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3D MODEL OF THERMAL INTERACTIONS BETWEEN HUMAN FOREARM AND ENVIRONMENT

***Mateusz Duda*[1], *Bohdan Mochnacki*[2]**

[1]*Department of Foundations of Technology and Quality*
University of Labour Safety Management, Katowice, Poland
[2]*Department of Mathematics and Computer Science*
University of Labour Safety Management, Katowice, Poland
mduda@wszop.edu.pl, bmochnacki@wszop.edu.pl

Abstract. Thermal processes in the domain of a human forearm are considered. The external surface of forearm is in the direct thermal contact with the environment. The steady state problem is considered. From the mathematical point of view, the task is described by the system of the Poisson-type equations, the boundary conditions given on the contact surface between tissue sub-domains, the boundary conditions determining heat transfer between blood vessels and tissue and the boundary conditions on the external surface of the system. The non-homogeneous forearm domain is reconstructed as accurately as possible (3D task). At the stage of numerical modelling, the finite element method has been used. In the final part of the paper the example of computations is presented.

Keywords: *bioheat transfer, temperature field in forearm domain, finite element method*

1. Introduction

Heat transfer processes proceeding in the domain of biological tissue can be described by the Poisson-type equation called the Pennes equation [1, 2] (in literature the other models are also discussed [3]). The characteristic feature of the Pennes equation is the introduction of internal heat sources connected with blood perfusion and metabolism. The mathematical form of perfusion heat source results from the assumption that the tissue is supplied with a large number of capillary blood vessels uniformly distributed throughout its volume. The Pennes model belongs to the group of the so-called soft tissue models [4].

In the field of bio-heat transfer the so-called vessel models are also considered [5]. They take into account the presence of large, thermally significant blood vessels and the interactions between them and the tissue. In this paper the influence of vessels is treated in a simplified manner. Heat exchange between tissue and vessels is approximated by the Robin boundary condition, while the blood temperature along the vessels (arteries and veins) is treated as the constant value.

The non-homogeneous 3D forearm domain is considered in which the sub-domains corresponding to scarfskin and skin tissue (epidermis and dermis), fat (hypodermis), muscles, bones and blood vessels are selected.

2. Governing equations

Below, the mathematical model of the task discussed is presented in the version concerning the transient bio-heat transfer process (the authors have a proven and effective program for this type of problems). The solution of the steady state problem corresponds to the border results of calculations when the temperature field is stabilized ($\partial T_e(x, y, z, t) / \partial t = 0$). It should be pointed out that the initial temperature distribution can be assumed in an optional way.

The transient temperature field in the domain considered is determined by the following system of equations:

$$c_e(T)\frac{\partial T_e(x,y,z,t)}{\partial t} = \nabla \cdot \left[\lambda_e(T)\nabla T_e(x,y,z,t)\right] + Q_{per\,e}(T) + Q_{met\,e}(T) \tag{1}$$

where $e = 1,\ldots,4$ identifies the tissue sub-domains: skin, fat, muscle and bone respectively, c_e is the volumetric specific heat, λ_e is the thermal conductivity, Q_{per} and Q_{met} are the capacities of volumetric internal heat sources connected with the blood perfusion and metabolism, and also T, x, y, z, t denote temperature, spatial co-ordinates and time, respectively. The perfusion heat source is given by the formula:

$$Q_{per\,e}(T) = c_b G_{be}(T)\left[T_b - T_e(x,y,z,t)\right] \tag{2}$$

where G_{be} is the blood perfusion [m^3 blood/(s m^3 tissue)], c_b is the blood volumetric specific heat and T_b is the arterial blood temperature. Metabolic heat source Q_{met} can be treated both as the constant value or the temperature-dependent function.

