Steady-state temperature distribution in man[1]

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WISSLER, EUGENE H. *Steady-state temperature distribution in man.* J. Appl. Physiol. 16(4): 734–740. 1961.—A steady-state, mathematical model for the human heat transfer system has been developed. This model includes the following factors: *a*) the distribution of metabolic heat generation, *b*) conduction of heat in tissue, *c*) convection of heat by flowing blood, *d*) loss of heat by radiation, convection and evaporation at the surface, *e*) loss of heat through the respiratory tract, and *f*), countercurrent heat exchange between large arteries and veins. Computed results were compared with experimental results for the nude basal man and found to be satisfactory.

ALTHOUGH THE INTRACORPOREAL TRANSPORT of heat by circulating blood has been recognized for some time as an important factor in thermal physiology, the quantitative description of this phenomenon is still not satisfactory. This is certainly owing, in part, to the extreme difficulty associated with making experimental measurements of quantities such as the local blood flow rate and the local rate of heat generation by metabolic reactions. Because of this difficulty a need exists for valid mathematical models which provide a method for estimating certain quantities that cannot be measured directly, as well as a yardstick by which the consistency of measured data can be gauged.

Pennes (1) has demonstrated the utility of this approach by comparing measured and computed temperature profiles in the human forearm. Although there are sizeable discrepancies in the vicinity of large arteries and veins, the agreement between mean experimental points and the computed curve is generally satisfactory. An extension of Pennes' work is presented in this report. This extension yields information about the steady-state temperature distribution in the human body when the environmental conditions, the distribution of metabolic heat generation, the distribution of blood flow, and the size of the body are specified. Although a number of relatively important factors are omitted in the model used, it provides a way toward a more satisfactory description of the human body than the "core and shell" concept which is often used.

In developing this model the human body has been subdivided into six elements, as illustrated in Fig. 1. Each element has a uniformly distributed heat production rate, owing to metabolic reactions, and a uniformly distributed blood supply. The interdependence between the elements is provided in the heart and lungs where the six venous streams are mixed, producing an arterial stream at an intermediate temperature. Thermal equilibrium is established when the rate of heat loss through the surface and respiratory system equals the total rate of heat production caused by metabolic reactions. Since the surface to volume ratio of the trunk is smaller than that of any of the other elements and, in the basal or resting state, the rate of heat generation is larger in the trunk than in the extremities, there is a net transport of heat from the trunk to the extremities by the circulating blood. When an individual is working the rate of heat generation in the extremitites may become great enough to reverse the direction of heat transport by circulating blood. In either case the existence of countercurrent heat exchange between the large arteries and veins tends to prevent the transport of heat between the trunk and the extremities.

The derivation of the equations is given in the next section. Although the final equations are not unduly complex, the actual computations are time consuming and it was deemed worthwhile to code the equations for the IBM 650 computer. The results computed for a number of different cases are presented in the third section.

STATEMENT OF PROBLEM

Two steps are involved in the derivation of the equations. In the first step a relation between the arterial temperature, the venous temperature and the metabolic heat generation rate is obtained for each element. The second step consists of writing a thermal energy balance for the heart and lungs. A combination of these seven equations yields a single equation for the arterial temperature at the heart in terms of the heat generation rates, blood flow rates, dimensions, and surface conditions of the six elements.

In analysis of each element the effect of longitudinal conduction of heat is neglected. This is probably a valid approximation in long, slim elements such as the

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arms and legs, but it may be the source of considerable error in the head. Each element is considered to be a homogeneous, isotropic cylinder in which only the radial conduction of heat occurs. Under these conditions the heat conduction equation may be written:

$$k_i\left(\frac{d^2T_i}{dr^2} + \frac{1}{r}\frac{dT_i}{dr}\right) + h_{mi} + (Vs)_i(T'_{ai} - T_i) = 0 \qquad (1)$$

in which

T_i = temperature at a distance r from the axis of the ith element
h_{mi} = rate of heat generation due to metabolic reactions
V = volumetric flow rate of blood in the capillary bed
s = product of the density and specific heat of blood
k = thermal conductivity of tissue
T'_{ai} = temperature of the arterial blood entering the capillary bed

