INTRACORPORAL HEAT LOAD
EVOKED BY ELECTROMAGNETIC FIELDS

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INTRODUCTION

For a realistic assessment of tlie thermal effects of electromagnetic fields applied
accidentally or intentionally in the course of diagnostic or therapeutic procedures it
is necessary to take into account tlie external conditions influencing heat loss, tlie
nonliomogeneities of tlie body, and the regulatory processes such as sweat
production and blood flow distribution and redistribution, which have an essential
impact on the temperature gradient between core and shell of the body and the
environment and thereby on the formation of intracorporal temperature fields. An
intricate problem is tlie determination of heat transfer between tlie blood vessels
and the tissue.

Former approaches avoided the explicit representation of the three-dimensional
vascular architecture and tried to compute tlie heat transfer between tissue and
blood using substitutional processes, so called "non-vascular models", either in tlie
form of distributed heat sources and sinks ("bio-heat" approach, Pennes, [1]) or by
using an enhanced thermal conductivity index (K_{eff}-approach, Weinbaum & Jiji,
[2]). A one-dimensional model which comprised the local temperature in tlie
arteries, in tlie veins and in the tissue in tlie direction of blood flow using three
separate heat balance equations **was** proposed by Wissler [3]. The necessary heat
transfer coefficients were computed by Baish et al. [4] in tlie case of closely coupled
countercurrent vessels. Both approaches taken together represent tlie first approach
based on three separate energy balances for the local temperatures of tissue, arteries
and veins. Cliarny and Levin [5] presented a similar and complete one-dimensional
"three equation model", wlucli later on was also used to evaluate the K_{eff}-approach.

METHODS

We developed a three-dimensional model of tlie thermal processes in a liuman
extremity, especially within tlie muscle tissue, wliich quantifies the convective heat
transport on the basis of a detailed simulation of a complete countercurrent vascular
network using tlie relevant physical laws ("vascular" model, Brinck & Werner, [6]).
The model computes the three-dimensional temperature profiles within tlie tissue
and tlie arterial and venous temperatures of thermally significant vessels along tlie

branching countercurrent vessel network evoked by internal or external heat sources. The vascular geometry varies with the distance from the skin surface. The idealized cross-section of an extremity has a four-layer tissue structure (core-muscle-fat-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 form 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 (ADI-method) with a highly irregular grid. The grid width is small in the vicinity of the vessel (minimum 7 μm), while at the maximal distance it is about 2 mm. Because of stability problems the computational time step has to be small ($A t = 0.1$ s). The time consumption for a steady-state computation is about 30 CPU-h on a CYBER 205 vector computer. Unfortunately, such an extremely complex vascular model, although delivering valuable results substantially more reliable than those of former non-vascular models, can hardly be used routinely, e.g. as a module for thermoregulatory whole body problems (Werner & Buse, [7]; Werner & Webb, [8]). On the other hand, the results of the vascular model confirm the assumption that non-vascular approaches, although very easy to use, may lead to wrong computations and conclusions, especially at a low perfusion rate or, worse, under inhomogeneous conditions (Brinck & Werner, [9]). Therefore we computed an efficiency function EF, dependent on perfusion and the local coordinate of blood flow, which compensates for the deficiencies of the bio- heat approach, by multiplying the bioheat perfusion term with EF.

RESULTS

For an estimation of the temperature profiles induced by an external electromagnetic heat source we used the vascular model and compared the results obtained with those computed by use of non-vascular models. A human extremity under resting conditions (air temperature $T_a = 29°C$, relative humidity RH = 40%, air velocity $v_a = 0.2$ m/s) was submitted to a heat source distributing 77275 W/m^3 homogeneously in the tissue. This means that about 75 W/kg were absorbed. The hyperthermia simulation lasted 15 minutes. We used a simple control algorithm of blood flow assuming an initial blood flow level of 5.4 10^{-4} m^3/sm^3, which is augmented by a factor of 10 if tissue temperature exceeds a threshold of 42.5°C.

The results show that it is not sufficient to analyze only mean tissue temperatures, as the temperature fields are very inhomogeneous. Figure 1 shows arterial and venous temperatures, mean tissue temperature, and the mean temperature in the space between countercurrent vessels as a function of depth of
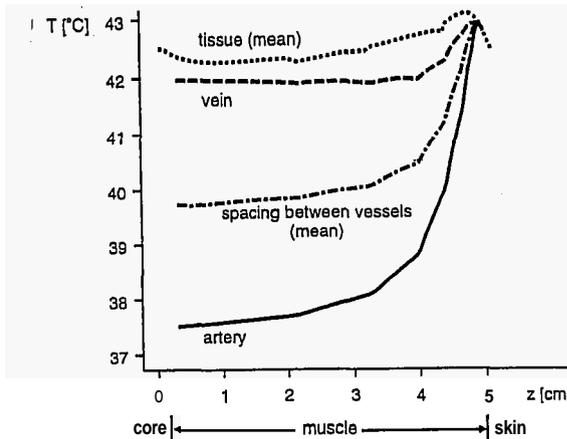
Fig. 1. Various radial temperature profiles T in tlie extremity after 15-min
         application of 75 W/kg computed by tlie vascular model (see text).

