A COMPARTMENT MODEL TO EVALUATE THE HEAT TRANSFER IN THE HUMAN RESPIRATORY TRACT

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Abstract. *A mathematical model is proposed to determine the heat transfer in the respiratory tract, taking into account the tissue temperature. The respiratory tract is divided into compartments representing the inspiration path, the expiration path and the alveolar space. Flows of dry air and water vapor take place between the compartments and with the environment. The compartments exchange heat and water vapor with the tissues. Mass and energy balances allow the calculation of their temperature and humidity. Results of the model are similar to the results from the classical methodology, but has the improvement of considering the tissue temperatures, besides the environmental conditions and the pulmonary ventilation.*

Keywords: *bioheat transfer, respiratory tract, thermoregulation*

1. INTRODUCTION

The determination of the heat flux through the respiration is useful to model the thermoregulatory system of the human body. In the usual methodology first described by Fanger (1970), the heat flux through the respiration is determined from the pulmonary ventilation and the temperature and humidity of the inspired and expired gases. The temperature and the humidity of the expired gases are obtained by empirical equations from McCutchan and Taylor (1951). In the present work, a compartment model where the temperature and the humidity are calculated from energy and mass balance is proposed. The model includes the heat and mass transfers with the tissues of the respiratory tract, besides the ambient conditions.

2. MATHEMATICAL MODEL

The model divides the gas path in the respiratory tract into compartments, according to Figure 1. The compartments are identified by indexes (1 to 7). The index 0 represents the environment air. The number of compartments and their sizes were chosen aiming the use of the model in the thermoregulatory model of Ferreira and Yanagihara (2009). Besides this, other configurations could be set to adapt the compartments to other thermoregulatory model.

The first compartment (1) is in contact with the environment air and contains the mouth and pharynx gases. The second (2) contains the trachea gases. The third (3) contains the gases between the bronchus and the bronchiole. Those three compartments represent the gases path during the inspiration. The last three compartments (5, 6 and 7) represent those same locales, nevertheless, during the expiration. This separation was done to represent the ventilation periodicity in a simplified way. The ventilation through the compartments is then continuous and in the same direction. The fourth compartment (4) represents the alveolar space.

The gases inside the compartments and in the environment are separated into dry air and water vapor. The following hypotheses were adopted: uniform compartments, perfect gas, constant pressure (equal to the barometric pressure), constant compartment volume, negligible kinetic and potential energy. The compartments are in contact with the tissues. Between them occurs heat transfer by convection and water evaporation.

The gas flow between two compartments, or between one compartment and the environment air, is divided into dry air and water vapor flows. They receive the index of both the compartments, in the flow direction. The dry air mass flow between the compartments is obtained from the expired pulmonary ventilation and their volumes.

The volumes and the surface areas of the compartments were obtained from literature (Tab. 1). Besides the compartment 4, the surface areas were calculated from the diameters, lengths and the number of branches.

The absolute humidity of the compartments is obtained from water vapor balances. It takes into account the water vapor flow between compartments and with the environment, and the evaporation in the tissues of the respiratory tract. The absolute humidity of the compartment i is:

$$m_{a(i)} \frac{\mathrm{d}\omega_{(i)}}{\mathrm{d}t} = \dot{m}^{in}_{w(i)} - \dot{m}^{out}_{w(i)} + \dot{m}^{e}_{w(i)} \tag{1}$$

where $m_{a(i)}$ is the dry air mass of the compartment i, kg; $\omega_{(i)}$ is the absolute humidity of the compartment i, kg/kg; $\dot{m}^{in}_{w(i)}$ is the input mass flow of water vapor of the compartment i, kg/s; $\dot{m}^{out}_{w(i)}$ is the output mass flow of water vapor of the compartment i, kg/s; and $\dot{m}^{e}_{w(i)}$ is the water vapor flow from the tissue to the compartment i, kg/s.

