DEVELOPMENT OF A TRANSIENT MODEL OF THE HUMAN THERMAL AND RESPIRATORY SYSTEMS

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Abstract. *The aim of this work is the development of a mathematical model of the human body, which allows the determination of the temperature, oxygen and carbon dioxide distributions, depending on the ambient conditions and the physical activity level. The human body was divided into 15 segments: head, neck, trunk, arms, forearms, hands, thighs, legs and feet. Each segment contains an arterial and a venous compartment, representing the large vessels. The blood in the small vessels is considered together with the tissues – muscle, fat, skin, bone, brain, lung, heart and viscera. The gases – oxygen and carbon dioxide – are transported by the blood and stored by the tissues dissolved and chemically reacted. Metabolism takes place in the tissues, where oxygen is consumed generating carbon dioxide and heat. The skin exchanges heat with the environment by conduction, convection, radiation and evaporation. The respiratory tract exchanges heat by convection and evaporation. In the lungs, mass transfer happens by diffusion between an alveolar compartment and several pulmonary capillaries compartments. Two different forms were used to model the transport of mass and heat in the tissues. For the mass transfer, the tissues were represented by compartments inside the segments. For the heat transfer, the tissues were represented by layers inside the segments, which have the geometry of a cylinder (circular cross-section) or a parallelogram – hands and feet. The regulatory systems were divided into four mechanisms: metabolism, circulation, ventilation and sweating. The metabolism is modified by the shivering (which depends on the body temperature) and the physical activity; the circulation depends on the body gas concentrations, the temperature and the metabolism; the ventilation depends on the gas concentrations; the sweating depends on the temperature. Implicit methods were used to solve the differential equations. The discretization of the partial differential equations was obtained applying the finite volume method. Comparisons of model results with experimental data found in literature show that the model is suitable to represent the exposure to cold and warm ambients, to low amounts of oxygen, to carbon dioxide, and physical activity.*

Keywords: *bioengineering, mathematical model, bioheat transfer, respiratory system*

1. INTRODUCTION

Mathematical models of the human thermal and respiratory systems have been developed around the world since the middles of the last century. Grodins *et al.* (1954) developed the first respiratory system model including the whole body. The blood, tissues and lung were represented by compartments. The purpose was the study of carbon dioxide regulation. After that, several other models were developed for different applications. Most of them were focused on the study of regulation. Some examples are the works of Horgan and Lange (1965), Khoo *et al.* (1982), Ursino *et al.* (2001), Longobardo *et al.* (2002), and Albuquerque-Neto *et al.* (2008).

Two pioneers models of the thermal system brought important distinct features. One is the model of Wissler (1961), which divides the human body into several segments in order to determine the temperature distribution. The other is the model of Stolwijk and Hardy (1966a), which includes the regulatory mechanisms. Several other models were developed after that. Some examples with a complete description of the human body are the works from Tikuisis *et al.* (1988), Werner and Buse (1988), Huizenga *et al.* (2001), and Ferreira and Yanagihara (2009).

Models taking into account the interactions of heat, oxygen and carbon dioxide transport have been developed in some recent works. Downey and Seagrave (2000) studied the body water changes. The model of Ji and Liu (2002) was applied to study the blood viscosity increase in the brain hypothermia resuscitation. Gaohua and Kimura (2008) applied their model to study the use of mechanical ventilators during brain hypothermia treatment.

The present work is focused on the heat and gas transport in the human body, and their influences on each other. The model development is based on two previous works developed in the same laboratory. Those are the thermal system model of Ferreira and Yanagihara (2009) and the respiratory system model of Albuquerque-Neto *et al.* (2008).

2. MATHEMATICAL MODEL

2.1 Human body geometry

The human geometry is based on the anatomic model of Ferreira and Yanagihara (2009) for a male 1.76 m height, 67 kg of mass, 1.8 m^2 of body surface area, and 14% of fat. The human body is divided into 15 segments: head, neck, trunk, arms, forearms, hands, thighs, legs and feet. They have either the form of a parallelogram – hands and feet –, or the form of a cylinder with circular cross-section (other segments).

The kinds of tissues considered were defined based on their particular characteristics: skin, fat, muscle, bone, brain, lung, heart and viscera (Ferreira and Yanagihara, 2009). These tissues were separated into layers inside each segment. The size of each layer depends on its volume, which was obtained from Ferreira and Yanagihara (2009), who used the detailed data of Werner and Buse (1988).

The tissue distribution in each segment is represented on Fig. 1. Cylindrical or Cartesian coordinates were adopted depending on its geometry. As the segments have symmetries on some directions, not all coordinates were considered. For the head and the trunk, the cylindrical r and z coordinates are used; the forearms and legs use the cylindrical r and θ coordinates; the hands and feet use the Cartesian x and y coordinates; and the neck, arms and thighs use only the r coordinate. The layer limits along each coordinate are in Tab. 1.

The present geometry was defined based on a man with standard characteristics. The layers would have to be re-sized for different anthropometric percentiles. Other limitation is the simple form of the segments and tissue distribution, which would have to be more complex if the objective is to obtain more detailed data.

