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A Dynamic Model of the Human/Clothing/Environment-System

Xiaojiang Xu and Jürgen Werner

Institut für Physiologie, Abt. Biokybernetik, Germany

Abstract. In this paper a dynamic model of the human/clothing/environment-system is developed. The human body (controlled system) is subdivided into six segments consisting of the head, trunk, arms, hands, legs and feet. Each segment is further divided into the core, muscle, fat, and skin layer. The afferent signal of the controlling system is composed of the weighted temperatures measured by thermal receptors at sites distributed in the body. The difference between this signal and its threshold activates the thermoregulatory actions: vasomotor changes, metabolic heat production and sweat production. The model considers the competition between skin and muscle blood flow during exercise in hot environments because of limited cardiac capacity, as well as cold induced vasodilatation. Additionally a combined model of heat and mass transfer from the skin through clothing to the environment is developed and incorporated into the thermoregulatory model. The human/clothing model can be used to investigate the interaction between the human body, clothing and environment. The model is validated by comparing the simulation with experimental results under different conditions: heat, cold, exercise, clothing and transient phases. It turns out that the simulation is compatible with the experimental results. We conclude that the model can be applied in a broad range of environmental conditions. Application of the model is easy via a user-friendly interface i.e. a WINDOWS-shell.
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Keywords: model, simulation, thermoregulation, clothing

Introduction

Many mathematical models of thermoregulation in humans have been developed, and some of them have been successfully used in practice. For reviews of these models, see Hardy (1972), Hwang and Konz (1977), Wissler (1988) and Werner (1989). The large amount of work on models indicates that they have always been of great interest, because models are very useful tools for studying temperature regulation in humans. For example, models could be used to design and analyse physiological experiments to save time and cost; they could be used to extrapolate and interpolate the experimental results to predict non-performable experiments e.g. the measurement of the temperature distribution in human tissue during local hyperthermia and prediction of survival time during immersion, and to investigate the interaction between humans and the thermal environment.

One of the models used in many applications was developed by Werner (Werner and Webb, 1993), which is based on a previous former essential development of Stolwijk and Hardy (1966) and of Wissler (1964). It is a six cylinder model and generally available for use on personal computers. In this model, each cylinder consists of a core and a shell layer. The model described in this paper supplements this six cylinder model and is further developed by introducing a muscle layer and a fat layer as well as a clothing layer. The clothing layer is described by a combined model of heat and mass transfer from the skin through clothing to the environment. These modifications provide overall improved performance of the model and enhance the range of application of the model substantially.

Methods—Development of the model

The thermal system of the human body is conveniently analysed by considering a controlled system and a controlling system. The controlled system is associated with the geometric characteristics, various thermal characteristics and energy transfer mechanisms found in the human body. Body temperature regulation through sweating, shivering, and variable blood flow rate is a function of the controlling system. The simplified diagram of the thermoregulatory system is shown in Fig. 1. The six cylinders $i=1\ldots6$ are head, trunk, arms, hands, legs and feet, the four layers $j=1\ldots4$ of each cylinder are core, muscle, fat and skin. The model takes into account the radial dependency of the temperatures. A one-loop circulatory system is assumed. A central pool of blood at temperature T_a delivers the arterial blood to capillaries and tissue (temperature T_i). Through the veins blood at temperature T_{vi} flows back to the central pool. Body temperature controls the effector mechanisms: evaporation, metabolism and vasomotor action.

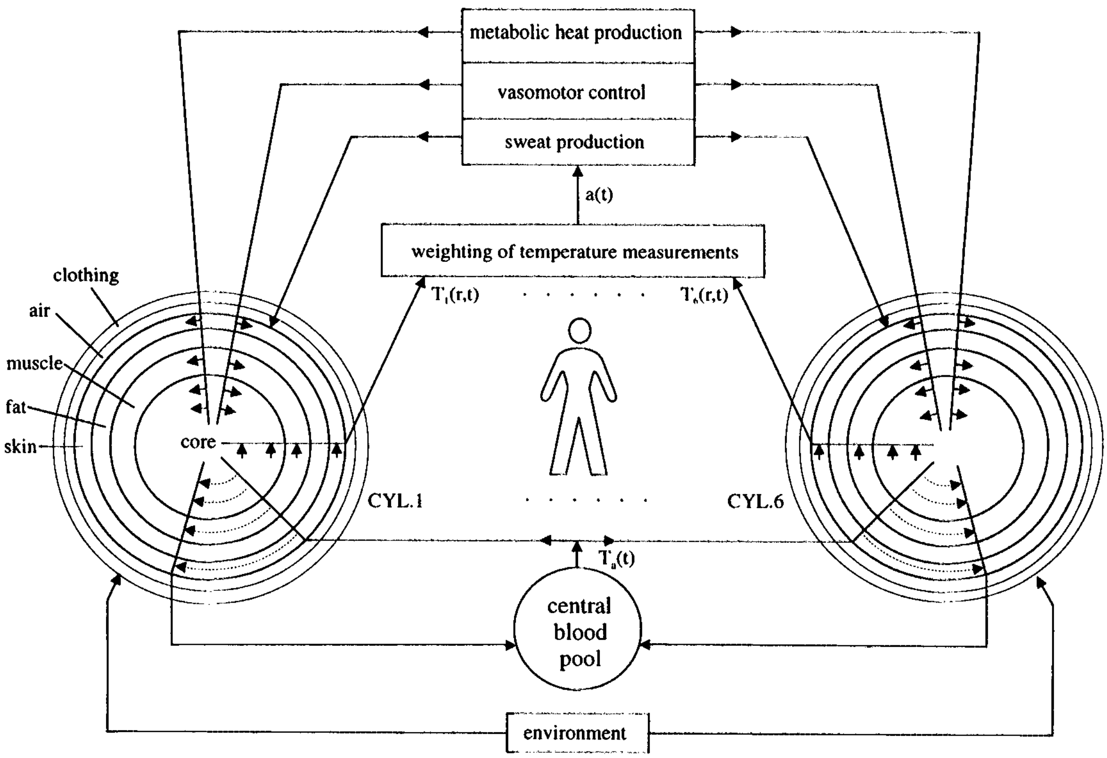

Fig. 1 Scheme of the thermoregulatory model. For meaning of variables, see text.

Controlled system

1) Energy equation

The energy equation for each cylinder in one-dimensional cylindrical coordinate is:

$$\rho_i c_i \frac{\partial T_i}{\partial t} = M_i + M_{wi} + \lambda_i \left\{ \frac{\partial^2 T_i}{\partial r^2} + \frac{1}{r}\frac{\partial T_i}{\partial r} \right\} + \beta_i Q_i \rho_a c_a (T_a - T_i) \quad (1)$$

where $\rho_i(r)$ is the density of tissue plus capillaries; $c_i(r)$ is the specific heat of tissue plus capillaries; $T_i(r,t)$ is the temperature of tissue plus capillaries; t is time; $M_i(r, t)$ is the heat production by metabolism per volumetric unit; $M_{wi}(r,t)$ is the extra heat production due to exercise per volumetric unit; $\lambda_i(r)$ is the thermal conductivity of tissue; r is radius; β_i is the countercurrent factor, by which the heat exchange between arterial blood and venous blood is approximately considered; $Q_i(r,t)$ is the blood flow per volumetric unit; ρ_a is the density of central blood; c_a is the specific heat of central blood; $T_a(t)$ is the temperature of central blood (lungs, heart, large vessels). The term on the left-hand side is the rate of accumulation of thermal energy per unit volume. The terms on the right-hand side represent the metabolic heat production, extra heat production due to exercising, the rate of heat conduction in the tissue and heat transfered from the tissue to the blood flow.