On the contact surface between the tissue sub-domains, the continuity of temperature and heat fluxes are assumed:

$$(x,y,z) \in \Gamma_{e,e+1}: \begin{cases} -\lambda_e \dfrac{\partial T_e(x,y,z,t)}{\partial n} = -\lambda_{e+1}\dfrac{\partial T_{e+1}(x,y,z,t)}{\partial n}, & e = 1,2,3 \\ T_e(x,y,z,t) = T_{e+1}(x,y,z,t) \end{cases} \tag{3}$$

where $\partial / \partial n$ is a temperature derivative in normal direction.

On the external surface of the skin, the Robin boundary condition is taken into account:

$$(x,y,z) \in \Gamma_0: \quad -\lambda_1 \frac{\partial T_1(x,y,z,t)}{\partial n} = \alpha_{out}\left[T_1(x,y,z,t) - T_a\right] \tag{4}$$

where α_{out} is the heat transfer coefficient, T_a is the ambient temperature. The same type of boundary conditions is given on the surfaces between the blood vessels and soft tissue sub-domains (in the place of α_{out} the heat transfer coefficient between vessels and tissue should be introduced, while the arterial or vein blood temperatures play a role of ambient temperature).

The initial condition is also given:

$$t = 0: \quad T_e\left(x, y, z, t\right) = T_{0e}\left(x, y, z\right), \qquad e = 1, ..., 4 \tag{5}$$

As it was previously mentioned, the initial condition can be assumed optionally, for example T_{0e} = 35°C.

3. Process of model creation

The base geometry of a forearm was created using the CAD approach as the way of modelling. The shape and position of successive sub-domains were obtained based on literature [6, 7] as well as the virtual internet atlas of human body [8]. The sub-models corresponded with the anatomical structures as well as the geometrical dimensions of the whole model of a human forearm are presented in Figure 1 and Figure 2, respectively. The human epidermis and dermis were collected into one sub-region which was created in the next step of the FEM program.

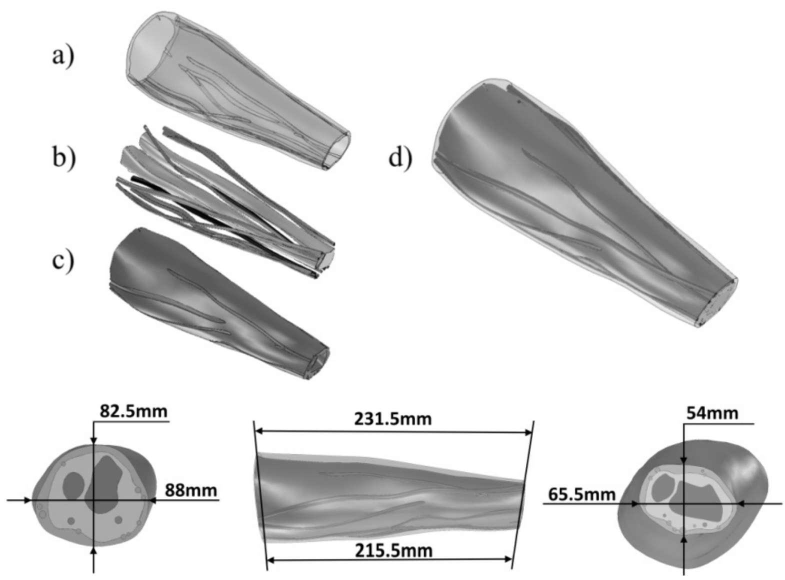

Fig. 1. The CAD model of a human forearm without epidermis and dermis tissues as well as the dimension of the model. Legend: a) hypodermis, b) bones with the veins and artery system, c) muscle sub-region, d) collected model of a human forearm

The solid model of a human forearm had been divided using 4-nodal finite elements in the number of 1,620,000 (592.000 number of nodes). This process was realized using the MSC.Patran. The resultant FEM model is presented in Figure 2. The physical parameters assigned to each sub-domain are collected in Table 1.

