

INTRACORPORAL HEAT LOAD EVOKED BY ELECTROMAGNETIC FIELDS

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INTRODUCTION

For a realistic assessment of the thermal effects of electromagnetic fields applied accidentally or intentionally in the course of diagnostic or therapeutic procedures it is necessary to take into account the external conditions influencing heat loss, the nonhomogeneities of the 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 the determination of heat transfer between the blood vessels and the tissue.

Former approaches avoided the explicit representation of the three-dimensional vascular architecture and tried to compute the heat transfer between tissue and blood using substitutional processes, so called "non-vascular models", either in the 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 the arteries, in the veins and in the tissue in the 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 the case of closely coupled countercurrent vessels. Both approaches taken together represent the first approach based on three separate energy balances for the local temperatures of tissue, arteries and veins. Charny and Levin [5] presented a similar and complete one-dimensional "three equation model", which later on was also used to evaluate the K_{eff} -approach.

METHODS

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

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 ($\Delta t = 0.1$ 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 $T_a = 29^\circ\text{C}$, 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 $5.4 \cdot 10^{-4} \text{ m}^3/\text{sm}^3$, 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

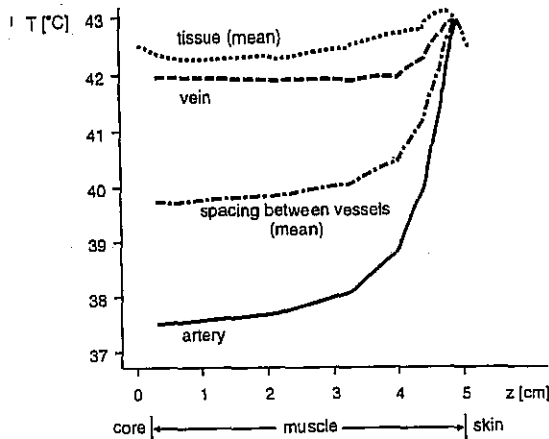


Fig. 1. Various radial temperature profiles T in the extremity after 15-min application of 75 W/kg computed by the vascular model (see text).

tissue at the end of the hyperthermia simulation using the complex vascular model. Eight generations of countercurrent blood vessels in the muscles are taken into account. Blood temperatures in these eight muscle "layers" are distinctly lower than mean tissue temperatures, which are between 42.2°C and 43.2°C. The temperatures between the vessels are substantially lower and in spite of the 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 the 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 the area has a temperature > 42.2°C. Cooler areas, although comprising a very low portion of the tissue, are especially obvious around the vessels of the first generation and may be of essential importance for hyperthermia treatment. In the area of the first vessel generation we compute that 9.6% of the tissue is cooler than 42.0°C. The total area with a temperature \leq 42°C is about 6%.

The dependence of tissue temperatures on the the depth of tissue computed by the vascular model may also be obtained approximately by the Baish-Wissler/Charny-Levin or by the EF-approach. The results of the K_{eff} -approach are far beyond the 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. The bio-heat approach exhibits an extremely flat profile around the chosen threshold 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.

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.

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