The blood flow rate is variable and controlled by the controlling system. The temperature T_a of the central blood is considered to be independent of radius and determined by an energy balance equation of the form:

$$m_a c_a \frac{dT_a}{dt} = \sum_{i=1}^{6} \{\beta_i \rho_a c_a Q_{gi} (T_{vi} - T_a)\} - R_R \quad (2)$$

where m_a is the mass of the central blood and c_a is the specific heat of the central blood; T_{vi} is the venous temperature; R_R is respiratory heat loss. R_R is computed according to a recently developed formula by Paul Webb (private communication). Q_{gi} is the total blood flow to cylinder i and is obtained by an integration over the volume of cylinder with length L:

$$Q_{gi} = 2\pi L_i \int_0^{r_{si}} Q_i r dr \quad (3)$$

where r_{si} is the radius of cylinder i. Assuming that the temperature of blood in the capillaries and venules is equal to the temperature of the neighbouring tissue, we get the following balance for convective heat flow from each cylinder to the central blood pool:

$$\beta_i \rho_a c_a Q_{gi} T_{vi} = 2\pi L_i \beta_i \rho_a c_a \int_0^{r_{si}} Q_i T_i r dr \quad (4)$$

From this, T_{vi} is computed:

$$T_{vi} = \frac{\int_0^{r_{si}} Q_i T_i r dr}{\int_0^{r_{si}} Q_i r dr} \quad (5)$$

2) Boundary and initial conditions

The boundary condition at the centre of each cylinder is:

$$\left.\frac{\partial T_i}{\partial r}\right|_{r=0} = 0 \tag{6}$$

due to axial symmetry. The continuity of temperature and heat flux at an interface between two layers of different tissue type are expressed as:

$$T_i\,(r_{ji} - 0,t) = T_i\,(r_{ji} + 0,t) \tag{7}$$

$$\lambda_{ji}\left(\frac{\partial T_i}{\partial r}\right)_{r_{ji}-0} = \lambda_{j+1,i}\left(\frac{\partial T_i}{\partial r}\right)_{r_{ji}+0} \tag{8}$$

At the skin surface, the rate at which heat is brought to the surface by conduction is equal to the rate of heat removal from the surface by radiation, convection/conduction and evaporation. Hence the boundary condition at the skin surface of each cylinder is:

$$\lambda_i \frac{\partial T_i}{\partial r} = h_{ri}\,(T_{A,\,rad} - T_i) + h_{ci}\,(T_A - T_i) - \frac{E_i}{S_i} \quad (r = r_{si}) \tag{9}$$

where h_{ri} is the radiation heat transfer coefficient; h_{ci} is the convection heat transfer coefficient; $T_{A,rad}(t)$ is the radiant temperature; $T_A(t)$ is the air temperature; $E_i(t)$ is the heat loss by evaporation; S_i is the skin surface. The convective heat transfer coefficient is corrected from air velocity v and its basal value h_{coi} as following:

$$h_{ci} = 3.16\;h_{coi}\;V^{0.5} \tag{10}$$

In addition to boundary conditions, one must have initial conditions which specify the values of all dependent variables at time zero. The initial values may be equilibrium values which are obtained from a previous steady state calculation, or they may be nonequilibrium values which result from a previous transient. In either case, they consist of temperature specifications at the instant the transient begins:

$$T_i\,(r,0) = T_i\,(r) \tag{11}$$

$$T_a = T_a\,(0) \tag{12}$$

$$T_{vi} = T_{vi}\,(0) \tag{13}$$

3) Parameters of the controlled system

Weight, height and percentage body fat (if available) can be used as input. Their default values are 78 kg and 1.7 m respectively, which are considered to be the values for the standard human of the model. The geometrical parameters i.e. the dimension of cylinders and their concentric layers are determined according to the weight, height, percentage body fat and the distribution factors of relative volume and surface of the body compartments. The physical and physiological parameters are mostly taken from the previous model. For detailed information, see Appendix or Xu (1996).

Controlling system

The temperatures from the core, muscle and skin layer are weighted by weighting factors g_{ij} (see Appendix) and summed to form an integrated body temperature. The afferent signal a(t) for the controlling sytem is the difference between the integrated body temperature and its threshold a_0 (36.6°C):

$$a = \sum_{i=1}^{6}\sum_{j=1}^{4}\{g_{ij}T_{ij}\,(r,t)\} - a_0 \tag{14}$$

The integrated afferent signal is then transformed into control actions: sweat production, metabolic heat production and vasomotor activity. The sweat production is calculated as following:

$$E_i - E_{i0} = \varepsilon_{Ei}a \qquad (\varepsilon_{Ei} = 0 \quad \text{when } a \leq 0) \tag{15}$$

where E_{io} is the basal evaporation value; ε_{Ei} is distribution factor for evaporation. The maximum evaporative capacity is dependent on the vapour pressure difference between the skin and the environments and can be expressed as:

$$E_{max,i} = 0.0166h_{ci}\,(P_{sat}\,(T_i\,(r_{si},t)) - P_A) \tag{16}$$

where P_{sat} is saturated vapour pressure at the skin and P_A is ambient vapour pressure.

The metabolic heat production is changed due to shivering in cold stress i.e. a≤0 or "Q_{10}-effect" in heat stress i.e. a≥0, which lead to the following equations:

$$M_i - M_{i0} = \varepsilon_{Mi}a \qquad (a \leq 0) \tag{17}$$

$$\frac{M_i}{M_{i0}} = 2^{\frac{a}{\kappa}} \qquad (a \geq 0) \tag{18}$$

where M_{io} is the basal metabolic rate; ε_{Mi} is the distribution factor for metabolic heat production; κ is a constant.

The blood flow to the core compartments is slightly reduced during heat stress and this small reduction is calculated by:

$$Q_i - Q_{i0} = -\varepsilon_{Qi}a \quad (core) \tag{19}$$

where Q_{io} is basal blood flow rate; ε_{Qi} is a distribution factor for vasomotoric activity and has different values for the core compartments, the muscle compartments, the skin compartments (warm) and the skin compartments (cold). During exercise in hot environments there is competition for circulation between the active muscles to support metabolism and the skin to dissipate heat, because the cardiac capacity is limited (Werner, 1993). This is considered in the controlling equations by a coefficient δ_i which was taken from experimental data (Rowell, 1986). It is also assumed that the blood flow to the muscle compartments is proportional to their metabolic heat production with a factor ξ=0.00086 m^3/hW

(Stolwijk and Hardy, 1977). As a result, the following equations approximately describe the blood flow to the muscle compartments and to the skin compartments:

$$Q_i - Q_{i0} = -\varepsilon_{Qi}a + M_{wi}\xi(1 - 0.1a) \quad (muscle) \qquad (20)$$

$$Q_i - Q_{i0} = (\varepsilon_{Qi} + \mu_i\dot{a})\, a - M_{wi}\delta_i e^{-2a} \quad (skin,\ \mu_i=0 \ \ when\ \dot{a}\geq 0) \qquad (21)$$

where μ is dynamic sensitivity of skin sensors. The dynamic term $\mu_i\dot{a}$ is set to zero when the change rate of the afferant signal is positive. This is a modification of the controlling equation of Stolwijk and Hardy (1977). The blood flow to the fat compartments is assumed to be practically zero.

