

Chapter 6: HUMAN THERMOREGULATION MODEL

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References:

[1] D. Fiala et al., A computer model of human thermoregulation for a wide range of environmental conditions: the passive system, *Modeling in Physiology* (<http://www.jap.org>), 8750-7587, pages 1957-1972, 1999.

[2] K. Katic et al., Thermophysiological models and their applications: A review, *Buildings and Environment*, 106, pages 286-300, 2016.

6.1 Introduction

The nature of the human body is to maintain a constant body core temperature under different thermal disorders.

Human beings are **homeotherms** who regulate their internal body temperature with physiological and behavioral actions.

Body temperature regulation represents the balance between heat production from metabolic sources (sum of chemical reactions) and heat loss (evaporation, respiration, radiation, convection, conduction).

Under adequate conditions, a constant core body temperature of 36.5°C is maintained within a narrow range between 36°C - 38°C (normal range at rest), and up to 41°C for heavy exercise.

Exposure of the human body to extreme environmental conditions can result in poor regulation of the core body temperature thus inducing hyperthermia and hypothermia. In addition, if the body core temperature exceeds the normal narrow range, human body functions could be severely affected.

From the mathematical point of view, the human organism can be separated into two interacting systems of thermoregulation:

- The controlling active system simulated by means of cybernetic models predicting regulatory responses, i.e., shivering, vasomotion, and sweating.
- The controlled passive system modeled by simulating the physical human body and the heat transfer phenomena occurring in it and at its surface.

Here, we consider only the **passive model**. However, only the complete model, i.e., the passive system plus active system, can be compared with field measurements of human responses to environmental conditions.

The **metabolic heat** is produced within the body, then it is distributed over body regions by blood circulation (**convection** and **conduction**) and finally, it is carried by **conduction** to the body surface, where the **heat is lost to the surroundings by convection, radiation, evaporation and respiration**.

To simulate adequately all these heat-transport phenomena, the present passive system model accounts for the geometric and anatomic characteristics of the human body and considers the thermophysical and the basal physiological properties of tissue materials.

Despite all development, **the application of thermophysiological models**, as part of the methodology for predicting thermal sensation, is **still not recognized by international standards**. This is related to the fact that there is still doubt about the predictive abilities of the models, and their application limitations.

The uncertainty of the model's predictability is questioned because validation of the models is often carried out by the developer's own experiments rather than with independent experimental data. **Further research is required** before the models can be applied.

The research work has been inspired by the desire to **evaluate environmental conditions in buildings**, it also has applications in other areas, e.g., in the **car industry**, in **textile industries**, in the **aerospace industry**, in **meteorology**, in **medicine** and in **military applications**. In these disciplines, the model can serve for research into human performance, thermal acceptability and temperature sensation, clinical and therapeutic treatments, safety limits, etc.

6.2 The human body construction

The humanoid is formulated to represent an average human (Table 1 in [1]).

- Weight: 73.5kg
- Body fat: 14.0%
- Skin surface area: 1.86m²
- Wetted skin area ratio: 6%
- Basal cardiac output (CO): 4.9l/min
- Basal metabolism: 87.1W

The body is idealized as **15 spherical or cylindrical body elements**:

head, face, neck, shoulders (2), arms (2), hands (2), thorax, abdomen, legs (2), feet(2).

The present multilayer model consists of annular concentric tissue layers and uses **7 tissue materials**:

brain, lung, bone, muscle, viscera, fat, skin.

Each of these is subdivided into **one or more tissue nodes** (Table 2 in [1]).

The skin is modeled as two layers with distinctly different physiological properties: the **inner skin** and the **outer skin**.

- The inner skin is 1 mm thick and simulates the cutaneous plexus, a region in which metabolic heat is generated and blood is perfused.
- The outer layer of skin is of similar thickness; however, it contains neither any heat source nor any thermally significant blood vessels. This cutaneous layer plays a role when evaporative heat losses are modeled.

The body elements (except face and shoulders) are divided into **3 sectors**:

anterior, posterior, inferior

Anterior and posterior segments permit the treatment of lateral environmental asymmetries. Inferior segments account for body sides, which are “hidden” by other body parts and thus have reduced radiant heat exchange with the environment.