Equation 1 is a mathematical statement of the first law of thermodynamics in which the first term is the net rate of conduction of heat into a unit volume; the second term is the rate of heat generation due to metabolic reactions; and the last term is the net rate of transfer of heat from blood to tissue in the capillary bed. The local transport of heat by circulating blood has been neglected in the formulation of this equation. Burton (2) has indicated that this may be important, and more recently Hertzmann (3) has shown that vascular convection of heat by venous flow from active muscle to the overlying skin is important. *Equation 1* must be solved subject to the following boundary condition:

$$-k_i\frac{dT_i}{dr} = H_i(T_i - T_{ei}) \qquad \text{at } r = a_i \qquad (2)$$

in which:

H_i = effective heat transfer coefficient at the surface of the ith element
T_{ei} = effective temperature of the environment at the surface of the ith element
a_i = radius of the ith element

This equation states that the rate of conduction of heat to the surface through the tissue equals the rate of heat transfer from the surface to the environment. Since heat may be transferred from the surface by conduction, convection, radiation, and evaporation, the effective heat transfer coefficient depends on the physical properties of the surrounding medium, the motion of the medium, and the relative humidity, if the fluid is a gas. The heat transfer coefficients for a particular set of circumstances can be estimated using empirical correlations.

The coefficient for radiant transfer, H_r, is most easily determined. Assuming that the human skin has an emissivity of unity and that the ratio of the area of the walls to the surface area of the subject is large, the rate of heat loss per unit area is given by:

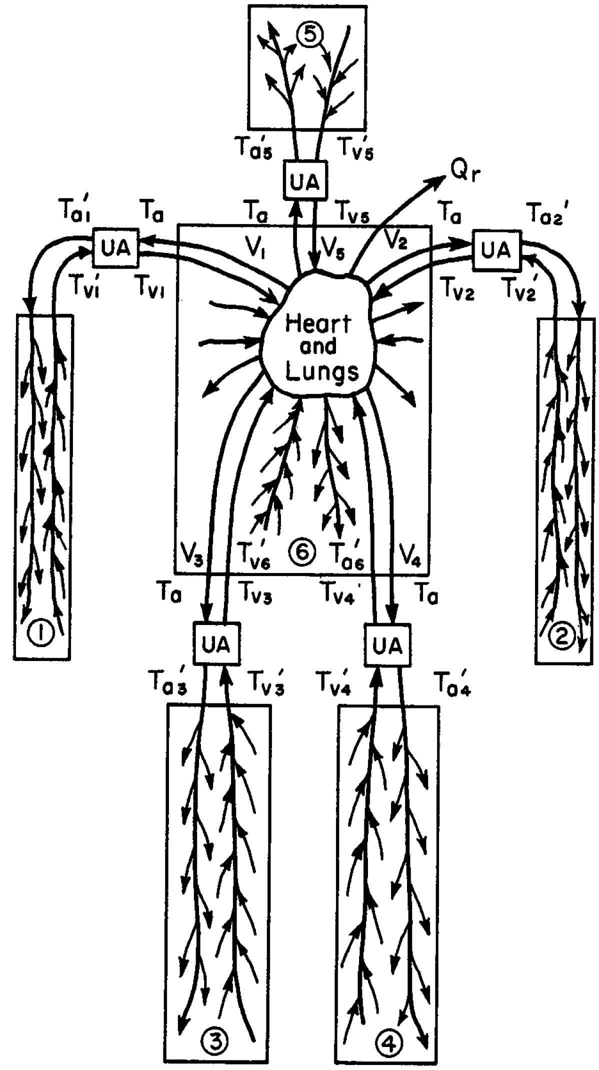


FIG. 1. Components used in thermal system of the six-element man.

$$Q_{rad} = 1.356 \times 10^{-12}(T_s^4 - T_w^4)\ \frac{\text{cal}}{\text{cm}^2 \times \text{sec}}$$

in which T_s and T_w are measured in degrees Kelvin. Defining the heat transfer coefficient for radiation to be $Q_{rad}\ (T_s - T_w)$, one obtains:

$$H_r = 1.356 \times 10^{-12}(T_s^3 + T_s^2T_w + T_sT_w^2 + T_w^3)\ \frac{\text{cal}}{\text{cm}^2 \times \text{sec} \times \text{C}} \qquad (3)$$

Over the range of temperatures from 10 C to 40 C, H_r increases from 0.000145 cal/cm² × sec × C to 0.0001663 cal/cm² × sec × C. Although the heat transfer coefficient for radiation is nearly constant and should be readily determinable, the effective area for radiant heat transfer is not as easily determined. Because of the complex geometry of the human body, the area for radiant transfer varies markedly as the posture of the individual changes.