The cold induced vasodilation "CIVD" i.e. Lewis-reaction occurs when the finger skin temperature sinks below about 10°C. It generally occurs in a periodic manner that is attenuated in amplitude and decreased in frequency as deep core temperature decreases (Werner, 1977; Lotens, 1991). On the basis of the work of Lotens (1991), CIVD is approximated by:

$$Q_{kv} = 2\,(15 + 10\,(T_2\,(0,t) - 36.8) - T_4\,(r_{S4},t)) \qquad (22)$$

$$\tau_{kv} = 2^{3 + \frac{(36.8 - T_2\,(0,t))}{0.8}} \qquad (23)$$

where Q_{kv} is the CIVD blood flow, τ_{kv} is period. Q_{kv} is set to be zero if it is negative. Furthermore, a sinusoidal function with amplitude Q_{kv} and period τ_{kv} is used to simulate CIVD blood flow and added to the blood flow to the finger skin compartment.

The work efficiency η is defined by:

$$\eta = \frac{W}{M_w + M_0 + W} \qquad (24)$$

where M_o is the metabolic heat production before exercising. The extra metabolic heat production M_w due to exercising is calculated from the above equation if mechanical output W and efficiency are known. This extra heat production is then distributed to the muscle compartments of each cylinder.

The metabolic heat production and blood flow are physiologically limited by maximum and minimum values. For detailed information about parameters mentioned above e.g. coefficients, distribution factors, maximum and minimum values, see Appendix or Xu (1996).

Model of heat and mass transfer through clothing

The traditional clothing parameters such as heat and vapour resistance are static and therefore not always sufficient to describe the processes of heat and mass transfer from the skin through clothing to the environment. With changing environmental conditions, moisture absorption/desorption and condensation/evaporation in clothing play an important role and affect the transfer processes. Therefore a mathematical model which describes the thermal response of the clothing system to the skin and the environment was developed.

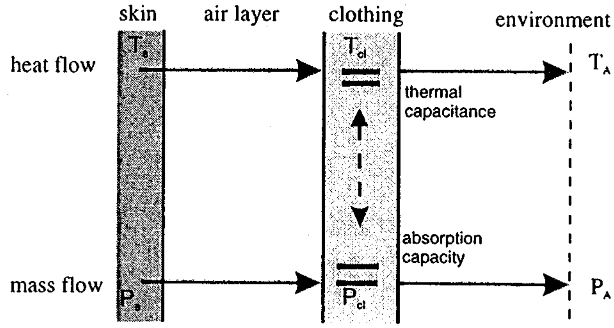

Fig. 2 Heat and mass transfer from the skin through clothing to the environment. T: temperature, P: vapour pressure. Subscript s: skin, cl: clothing, A: environment.

A simplified physical model of human/clothing/environment system is shown in Fig. 2. Both heat and mass flow are taken into account. The heat is transferred from the skin to the clothing by convection/conduction and radiation, and then is further transferred from the clothing to the environment by convection/conduction and radiation. Part of the heat could be absorbed by the clothing. The vapour evaporated at the skin diffuses in the direction of the clothing, and then diffuses further from the clothing to the envionment. Part of the vapour could be absorbed by the clothing. These two flows interact due to the moisture absorption/desorption and condensation/evaporation in clothing.

1) Heat and mass transfer equation

The heat flow can be expressed as (Farnworth, 1986):

$$C_{cl}\frac{dT_{cl}}{dt} = \frac{T_s - T_{cl}}{R_{h,1}} - \frac{T_{cl} - T_A}{R_{h,2}} + q \qquad (25)$$

where C is the heat capacity of the clothing per area unit; T is the temperature; R_h is the heat resistance; q is the heat liberated in the clothing layer by the condensation or absorption of the water vapour; the index cl is clothing; the index s is skin; index A is ambient. The left-hand side is changes in heat storage of clothing and the right-hand side is heat flow into and out of the clothing, and the heat which is released by the condensation or absorption of the water vapour.

The mass flow can be expressed as (Farnworth, 1986):

$$\frac{dm_w}{dt} = \frac{E}{SH} - \frac{P_{cl} - P_A}{R_{v,2}} \qquad (26)$$

where m_w is the water absorbed by clothing per area unit; E is evaporation rate; S is the surface area of the human body; H is the latent heat; P is the vapour pressure; R_v is the vapour resistance. The left-hand side is the change

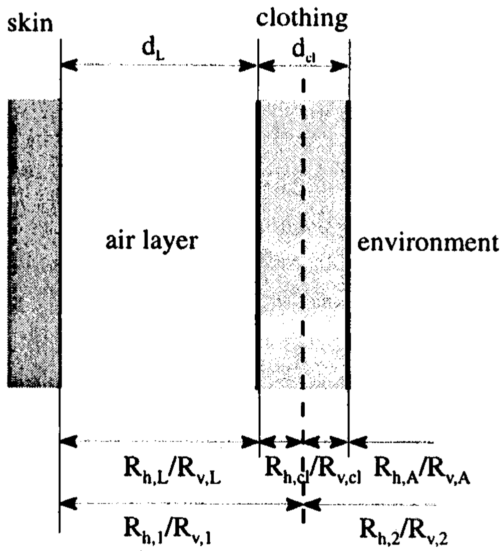

Fig. 3 Heat and vapour resistance in the man-clothing-environment system. d_L: thickness of the air layer, d_{cl}: thickness of the clothing. For meaning of variables for resistances, see text.

rate of the water absorbed by clothing, the right-hand side is the mass flow into the clothing i.e. the evaporation rate at the skin and the mass flow out of the clothing.

The heat released in the clothing layer by the condensation or absorption of water vapour is determined by:

$$q = H^* \frac{dm_w}{dt} \tag{27}$$

where H* is the differential heat of sorption (heat of absorption) which consists of the latent heat and the heat of swelling. It is calculated from the emperical equation (Morton and Hearle, 1975; Lotens, 1993). The water absorbed by clothing depends on the characteristics of the clothing and relative humidity in the clothing, which is expressed by the regain function:

$$\frac{m_w}{m_{cl}} = f\left(regain, \frac{p_{cl}}{p_{cl,sat}}\right) \tag{28}$$

where m_{cl} is the mass of dry clothing per area. The regain (g absorbed water per 100 g dry fibre at RH65%) for various types can be obtained from the literature e.g. Morton and Hearle (1975).

2) Heat and vapour resistance

As shown in Fig. 3, in the man/clothing/environment system there are basically three partial resistances: the resistance ($R_{h,L}/R_{v,L}$) provided by air layer between the skin and the clothing, the resistance ($R_{h,L}/R_{v,L}$) provided by the clothing and the resistance ($R_{h,A}/R_{v,A}$) provided by the outer air layer. The resistance of the clothing is divided into two parts, one is added to the resistance of the air layer to calculate the resistance ($R_{h,l}/R_{v,l}$) from the skin to the clothing, and the other one is added to the resistance of the outer air layer to calculate the resistance ($R_{h,A}/R_{v,A}$) from the clothing to the environment.

In the air layer there are parallel paths for dry heat flow, one by conduction and convection through the air layer and one by radiation between the skin and the clothing. The radiant heat transfer coefficient is approximated to be about 4 W/m²°C (Cain and Farnworth, 1986; Lotens, 1993) and thus total heat resistance is given by:

$$R_{h,L} = \frac{1}{4 + \frac{\lambda_L}{d_L}} \tag{29}$$

where thermal conductivity of the air λ_L=0.026 $Wm^{-1}{}^\circ C^{-1}$. It was found by Lotens (1993) and McCullough et al. (1989) that heat resistance of a variety of fabrics is proportional to their thickness, despite the difference between the materials. This is due to their common insulation material: air. Hence the heat resistance of the clothing could be estimated from its thickness:

$$R_{h,cl} = \frac{d_{cl}}{\lambda_{cl}} \tag{30}$$

where λ_{cl} is 0.042 $Wm^{-1}{}^\circ C^{-1}$. The heat resistance of the outer air layer could be calculated by considering convection and radiation:

$$R_{h,A} = \frac{1}{h_c + h_r} \tag{31}$$

Thus the heat resistance from the skin to the clothing and from the clothing to the environment are obtained by:

$$R_{h,1} = R_{h,L} + 0.5\frac{R_{h,cl}}{f_{cl}} \tag{32}$$

$$R_{h,2} = 0.5\frac{R_{h,cl}}{f_{cl}} + \frac{R_{h,A}}{f_{cl}} \tag{33}$$

where f_{cl} is clothing area ratio of the clothing to the body surface, by which the area difference between the skin surface and the clothing surface is taken into account.