tissue at the end of tlie liypertliermia siinulation using the complex vascular model.
Eiglit generations of countercurrent blood vessels in tlie muscles are taken into
account. Blood temperatures in these eiglit muscle "layers" are distinctly lower than
mean tissue temperatures, which are between 42.2°C and 43.2°C. Tlie temperatures
between the vessels are substantially lower and in spite of tlie external heat source,
essentially influenced by blood temperatures. They are approximately equal to the
arithmetic mean of both blood temperatures and are thereby rather low over a wide
area, meaning that there is insufficient heating at least between the vessels. 'Cooler'
areas are in tlie vicinity of the artery. Temperatures < 40.7°C are found in layers
around the artery of about double vessel radius. However, it is computed that > 90%
of tlie area has a temperature > 42.2°C. Cooler areas, although comprising a very
low portion of tlie tissue, are especially obvious around the vessels of the first
generation and may be of essential importance for hyperthermia treatment. In tlie
area of the first vessel generation we compute that 9.6% of tlie tissue is cooler tlian
42.0°C. Tlie total area with a temperature ≤ 42°C is about 6%.

Tlie dependence of tissue temperatures on tlie the depth of tissue computed by
the vascular model may also be obtained approximately by tlie Baish-
Wissler/Charny-Levin or by tlie EF-approach. Tlie results of tlie K_{eff}-approach are
far beyond tlie range of such results if we apply realistic boundary conditions
between skin and environment. The profiles would become comparable to the other
computations only if arterial influx temperature were changed. Tlie bio-heat
approach exhibits an extremely flat profile around the chosen tlireshold temperature
for blood flow control (42.5°C). As it does not take into account any local
convective processes, an accurate temperature profile cannot be obtained.

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CONCLUSION

Electromagnetic fields may evoke a **high** specific absorption rate and an extremely nonhomogeneous temperature field caused by the vicinity of vessels. We conclude that both the K_{eff}- and the bio-heat approach should be considered to be unsuitable for simulating loco-regional variations of temperature profiles evoked by electromagnetic fields. On the other hand, both the Baish-Wissler/Charny-Levin- and the efficiency function (EF)-approach show minimal deviations from the results of the complex vascular model. The advantage of the efficiency factor model is that its implementation into whole body models is very easy, like that of the bio-heat approach. However, any analysis of the exact three-dimensional local temperature distribution after loco-regional application of electromagnetic fields necessitates to take explicitly into account the vascular pattern, as in our vascular model.

REFERENCES

1. Pennes, H. H. 1948, Analysis of tissue and arterial blood temperatures in resting forearm. Journal of Applied Physiology, 1, 93-122.
2. Weinbaum, S. and Jiji, L. M. 1985, A new simplified bioheat equation for the effect of blood flow on local average tissue temperature. ASME Journal of Biomechanical Engineering, 107, 131-139.
3. Wissler, E. H. 1987, Comments on the new bioheat equation proposed by Weinbaum and Jiji. ASME Journal of Biomechanical Engineering, 109, 226-233.
4. Baish, J. W., Ayyaswamy, P. S. and Forster, K. R. 1986, Small-scale temperature fluctuations in perfused tissue during local hyperthermia. ASME Journal of Biomechanical Engineering, 108, 246-250.
5. Charny, C. K. and Levin, R. L. 1989, Bioheat transfer in a branching countercurrent network during hyperthermia. ASME Journal of Biomechanical Engineering, 111, 263-270.
6. Brinck, H. and Werner, J. 1994a, Estimation of the thermal effect of blood flow in a branching countercurrent network using a three-dimensional vascular model. ASME Journal of Biomechanical Engineering, 116, 324-330.
7. Werner, J. and Buse, M. 1988, Temperature profiles with respect to inhomogeneity and geometry of the human body. Journal of Applied Physiology, 65, 1110-1118.
8. Werner, J. and Webb, P. 1993, A six-cylinder model of human thermoregulation for general use on personal computers. Annals of Physiological Anthropology, 12, 123-134.
9. Brinck, H. and Werner, J. 1994b, The efficiency function - an improvement of the classical bioheat approach. Journal of Applied Physiology, 77, 617-1622.