The heat transfer coefficient for convection, H_c, is not the same for all areas of the body. It depends on the size of the element, the size and relative position of adjacent elements and the nature of the fluid motion. If care is taken to prevent motion of the individual and eliminate drafts, then the motion of the fluid immediately adjacent to the surface exists only as a result of natural convection. In this case the heat transfer coefficient is determined by the orientation of the surface, the temperature difference between the surface and the fluid, and the density, specific heat, thermal conductivity, viscosity, and volumetric coefficient of expansion of the fluid. For horizontal cylinders the following equation may be used to predict H_c (4):

$$\frac{H_c D}{k_f} = 0.53 \left[\left(\frac{D^3 \rho_f^2 \beta g \Delta t}{\mu_f^2} \right) \left(\frac{C_p \mu_f}{k_f} \right) \right]^{0.25} \quad (4)$$

in which

- D = diameter of the cylinder
- g = acceleration due to gravity
- C_p = specific heat of the fluid
- ρ = fluid density
- μ = viscosity of the fluid
- k = thermal conductivity of the fluid
- β = volumetric coefficient of expansion of the fluid
- f = subscript indicating that the fluid properties are to be evaluated at the mean film temperature, the mean of the surface, and undisturbed air temperatures.

For vertical planes or large vertical cylinders, the value of H_c can be estimated using:

$$\frac{H_c L}{k_f} = 0.59 \left[\left(\frac{L^3 \rho_f^2 g \beta \Delta t}{\mu_f^2} \right) \left(\frac{C_p \mu_f}{k_f} \right) \right]^{0.25} \quad (5)$$

in which L = height of the surface (4). *Equations 4* and *5* apply to situations in which the flow of fluid over the surface is laminar. When the value of

$$(L^3 \rho_f^2 \beta g \Delta t / \mu_f^2)(C_p \mu_f / k_f)$$

exceeds 10^9, the flow becomes turbulent and the heat transfer coefficient increases accordingly (4). Then one should use the following equation to calculate H_c:

$$\frac{H_c L}{k} = 0.12 \left[\left(\frac{L^3 \rho_f^2 \beta g \Delta t}{\mu_f^2} \right) \left(\frac{C_p \mu_f}{k_f} \right) \right]^{1/3} \quad (6)$$

Since the heat transfer coefficient for natural convection depends on the difference between the surface and air temperatures, a wide range of values is possible. The values predicted for typical situations using the equations given above are consistent with those listed by Hardy (5).

Several factors tend to increase the heat transfer coefficient for convection to values greater than those predicted above. If the subject is shivering, the vibration of his skin will increase the heat transfer coefficient. At the present time, there is no way to predict accurately the magnitude of this effect, but it may increase the value of H_c by a factor of two or three (6).

An additional increase in the heat transfer coefficient may be caused by the simultaneous mass transfer occurring in the form of evaporation of perspiration. Since the density of inhomogeneous air-water mixtures is lowest in the regions of highest concentration, the existence of a concentration gradient affects the flow pattern immediately adjacent to the skin. If the temperature of the air is less than the temperature of the skin, the air will flow upward around the skin and the existence of simultaneous evaporation will enhance the motion, thereby increasing H_c. Conversely, if the temperature of the air is greater than the skin temperature, the air will flow downward around the skin and the existence of simultaneous evaporation will retard the motion, thereby reducing H_c.

If the fluid flows past the body at a greater speed than that produced by natural convection alone, there is a very strong probability that the motion will be turbulent. In that case the heat transfer coefficient can be predicted using the following equation (4):

$$\frac{H_c D}{k_f} = 0.26 \left(\frac{D V \rho}{\mu_f} \right)^{0.6} \left(\frac{C_p \mu_f}{k_f} \right)^{0.3} \quad (7)$$

in which D = diameter of the cylinder and V = velocity with which the fluid approaches the cylinder. This equation is applicable to single cylinders when the fluid approaches the cylinder from a direction perpendicular to the axis of the cylinder. The heat transfer coefficient is proportional to the 0.6 power of the velocity and inversely proportional to the 0.4 power of the diameter. For a cylinder that is 8 cm in diameter,