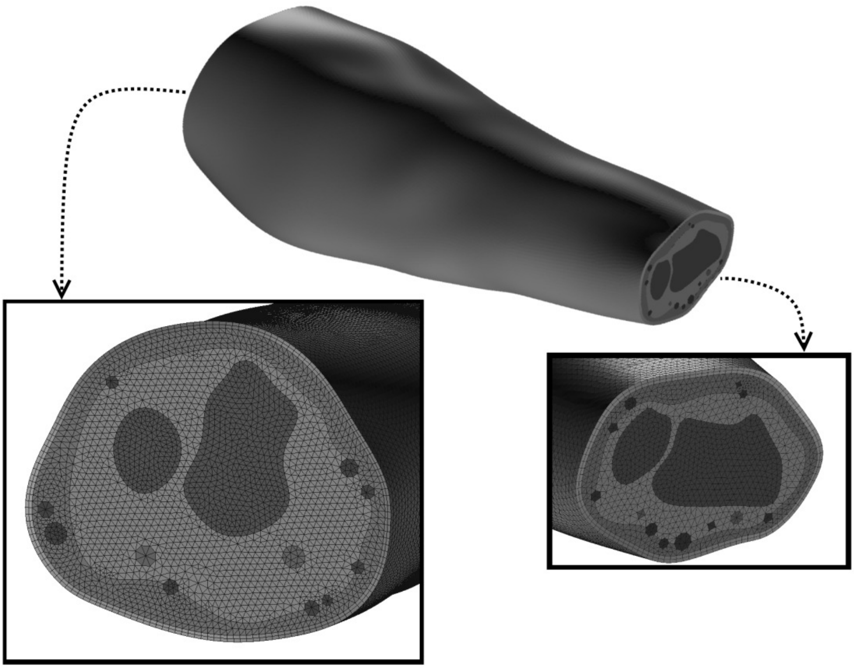

Fig. 2. The FEM model of human forearm

Table 1

The physical parameters and material density of particular anatomical structure

The anatomical structure	Conductivity λ [W/m·K]	Heat capacity C [J/kg·K]	Mass density ρ [kg/m^3]
Epidermis and dermis	0.47	3680	1085
Hypodermis	0.16	2300	850
Muscles	0.42	3768	1085
Veins and arteries	0.49	3650	1069
Bones	0.75	1700	1357

4. Results of computations

The computations were performed using MSC.Marc. The total time of computation was 5063 s, while the time of analysis t = 3600 s. After this time the temperature field in the considered domain was stabilized. The ambient temperature equals 20°C (T_a = 20°C), when the heat transfer coefficient α_{out} = 3.7 W/m^2·K.

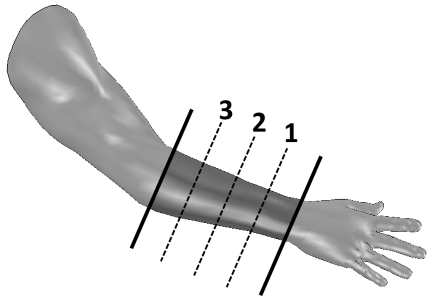

Fig. 3. Cross-sections of forearm

The examples of the results of computations are presented in Figures 4, 5 and 6. The successive sub-domains are marked with various shades of gray. The temperature distributions are presented in the form of isotherms. Presented below results of computations correspond to the cross-sections marked in Figure 3.

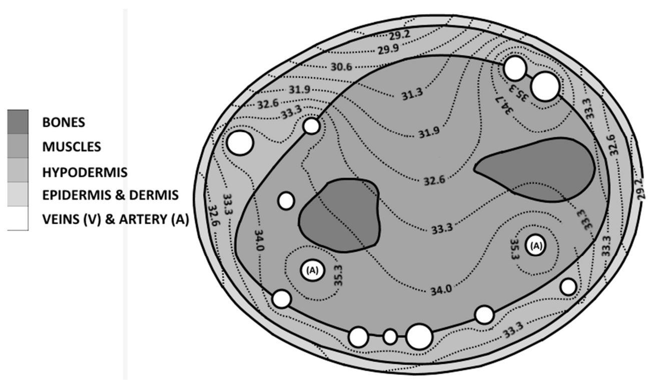

Fig. 4. Temperature field (section 1)