It is a particularly convenient way to express the vapour resistance as an equivalent thickness (d*), which is the thickness of a still air layer that would give the same resistance as the clothing. According to Fick's law, evaporation rate is expressed as:

$$E = \frac{D}{d^*}\Delta C \tag{34}$$

where D is the diffusion coefficient (25 10^{-6} m²/s); ΔC is the vapour concentration gradient. If it is further assumed that the vapour is an ideal gas, then the equation can be transformed into:

$$E = \frac{\Delta P}{R_v} \tag{35}$$

with

$$R_v = \frac{d^*}{\frac{D}{RT}} \quad (36)$$

where **R** is the universal gas constant (461.67 J/kg K). Therefore it is possible to estimate the vapour resistance from its equivalent thickness.

For the air layer the equivalent thickness is the same as its thickness. For clothing it can be estimated as follows (Lotens, 1993):

$$d^*_{cl} = 1.3\, d_{cl} + 0.001 \quad (37)$$

The vapour resistance of the outer air layer is estimated by the so-called Lewis-relation. It is therefore possible to obtain the vapour resistance from the skin to the clothing and that from the clothing to the environment by the same method as used to obtain the heat resistance.

3) Initial conditions for the clothing model

The temperature in the clothing, the vapour pressure in the clothing and the water absorbed by the clothing at time zero could be specified according to different conditions. For example, the m_w is set to be zero if the clothing at the beginning is dry.

Numerical methods and program

The numerical technique for the human model is a simple implicit method with central differences, which remains unchanged from the previous model. The spatial grid is 101 nodes in each half-cylinder. The time increment (Δt) begins at 3.6 s and is adjusted to each computed temperature increment (ΔT) in the following manner: if the latter is smaller than 0.025°C, Δt is doubled; if, on the other hand, ΔT is greater than 0.05°C, Δt is divided by two. The final profiles are stored to serve as initial profiles for further computations.

The numerical technique for the clothing model is an explicit differential method. Thus the time increment is restricted by the stability. The clothing model uses its own time step if the limit of the time increment is greater than the time increment of the human model. Otherwise it uses the same time increment as the human model.

The simulation program is written in FORTRAN and its flow sheet is shown in Fig. 4. It consists of 6 parts: main program, subroutines HMAN, OUTPUT, NEWTEM, SIGNAL and CLOTH. Their functions are:

Main program: read initial and simulation conditions, control the program.

HMAN: calculate the geometric, physiological and physical parameters of the passive system.

OUTPUT: prepare for the output of the simulation results.

SIGNAL: calculate the parameters of the controlling system and the heart-lung pool.

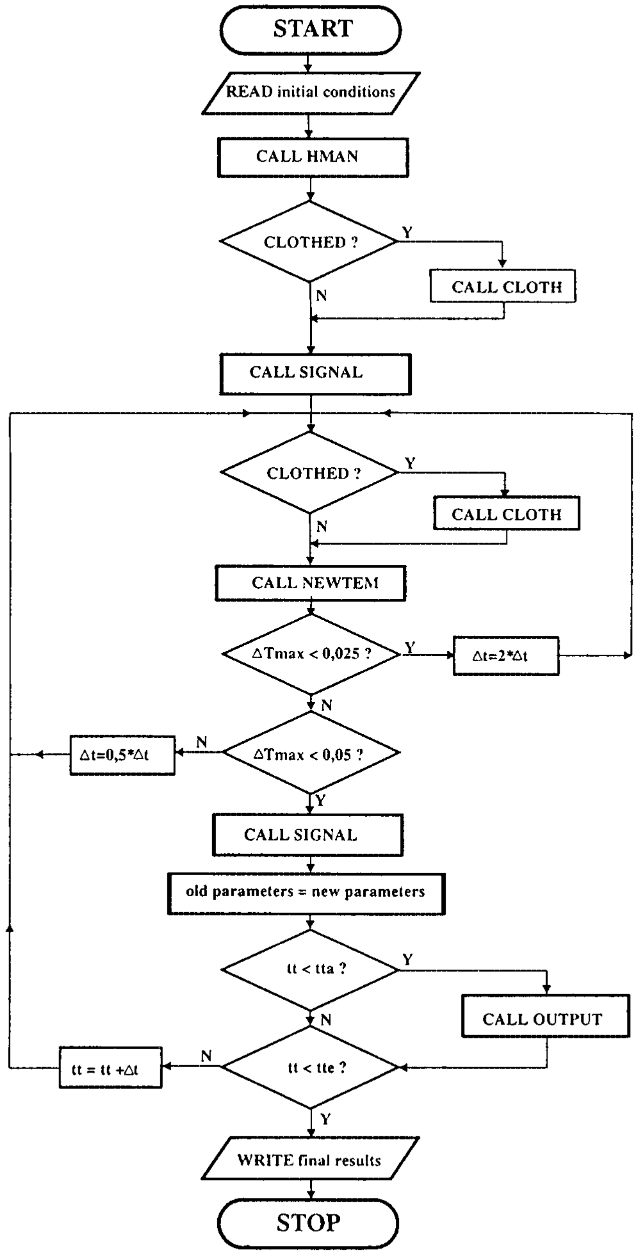

Fig. 4 Flow chart of the simulation program. Δt: time step, tta: output interval, tte: simulation time.

NEWTEM: calculate the new temperature from their previous temperature.

CLOTH: calculate the parameters of the clothing.

Results—Validation of the model

A model is by definition simpler than the system it attempts to represent. Therefore it must be validated by comparing its simulation with the experimental data from human subjects. Not only does this process establish the accuracy of the model, but also it helps to define the range of conditions for which the model is applicable.

The experimental data are usually expressed as a span of measurements because of intraindividual differences, interindividual differences and differences due to different sites in the same compartment. Therefore, the results of a model are considered as reasonable if the predictive results stay within the experimental span.

Six experimental data from human subjects under a great range of conditions have been used to validate the model:

Case 1: nude subjects, exercising in changing environments (29°C -▸ 35°C or 29°C -▸ 12°C).
Case 2: sedentary clothed subjects in changing environments (28°C -▸ 45°C -▸ 28°C).
Case 3: nude sedentary subjects in cold environments (1°C).
Case 4: sedentary clothed subjects in extreme cold environments (- 20°C).
Case 5: nude subjects, exercising in warm and humid environments (35°C/RH80%).
Case 6: clothed subjects in step changing environments (RH20% -▸ RH80%).

Case 1 (exercising in changing environments)

Experiments were carried out to collect data for validation of the model. Three healthy, physically active male students served as subjects. Mean age was 23 (± 3.5) y, mean body weight 79.2 (± 2.1) kg and mean height 1.84 (± 0.08) m. The subjects, wearing only a bathing suit, exercised (60W) on a cycle ergometer in a neutral environment (29°C/40%) till a steady state was reached. Then the environment was changed from the neutral condition to a warm condition (35°C/40%) or from the neutral condition to a cold condition (12°C/40%). The subjects continued to exercise for 90 min or 80 min.

