MODELLING OF HEAT TRANSFER

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INTRODUCTION

Heat transfer is essential to maintaining a thermal balance. While it is generally understood that the passive flow of heat is in a direction from high to low temperature, the active transfer of heat via blood flow plays a very important role in thermoregulation. The former mechanism is labelled conductive heat transfer while the latter is labelled convective and is the primary means of transferring heat between different body segments (eg. trunk to extremities). Both mechanisms are inherently involved and very complex to isolate. This paper will discuss each of these mechanisms in a modelling context and refer exclusively to the limb segments of the body for application. Heat transfer with the environment will not be considered.

CONVECTIVE HEAT TRANSFER

The importance of convective heat transfer has been demonstrated through experiments involving cold exposure where it has been shown that the limbs are responsible for most of the body's heat loss while the trunk is responsible for most of the body's heat production. The excess heat produced in the trunk is convected to the limbs by the arterial blood. One striking example is the civd response to maintain warm fingers.

Direct exchange of heat between the blood vessel and tissue can take place at all branches of the circulation system but with decreasing effectiveness with increasing vessel size. Weinbaum et al. (1) have demonstrated that the thermally significant vessels range from 40 to 300 μm in diameter and that smaller vessels are essentially in thermal equilibrium with the surrounding tissue. This is contrary to the Pennes's (2) assumption that convective heat transfer occurs only at the capillary level which has been used in several models of thermoregulation. The direct exchange of heat between counter-current pairs of vessels (i.e., the rewarming of venous blood via cooling of arterial blood) is an important mechanism of heat conservation, although the efficiency of counter-current heat exchange depends on many factors and is still debated.

For practical modelling purposes, it is convenient to construct concentric annular compartments in a limb segment and place the major blood vessels parallel to the axis of the innermost compartment. Blood flow to the outer compartments is considered to occur in a radial direction. Convective heat transfer between tissue and blood is thus assumed to take place at three levels (3); i) with the major axial vessels, ii) with the radial vessels passing through a compartment and iii) with the perfusing blood vessels within a compartment Counter-current heat exchange is assumed to take place only between the major axial vessels.

CONDUCTIVE HEAT TRANSFER

The rate of heat flow through tissue is determined by the temperature difference across the tissue divided by its thermal resistance. If no heat is internally generated, then the thermal resistance is a function of the tissue's geometry and intrinsic thermal conductivity, and can be termed as the passive thermal resistance. value. This is a good approximation for poorly perfused tissues such as fat and cold skin. However, in most cases, heat is internally generated in tissue through metabolism and/or convective heat transfer with the blood. Any internally generated heat will cause a temperature distribution that is dependent on the location of the sources of heat. It has been common to define an effective value of thermal resistance or its reciporcal, effective thermal conductivity (k_{eff}), to describe heat flow in this situation.

EFFECTIVE THERMAL CONDUCTIVITY

Two approaches on the determination of k_{eff} are discussed. One approach has been to use a finite-element model in which several concentric annular compartments are treated as having uniform properties but different values of internal heat generation. Application of the bioheat equation to this finite-element configuration in the analysis of a thermal *stress* to the forearm (4) revealed that the level of internal heat generation increased towards the axis of the forearm. This feature could be modelled by allowing significant convective heat transfer to take place between tissue and the blood passing through the tissue in the radial direction. Following this approach, the mean k_{eff} for the whole tissue was found to increase linearly with increased blood flow; values increased almost four-fold from a cold to warm condition. In the cold condition, k_{eff} was found to be slightly higher than the *in vitro* value in similar tissue.

The other approach to calculate k_{eff} stems directly from knowing the distribution of internal heat sources and determining the tissue's effective thermal resistance, R_{eff}. This is found by integrating the product of the intensity of heat generation (q) and the corresponding passive thermal resistance value (R) in the tissue. Hence, assuming a cylindrical geometry:

$$R_{eff} = \int_0^{r_s} q \cdot r \cdot R \cdot dr \Big/ \int_0^{r_s} q \cdot r \cdot dr$$

where r is radius and r_s is its value at the cylindrical surface. The nearly linear radial steady-state temperature profiles measured in the forearm muscle of the experiment cited above (4) leads to an effective thermal resistance value equal to the ratio r_s / k_{eff}. Equating this value to the ratio of the temperature difference across the tissue over the heat flux measured at the surface leads to k_{eff} values that agree within the SE of the values obtained using the finite-element approach

Whenever internal heat generation exists, R_{eff} is less than the tissue's passive value of thermal resistance. For example, the passive thermal resistance of a rectangular section of tissue is twice its R_{eff} value if internal heat generation is uniform. Hence, given the heat flux from a body, use of the passive value will lead to an overprediction of the temperature difference across the body. This has implications for the correct determination of heat flux using heat flux transducers where the thermal resistance of the underlying body must be known, and for the determination of the insulative qualities of fat and skin with changing blood flow. The latter is demonstrated with a core-shell model through a re-examination of data involving low and high skin blood flows.

REFERENCES

1. Weinbaum S., Jiji L.M., and Lemons D.E. 1984. Theory and experiment for the effect of vascular microstructure on surface tissue heat transfer - Part 1, *J. Biomechanical Eng.* 106, 321-330.

2. Pennes H.H. 1948. Analysis of tissue and arterial blood temperatures in the resting human forearm, *J. Appl. Physiol.* 1, 93-122.

3. Tikuisis P. 1989. Prediction of the thermoregulatory response for clothed immersion in cold water, *Eur. J. Appl. Physiol.* 59, 334-341.

4. Tikuisis P. and Ducharme M.B. 1991, Finite-element solution of thermal conductivity of muscle during cold water immersion, *J. Appl. Physiol.* 70(6), 2673-2681.