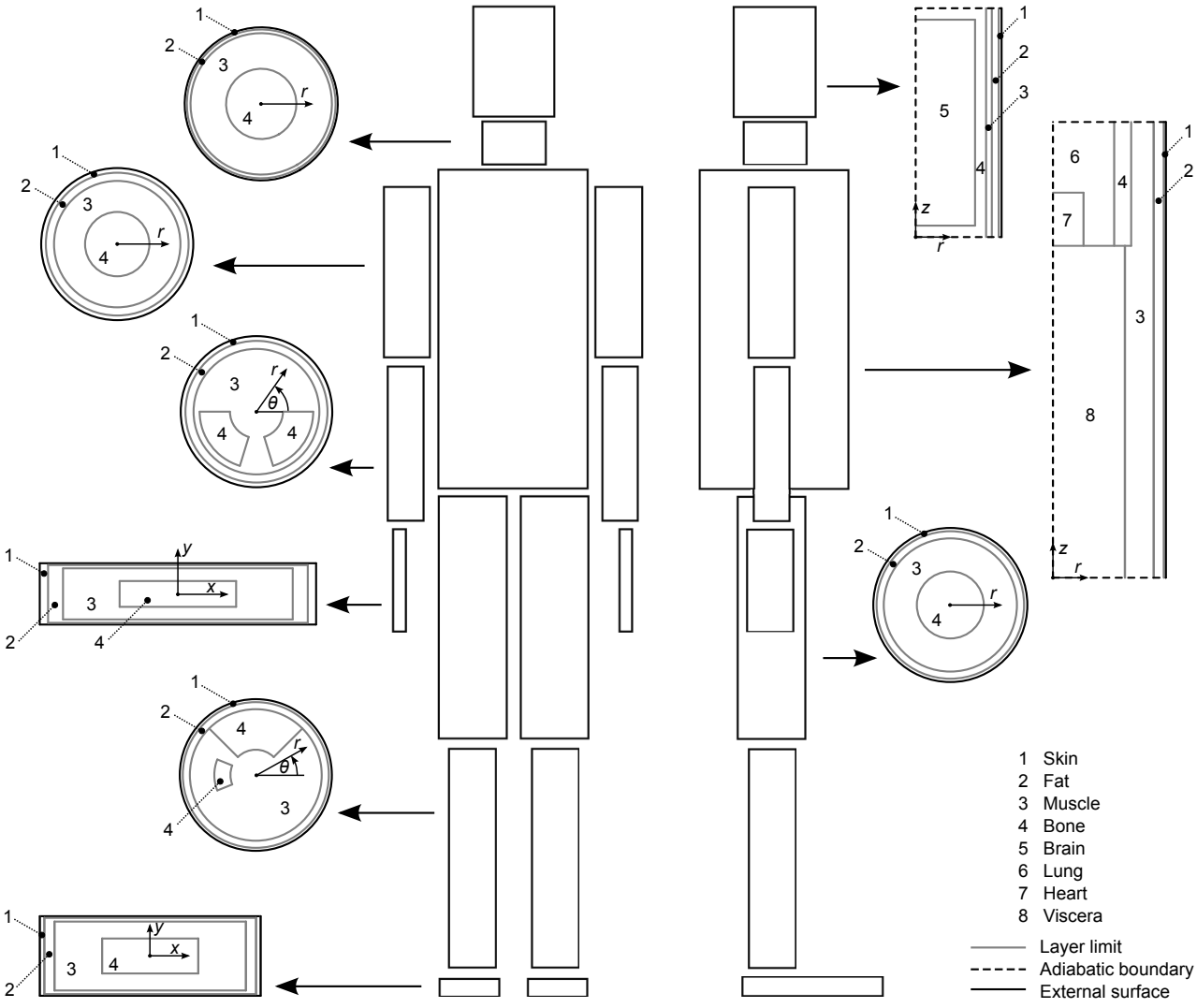

Figure 1. Model geometry

Table 1. Segment layer limits

Segment	Coordinate	
	r [cm] or x [cm]	θ [°], z [cm] or y [cm]
Head	5.17 6.15 6.64 7.24 7.51	1 19 20
Neck	2.68 5.40 5.71 5.82	8
Trunk	3.68 7.37 8.66 9.41 12.13 13.36 13.58	43.7 50.7 60.0
Arm	1.80 3.54 4.00 4.26	31
Forearm	1.17 2.51 2.78 3.14 3.35	180 253 287 360
Hand	3.31 9.22 3.15 7.74 9.96 10.55 10.89	0.0736 0.205 0.699 1.72 2.21 2.34 2.42
Thigh	2.68 5.33 5.90 6.15	44
Leg	1.43 3.43 3.72 4.12 4.29	45 135 158 202
Foot	0.210 0.680 2.88 7.33 9.53 10.00 10.21	0.0760 0.246 1.04 2.65 3.45 3.62 3.70

2.2 Circulation

The segments are connected by arterial and venous blood flow. The arterial blood goes from the trunk to the extremity segments (head, hands and feet). On the other hand, the venous blood goes from the extremity segments to the trunk.

Figure 2 shows the blood circulation inside a segment. The large vessels of each segment are represented by two compartments: arterial and venous. The tissues, together with the blood in the small vessels, are modeled in different forms for the heat and mass transfer. The former considers the geometry of the segments and layers. The latter represents each kind of tissue inside a segment by one small vessel compartment and one tissue compartment. It was considered as small vessels the terminal branch, small artery, arteriole, capillary, venule and terminal vein. The blood of these vessels are in thermal equilibrium with the tissues, according to Chen and Holmes (1980).

If the segment is the trunk, there is not a previous segment. Besides, the blood that exits the venous compartment follows to the pulmonary capillaries compartments (disposed in series), where exchanges O_2 and CO_2 with an alveolar compartment.