$$H_c = 1.8 \times 10^{-4} V^{0.6} \frac{\text{cal}}{\text{cm}^2 \times \text{sec} \times \text{C}} \quad (8)$$

when V is measured in centimeters per second, or

$$H_c = 0.43 \times 10^{-4} V^{0.6} \frac{\text{Kcal}}{\text{cm}^2 \times \text{hr} \times \text{C}} \quad (9)$$

when V is measured in feet per minute. For a cylinder that is 26 cm in diameter the corresponding equations are:

$$H_c = 0.95 \times 10^{-5} V^{0.6} \frac{\text{cal}}{\text{cm}^2 \times \text{sec} \times \text{C}} \quad (10)$$

or

$$H_c = 0.27 \times 10^{-4} V^{0.6} \frac{\text{Kcal}}{\text{cm}^2 \times \text{hr} \times \text{C}} \qquad (11)$$

Since the human body is composed of several elements having different diameters, it is difficult to compare measured values of H_c, which are mean values for the entire body, with the values predicted using *equation 7*. *Equations 9* and *11* predict larger values for H_c than the equation

$$H_c = 0.23\ V^{0.62} \qquad (12)$$

used by Clifford, Kerslake and Waddell (7).

Heat is also lost because of the evaporation of water from the surface of the skin. In the absence of the secretion of sweat, this seems to represent the passive diffusion of water through the epidermis. Recent measurements (8) on two subjects show that the rate of water loss in grams per hour is roughly 0.8 ($p_s - p_e$), in which p_s and p_e are the vapor pressure of saturated water at the temperature of the skin and the ambient partial pressure of water. Both pressures are measured in millimeters of mercury. Since the vapor pressure of water changes roughly 2.2 mm Hg/ C and the latent heat of vaporization of water at 30 C is 580 cal/g, the rate of heat loss owing to evaporation is

$$Q_e = 0.16 \times 10^{-4}\left[T_s - \left(T_e - \frac{(1-H)\,p_e}{2.2}\right)\right] \frac{\text{cal}}{\text{cm}^2 \times \text{sec}} \qquad (13)$$

Hence, the heat transfer coefficient for evaporation in the absence of sweating is

$$H_e = 0.16 \times 10^{-4} \frac{\text{cal}}{\text{cm}^2 \times \text{sec} \times C} \qquad (14)$$

and the effective ambient temperature is $(1 - H)p_e/2.2$ C lower than the ambient air temperature. H is the relative humidity of the ambient air.

If the subject is actively secreting sweat, the fractional area that is actually wet must be known before the rate of evaporation can be determined. Unfortunately, this seems to be a variable that cannot be accurately predicted. In the limiting case of a completely wetted surface and forced convection, the heat transfer coefficient for evaporation is simply 4.4 times the coefficient for convection. This fact has been used for years in constructing psychrometric charts for water (9), and it has been confirmed experimentally that it also applies to the cooling of human beings (10). Of course, the effective ambient temperature will be lower by $(1 - H)p_e/2.2$ than the air temperature.

Finally, the rate of heat loss through the respiratory tract must be evaluated. This can be done if the respiratory rate, ambient temperature, and relative humidity are known. The rate of heat loss, Q_r, can be formulated as

$$Q_r = 4.2 \times 10^{-4} R\{T_a - [T_e - 0.370\,(1 - H)\,p_e]\}\ \text{cal/sec} \qquad (15)$$

in which R = respiratory rate measured in liters per hour, and T_a = arterial temperature at the heart.

SOLUTION OF EQUATIONS

For the purpose of this report it will be permissible to assume that the environmental temperature is the same for all elements of the body. One need be concerned then only with the difference between the temperatures of the body and the environment. For convenience, let

$$\theta_i = T_i - T_e$$

$$\theta_a = T_a - T_e$$

$$\theta'_{ai} = T'_{ai} - T_e$$

$$\theta_{vi} = T_{vi} - T_e$$

$$y = r/a_i$$

Equations 1 and *2* then become:

$$\frac{k_i}{a_i^2}\left(\frac{d^2\theta_1}{dy^2} + \frac{1}{y}\frac{d\theta_i}{dy}\right) + h_{mi} + (Vs)_i\,(\theta'_{ai} - \theta_i) = 0 \qquad (16)$$

and

$$\frac{d\theta_i}{dy} + \frac{H_i\,a_i}{k_i}\,\theta_i = 0 \qquad \text{at } y = 1 \qquad (17)$$