The predicted and experimental results of rectal, trunk skin and leg skin temperature were shown in Figs. 5 and 6. In Fig. 5 there is a good agreement between the calculated and experimental skin temperature. The rectal temperature has a very small deviation which is less than 0.2°C. In Fig. 6 the predicted rectal temperature and leg skin temperature agree well with the experimental results. The calculated trunk skin temperature is lower than the experimental results with a maximal deviation 0.8 °C in the end.

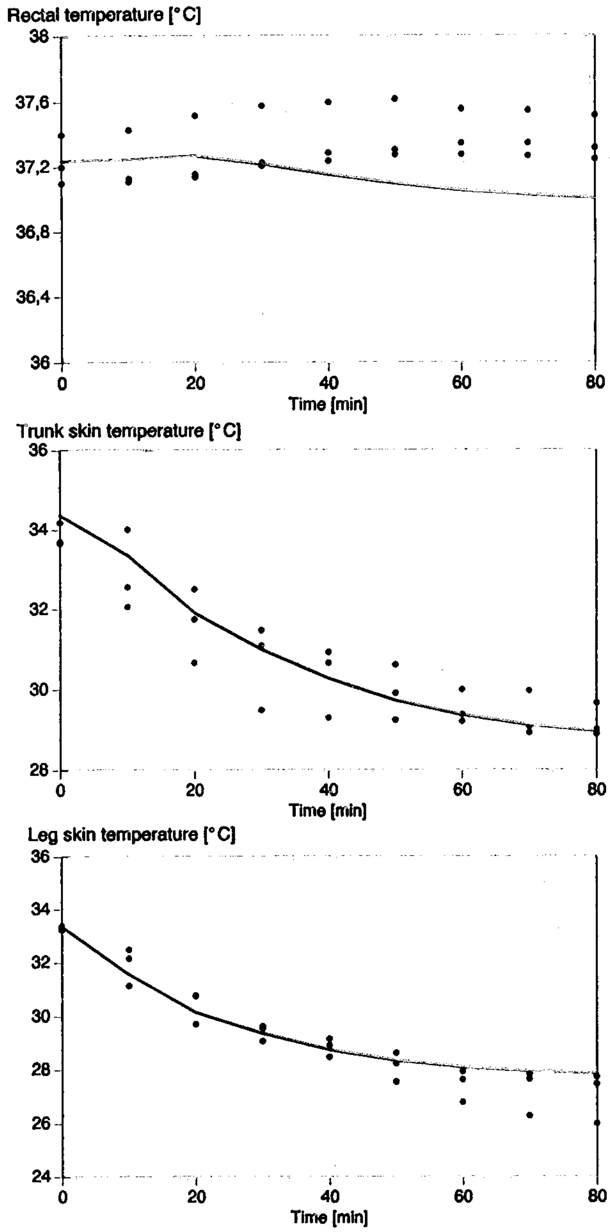

Fig. 5 Comparison of the simulation (line) and the experimental results (symbol) in case 1. Nude, exercise (60W) on an ergometer during transition from 28°C to 12°C, RH40%, air velocity 0.2 m/s.

The calculated and experimental rectal and mean skin temperature are shown in Fig. 7. The overall agreement between the simulation and the experiment is acceptable, although the calculated skin temperature is lower than the experimental results during the phase 45°C/40%.

Case 2 (clothed subjects in changing environments)

Further experiments were carried out to validate the performance of the model under clothing conditions. The same subjects as in case 1 took part in these experiments. They were dressed in cotton clothing (cotton 100%, density 0.195 kg/m^2 and regain 8%) and were sedentary in a changing environment: 28°C/40% for 30 min, 45°C/40% for 120 min and 28°C/40% for 30 min.

Case 3 (sedentary subjects in cold environments)

The experimental data was provided by Bittel and Savourey (Bittel et al., 1988, Division de Physiologie,

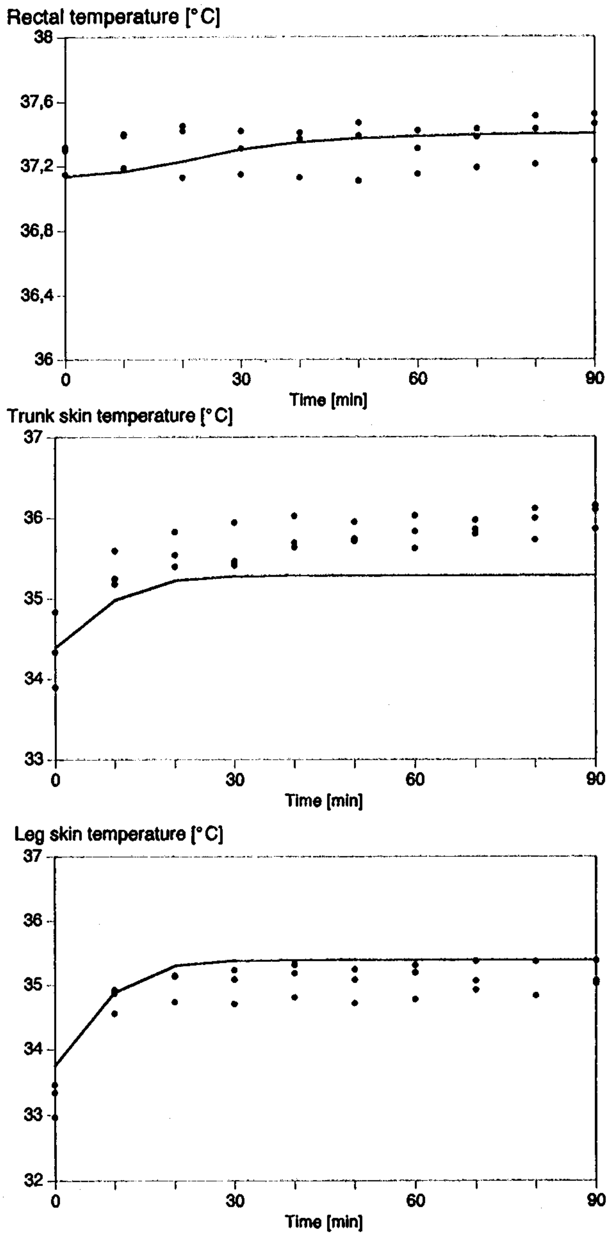

Fig. 6 Comparison of the simulation (line) and the experimental results (symbol) in case 1. Nude, exercise (60W) on an ergometer during transition from 28°C to 35°C, RH40%, air velocity 0.2 m/s.

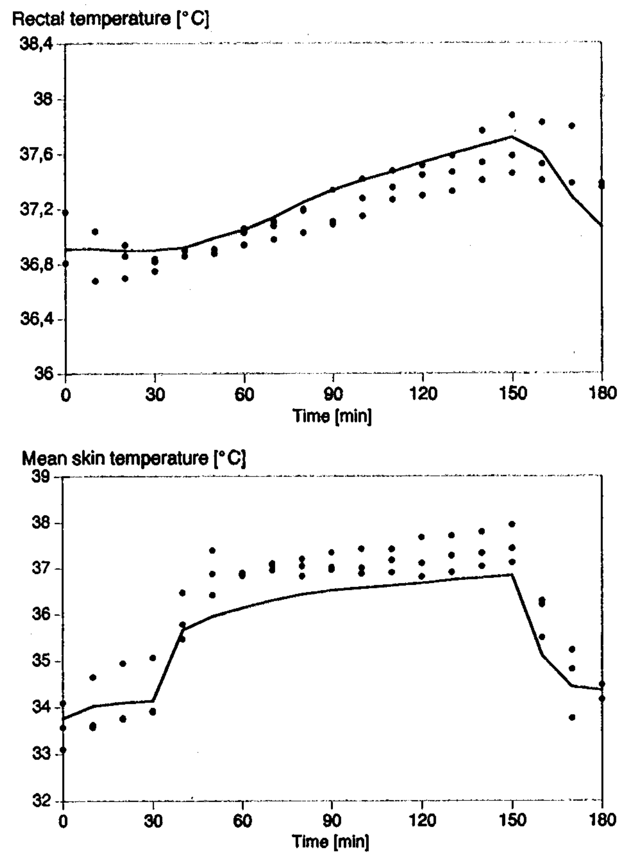

Fig. 7 Comparison of the simulation (line) and the experimental results (symbol) in case 2. Clothed (cotton 100%, 0.195 kg/m², regain 8%), sedentary during transition from 28°C to 45°C and back to 28°C, RH40%.

