy of the refinements embodied in the present model as compared with those previously reported, a comprehensive series of sensitivity analyses were conducted for study SC XVII. The effect on the calculated temperatures of variations in each of the basic parameters in the model equations shown in Table 1 was considered. The calculated temperatures were found to be relatively insensitive to variations in thermal conductances and metabolic heat distribution. The importance of allowing for variations with respect to anatomical skin section of both evaporation rate and environmental coefficient (through weighting of the radiative view factors) was demonstrated. Failure to account for these factors produced shifts in calculated values as high as 0.5°C in some of the skin temperatures. Likewise, failure to allow for blood cooling on passing through arms and legs can cause a change of 0.5°C in the predicted hand skin and foot skin temperatures.

Varying the total cardiac output over a range of ± 1 liter/min around the standard value of 6 liters/min produced variations of 0.2°C in both head and trunk core temperatures with only 0.1°C change in skin temperatures. The greatest sensitivity, however, occurs in connection with the blood flow distribution. Shifts in the distribution of the standard 6 liters/min among the 24 segments cause sizable errors in the calculated temperatures. For instance, a 50% variation in hand skin or foot skin flow can produce close to 1°C change in the calculated values of the corresponding skin temperatures.

DISCUSSION OF RESULTS

In view of the good agreement between calculated and observed values as shown in Table 6, it is concluded that the model is adequate for calculating steady state temperature distributions in the human body. In contrast with the results reported by previous investigators, we have subjected our model to a more critical test by comparing individual skin temperatures rather than mean skin temperatures.

There are several areas, especially with respect to the evaluation of the basic parameters, in which we believe that significant improvements have been achieved. Allowing for the temperature gradient of the blood as it passes through the arm to the hand is supported by physiological evidence (Aschoff and Wever, 1958). Moreover, the blood flow distribution as listed in Table 3 would appear to reflect more accurately the conditions that actually exist in a resting subject, since it has included experimental observations. 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 on the calculations, combine to make the blood distribution the most difficult of all of the variables in the heat balance equations to specify. It was only by a meticulous trial and error procedure that the blood distribution given in Table 4 was obtained. Once available, though, it was gratifying that the same distribution led to satisfactory results for all seven studies at 30°C ambient involving four subjects having different physical characteristics.

Another important factor leading to the close agreement between the calculated and observed temperatures is the use of an environmental heat transfer coefficient applying to the same subject-room conditions under which the experimental studies were conducted. In view of the significant role of radiation and convection heat losses in the overall heat balance, predicted temperatures can be affected by relatively small changes in this environmental coefficient.

Although attempts were made to use more realistic values of anatomical parameters, total metabolism and metabolic heat distribution, and thermal conductances, it was not found that our adjustments in any of these parameters greatly affected the results. In some instances there was little difference between our values of these parameters and those employed by Stolwijk (1971), and in other cases the calculated results appeared to be relatively insensitive to changes in values.

Although there still remain opportunities for effecting further refinements in the steady state computation procedure, in view of the inherent variability of physiologic systems and the precision with which physiologic variables can be monitored, further adjustments in the basic model do not appear warranted at this time. As work proceeds on the development of a computation procedure for dynamic conditions, if the initial conditions supplied by this steady state model appear to be inadequate, a further reevaluation will be made.

NOTATION

A_s = skin area, m^2
BF = blood flow to any given node, g/hr
c_B = specific heat of blood, Kcal/(g)(°C)
CBF = core blood flow rate, g/hr
$C.O.$ = cardiac output, liters/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_B = heat lost by blood to arms and legs (see Table 1), Kcal/hr
H_s = environmental coefficient, Kcal/(hr)(m^2)(°C)
M = metabolic heat production, Kcal/hr
MBF = muscle blood flow rate, g/hr
Q = total metabolism, Kcal/hr
SBF = skin blood flow rate, g/hr
T = temperature, °C
TC = thermal conductance, Kcal/(hr)(°C)

Subscripts

c = core
e = entering value
f = fat
i = individual value
m = muscle
s = skin

LITERATURE CITED

Abramson, D. I., *Circulation in the Extremities,* Academic Press, New York (1967).
Aschoff, Y., and R. Wever, "Kern und Schale in Wärmehaushalt des Meuschen," *Naturwinenschaften,* **45**, 477 (1958).
Chien, S., Department of Physiology, Columbia University, New York private communication (1971).
Consolazio, C. F., R. E. Johnson, and E. Marek, *Metabolic Methods: Clinical Procedures in the Study of Metabolic Functions,* p. 320, C. V. Mosby, St. Louis (1951).
Downey, J. A., C. E. Huckaba, R. C. Darling, L. E. Bonilla, and W. K. Luke, "The Role of Skin Temperature in Human Thermoregulation," *Chem. Eng. Progr. Symp. Ser. No. 114,* **67**, 211 (1971).
Fanger, F. O., *Thermal Comfort,* p. 29, Danish Technical Press, Copenhagen (1970).
Gemmill, C. L., and J. R. Brobeck, "Energy Exchange," in *Medical Physiology,* p. 488, C. V. Mosby, St. Louis (1968).
Greenfield, A. D. M., R. J. Whitney, and J. F. Mowbray, "Methods for the Investigation of Peripheral Blood Flow," *Brit. Med. Bull.,* **19**, 101 (1963).
Kuno, Y., *Human Perspiration,* p. 30, C. C. Thomas, Springfield, Ill. (1956).
Smith, P. E., and E. W. James, "Human Responses to Heat Stress," *Arch. Environ. Health,* **9**, 332 (1964).
Stolwijk, J. A. J., "Mathematical Model of Thermoregulation," in *Physiological and Behavioral Temperature Regulation,* C. C. Thomas, Springfield, Ill. (1970).
———., "A Mathematical Model of Physiological Temperature Regulation in Man," NASA CR-1855 (1971).
———., and J. D. Hardy, "Temperature Regulation in Man: A Theoretical Study," *Arch. Ges. Physiol.,* **291**, 129 (1966).
Wade, O L., and J. M. Bishop, *Cardiac Output and Regional Blood Flow,* p. 107, Blackwell, London (1962).
Wissler, E. H., "The Use of Finite Difference Techniques in Simulating the Human Thermal System," in *Physiological and Behavioral Temperature Regulation,* C. C. Thomas, Springfield, Ill. (1970).

Manuscript received November 6, 1972; revision received January 12, 1973, and accepted January 15, 1973.