CONVECTIVE HEAT TRANSFER IN TISSUE

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INTRODUCTION

The mathematical description of convective heat transfer in tissue is a very intricate problem. The classical "bio-heat approach" by Pennes (1) assumed that heat transfer is proportional to the perfusion rate and the difference of arterial and tissue temperature. Recent attempts accounted for convective heat transfer by an enhanced conductivity index *(2, 3),* an approach which was questioned by Wissler (4), who presented a concept using the spatial variations in the arterial, venous, and tissue temperatures. Baish et al. (5) rigorously derived the relationship between the countercurrent and vessel/tissue heat transfer parameters and the morphology of the vascularity, but only heat transfer perpendicular to a vessel pair is described. Charny and Levin (6) incorporated the Baish model into a system of heat balance equations similar to those proposed by Wissler. In a recent paper, Charny et al. (7) proposed that a "hybrid model would be most appropriate for simulations of bioheat transfer in perfused tissue."

METHODS

To investigate the thermal processes in a human extremity, we developed a three-dimensional model which quantifies the convective heat transport on the basis of a detailed simulation of the vascular architecture **(8).** Computation of heat flow via the vessel walls is carried out using the Nusselt-number, the wall temperatures, the blood temperature and the vessel diameters. In contrast to former approaches, no serious assumptions have to be made. The model approximates the three-dimensional temperature profiles within the tissue and the arterial and venous temperatures of thermally significant vessels along a branching countercurrent vessel network. The geometry varies with the distance from the skin surface. The idealized cross-section of an extremity has a three-layer tissue structure (core-muscle-skin) and the adequate structure of peripheral circulation. The core comprises the larger central vessels and the directly adjacent tissue. The central artery and vein are the origin for a countercurrent arterio-venous network in the muscle layer. The outer skin layer is provided with separate rising vessels. The three-dimensional heat balance equation with a convective boundary condition at the vessel walls is solved using local central differences with a highly irregular grid. The grid width is **7** μm in the vicinity of the vessels, at the maximal distance it is 2 mm. The three-dimensional profiles of tissue temperatures and the one-dimensional profiles of temperatures of the arterial and venous blood were computed for rest, for maximal exercise and for cold. Based on the results of the outlined three-dimensional model, it was possible to develop a simple efficiency-function model (9) to be used in whole body thermoregulatory models. The efficiency function EF is dependent on blood flow and the local coordinate of blood flow and compensates for the deficiencies of the Pennes-approach. The parameters of EF were determined in such a way that the computed temperature profiles exhibit good compatibility with the results of the complex vascular model **(8).** Although this EF-approach is formally very similar to the Pennes-approach, it has essentially different properties. It comprises implicitly pre-arteriole and post-venule heat transfer, as well as countercurrent heat transfer in neighboring artery-vein pairs. The simplicity of the essential equations, however, has not changed.

RESULTS

In a cold environment (5°C), the arterial blood temperature decreases by about 7°C on its way to the outer section of the muscle tissue. There must be a prearteriole heat transfer between the blood and the tissue which cannot be neglected especially in the cold environment and when the perfusion rate is small. At the end of the vascular tree, blood temperature is equilibrated with the temperature of the surrounding tissue. In the cold, there is heat loss from the arterial blood and heat gain to the vein. The heat flow out of the artery is slightly greater than the heat flow into the vein. At a high metabolic rate due to exercise, the direction of heat flows is reversed. It is interesting that in spite of the fact that mean tissue temperature is above both arterial and venous temperatures, there **is** a heat flow out of the vein. This is a consequence of the tissue cooling by the artery in the neighbourhood of the vessel pair (10).

Various nonvascular modeling approaches were evaluated by comparing the predicted tissue temperature profiles with those from the complex vascular model (Fig. 1). As heat transfer from the vessels to the tissue is neglected in the Weinbaum-Jiji model (WJ) the tissue profile exceeds or falls below the expected profile. Especially in a cold environment and when the perfusion rate is small poor predictions will be obtained. Only if the perfusion rate is high, is the Pennes-approach an acceptable approximation for the tissue temperature. The deficiencies of these two models become even more obvious in the case of local hyperthermia treatment (11). *An* approximation of acceptable quality is achieved by the simple EF-model and the Baish-Wissler/Charny-Levin approach (SIG).
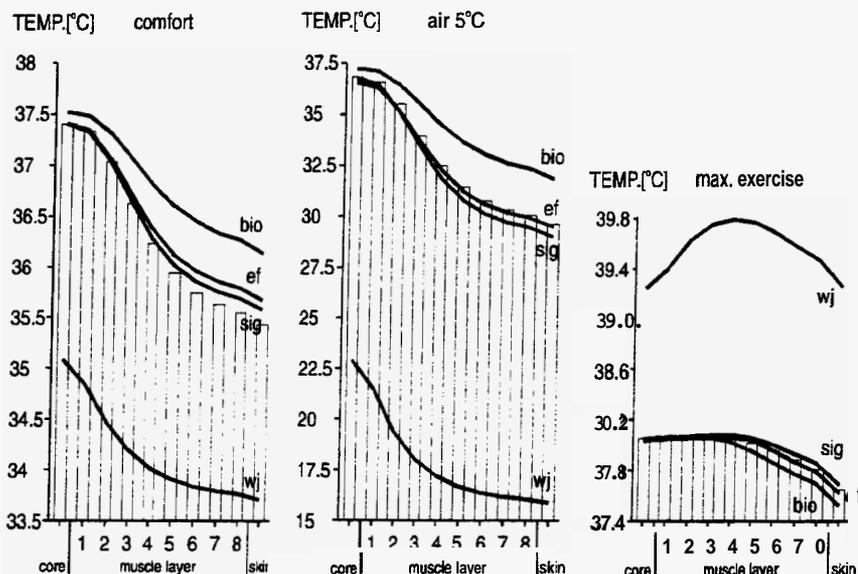
Fig. 1: Predicted temperature profiles for comfort conditions, cold and maximal exercise. Temperature of central artery of core assumed to be 37.5°C. **8** muscle layers (of decreasing thickness) according to vessel generations of counter current arterio-venous tree. Bars: exact vascular model. Non-vascular approaches: bio = Pennes' bio-heat, ef = efficiency function, sig = Baish/Wissler/Charny-Levin, wj = Weinbaum-Jiji.

CONCLUSIONS

It is concluded that countercurrent heat exchange in small arteries and veins is not negligible. Therefore Pennes predictions are acceptable only when the perfusion rate is **high.** The assumptions made in the WJ-bioheat transfer equation are valid only in a small region of the muscle tissue near skin where the blood is nearly equilibrated with the tissue. Using a "hybrid" model is not necessary, because the SIG-model or the EF-model reveal a good prediction of temperature profiles along the whole length of the muscular countercurrent vessel network. The advantage of the EF-model is that it can very easily be incorporated into thermal whole body models.

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