Centre de Recherches du Service de Santé des Armées, Grenoble, France). Eight subjects, wearing only a bathing suit, were resting in a recumbent position on a wire mesh bed for 2 hours in a cold environment: 1°C, 40–50% and air verlocity 0.8 m/s.

Figure 8 shows results of the rectal temperature, arm temperature (measurements from lower and upper arm superimposed) and hand temperatures. It is clear that the computations give results within the experimental span. The results are satisfactory.

Case 4 (clothed subjects in extreme cold environments)

The experimental data was provided by USARIEM (Gonzalez et al., 1989, US Army Research Institute of Environmental Medicine, Natic, USA). Six subjects dressed in the Extended Cold Weather Clothing System (ECWCS) at rest were exposed to an extreme cold environment − 20°C, RH20% and air velocity 1.34 m/s. A maximal 120 min cold exposure was designed, but the exposure was withdrawn because of rectal temperature reaching ≤35°C and/or finger-tip skin temperature ≤5°C.

Figure 9 shows the trunk and hand/finger skin temperature from experiments vs model. Only one subject finished 120 min exposure, the exposures of the other subjects were withdrawn. As shown in Fig. 9, there is satisfactory agreement between the simulation and the experiments. The calculated hand skin temperature is between the hand and the finger skin temperature, as the model has no finger compartments. Thus, "hand" computations should be interpreted as an average of hand

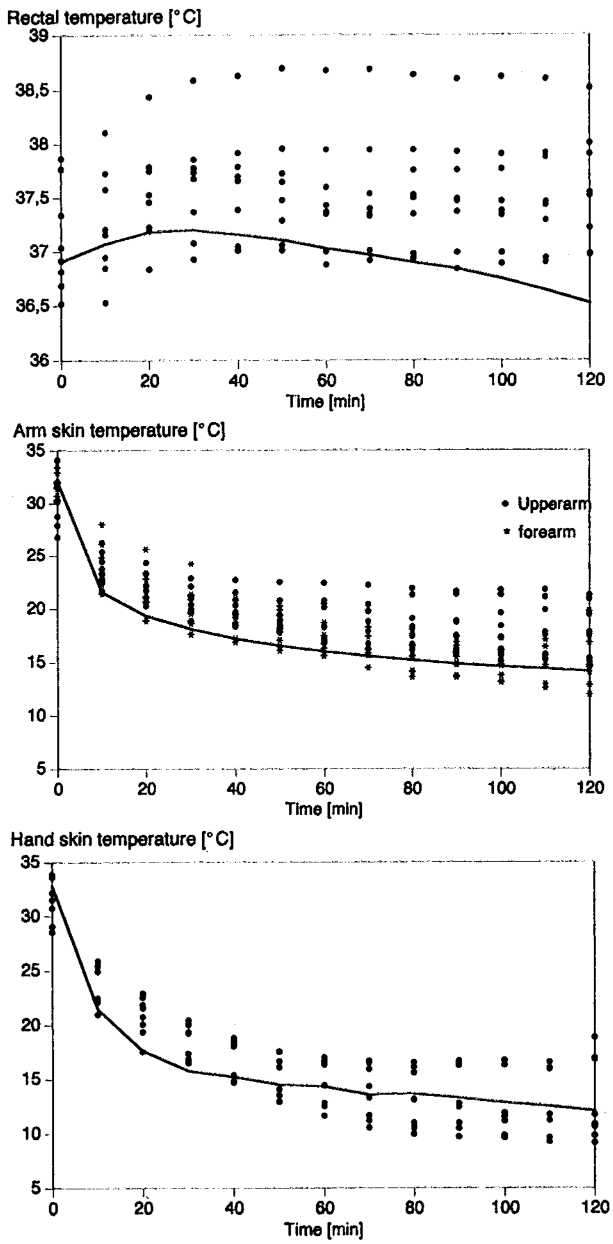

Fig. 8 Comparison of the simulation (line) and the experimental results (symbol) in case 3. Nude, lying at 1°C, RH40%, air velocity 0.8 m/s.

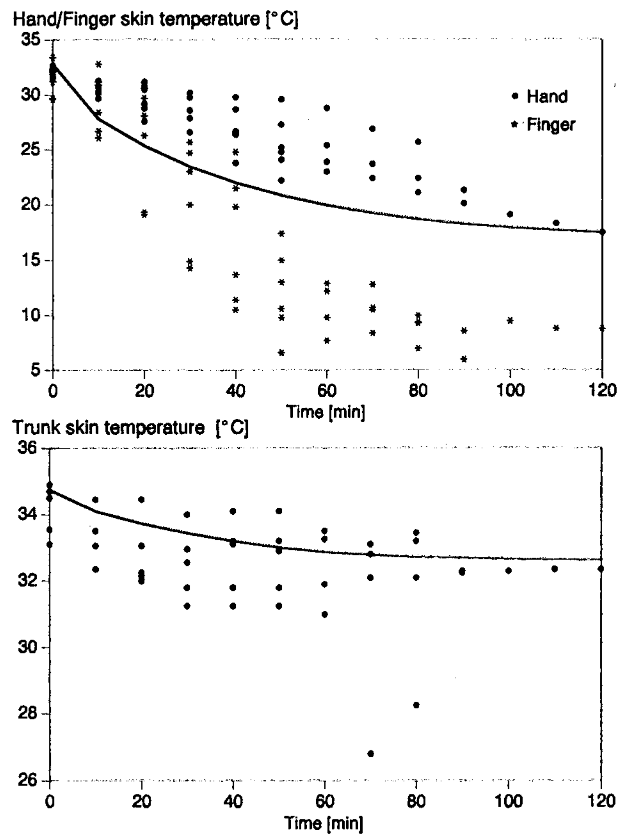

Fig. 9 Comparison of the simulation (line) and the experimental results (symbol) in case 4. Dressed in ECWCS, sedentary at − 20°C, RH20%, air velocity 1.34 m/s.

and finger temperature. For higher resolution, the arm/hand-model (Tikuisis, 1995) and finger model (Shitzer et al., 1995) should be incorporated into the model.

Case 5 (exercising in warm and humid environments)

The experimental data was provided by Havenith (Havenith et al., 1995, TNO Human Factors Research Institute, Soesterberg, the Netherlands). 56 subjects, wearing bathing suits, were at rest for 30 min and then exercised with 60 W on an ergometer for 60 min in a warm and humid environment (35°C/RH80%).

The rectal and mean skin temperatures are shown in Fig. 10. The experimental results are expressed as mean value, minimum and maximum value, as the number of the subjects was very large. The agreements between the simulation and the experiment are good. The predicted rectal temperature is slightly lower than the experimental result, but predicted mean skin temperature is very close to that from the experimental results.

Case 6 (clothed subjects in step change environments)

The experimental data was provided by Fanger (De Dear et al., 1989, The Technical University of Denmark, Copenhagen, Denmark). Two subjects, wearing a 1 clo woolen or polyester ensemble, were at rest in the first environment with RH 20% and then moved to the second environment with RH80%, while the environmental temperature was the same 23.3°C.