2.3 Large vessels

The temperature of the arterial and the venous compartments are determined from energy balances. Besides the blood passage, it includes the heat transfer between the compartments. The arterial and venous compartment temperatures of each segment are determined by the following equations:

$$V_{ar}\,\rho_{bl}\,c_{bl}\,\frac{\mathrm{d}T_{ar}}{\mathrm{d}t} = \dot{V}_{ar}\,\rho_{bl}\,c_{bl}\,\left(T_{ar}^{in} - T_{ar}\right) + H_{av}\,\left(T_{ve} - T_{ar}\right) \tag{1}$$

$$V_{ve}\,\rho_{bl}\,c_{bl}\,\frac{\mathrm{d}T_{ve}}{\mathrm{d}t} = \rho_{bl}\,c_{bl}\,\left(\dot{V}_{sv}\,\bar{T}_t + \dot{V}_{ve}^{in}\,T_{ve}^{in} - \dot{V}_{ve}\,T_{ve}\right) + H_{av}\,\left(T_{ar} - T_{ve}\right) \tag{2}$$

where: V_{ar} is the arterial compartment volume [m^3]; ρ_{bl} is the blood density, equal to 1059 kg/m^3 (Werner and Buse, 1988); c_{bl} is the blood heat capacity, equal to 3850 J/(kg.K) (Werner and Buse, 1988); T_{ar} is the arterial compartment temperature [°C]; $\dot{V}_{ar}$ is the total arterial compartment blood flow [m^3/s]; T_{ar}^{in} is the temperature of the arterial blood from the previous segment or the lung (if the present segment is the trunk) [°C]; H_{av} is the heat transfer coefficient between arterial and venous compartment [W/°C] (determined by Ferreira and Yanagihara (2009) as a two-dimensional conduction problem between two cylinders); V_{ve} is the venous compartment volume [m^3]; T_{ve} is the venous compartment temperature [°C]; $\dot{V}_{sv}$ is the total small vessel blood flow of the segment [m^3/s]; $\bar{T}_t$ is the average tissue temperature of

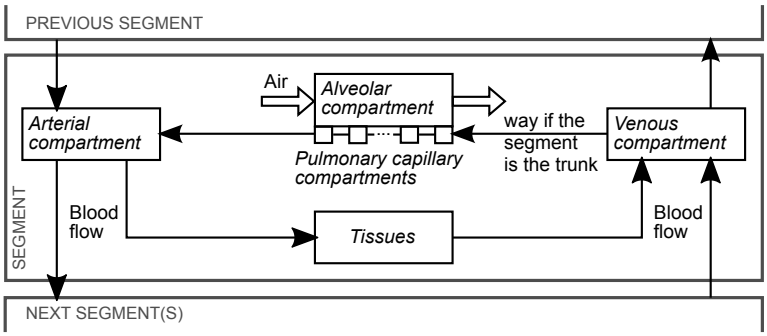

Figure 2. Circulation inside a segment

the segment [°C]; $\dot{V}_{ve}^{in}$ is the venous blood flow from the next segments [m^3/s]; T_{ve}^{in} is the average temperature of the venous blood from the next segments [°C]; and $\dot{V}_{ve}$ is the total venous compartment blood flow [m^3/s].

Some important parameters of the model that depend on the segment or the tissue kind are found on Tab. 2.

The gas concentrations in the arterial and venous compartments depend only on the blood passage. They are determined by the following equations:

$$V_{ar}\,\frac{\mathrm{d}C_{g,ar}}{\mathrm{d}t} = \dot{V}_{ar}\left(C_{g,ar}^{in} - C_{g,ar}\right) \tag{3}$$

$$V_{ve}\,\frac{\mathrm{d}C_{g,ve}}{\mathrm{d}t} = \dot{V}_{sv}\,\bar{C}_{g,sv} + \dot{V}_{ve}^{in}\,C_{g,ve}^{in} - \dot{V}_{ve}\,C_{g,ve} \tag{4}$$

where: g is the gas [O_2 or CO_2]; $C_{g,ar}$ is the g blood concentration of the arterial compartment [mol/m^3]; $C_{g,ar}^{in}$ is the g concentration of the arterial blood from the previous segment or the lung [mol/m^3]; $C_{g,ve}$ is the g blood concentration of the venous compartment [mol/m^3]; $\bar{C}_{g,sv}$ is the average g blood concentration of the segment small vessels [mol/m^3]; and $C_{g,ve}^{in}$ is the g blood concentration of the venous blood from the next segments [mol/m^3].

In order to solve the O_2 and CO_2 transport equations of the present model it is necessary to determine the relations between their concentrations and partial pressures. These relations have several approaches reported in the literature. In the present work, the equations of Thomas (1972), with corrections from Severinghaus (1966), are used to obtain the blood O_2 saturation; the equations of Douglas *et al.* (1988) are used to obtain the CO_2 concentration; and a methodology from Turri and Yanagihara (2011), which includes relations from Siggaard-Andersen (1966), is used to determine the pH. Those calculations depend on blood temperature, base excess and hemoglobin concentration. A complete description of the present methodology is found elsewhere (Turri and Yanagihara, 2011; Albuquerque-Neto *et al.*, 2008).

2.4 Tissues and small vessels

The tissue heat transfer depends on four mechanisms: the blood perfusion, the conduction with the neighbors, the heat generation, and the environment heat exchange. The bioheat equation (Pennes, 1948) is used to obtain the tissue temperature distribution:

$$\rho_t\,c_t\,\frac{\partial T_t}{\partial t} = k_t\,\nabla^2 T_t + \hat{\dot{V}}_{sv}\,\rho_{bl}\,c_{bl}\,(T_{ar} - T_t) + \hat{\dot{q}}_t \tag{5}$$

where: ρ_t is the tissue density [kg/m^3]; c_t is the tissue heat capacity [J/(kg.K)]; T_t is the tissue temperature [°C]; k_t is the tissue heat conductivity [W/(m.°C)]; $\hat{\dot{V}}_{sv}$ is the specific small vessel blood flow [m^3/(m^3.s)]; and $\hat{\dot{q}}_t$ is the specific tissue heat generation [W/m^3].

