THE THERMAL EFFECT OF BLOOD FLOW IN A BRANCHING COUNTERCURRENT NETWORK

Heinrich Brinck and Jürgen Werner
Institut fiir Physiologie, Ruhr-Universität
MA 4/56, D4630 Bochum 1, Germany

In 1948 Pennes [1] proposed that heat transfer effects in perfused biological tissue be quantified by a heat source/sink term. This term is proportional to the perfusion rate and the temperature difference between the tissue and the arterial blood. Several research groups [2,3,4] questioned the underlying assumption that all heat transfer occurs in the capillaries. They drew attention to the fact that countercurrent heat exchange in small arteries and veins is not negligible and proposed new bioheat transfer equations.
This contribution presents a three-dimensional vascular model in which convective heat exchange between blood and tissue is calculated without any assumptions other than values for the Nusselt number.
Going back to a suggestion given by Wissler in [5] we developed a simple but effective model to account for countercurrent heat transfer in perfused tissue in whole body models.
Bioheat transfer concepts are evaluated by a comparison between the predictions of these concepts and the predictions of the vascular model. As our vascular model is calculated without any crucial assumption it is possible to test the validity of the assumptions inherent in the formulations of all the other bioheat transfer concepts.

OUTLINE OF THE VASCULAR MODEL

We constructed a three-dimensional thermal model in which the bioheat equation is defined explicitly in terms of the physical details of the vascular system. Closely spaced, countercourrent pairs of thermally significant vessels are considered. The model can predict the spatial variations in the arteriole, venule, and tissue temperatures in a branching countercurrent network.
It is applied to the cross-sectional area of a human extremity with an idealized three layer organization of the vasculature of the peripheral circulation: The core contains the countercurrent central artery and vein and the immediate surrounding tissue. The major artery and vein are the starting points of a countercurrent arterio-venous network in the muscle layer. The countercurrent pairs of arteries and veins are constantly branching. The countercurrent network in the muscle tissue consists of eight generations of paired vessels. The muscle layer is surrounded by the skin layer in which the blood is supplied by isolated larger riser vessels. Convenient functional forms for the variation of the vascular geometry in the muscle layer in the radial direction have been proposed in [6].
The three dimensional energy balance equation for the tissue temperature is subject to a convective boundary condition along the arteriole and venule walls. A central difference approximation is done on an irregular grid. The nodal spacings are small around the vessels and in the spacing between the vessels. They are up to 64 times smaller than the nodal spacings at the tissue cylinder wall.

OUTLINE OF THE "EFFICIENCY FACTOR MODEL"

An "efficiency factor" EF is computed by the vascular model to account in a simple and tractable way for the effect of countercurrent heat exchange in muscle tissue near the skin surface. The usual perfusion term in the conventional bioheat equation has to be multiplied with the "efficiency factor" EF of the form

$$(1)\quad EF_i [\omega_i] = L_i / (1 + F_i / \omega_i).$$

ω_i is the local blood perfusion rate. The parameter values F and L are determined for the vascular generations 1-4 (i.e. the inner 43 [mm] of the muscle layer) and for the vascular generations 5-8 (i.e. the outer 5 [mm] of the muscle layer).

$$(2)\quad F_{1-4} = 0.00042 \quad L_{1-4} = 1.0647 \quad F_{5-8} = 0.00501 \quad L_{5-8} = 1.0231$$

To calculate the mean venous temperature T_v of the blood returning from the muscle tissue to the central vein a local effective tissue temperature $T_{tef}(z)$ is defined.

(3) $T_{tef}(z) = EF(\omega,z) * T_t(z) + (1 - EF(\omega,z)) * T_a$

T_a is the global arterial blood temperature. The mean venous temperature T_v is calculated using an perfusion-weighted average of the effective tissue temperature $T_{tef}(z)$.

(4) $T_v = \int_z(\omega(z)*T_{tef}(z))dz \,/\, \int_z(\omega(z))dz$

RESULTS

The vascular model computes the spatial variations in the arteriole, venule and tissue temperatures under basal conditions, hyperthermic conditions and in a cold enviroment.
It was found that countercurrent heat exchange in small arteries and veins is not negligible. The assumptions made in Pennes equation and in the Weinbaum/Jiji bioheat transfer equation are not valid; e.g. it is shown that the mean of arteriole and venule blood temperature is not equal to the mean tissue temperature and that the heat transfer between the Countercurrent artery-vein pairs and the surrounding tissue is not negligible. The prediction of tissue temperatures by Pennes model is acceptable when the perfusion rate is high, otherwise not. The prediction of tissue temperatures by the model of Weinbaum/Jiji is unacceptable.
Heat transfer coefficients are parameters in a complete model which computes the arterial and venous temperatures and the tissue temperatures. They are quantified by the vascular model. They are equivalent to the Baish values which *can* be calculated from the vascular geometry. There are discrepancies between the Baish values and our calculations which *can* be attributed to the simplifying assumptions inherent in the model of Baish. In spite of this the prediction of tissue temperatures is acceptable using the Baish values and the complete model equations of Wissler.
The prediction of tissue temperatures by the "efficiency factor model" is quite good.

CONCLUSION

Except for relative dimensions and thickness the basic organization of the tissue in our model is representative for surface tissue in general. Countercurrent heat exchange in small arteries and veins is of considerable importance only in muscle tissue near the skin surface. To account for this effect take the efficiency factor EF_5-8 in the outer part of the muscle layer and EF_1-4 in the inner part of the muscle layer. This simple method can easily be incorporated into whole body models.
We are convinced that a source/sink term similar to the form proposed by Pennes belongs to each bioheat equation.

ACKNOWLEDGEMENT: Supported by DEUTSCHE FORSCHLTNGSGEMEINSCHAFT

REFERENCES

1. Pennes H.H. **1948,** Analysis of tissue and arterial blood temperatures in resting forearm, J.Appl.Physiol.,1, 93-122
2. Jiji L.M.,Weinbaum S.,Lemons D.E. **1984,** Theory and experiment for the effect of vascular microstructure on surface tissue heat transfer-part II: Model formulation and solution, ASME J.Biomech.Eng.,106, 331-341
3. Baish J.W.,Ayyaswamy P.S.,Forster K.R. **1986,** Small-scale temperature fluctuations in perfused tissue during local hyperthermia, ASME J.Biomech.Eng.,108, 246-250
4. Charny C.K.,Weinbaum S.,Levin R.L. **1990,** An evaluation of the Weinbaum-Jiji bioheat equation for normal and hyperthermic conditions, ASME J.Biomech.Eng.,112, 80-87
5. Wissler E.H. **1987,** Comments on the new bioheat equation proposed by Weinbaum and Jiji, ASME J.Biomech.Eng.,109, 226-233
6. Song W.J.,Weinbaum S.,Jiji L.M.,Lemons D. **1988,** A combined macro and microvascular model for whole limb heat transfer, ASME J.Biomech.Eng.,110, 259-268