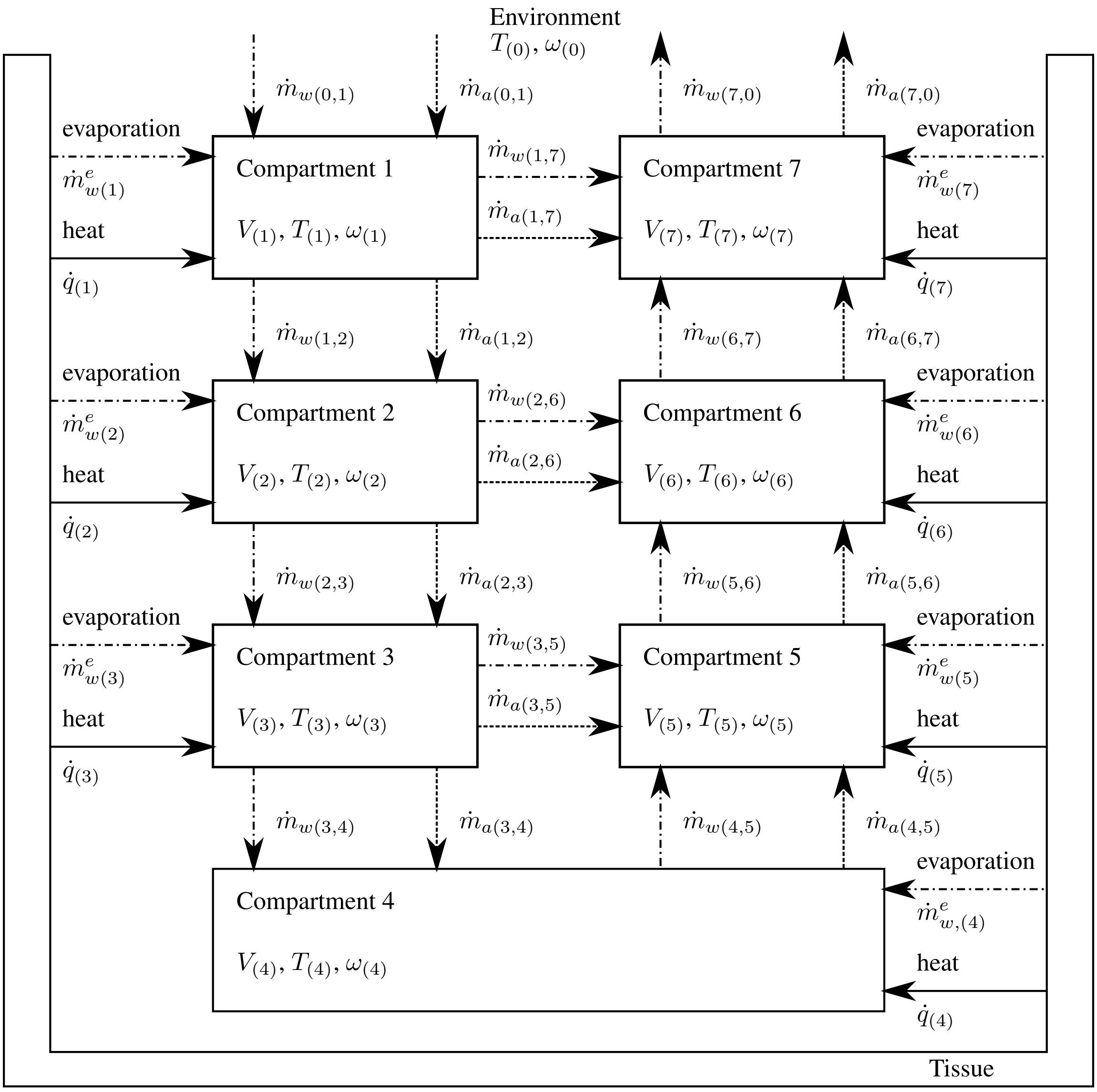

Figure 1. Compartment model description. The arrows represent the heat from the tissues to the compartment (solid line), the dry air flow between compartments (dashed line), and the water vapor flow between compartments and from the evaporation (dash-dot line).

Table 1. Compartment parameters.

Compartment	Volume [cm^3]	Superficial Area [m^2]	Reference
1 and 7	22.0	0.00440	Olson *et al.* (1970)
2 and 6	30.5	0.00679	Olson *et al.* (1970)
3 and 4	103.5	0.595	Fowler (1948); Olson *et al.* (1970)
5	2180	70	Lambertsen (1974)

The input and output flows of water vapor are:

$$\dot{m}_{w(i)}^{in} = \begin{cases} \dot{m}_{a(i-1,i)}\,\omega_{(i-1)} & \text{if } i \leq \frac{N+1}{2} \\ \dot{m}_{a(i-1,i)}\,\omega_{(i-1)} + \dot{m}_{a(N-i+1,i)}\,\omega_{(N-i+1)} & \text{if } i > \frac{N+1}{2} \end{cases} \tag{2}$$

$$\dot{m}_{w(i)}^{out} = \begin{cases} \left(\dot{m}_{a(i,i+1)} + \dot{m}_{a(i,N-i+1)}\right)\omega_{(i)} & \text{if } i < \frac{N+1}{2} \\ \dot{m}_{a(i,i+1)}\,\omega_{(i)} & \text{if } i \geq \frac{N+1}{2} \end{cases} \tag{3}$$

where $\dot{m}_{a(i,j)}$ is the dry air mass flow between the compartments i e j, kg/s; and N is the number of compartments (= 7).

The water vapor from evaporation, between the respiratory tract tissues and the compartment, is proportional to the difference between the saturated absolute humidity (relative humidity of 100% at the compartment temperature) and the compartment absolute humidity:

$$\dot{m}_{w(i)}^{e} = DA_{(i)}\left(\omega_{sat(i)} - \omega_{(i)}\right) \tag{4}$$

where D is the diffusion coefficient, equal to $3{\times}10^{-6}$ kg/(m^2.s), adjusted with data from Hanson (1974); $A_{(i)}$ is the surface area of the compartment i, m^2; and $\omega_{sat(i)}$ is the saturated absolute humidity of the compartment i, kg/kg.