The sectors are coupled thermally by introducing a **core element** around the cylinder axis or the midpoint of the sphere. The radius of the core (except for the head) was defined to be identical to the radius of the innermost tissue material layer in each body element.

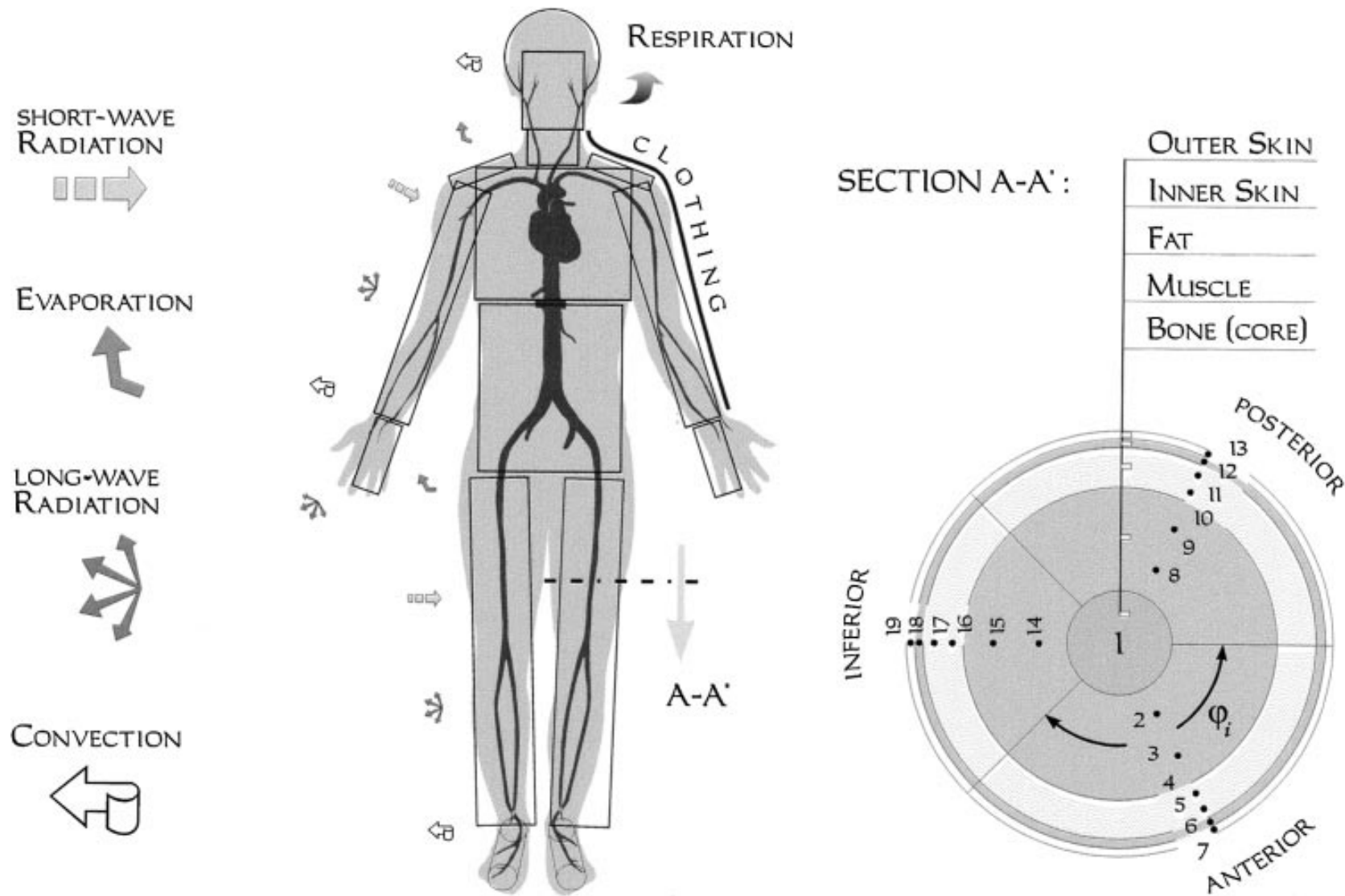


Fig. 6.1: Schematic diagram of the passive system model including body subdivisions, components of the environmental heat exchange and a cross section through the upper leg.