The solution of these equations, subject to the additional restriction that the temperature remain finite at the center, is:

$$\theta_i = \left[\theta'_{ai} + \frac{h_{mi}}{(Vs)_i}\right][1 - G(y)] \qquad (18)$$

$$G(y) = \frac{\left(\frac{H_i\,a_i}{k_i}\right) I_0\left(\sqrt{\frac{(Vs)_i}{k_i}}\,a_i\,y\right)}{a_i\sqrt{\frac{(Vs)_i}{k_i}}\,I_1\left(\sqrt{\frac{(Vs)_i}{k_i}}\,a_i\right) + \left(\frac{H_i\,a_i}{k_i}\right) I_0\left(\sqrt{\frac{(Vs)_i}{k_i}}\,a_i\right)} \qquad (19)$$

in which I_0 and I_i are Bessel functions of imaginary argument. Setting $y = 1$ in the preceding equation yields the temperature at the surface,

$$\theta_{si} = \left[\theta'_{ai} + \frac{h_{mi}}{(Vs)_i}\right] G_i \qquad (20)$$

in which

$$G_i = \frac{a_i\sqrt{\frac{(Vs)_i}{k_i}}\,I_1\left(\sqrt{\frac{(Vs)_i}{k_i}}\,a_i\right)}{a_i\sqrt{\frac{(Vs)_i}{k_i}}\,I_1\left(\sqrt{\frac{(Vs)_i}{k_i}}\,a_i\right) + \left(\frac{H_i\,a_i}{k_i}\right) I_0\left(\sqrt{\frac{(Vs)_i}{k_i}}\,a_i\right)} \qquad (21)$$

Now a relationship can be obtained between the temperature of the arterial blood entering the capillary bed of an element and the temperature of the venous blood leaving the bed. The net rate of heat transport into an element plus the rate of heat generation by metabolic reactions is equal to the rate of heat loss at the surface:

$$\theta'_{ai} - \theta'_{vi} = \frac{2H_i\,\theta_{si}}{a_i(Vs)_i} - \frac{h_{mi}}{(Vs)_i} \qquad (22)$$

Due to countercurrent heat exchange between adjacent arterial and venous streams in an element, the temperature of the blood entering the capillary bed will not be the same for all the elements. In reality the sites at which countercurrent exchange occurs are distributed throughout an element, but in the model developed in this report all the exchanges for an element are lumped together in one countercurrent heat exchanger located between the element and the heart.

The capacity for heat exchange is measured by the product of the over-all heat transfer coefficient, U_i, and the effective area of the heat exchanger, A_i. Multiplying this product by the over-all thermal driving force

$$\left(\frac{\theta_a + \theta'_{ai}}{2} - \frac{\theta_{vi} + \theta'_{vi}}{2}\right) \qquad (23)$$

yields the net rate of transfer from arterial to venous blood. The following relations are easily obtained by writing energy balances:

$$\theta_a - \theta'_{ai} = \theta_{vi} - \theta'_{vi} \qquad (24)$$

$$\theta_a - \theta'_{ai} = \frac{(UA)_i}{\pi a_i^2 L_i (Vs)_i}\,(\theta_a - \theta_{vi}) \qquad (25)$$

Finally, an energy balance must be written for the heart and lungs. This equation states that the rate at which heat is transported to the heart by the venous streams is equal to the rate at which heat is transported away from the heart by the arterial stream plus the rate of heat loss through the respiratory tract. Hence:

$$\sum_{i=1}^{6} \pi a_i^2 L_i (Vs)_i (\theta_a - \theta_{vi}) = -Q_r = -H_r\theta_a \qquad (26)$$

By combining *equations 20, 22, 25* and *26*, a single equation for θ_a is obtained.

$$\theta_a = \frac{\displaystyle\sum_{i=1}^{6} \frac{a_i^2 L_i\,h_{mi} - 2a_i\,L_i\,H_i\,G_i\,h_{mi}/(Vs)_i}{1 + \dfrac{2(UA)_i\,H_i\,G_i}{\pi a_i^3 (Vs)_i^2 L_i}}}{\dfrac{H_r}{\pi} + \displaystyle\sum_{i=1}^{6} \frac{2a_i\,L_i\,H_i\,G_i}{1 + \dfrac{2(UA)_i\,H_i\,G_i}{\pi a_i^3 (Vs)_i^2 L_i}}} \qquad (27)$$

Having computed θ_a, one can then compute the temture at any point in the body using the other equations presented above.