The temperature is determined by an energy balance, which includes the flows of dry air and water vapor between the compartments and the with the environment, the heat transfer by convection with the tissues, and the evaporation:

$$m_{(i)}\,c_v(i)\,\frac{\mathrm{d}T_{(i)}}{\mathrm{d}t} = \dot{E}_{(i)}^{in} - \dot{E}_{(i)}^{out} - \dot{m}_{w(i)}^{e}\,h_{lv(i)} + UA_{(i)}\left(T_{t(i)} - T_{(i)}\right) \tag{5}$$

$$\dot{E}_{(i)}^{in} = \begin{cases} \dot{m}_{(i-1,i)}\,c_{p(i-1)}\,T_{(i-1)} & \text{if } i \leq \frac{N+1}{2} \\ \dot{m}_{(i-1,i)}\,c_{p(i-1)}\,T_{(i-1)} + \dot{m}_{(N-i+1,i)}\,c_{p(N-i+1)}\,T_{(N-i+1)} & \text{if } i > \frac{N+1}{2} \end{cases} \tag{6}$$

$$\dot{E}_{(i)}^{out} = \begin{cases} \left(\dot{m}_{(i,i+1)} + \dot{m}_{(i,N-i+1)}\right)c_{p(i)}\,T_{(i)} & \text{if } i < \frac{N+1}{2} \\ \dot{m}_{(i,i+1)}\,c_{p(i)}\,T_{(i)} & \text{if } i \geq \frac{N+1}{2} \end{cases} \tag{7}$$

where $m_{(i)}$ is the mass of dry air and water vapor of the compartment i, kg; $c_{v(i)}$ is the specific heat at constant volume of the dry air and water vapor of the compartment i, J/(kg.°C); $c_{p(i)}$ is the specific heat at constant pressure of the dry air and water vapor of the compartment i, J/(kg.°C); $T_{(i)}$ is the temperature of the compartment i, °C; $\dot{E}_{(i)}^{in}$ is the input flow energy of the compartment i, W; $\dot{E}_{(i)}^{out}$ is the output flow energy of the compartment i, W; $\dot{m}_{(i,j)}$ is the total mass flow between the compartments i e j, kg/s; $h_{lv(i)}$ is the vaporization enthalpy of the compartment i, J/kg; U is heat transfer coefficient between tissue and compartment, equal to 10 W/(m^2.°C), based on data from Kandjov (2001); and $T_{t(i)}$ is tissue temperature of the compartment i, °C.

3. RESULTS AND DISCUSSION

Figure 2 shows a comparison between the total energy transfer obtained with the present model and with the model of Fanger (1970). Their behaviors are similar from 0 to 50 °C for different relative humidity values. Nevertheless, the values from the present model are larger. A positive value of energy transfer means that the respiration is cooling the body. Negative values are only found when the relative humidity is large and the environment temperature is larger than the tissue temperature. The curve with relative humidity equal to 100% shows the behavior of the heat transfer without the cooling effect of the evaporation.

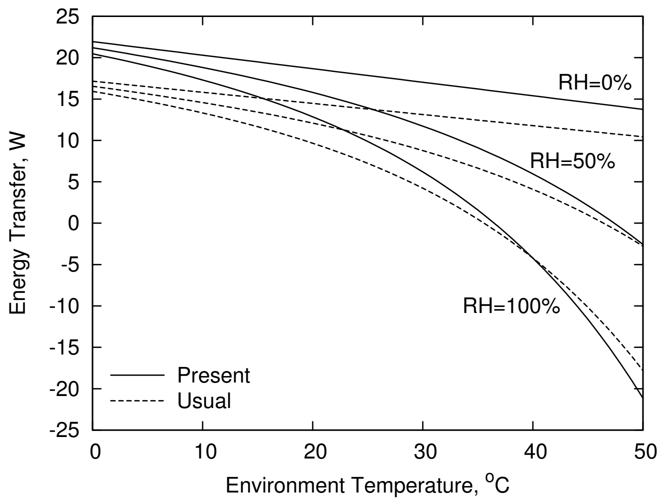

Figure 2. Comparison of energy transfer through the respiratory tract obtained by the present model and the usual methodology proposed by Fanger (1970), for relative humidity equal to 0%, 50% and 100%. The tissue temperature was set to 37 °C and the pulmonary ventilation to 8 L/min.

The Fanger (1970) methodology determines the energy transfer through the respiratory tract from empirical equations for the expired temperature and humidity. Those variables are calculated in the present model by mass and energy conservation. It still depends on experimental data for the heat transfer and the diffusion coefficients between the tissues and the compartments. Furthermore, those coefficients might increase with the ventilation.

4. CONCLUSION

A compartment model was developed to determine the energy transfer through the respiratory tract, based on mass and energy conservation. The model reproduces the results of the most common methodology used in thermoregulatory models of the human body. It has the advantage of depending on the tissue temperature, besides the environmental conditions, which makes it appropriate to simulate conditions with significant variation in internal body temperature.

5. ACKNOWLEDGEMENTS

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