The mean skin temperature is shown in Fig. 11. The simulation agrees well with the experimental results. It shows that the model is able to simulate the impact of the clothing i.e. moisture absorption and/or condension on thermoregulation.

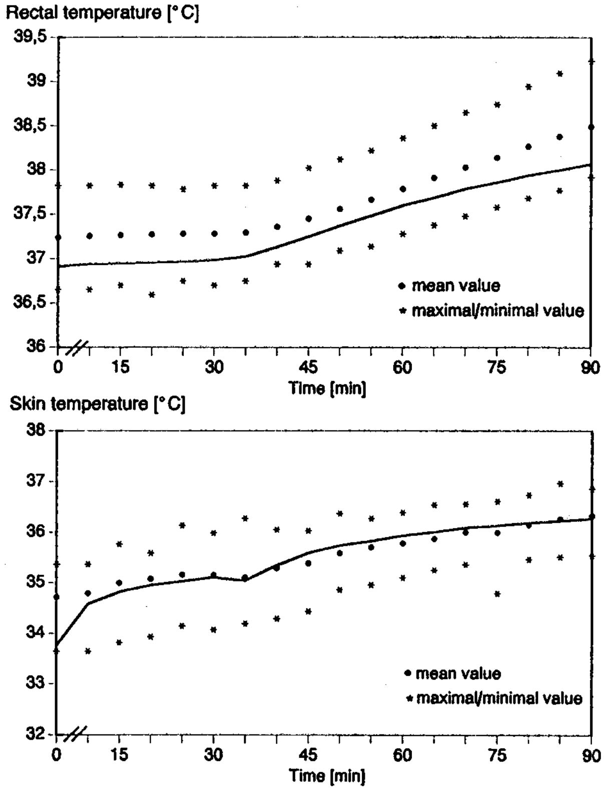

Fig. 10 Comparison of the simulation (line) and the experimental results (symbol) in case 5. Nude, exercising (60W) on an ergometer at 35°C, RH80%, air velocity 0.2 m/s.

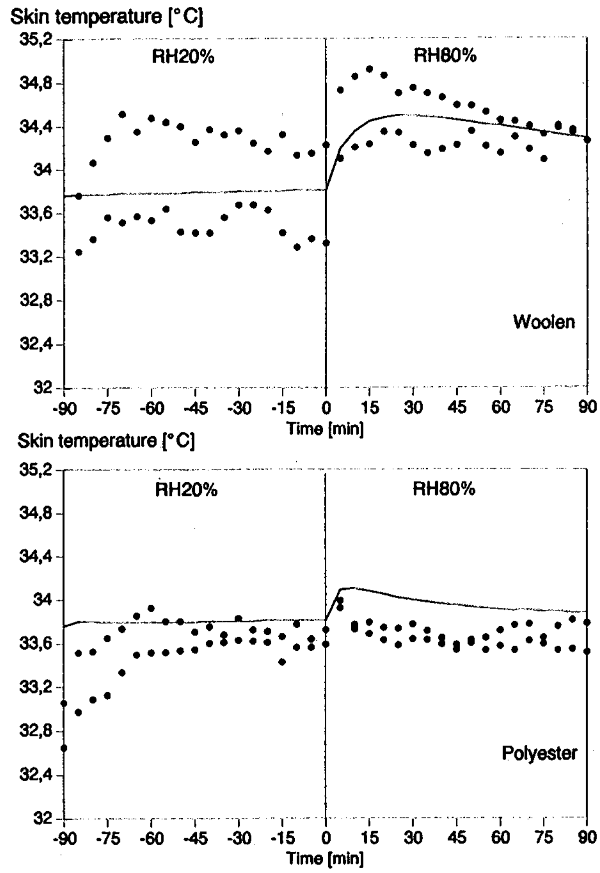

Fig. 11 Comparison of the simulation (line) and the experimental results (symbol) in case 6. Clothed (clothing ensemble: woolen or polyester, 1 clo), sedentary during step-changes RH20% → RH80% at 23.3°C.

Discussion

A new transient model of thermoregulation in the clothed human has been presented. The model can be used to investigate the interaction between the human body, clothing and the environment. The model has been validated by comparing its simulation with experimental results under different conditions: heat, cold, exercise, clothing and transient phases. Although the agreement between the model predictions and the experimental results was sometimes not perfect, the overall consistency was quite satisfactory. Therefore the model can be applied in a broad range of conditions.

The clothing model

The clothing model describes the dynamic thermal response of clothing to the skin and the environment by considering moisture absorption/desorption and condensation/evaporation in clothing, which could play a significant role during transients. Nordon and David (1967) and Farnworth (1986) developed a combined model of heat and mass transfer through clothing respectively, but they did not incorporate their clothing model into any human model to investigate the interaction in a man-clothing system. Recently Jones and Ogawa (1991) and Lotens (1993) have developed transient clothing models and furthermore incorporated them into a thermoregulatory model i.e. the Gagge-model, so that homogeneous clothing systems over body surface can be taken into account. But the body is usually not uniformly covered, so that it is necessary to consider the inhomogeneous coverage of the body surface. Our model is a six cylinder model which makes it possible to consider the clothing difference on the six body parts. The results in Figs. 7, 9 and 11 indicate that our model is able to simulate both static and dynamic effect of clothing system on human temperature regulation. The model can be applied to simulate the effects of different clothing ensembles, for example, different fabric and inhomogeneous coverage etc.

The clothing model should be further developed to consider the effect of human movement on the heat and mass transfer from the skin through clothing to the environment, pumping effect, for example. These effects, which are affected by the properties of the clothing system such as porosity, permeability, design, fit and so on, are very difficult to quantify. There has been much research work on this area (Lotens, 1991; McCullough and Hong, 1992; Nilsson, 1992; Danielsson, 1993; Holmér, 1994), but some of the results do not seem to be consistent. This is not because the experiments were not accurately carried out, but the experimental results can be affected by many factors, which can be defined in different ways. A more practical and effective way is to develop a data bank which is based on the important results of different studies including data and empirical equations. The data bank serves as one part of the clothing model, so that users of the model need only to select the correspondent conditions and insert some minimum input parameters, and then the program will choose relative experimental data and empirical equations from the data bank and calculate the necessary information for the simulation. It will not only enhance the application range of the model, but also make it easier for others to use the model and the results of these studies on clothing.

The rectal temperature in cold environments

The rectal temperature, which is often used as the core temperature, is an important parameter for the temperature regulation. In hot environments, the rectal temperature can be well simulated by our model (see Figs. 6, 7 and 10), as well as the Gagge-model and Stolwijk-model (Haslam and Rarsons, 1994). But in cold environments, the Gagge-model and Stolwijk-model often overestimated the core temperature (Haslam and Rarsons, 1994). Our model can reasonably simulate the core temperature in some cold conditions (see Figs. 5 and 8), but the accuracy is not very good. The reason might be that the heat transfer mechanism within the body is changed in cold envrionments. The conductive heat transfer within the human body plays a more important role in the cold than in the heat, because the temperature gradient between the core and the skin increases greatly while vasoconstriction at the skin occurs. It is therefore necessary to calculate the conduction more exactly. For this purpose, it is necessary to represent the human body in geometry and anatomy in a more exact way and to have more exact values of physical parameters of the body such as conductivity of the tissue. It might be expected that a better simulation of the rectal temperature in the cold be obtained if a three dimensional model, for example the model of Werner (Werner and Buse, 1988) is used.