In the mass transfer case, for each kind of tissue inside a segment, exist one tissue compartment and one small vessel compartment. The partial pressure of a gas is considered the same in both compartments. Its determination depends on the blood passage and the gas generation (which is negative for the O_2):

$$\left(V_{sv(i)}\,\frac{\mathrm{d}C_{g,sv(i)}}{\mathrm{d}P_{g,t(i)}} + V_{t(i)}\,\frac{\mathrm{d}C_{g,t(i)}}{\mathrm{d}P_{g,t(i)}}\right)\frac{\mathrm{d}P_{g,t(i)}}{\mathrm{d}t} = \dot{V}_{sv(i)}\,\left(C_{g,ar} - C_{g,sv(i)}\right) + \dot{n}_{g,t} \tag{6}$$

where: i is the identification of each kind of tissue inside a segment; $V_{sv(i)}$ is the volume of the small vessel compartment i [m^3] (determined for each kind of tissue as a fraction of the small vessel volume weighted by the specific small vessel

Table 2. Model parameters

Segment dependent parameters	Head	Neck	Trunk	Arm	Forearm	Hand	Thigh	Leg	Foot
Arterial compartment volume [cm^3]	40	15	446	24	13	7	78	35	15
Venous compartment volume [cm^3]	180	66	1484	107	60	30	349	155	66

Tissue dependent parameters	Skin	Fat	Muscle	Bone	Brain	Lung	Heart	Viscera
Tissue volume [cm^3][(1)]	245	528	393	860	1514	2481	298	10301
Density [kg/m^3][(1,2)]	1085	920	1085	1357	1080	560	1080	1080
Basal specific blood flow [cm^3/(m^3.s)][(1,2)]	362	77	483[(3)]	0	9000		14400	5800[(4)]
Heat capacity [J/(kg.°C)][(1,2)]	3680	2300	3800	1700	3850	3520	2550	3504
Heat conductivity [W/(m.°C)][(1,2)]	0.47	0.21	0.51	0.75	0.49	0.28	0.47	0.49
Basal specific heat production [W/m^3][(1,2)]	368	78.2[(4)]	501[(5)]	0	9472	339	24128	3852[(4)]
Respiratory quotient [m^3/m^3][(6)]	0.85	0.71	0.85		1.00		0.85	0.85

[(1)] Ferreira and Yanagihara (2009), [(2)] Werner and Buse (1988), [(3)] Mottram (1955), [(4)] Adjusted to ensure coherence results, [(5)] Stolwijk and Hardy (1966a), [(6)] Brobeck (1974)

blood flow); $C_{g,sv(i)}$ is the g blood concentration of the small vessel compartment i [mol/m^3]; $P_{g,t(i)}$ is the g partial pressure of the tissue and small vessel compartment i [mol/m^3]; $V_{t(i)}$ is the volume of the tissue compartment i [m^3] (the total tissue volume of the geometric model less the small vessel blood volume); $C_{g,t(i)}$ is the g tissue concentration of the tissue compartment i [mol/m^3]; $\dot{V}_{sv(i)}$ is the blood flow of the small vessel compartment i [m^3/s]; and $\dot{n}_{g,t}$ is the tissue g production [mol/s].

The relations between the gas concentrations and partial pressures in the blood were commented above. In the tissues, the gas concentrations are considered proportional to their partial pressures, except when it concerns to the O_2 storage in the muscle, in which the myoglobin is included according to Schenkman *et al.* (1997). For the CO_2, it is used the coefficients for each kind of tissue from Farhi and Rahn (1960); for the O_2, the tissue solubility is considered the same as the water.

The respiratory quotient (RQ), which depends on the kind of tissue, is used to relate the heat production and the O_2 consumption according to ASHRAE (2005). Moreover, the heat production includes the temperature effect on the metabolic reactions (Werner and Buse, 1988).

The heat exchange between the skin and the environment takes into account the processes of convection, radiation, evaporation and conduction. They are included in the present model through the methodology described by ASHRAE (2005), with resistances through the clothes and air layers from McCullough *et al.* (1985) and McCullough *et al.* (1989), convection and radiation heat transfer coefficients from de Dear *et al.* (1997), and evaporation heat transfer coefficients from Ferreira and Yanagihara (2009).

2.5 Respiratory apparatus

The lung is represented by an alveolar compartment and some pulmonary capillary compartments. Inspired air gets in the alveolar compartment after being humidified in the dead space. Its O_2 and CO_2 partial pressure is equal to:

$$P_{g,I} = F_{g,I}\,(P_{bar} - P_w) \tag{7}$$

where: $P_{g,I}$ is the g inspired air partial pressure [Pa]; $F_{g,I}$ is the g fraction in the inspired air [0 to 1]; P_{bar} is the barometric pressure [Pa]; and P_w is the water vapor pressure at the lung temperature [Pa].

Another important process in the alveolar compartment is the gas transfer by diffusion with the pulmonary capillary compartments through the respiratory membrane. The O_2 or CO_2 partial pressure of the alveolar compartment is calculated by the following equation:

$$V_A \frac{\mathrm{d}P_{g,A}}{\mathrm{d}t} = \dot{V}_A \frac{P_{bar}}{P_{bar,0}} (P_{g,I} - P_{g,A}) + \beta_g P_{bar} \sum_{k=1}^{N_{cp}} D_{g,L(k)} \left(P_{g,cp(k)} - P_{g,A}\right) \tag{8}$$

where: V_A is the alveolar volume, equal to 2481 cm^3 (Lambertsen, 1974b); $P_{g,A}$ is the g partial pressure of the alveolar compartment [Pa]; $\dot{V}_A$ is the alveolar ventilation [m^3/s, STPD]; $P_{bar,0}$ is the sea level barometric pressure [Pa]; β is the correction from molar to volumetric base [STPD], equal to 0.0224 m^3/mol for O_2 and 0.02226 m^3/mol for CO_2; k is the index of the pulmonary capillary compartment [1 to 10]; N_{cp} is the number of pulmonary capillary compartments, equal to 10; $D_{g,L(k)}$ is the diffusion coefficient of g through the respiratory membrane [mol/(s.Pa)]; and $P_{g,cp(k)}$ is the g partial pressure of the pulmonary capillary compartment k [Pa].