For each body element the following data are provided:

- Shape: cylinder (length) or sphere (diameter)
- Countercurrent heat exchange coefficient: h_x
- Heat-exchange coefficient for mixed convection: $h_{c,mix}$
 - Corresponding regression coefficients (α_{nat} , α_{frc} , α_{mix})
- Skin sensitivity coefficients used for calculating mean skin temperature: α_{sk}
- Workload distribution coefficient: $\alpha_{m,w}$ (for sedentary and standing activities)
- Sector angle: φ
- View factor between a sector and the surroundings: ψ_{sf-sr}
- Surface emission coefficient: ε_{sf}
- Number of nodes: N
- Outer radius: r
- Heat conductivity: k
- Material density: ρ
- Heat capacitance: c
- Basal value for blood perfusion rate in thermal neutrality: $w_{bl,0}$
- Basal value for metabolic rate in thermal neutrality: $q_{m,0}$

Blood: $\rho = 1.069\text{kg/m}^3$, $c = 3.650\text{kJ}/(\text{kg K})$

6.3 Heat transfer within the tissue – the “bioheat” equation

The heat transport mechanisms occurring in the living tissue have been formulated in the so-called ‘**bioheat equation**’:

$$\rho c \frac{\partial T}{\partial t} = k \left(\frac{\partial^2 T}{\partial r^2} + \frac{\omega}{r} \frac{\partial T}{\partial r} \right) + q_m + \rho_{bl} w_{bl} c_{bl} (T_{bl,a} - T)$$

$T(t, r)$: tissue temperature, r : radius, t : time

ρ : tissue density, c : tissue heat capacity, k : tissue conductivity

$\omega = 1$: cylinder, $\omega = 2$ sphere

q_m : metabolism heat

$T_{bl,a}$: arterial blood temperature (it is unknown!)

ρ_{bl} : blood density, w_{bl} : blood perfusion rate, c_{bl} : blood heat capacity

Within a unit tissue volume the heat storage rate is equal to the net heat conduction plus the generated metabolism heat plus the net convection heat rate.

It is convenient instead of working with the blood perfusion rate to introduce the energy equivalent factor $\beta = \rho_{bl} w_{bl} c_{bl}$ [W/(m³ K)].

Conduction: only in the radial direction; angular heat flow is neglected since it is negligible compared to the radial one and it is partially taken into account by dividing a body element into sectors.

Metabolism: $q_m = q_{m,bas,0} + \Delta q_m$, $\Delta q_m = \Delta q_{m,bas} + q_{m,shivering} + q_{m,work}$

Blood circulation: vital for heat dissipation within the human body.

The blood circulation system is simulated as three main components: a) central blood pool, b) countercurrent heat exchanger, c) pathways to individual tissue nodes.

Body elements are supplied by warm blood from the central pool by the major arteries. Before the tissue of the extremities and the shoulder are perfused, the blood is cooled by heat lost to the countercurrent bloodstreams in the adjacent veins. The venous blood is rewarmed by heat from the adjacent arteries as it flows back to the central blood pool.

The decrease of the blood temperature in the arteries of an element corresponds to the increase of the blood temperature in the veins of the same body element:

$$Q_x = \rho_{bl} c_{bl} \left[\int w_{bl} dV \right] (T_{bl,p} - T_{bl,a}) = h_x (T_{bl,a} - T_{bl,v}) \Rightarrow T_{bl,a} = \frac{\rho_{bl} c_{bl} \left[\int w_{bl} dV \right] T_{bl,p} + h_x T_{bl,v}}{\rho_{bl} c_{bl} \left[\int w_{bl} dV \right] + h_x}$$

$T_{bl,v}$: venous blood temperature

$\left[\int w_{bl} dV \right]$: volumetric blood flow rate

h_x : corresponding countercurrent heat exchanger coefficient (few reliable data)