If the subject is located in a moving air stream, the heat transfer coefficients due to convection and evaporation are independent of the skin temperature. In this case the computation can be performed in a direct manner. If the subject is located in a quiescent atmosphere, the heat transfer coefficients due to convect and evaporation are functions of the skin temper and an iterative procedure must be used. One can compute values for the H_i's using assumed ski peratures. Values of the skin temperatures then computed. If the computed values are equal the assumed values, this part of the computation has been completed, and tissue temperatures can be computed. Since it was necessary to make several computations for a resting subject in a quiescent atmosphere, the computations were coded for an IBM 650 computer. With this program the discrepancies between computed a assumed skin temperatures are reduced to less than 0.001 C before tissue temperatures at 11 points in each element are computed. Performance of these computations requires about 4 min machine time.

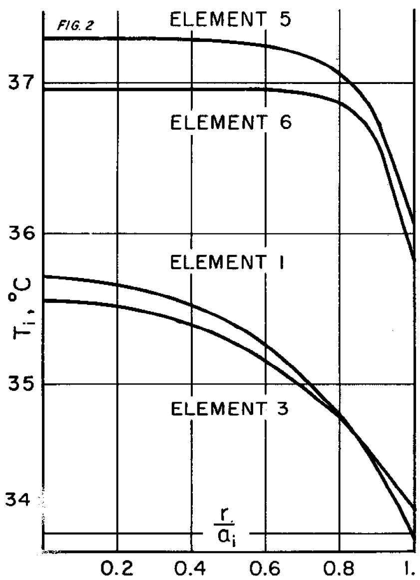
RESULTS AND DISCUSSION

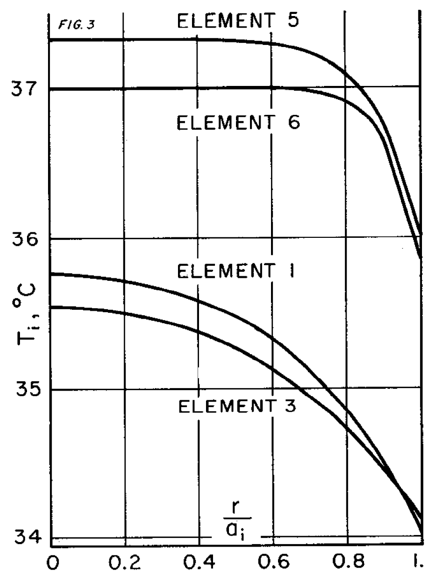
The model was tested by computing temperatures for the nude basal man. A total metabolic rate of 72 Cal/hr was distributed as follows: 20% in the head, 20% in the peripheral muscles, and 60% in the trunk. The cardiac output was distributed so as to provide a flow of 0.0003 cc/cc × sec in the arms and 0.0002 cc/cc × sec in the legs, with the remainder going to the head and trunk. A respiratory rate of 432 liters/hr and a relative humidity of 50% were used in evaluating the heat transfer coefficient for the respiratory tract. It was assumed that the subject was in a quiescent atmosphere so that heat transfer coefficients for the exposed surfaces could be computed using *equation 4*. Since no information could be found concerning the capacity of the countercurrent heat exchangers, the values for $(UA)_i$ were adjusted to obtain reasonable values of the com-