The pulmonary capillaries are represented by a series of compartments. The blood not shunted from the lung flows through them. Venous blood enters the first compartment. Then, the blood flows to the next pulmonary capillary compartment exchanging gases with the alveolar compartment through the respiratory membrane. After leaving the last pulmonary capillary compartment, the blood mixes with a fraction of shunted venous blood (2%) and follows to the arterial compartment. Each pulmonary capillary compartment is connected with one tissue compartment, which represents the pulmonary tissue where its metabolism occur. Just as the other tissues, the partial pressure of a gas is considered the same in each set of a capillary pulmonary compartment and a pulmonary tissue compartment. The reason of using several compartments in series is the need of an adequate value of the local driving force since the gases change their concentrations as they flow in the capillaries. Considering the computational effort and the need of a smooth curve, 10 compartments were considered enough. The diffusion coefficients (for O_2 and CO_2) are considered to depend linearly on the cardiac output, according to Albuquerque-Neto *et al.* (2008). The following equation is used for calculation of the gas partial pressure in each pulmonary capillary (and tissue) compartment:

$$\left(V_{cp(k)} \frac{\mathrm{d}C_{g,cp(k)}}{\mathrm{d}P_{cp(k)}} + V_{t(k)} \frac{\mathrm{d}C_{g,t(k)}}{\mathrm{d}P_{cp(k)}}\right) \frac{\mathrm{d}P_{cp(k)}}{\mathrm{d}t} = \dot{V}_{cp} \left(C_{g,cp(k-1)} - C_{g,cp(k)}\right) + D_{g,L(k)} \left(P_{g,A} - P_{cp(k)}\right) + \dot{n}_{g,t(k)} \tag{9}$$

where: $V_{cp(k)}$ is the pulmonary capillary compartment k volume, equal to $140/N_{cp}$ cm^3 (Lambertsen, 1974a); $C_{g,cp(k)}$ is the g concentration of the pulmonary capillary compartment k [mol/m^3]; $V_{t(k)}$ is the pulmonary tissue compartment k

volume, equal to $161/N_{cp}$ cm^3 (calculated from the other volumes); $C_{g,t(k)}$ is the g concentration of the pulmonary tissue compartment k [mol/m^3]; $\dot{V}_{cp}$ is the blood flow through the pulmonary capillary compartments [m^3/s]; and $\dot{n}_{g,t(k)}$ is the g production of the pulmonary tissue compartment k [mol/s].

Besides the skin heat exchanges, the human body also exchanges heat with the environment along with the ventilation. In order to obtain the heat transfer by evaporation and convection, the respiratory tract was modeled as compartments in contact with the tissues, with passage of dry air and water vapor. Two of those compartments exchange heat with the muscle of the head, one representing the inspiration phase, and other the expiration phase. Gas flow takes place from the inspiration compartment to the expiration compartment, and also with the environment. These two compartments are connected by gas flow with two other similar compartments (with flow between them), which exchange heat with the muscle of the neck. Likewise, two other compartments exchange heat with the lung. The compartments described above represent the dead space. The last two compartments are connected by gas flow with the alveolar compartment, which also exchanges heat with the lung.

2.6 Regulation

The regulators of the thermal and respiratory systems are divided into four actuating systems: metabolism, circulation, ventilation and sweating. The muscle metabolism is considered to vary depending on two reasons: shivering and physical activity. For the determination of its increase by the shivering, it is used the equation from Tikuisis and Giesbrecht (1999), where the variation of the muscle metabolism is function of the hypothalamus and the average skin temperatures. In order to represent the increase of the muscle metabolism by the physical activity, it was used a first order time constant, therefore, the input signal is the performed work. The circulation varies differently depending on the kind of tissue. It can be affected by chemical factors, thermal factors or physical activity. The chemical factors are included regarding the model of Ursino *et al.* (2001), in which the brain is affected by the arterial P_{CO_2}, and the other tissues besides the viscera by the arterial P_{CO_2} and P_{O_2}. The thermal factor deal with the skin vasomotor mechanism. It is included taking into account the relations of Wissler (2008), which consider as input signals the hypothalamus and the local and average skin temperatures, besides the physical activity. The physical activity also changes the muscle perfusion, which is considered linearly related to the metabolic rate. The ventilation, which is represented by the model of Longobardo *et al.* (2002), has separated effects of the central and peripheral parts. The central part depends on the brain P_{CO_2}, and the peripheral part depends on the arterial P_{CO_2} and O_2 saturation. An equation from Nadel *et al.* (1971) is used to include the increase of the wet skin surface, which is function of the hypothalamus and the local and average skin temperatures.

2.7 Solution

A computational program in the C++ language was developed in order to solve the model equations. The algebric equations were solved using a successive approximation method. Implicit methods were used to solve the ordinary and partial differential equations. The partial differential equations of the heat transfer in the tissues and small vessels were discretized using the finite volume method, according to Patankar (1980) and Maliska (2004). Cartesian and cylindric coordinate systems were used according to the segment geometry. Each segment layer was divided into control volumes with faces between them. The number of control volumes in each tissue layer was determined from tests aiming a good approximation. It varies from 5 to 10 elements in each direction.