Assuming that capillary blood reaches an equilibrium temperature with the surrounding tissue results to

$$T_{bl,v} = \frac{\int w_{bl} T dV}{\int w_{bl} dV}.$$

Also it may be shown that

$$T_{bl,p} = \frac{\sum_j^{element} \left[\frac{\int \beta_j dV_j}{h_{x,j} + \int \beta_j dV_j} \int \beta_j T_j dV_j \right]}{\sum_j^{element} \left[\frac{\left(\int \beta_j dV_j \right)^2}{h_{x,j} + \int \beta_j dV_j} \right]}.$$

6.4 Heat exchange with environment

At the body surface, heat is exchanged by **convection with the ambient air**, by **radiation with surrounding surfaces**, by **irradiation from high-temperature sources** and by **evaporation of moisture from the skin**.

The rate of heat exchange varies over the body and is affected by the clothing ensemble worn. Hence, in the model, heat balances were established for each skin sector of each body element as boundary conditions to the bioheat equation.

In general, the net heat flux passing the surface of a peripheral sector is equivalent to the sum of the following individual heat exchanges:

$$q_{sk} = q_c + q_R - q_{sR} + q_e$$

Convection between skin surface temperature T_{sf} and ambient air temperature T_{air} :

$$q_c = h_{c,mix} (T_{sf} - T_{air}), \quad h_{c,mix} = \sqrt{\alpha_{nat} \sqrt{T_{sf} - T_{air}} + \alpha_{frc} v_{air,eff} + \alpha_{mix}}$$

The convection coefficient is obtained via regression analysis from experimental data.

Radiation:

The exchange of heat by **long-wave radiation** is usually of similar importance in the heat balance of the human body as the heat exchange by convection.

$$q_R = h_R (T_{sf} - T_{sr,m}), \quad h_R = \sigma \varepsilon_{sf} \varepsilon_{sr} \psi_{sf-sr} (T_{sf}^2 + T_{sr,m}^2) (T_{sf} + T_{sr,m})$$

Mean temperature of surrounding surfaces:
$$T_{sr,m} = \frac{\sum_{j=1}^n T_{sr,j} A_{sr,j}}{\sum_{j=1}^n A_{sr,j}}$$

Irradiation:

The irradiation of the body by high-temperature sources (sun, fireplaces, etc.) is also considered. The amount of heat absorbed at a sector surface is given by

$$q_{sR} = \alpha_{sf} \psi_{sf-sr} S$$

where S is the radiant intensity, α_{sf} is the surface absorption coefficient and ψ_{sf-sr} is the view factor between the sector surface and the surrounding envelope.

Evaporation:

The skin evaporation model ensures heat and mass transfer balances at each skin sector of each body element. The latent energy transport from a skin sector of area is given by

$$q_e = U_{e,cl}^* (P_{sk} - P_{air}) = \lambda_{H_2O} \frac{dm_{sw}}{A_{sk} dt} + \frac{P_{osk,sat} - P_{sk}}{R_{e,sk}}$$

P_{sk} : water vapor pressure at the skin temperature

P_{air} : vapor pressure of ambient air

$U_{e,cl}^*$: evaporation coefficient of garments covering the sector

λ_{H_2O} : heat of water vaporization

dm_{sw} / dt : rate of sweat production over A_{sk}

$P_{osk,sat}$: saturated vapor pressure within the outer skin layer of a body sector

$R_{e,sk}$: thermal evaporation resistance

The net heat transfer as driven by the evaporative potential between skin and air is equal to the evaporation of sweat from the skin surface plus the heat transport by moisture diffusion through the skin.

Respiration heat losses:

Heat exchange with the environment also occurs by respiration taking into account losses by **evaporation** and **convection**.