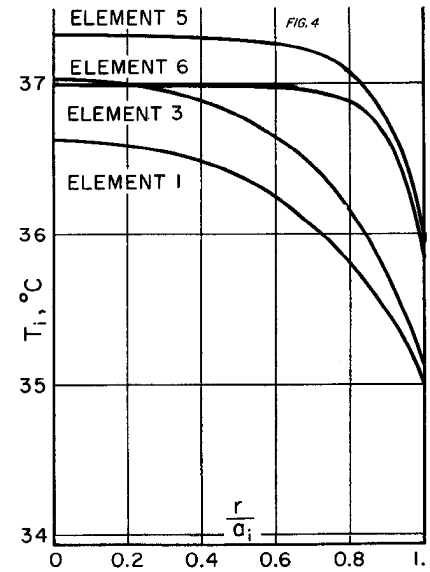
TABLE 1. *Data for basal man*

Element	a_i: cm	L_i: cm	h_{mi}: $\frac{\text{cal}}{\text{cm}^3 \times \text{sec.}}$	$(Vs)_i$: $\frac{\text{cal}}{\text{cm}^3 \times \text{sec} \times \text{C}}$	$(UA)_i$: $\frac{\text{cal}}{\text{sec.} \times \text{C}}$	T'_{ai}: C	T'_{vi}: C
1–3	4.5	65	0.000118	0.00030	1.0	35.9	34.9
3–4	7.0	83	0.000118	0.00020	5.0	35.5	35.0
5	8.9	25	0.000643	0.00118	0.0	36.7	37.0
6	13.0	80	0.000282	0.00118	0.0	36.7	36.8

$k = 0.001 \dfrac{\text{cal}}{\text{cm}^2 \times \text{sec} \times \text{C/cm}}$; $\rho C = 0.9 \dfrac{\text{cal}}{\text{cm}^3 \times \text{C}}$; $Q_r = 2.41 \dfrac{\text{cal}}{\text{sec}}$; $T_a = 36.7$ C.







2. Computed steady-state temperature profiles in the basal man. Environmental temperature is 30.3 C and there is no wind.

FIG. 3. Computed steady-state temperature profiles in the basal man. Environmental temperature is 31.5 C and wind speed is 120 ft/min.

FIG. 4. Computed steady-state temperature profiles in a non-basal man whose blood flow rates and metabolic rates are twice basal in arms and legs and whose respiratory rate is 25% above basal. Environmental temperature is 31.5 C and wind speed is 120 ft/min.

puted temperatures. The data used are summarized in Table 1.

The most reasonable choices for $(UA)_i$ produced the temperatures presented in Fig. 2. The temperature along the axis of the trunk was 37 C when the environmental temperature was 30.4 C, and the corresponding surface temperatures were 35.8 C for the trunk, 36.1 C for the head, 34.1 C for the arms, and 34.0 C for the legs. Since the temperature of the arterial blood leaving the heart was 36.7 C and the temperatures of the venous streams returning from the trunk and the head were 36.8 C and 37.04 C, respectively, both of these elements produced more heat metabolically than they lost to the environment. On the other hand, the venous streams returning from the arms and legs were at 34.92 C and 34.97 C. Hence, there was a net transport of heat from the head and trunk to the arms and legs.

Because of countercurrent heat exchange between the arterial and venous blood, the temperature of the arterial blood entering the capillary beds in the arms was 0.8 C lower than that of the blood leaving the heart, and in the legs it was 1.1 C lower.

The temperature profiles existing in the various elements were very interesting. In the arms, and, to a lesser extent, in the legs, the profile was nearly parabolic, but in the trunk the temperature was nearly uniform over an inner cylinder having a radius of 10.4 cm, and then it dropped 1 C in the outer 2.6 cm. Hence, the core and shell concept does apply to some extent in the trunk, but not in the arms and legs.

The results of this first series of computations were encouraging. The model predicted that a nude basal man is in thermal equilibrium with an environment at 30 C. This is consistent with the comments of Winslow and Herrington (11). The temperature profiles computed for the arms and the temperature difference between the arterial blood in the arm and at the heart were consistent with the observations of Pennes (1). The surface temperatures of the legs were slightly lower than those of the arms, but the difference was not as large as expected.

Two other series of computations were performed. In both of them the air in the room was moving at a speed of 120 ft/min. Fig. 3 contains the temperatures for the basal man under these conditions. Because of the higher heat transfer coefficients existing at the surface of this man, the environmental temperature with which he is in equilibrium is 1.2 C higher than the corresponding temperature when there is no wind. Otherwise, the temperature profiles are very similar. Fig. 4 contains data for a man whose metabolic rates and blood flow rates are twice basal in the arms and legs. His respiratory rate is 25% above the basal rate, and the environmental wind speed is 120 ft/min. Comparison of the curves in Fig. 4 with those in Fig. 3 shows that the only effect of these changes is to increase the central temperatures in the arms and legs. The temperature profiles in the trunk and head are unchanged, and the man is still in equilibrium with an environmental temperature of 31.5 C.

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