3. RESULTS

The model simulation results were compared to experimental data found in the literature for different conditions. The experimental data are represented by points, and the simulation by lines. Figure 3 shows the experiment of Raven and Horvath (1970), where 11 subjects were exposed to 5 °C for 120 min. The graphs compare the rectal and the average skin temperatures and the heat generation. Figure 4 shows a 120 min exposition to 42,5 °C from Stolwijk and Hardy (1966b) with three subjects. The graphs compare the same two temperatures and the heat lost by evaporation through the skin. Figures 5 and 6 show experiments where 10 subjects were exposed, respectively, to a mixture with 9% of O_2 for 10 min (Reynolds and Milhorn Jr., 1973) and a mixture with 7% of CO_2 for 25 min (Reynolds *et al.*, 1972). The graphs compare the alveolar P_{O_2} and P_{CO_2} and the ventilation (expired). The last two comparisons are about the performance of physical exercise. Figure 7 shows the experiment of Cerretelli *et al.* (1966), where two subjects walked in a treadmill with the speed of 3,2 km/h and 8% of inclination for 4 min. The graphs compare the O_2 consumption, the CO_2 production, the ventilation, the cardiac output, and the venous P_{O_2} and P_{CO_2}. Figure 8 shows the experiment of Saltin *et al.* (1970), where one subject performed two half hour periods of exercise in an ergonomic bicycle. The graphs show the rectal and the average skin temperatures, the heat generation, and the heat lost by evaporation through the skin.

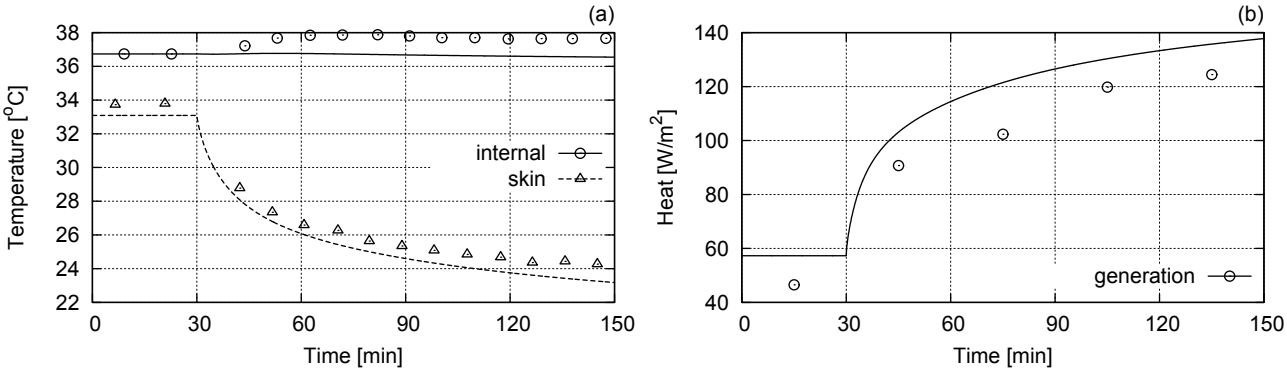

Figure 3. Comparison of the internal and average skin temperatures (a) and the metabolic heat generation (b) from the present model (lines) with the experimental data from Raven and Horvath (1970) (points)

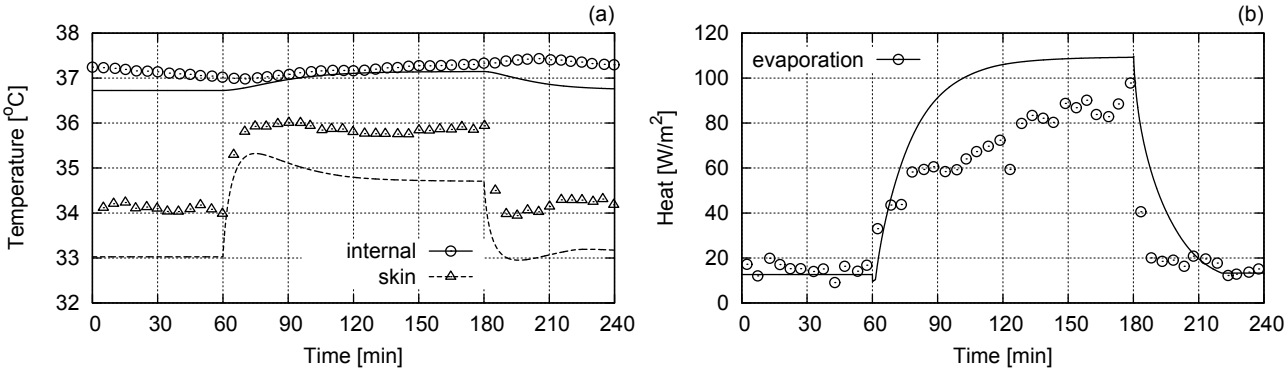

Figure 4. Comparison of the internal and average skin temperatures (a) and the heat lost by evaporation through the skin (b) from the present model (lines) with the experimental data from Stolwijk and Hardy (1966b) (points)