The **latent heat exchange** is calculated as a function of the whole body metabolism considering latent heat of water vaporization and the difference between the humidity of the expired and inspired air (depends on T_{air} and P_{air}):

$$E_{rsp} = 4.373 \left[\int q_m dV \right] \left(0.028 - 6.5 \times 10^{-5} T_{air} - 4.91 \times 10^{-6} P_{air} \right)$$

The **dry heat loss** of respiration due to the temperature difference between expired and inspired air can be expressed as:

$$C_{rsp} = 1.948 \times 10^{-3} \left[\int q_m dV \right] \left(32.6 - 0.066 T_{air} - 1.96 \times 10^{-4} P_{air} \right)$$

These heat losses appear in the nodal heat balances for these tissues as the volume derivative in the heat generation term q_m in the bioheat equation:

$$q_m = q_{m,bas,0} + \Delta q_m - \frac{\partial \left[\alpha_{rsp} \left(E_{rsp} + C_{rsp} \right) \right]}{\partial V}$$

6.5. The numerical model

Each sector of each tissue shell is divided into nodes.

The nodes are unequally spaced in the radial direction, being closer together in the outer regions where temperature gradients are generally the steepest.

A finite-difference scheme is used to discretize the bioheat equation approximating the partial derivatives by 2nd order central difference schemes (Crank-Nicolson). The method remains unconditionally stable.

The model can be easily integrated with other dynamic simulation programs (e.g., of the building or vehicle environment).

The resulting discrete formulation of the bioheat equation is applicable to the cylindrical and to the spherical body parts.

The passive system is organized as a structured system of time-independent “conduction” matrices, collecting all thermophysical tissue constants and time-dependent “blood” matrices, the coefficients of which have to be computed at each time step.

A quick solver is developed, which worked efficiently because it considered only the nonzero cells in the matrices.

Finite difference time-dependent equation:

$$\begin{aligned}
 (\gamma_r - 1)T_{r-1}^{(t+1)} + \left[\frac{\zeta_r}{\Delta t} + 2 + \delta_r \beta_r^{(t+1)} \right] T_r^{(t+1)} - (\gamma_r + 1)T_{r+1}^{(t+1)} - \delta_r \beta_r^{(t+1)} T_{bl,a}^{(t+1)} = \\
 = (1 - \gamma_r)T_{r-1}^{(t)} + \left[\frac{\zeta_r}{\Delta t} - 2 - \delta_r \beta_r^{(t)} \right] T_r^{(t+1)} + (1 + \gamma_r)T_{r+1}^{(t)} + \delta_r \beta_r^{(t)} T_{bl,a}^{(t)} + \delta_r (q_{m,r}^{(t+1)} + q_{m,r}^{(t)})
 \end{aligned}$$

Finite difference steady-state equation:

$$(\gamma_r - 1)T_{r-1} + [2 + \delta_r \beta_r] T_r - (\gamma_r + 1)T_{r+1} - \delta_r \beta_r T_{bl,a} = \delta_r q_{m,r}$$

Note that for cylinder $\gamma_r = \Delta r / (2r)$ and for sphere $\gamma_r = \Delta r / r$, while $\delta_r = \Delta r^2 / k_r$, $\zeta_r = 2\Delta r^2 \rho_r c_r / k_r$, $\beta_r = \rho_{bl,r} w_{bl,r} c_{bl,r}$.

The accuracy of the numerical scheme depends on the formulation of the boundary conditions!!!

For simplicity in steady-state modeling temperature nodes may be taken at the interfaces and the corresponding heat fluxes are computed assuming plane geometry.

The **boundary condition in the core** of each body element is formulated by establishing an isothermal core element around the cylinder axis or the midpoint of the sphere. As an example, Fig. 1 shows this domain for a leg (node no. 1).

The bioheat equation at node 1, serving as the boundary condition in the core, is written as

$$\rho_1 c_1 \frac{\partial T_1}{\partial t} = q_{m,1} + \beta_1 (T_{bl,a} - T_1) - \frac{\kappa}{\pi r_1} \sum_{j=1}^{sectors} \varphi_j q_{ifc,j}$$

where the last term in the right hand side refers to the heat fluxes passing the interface between the core and the adjacent tissue sectors ($\kappa = 1$ for cylinders, $\kappa = 1.5$ for spheres).

The interface heat fluxes are obtained by the Fourier law based on T_1 and the temperature of adjacent nodes:

$$\text{Cylinders: } q_{ifc} = \frac{k_r (T_- - T_+)}{r_{ifc} \ln \left(\frac{r_{ifc} + \Delta r / 2}{r_{ifc} - \Delta r / 2} \right)} \quad \text{Spheres: } q_{ifc} = \frac{k_r (T_- - T_+)}{r_{ifc}^2 \left(\frac{1}{r_{ifc} - \Delta r / 2} - \frac{1}{r_{ifc} + \Delta r / 2} \right)}$$

In steady-state conditions the time-dependent term is vanished.

