VALIDATION OF A SIX CYLINDER THERMOREGULATORY MODEL

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This contribution outlines the basics of a six-cylinder-model which has been written in Microsoft^R-FORTRAN for use on personal computers. As such a model is never a final product and has to be adapted more or less to special applications by prospective users, special emphasis is laid on the problems and status of validation.

OUTLINE OF THE MODEL

The six cylinders i= 1...6 are head, trunk, arms, hands, legs and feet. The model takes into account the radial dependency of the essential variables. 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 temperatures control the effector mechanisms evaporation, metabolism, vasomotor action. The instationary heat-flow is affected by three mechanisms within the passive system: metabolism, conduction through the tissue and convection through the blood. Assuming a purely radial conduction within the cylindrical elements and the classical Pennes bio-heat approach, we get the following heat balance for each cylinder: heat flow = metabolic heat production + conduction through tissue + heat flow input through blood - heat flow output through blood.

Initial conditions and boundary conditions are formulated. Transition conditions at sites r_{ji} between concentric layers j are taken into account. A further heat balance equation is formulated for the central blood pool. The afferent signal a(t) for the controller is the sum of weighted temperature measurements at sites r_k, using weighting factors g_{ij} and a threshold a_o. The integrated afferent signal then is transformed into effector signals Δe_{ij} using distribution factors c_{ij} which have different values for metabolic heat production, for sweat production and for skin blood flow.

$$a=\sum_{i=1}^{6}\sum_{j=1}^{2}\{g_{ij}T_{ij}(r_k)\}-a_0$$

$$\Delta e_{ij}=c_{ij}\cdot a$$

The dimensions of the cylinders and their, at present, two concentric layers are determined according to the given volume and surface of the 12 body compartments. Data of the passive system are mainly based on those used in former models (1 - 5). The controller parameters g_{ij}, a_o and c_{ij} were adjusted during the validation process.

VALIDATION OF THE MODEL

In order to validate the model, it is also necessary to specify and check conditions and methods of recording experimental data. Problems of validation will arise both from deficiencies of the model and the experiments. As a standard set of data we use the experimental results recently described by (6). A major problem is coordinating the sites of the measurements and the sites of the computed temperatures. The experimental data set comprises 3 core temperatures (auditory canal, oesophageal and rectal), 4 muscle temperatures, 3 subcutaneous temperatures and 16 skin temperatures, while the computation delivers radial temperature profiles from the centre to the skin surface for six compartments. So, one major aspect is that computation does not take into account the longitudinal and the angular coordinate, and that on the other hand, measurements comprise only one to four samples of the radial coordinate depending on the body compartment. The model has been validated for changes of environmental temperatures between 15° and 45°C for nude subjects at rest at 40 % relative humidity and 0.1 m/s air velocity. Compatibility of oesophageal temperature in simulation and experiment is optimal. Differences are less than 0.4°C, also the dynamics are satisfactory. As to the temperature of the auditory canal, the computation yields higher values in the cold (up to about 1°C). This might be due to the fact that, in the cold, brain temperature, which is actually simulated by the model, should be higher than the temperature measured in the auditory canal which should be influenced more by ambient temperature. Rectal temperature varies considerably in the experiments, presumably due to influences of environmental temperature or to possibly varying depth of the sensors. On the whole, the model predictions of core temperature, particurlarly if oesophageal temperature is considered, are sufficiently reliable. Regarding muscle temperatures (trunk and leg), compatibility of simulation and experiment is very good for the extremity, especially for 2 cm depth. It is remarkable that for this site also the differnces measured in the experiments are minimal. The computed temperatures at 4 cm depth (in the trunk also at 2 cm) are more stable than those recorded in the experiments. This discrepancy might at least partially be due to environmental influences on the measurements but also to the fact that at present the model takes into account only two layers. As to the trunk, it must also be taken into account that only one mean temperature at 4 cm depth is computed for the whole trunk, whereas the experiment records the temperature of one special muscle. For the subcutaneous and cutaneous temperatures, the computed curves are within the span of the experimental ones.

CONCLUSION

So from the 16 computed temperatures examined (core, muscle, subcutaneous, skin) it is concluded, that within the range of environmental conditions tested (15 -45°C), the model, although simplifying the complex geometry of the human body to six cylinders, and although simplifying the complex heat transfer from the vessels by the classical bio-heat approach, gives reliable results for the nude subject at rest, for both the steady state and the dynamics of body temperatures. It can be expected that it will produce satisfactory extraplations for more complex and more extreme conditions, although some parameters will have to be adjusted further.

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