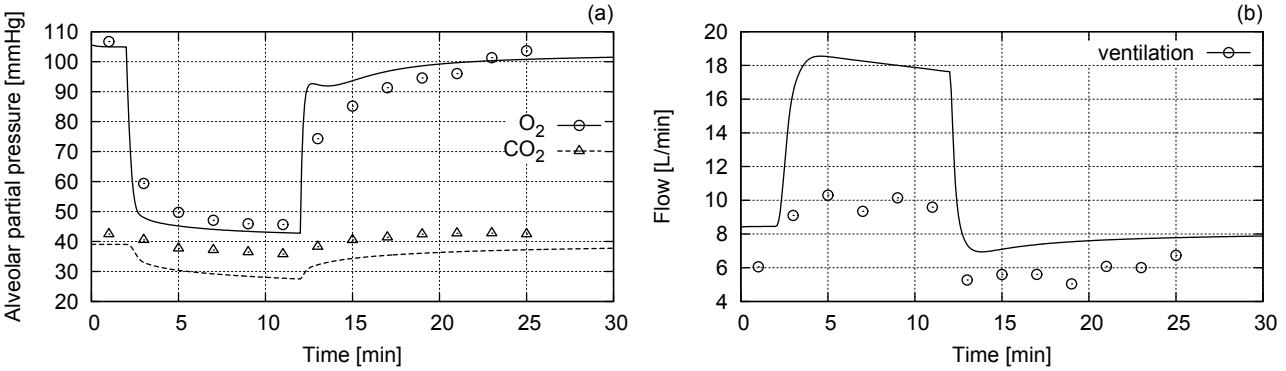

Figure 5. Comparison of the alveolar P_{O_2} and P_{CO_2} (a) and the ventilation (b) from the present model (lines) with the experimental data from Reynolds and Milhorn Jr. (1973) (points)

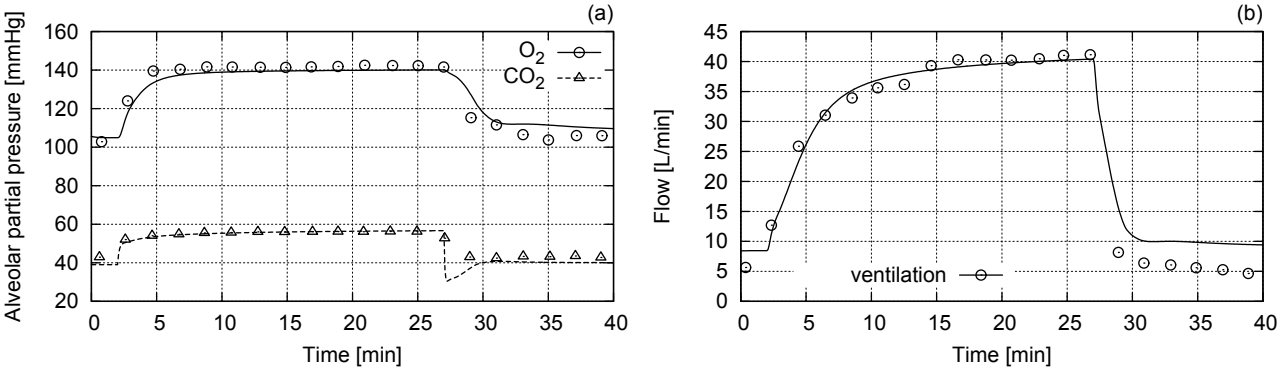

Figure 6. Comparison of the alveolar P_{O_2} and P_{CO_2} (a) and the ventilation (b) from the present model (lines) with the experimental data from Reynolds *et al.* (1972) (points)