The **boundary condition in a skin sector** is formulated by balancing the heat flux at the last skin node with the sum of the dry heat loss through the clothing and the evaporative heat loss from the skin:

$$q_{sk} = U_{cl}^* (T_{sk} - T_0) + U_{e,cl}^* (P_{sk} - P_{air})$$

where T_0 is an operative environmental temperature integrating the influences of convection, radiation and short-wave radiation absorbed by a body sector surface.

$$T_0 = \frac{h_{c,mix} T_{air} + h_R T_{sr,m} + \psi_{sf-sr} \alpha_{sf} S}{h_{c,mix} + h_R}$$

Also, U_{cl}^* incorporates three heat transport mechanisms: conduction through clothing, surface convection and long-wave radiation to surrounding surfaces.

To obtain the heat dissipation of the whole body, **the bioheat equation is applied to all tissue nodes and is coupled by the boundary conditions at the interfaces.**

To close the system of equations the following expressions for the arterial and blood temperatures are implemented:

$$T_{bl,a} = \frac{T_{bl,p} \sum_r^{nodes} \beta_r V_r + h_x \frac{\sum_r^{nodes} T_r \beta_r V_r}{\sum_r^{nodes} \beta_r V_r}}{h_x + \sum_r^{nodes} \beta_r V_r}$$

$$T_{bl,p} = \frac{\sum_j^{element} \left[\frac{\sum_r^{nodes} \beta_{j,r} V_{j,r}}{r} \sum_r^{nodes} T_{j,r} \beta_{j,r} V_{j,r} \right]}{\sum_j^{element} \left[\frac{\left(\sum_r^{nodes} \beta_{j,r} V_{j,r} \right)^2}{h_{x,j} + \sum_r^{nodes} \beta_{j,r} V_{j,r}} \right]}$$

The blood pool temperature $T_{bl,p}$ is a function of all tissue temperatures $T_{j,r}$ and underlines the coupling between blood circulation and heat dissipation.

The resulting set of linear equations is solved at each time of an exposure for the boundary conditions at the skin surfaces and the regulatory responses of the active system (not described here).

Exercises: Consider an average human body with the following boundary conditions: ambient air temperature and temperature of the surrounding surfaces : $T_{air} = T_{sr} = 30^{\circ}\text{C}$; air velocity: $v_{air} = 0.05 \text{ m/s}$; relative humidity: $rh = 40\%$; emissivity of the surrounding wall surfaces: $\varepsilon_w = 0.93$; reclining activity: $act_{bas,met} = 0.8$.

Proposal: Simulate first a single body element by assuming T_r , finding next $T_{bl,p}$, $T_{bl,a}$ and solving finally the system to compute the updated T_r . Iterate upon convergence.

1. Solve the steady-state bioheat equation for the head.
2. Solve the steady-state bioheat equation for the neck.

3. Confirm that applying the steady-state model for a reclining and unclothed human body with the above boundary conditions provides the following results [1]:

Head core (hypothalamus) temperature: $T_{hy} = 37.0 \text{ }^\circ\text{C}$

Abdomen core (rectal) temperature: $T_{re} = 36.88 \text{ }^\circ\text{C}$

Mean muscle (volume weighted) temperature: $T_{mus,m} = 36.2 \text{ }^\circ\text{C}$

Mean skin temperature: $T_{sk,m} = 34.4 \text{ }^\circ\text{C}$

Skin heat loss: $Q_{sk} = 78.5 \text{ W}$

Heat loss by convection: $Q_{sk,c} = 21.5 \text{ W}$

Heat loss by (long-wave) radiation: $Q_{sk,R} = 38.9 \text{ W}$

Heat loss by skin evaporation: $Q_{sk,e} = 18.1 \text{ W}$

Heat loss by respiration: $Q_{sk,rsp} = 8.5 \text{ W}$