On the other hand, it should be discussed whether the rectal temperature is a good index in cold air environments. Some experiments showed that rectal temperature alone is not a good index for cold air conditions, because the rectal temperature is not dependent on the environmental temperature i.e. cold stress. It is difficult to estimate the intensity of cold stress only from the rectal temperature. The experiments (Bittel et al., 1988), in which nude subjects lay on a bed for 2 hours in a climatic chamber at 1°C, 5°C and 10°C, demonstrated that the rectal temperature at the end of the cold exposure at 1°C was higher than at 5°C or 10°C. The experiments (Gonzalez et al., 1989), in which the subjects were dressed in ECWCS and exposed to an environment at 0°C, -20°C and -30°C, showed that the rectal temperatures were always higher than 36.6°C, and furthermore were not dependent on the environmental temperatures. The experiments had to be withdrawn, mainly because the finger temperatures fell below 5°C. It was concluded that the body temperature may be a better estimator or guide for subject withdrawal from the cold (along with finger skin temperature) than the rectal temperature (Gonzalez et al., 1989). Therefore the model can still be a good tool to simulate the temperature regulation in cold environments, if reasonable parameters (not rectal temperature only) are used as an index, for example the results in Fig. 9, although the model could not always provide a perfect rectal temperature in cold air environments.

Application of models

"Does a model work?" is a question which has been discussed for a long time. Some researchers criticized models. The reasons are very simple. They have used a model to simulate thermal response of the human body and compared the simulation with their experimental results. As the agreement was not good, they concluded that the model was not acceptable. But they overlooked facts: 1. it is possible that they did not choose a suitable model for their conditions; 2. it is possible that they did not use a model correctly, e.g. error inputs; 3. it is not difficult to find out inconsistency of experimental results from different laboratories, although the same conditions are used in the experiments.

A more useful and practical question should be "how should a model be used?" The purpose of a model is not to replace the physiological experiments, but support the physiological experiments. The experimental results from human subjects can be used to improve the simulation, and the simulation can be used to understand, analyse and interpolate and extrapolate the experimental results. For example, a model which was validated and calibrated by physiological experimental results was successful to be used in the Apollo Program (Kuznetz, 1975). Models were used to analyse the interaction between humans and environment in airplanes (Sa, 1991), vehicles (Althabegoity et al., 1994; Jones et al., 1994), buildings (Thellier et al., 1994). Models were also used to estimate immersion time which can not always be obtained by physiological experiments. The models seem to be a very effective and useful "bridge" between physiological knowledge from human experiments and their application in practice.

Interface for users

A user-friendly interface under WINDOWS named Thermosim was developed (Windows programming by A. Mehrle and G. Metz) to help other users to use our model. Thermosim is one part of a program system to run and control the model developed here. Thermosim is written in TurboPascal for Windows and is used to edit the data needed for the simulation, to start the simulation, and finally to process and display the results. All data mentioned in the model can be easily edited through Thermosim. The program Thermosim including the FORTRAN program is available for use on PC from the authors.

Conclusions

The dynamic model of the human/clothing/ environment-sytem has proved to be a valuable tool for predicting human thermal responses, the effects of clothing on humans, as well as the interaction between human, clothing and the environment in diverse conditions (i.e. heat, cold and exercise). The model is effective for both steady states and dynamic conditions. Acceptable and useful information can be obained if the model is reasonably used. Problems of reliability do not seem to be greater than those of experimental results. Integration of models and experiments can result in better understanding of physiological mechanisms. Although the application of the model is simple, use of the model beyond the tested range should be accompanied by thorough physiological knowledge and experience. For example the limits of regulation depend primarily on the minimal or maximal values of the effector mechanisms which have yet to be carefully and individually worked out. The value of the model in extreme boundary conditions will be tested in further studies.

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Correspondence to: Jürgen Werner, Institut für Physiologie, Abt. Biokybernetik, MA 4/59, D-44780 Bochum, Germany

Appendix: Parameters of the model

1. Geometrical distribution factors

	head	trunk	arms	hands	legs	feet
skin area, % of total	7.02	35.94	13.42	5.02	31.71	6.87
volume, % of total	5.417	55.293	9.17	0.949	27.86	1.31
volume (fat+skin), %of total	4.4	56.6	9.68	2.28	24.1	3.17
volume ratio, core to core+muscle	0.76	0.604	0.723	0.5	0.37	0.5
volume ratio, fat to fat+skin	0.4886	0.64	0.6912	0.6192	0.4774	0.6774

2. Physiological parameters

Basal heat production at neutral conditions [W/m³]

	head	trunk	arms	hands	legs	feet
core	4438	1798	414	352	345	228
muscle	684	684	684	684	684	684
fat	368	368	368	368	368	368
skin	363	349	242	273	244	278

Basal blood flow [m³/h m³(tissue)]

	head	trunk	arms	hands	legs	feet
core	17.52	6.6257	0.4982	0.606	0.3508	0.196
muscle	0.97	1.98	0.97	1.95	0.97	1.95
fat	0.0	0.0	0.0	0.0	0.0	0.0
skin	3.125	4.6	0.97	5.04	0.89	4.78

Bascal evaporation [W]

head	trunk	arms	hands	legs	feet
0.93	8.78	6.39	0.52	10.92	0.72

Counter current factor

head	trunk	arms	hands	legs	feet
1.0	1.0	1.0	0.8	0.95	0.8

3. Physical parameters

Heat capacity per volume [Wh/°Cm³]

	head	trunk	arms	hands	legs	feet
core	877	926	921	704	917	337
muscle	1155	1155	1155	1155	1155	1155
fat	587	587	587	587	587	587
skin	1109	1109	1109	1109	1109	1109

The heat capacity for blood pool: 1048 [Wh/°Cm³]

Heat conductivity [Wh/m°C]

core	muscle	fat	skin
0.51	0.41	0.21	0.42

Convective and radiant heat transfer coeffients [W/m²°C]

head	trunks	arms	hands	legs	feet
0.66	1.5	3.95	3.89	3.6	3.48
6.4	5.2	5.2	3.5	5.2	4.65

4. Controller parameters

Weighting factors for sensor signals

	head	trunk	arms	hands	legs	feet
core	0.54	0.285	0.0	0.0	0.0	0.0
muscle	0.0	0.03	0.005	0.0	0.04	0.0
fat	0.0	0.0	0.0	0.0	0.0	0.0
skin	0.007	0.049	0.015	0.007	0.019	0.003

Distribution factors for controlling equations

	head	trunk	arms	hands	legs	feet
ε_{Ei}[W/°C]	35	120	40	5	106	12
ε_{Mi}-core [W/m^3°C]	316	2188	0	0	0	0
ε_{Mi}-muscle [W/m^3°C]	316	6188	6188	108	6196	108
ε_{Qi}-core [m^3/hm^3°C]	0	0.66	0.0896	0.1091	0.0631	0.0353
ε_{Qi}-muscle [m^3/hm^3°C]	0.155	0.713	0.291	0.585	0.156	0.273
ε_{Qi}-skin (warm)	24.23	36.64	24.33	30.87	40.94	22.82
ε_{Qi}-skin (cold)	8	12	1.56	10.29	1.4	7.61
δ_i*10^4 [m^3/hW]	0	23.62	9.1	1.82	1.31	2.18
μ_i [m^3/(m^3°C)°C]	0	10	0.1	5	0.1	3

Minimal and maxmal values

	head	trunk	arms	hands	legs	feet
$M_{i\,max}$-core [W/m^3]	4540	9061	800	352	474	228
$M_{i\,max}$-muscle [W/m^3]	4540	9644	4347	850	6878	793
$Q_{i\,min}$-skin [m^3/hm^3]	0.8	0.46	0.46	2.85	0.46	2.58
$Q_{i\,max}$-skin [m^3/hm^3]	257.8	29.6	114.6	485.6	46.1	358.7
$Q_{i\,max}$-skin [m^3/hm^3]	63	63	63	63	63	63

For the meaning of the variable, see text.