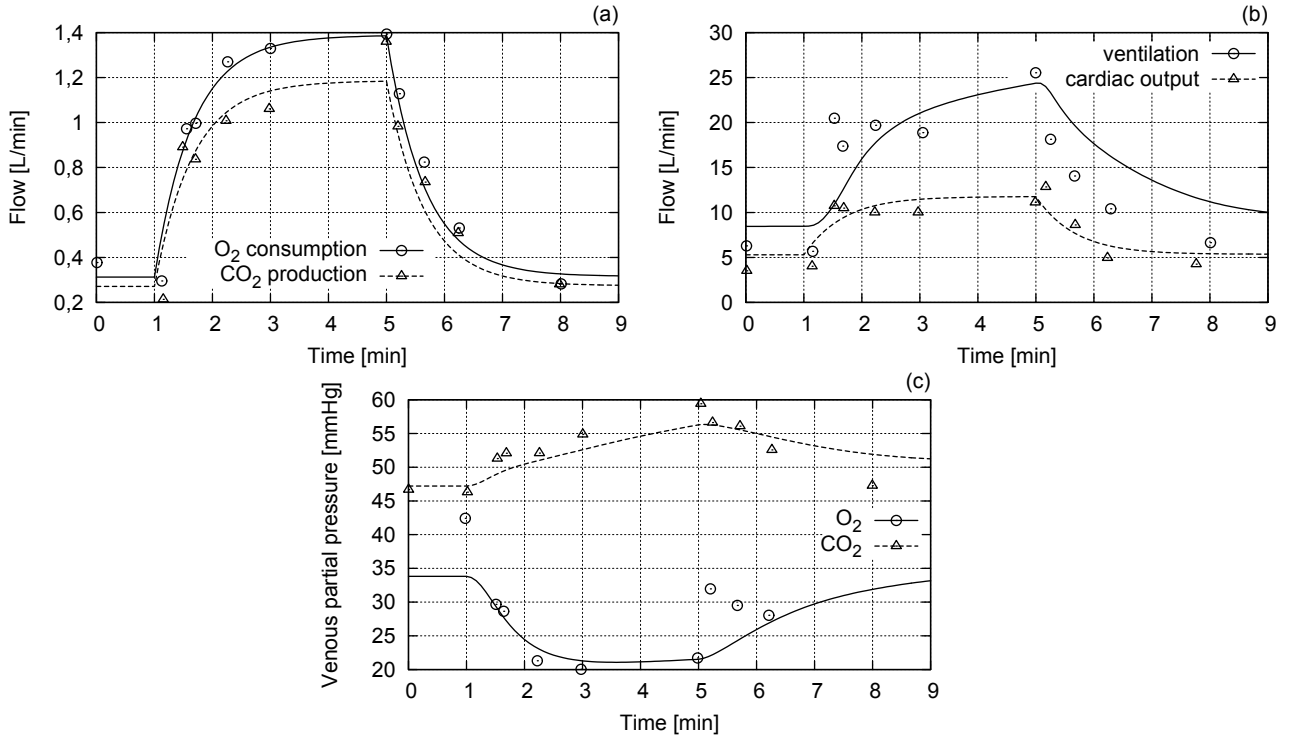

Figure 7. Comparison of the O_2 consumption and CO_2 production (a), the ventilation and cardiac output (b), and the venous P_{O_2} and P_{CO_2} (c) from the present model (lines) with the experimental data from Cerretelli *et al.* (1966) (points)

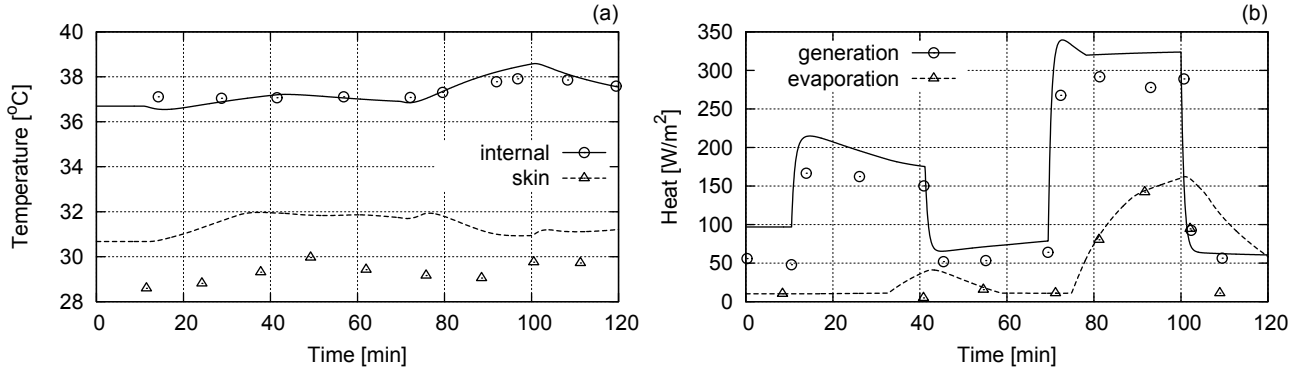

Figure 8. Comparison of the internal and average skin temperatures (a), the heat generation and the heat lost by evaporation through the skin (b) from the present model (lines) with the experimental data from Saltin *et al.* (1970) (points)

4. DISCUSSION

The results show an excellent agreement between the simulations and the literature experimental data. The only large discrepancy is the ventilation during the situation of hypoxia (Fig. 5b); despite that the form of the results are quite similar. The same forms are also found in the comparisons with small discrepancy between the experimental and theoretical results.

The skin temperature is strongly related to the ambient temperature. It decreases in the cold environment (Fig. 3a) and increases in the warm environment (Fig. 4a). The internal temperature increases in both expositions. Its small increase in the cold exposition is due to increase in the muscular activity by the shivering (Fig. 3b). Another example of regulation mechanism is the increase of the heat lost by evaporation in the warm environment (Fig. 4b), which is a direct consequence of the sweating increase.

Figures 5 and 6 show good examples of the mass transport behavior. In the first case, the decrease of the O_2 concentration results in an increase of the ventilation, so it continues available to the tissues. The increase in the ventilation reduces the CO_2 storage. During the CO_2 exposition, the increase of the CO_2 concentration also reflects in the increase of the ventilation, which rises the O_2 availability.

The interactions between the respiratory and the thermal systems are in evidence when performing physical exercise. The rise in the O_2 consumption and the CO_2 production (Fig. 7a) increases the CO_2 concentration and decreases the O_2 concentration (Fig. 7c). Both the gas concentration variations stimulate the regulation mechanisms of ventilation and

cardiac output. The skin temperature is practically constant during the performance of physical activity when comparing with its variation in a cold or warm environment (Fig. 8a). The internal temperature increases depending on the exercise level. One mechanism that the body uses to maintain the internal temperature in acceptable levels is the increase in the sweating (Fig. 8b). Other mechanisms are the skin vessel dilatation and the ventilation, which increases the heat lost through the respiratory tract.

5. CONCLUSION

This work describes the development of a mathematical model of the thermal and the respiratory human body systems. The model allows the representation of the heat, O_2 and CO_2 transfer mechanisms. The human body is divided into segments with tissue layers and blood, tissue and pulmonary compartments. It behavior is influenced by the surrounded environment and its level of physical activity.

Comparisons with experimental data found in the literature reveal that the model is suitable to represent several situations. In these can either occur variation in the ambient conditions (cold, warm, O_2 deficit or CO_2 excess), or physical exercise. The results show either the muscle metabolism increase by the shivering in a cold environment, or the increase in the heat lost by evaporation through the skin due to the sweating in a warm environment, both to maintain the internal temperature in acceptable levels. Other results show the increase in the ventilation to take more O_2 to the tissues when its amount in the inspired air is low, or to eliminate the excess of CO_2 when its amount in the air is elevated. The last results show that, during the physical exercise, both the thermal and respiratory systems are hardly involved. The increase of the muscle metabolism increases the amount of CO_2, decreases the O_2, and increases the internal temperature. Those changes actuate on the regulation system increasing the ventilation, cardiac output and sweating.

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