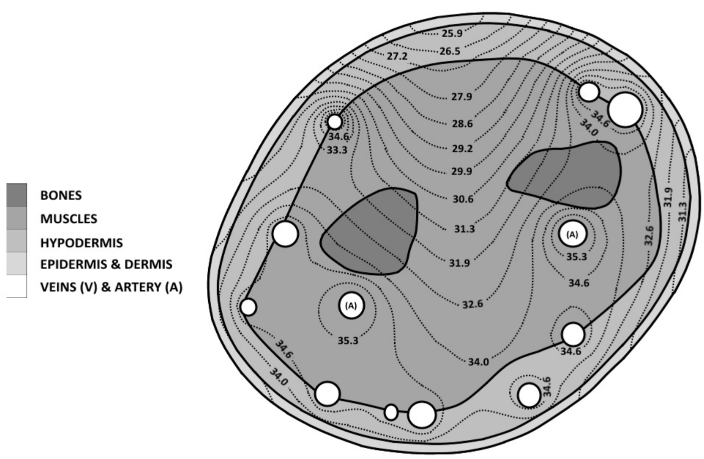

Fig. 5. Temperature field (section 2)

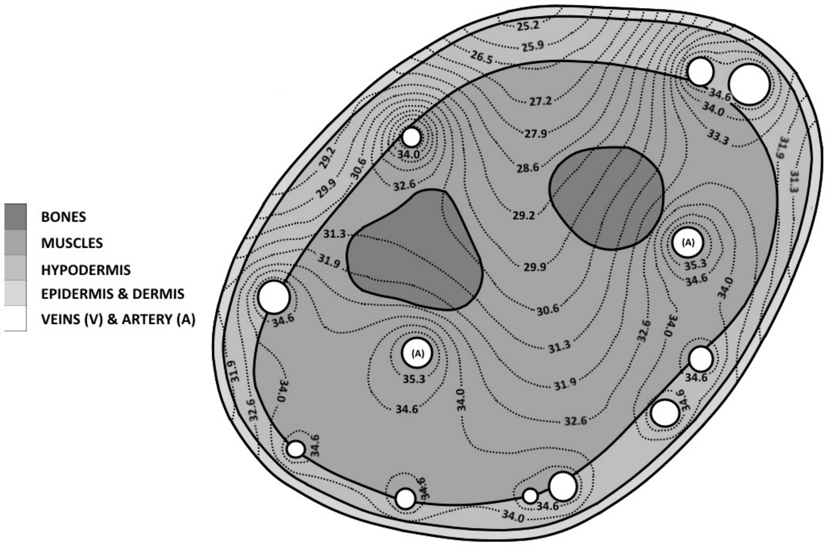

Fig. 6. Temperature field (section 3)

5. Conclusions

As seen from the results presented in Figures 4, 5 and 6, the body temperatures are not too different and reach the lowest values close to the external boundary (which is obvious). One can see the thermal effect of large blood vessels. The temperature in the vicinity of these vessels is significantly higher.

Taking into account the possibilities of computer program application, the numerical solution corresponds to the so-called tissue models [1, 2]. The arterial and venous blood temperatures have been assumed a priori as the constant values (36°C and 35°C, respectively) and they were not calculated.

The results obtained using the FEM approach were compared with the thermography image of man's forearm done by Dr. Eng. Miroslaw Dziewonski (*Silesian University of Technology, Faculty of Mechanical Engineering, Institute of Computational Mechanics and Engineering, Gliwice*) due to verification for credibility and accuracy (Fig. 7). One can see the similar areas of temperature distribution from the top view of human forearm, despite the fact that the FEM model does not apply to exactly the same object as the thermal image. The non-homogenous temperature distribution has the reason in the structure of veins system, which is much more sparse from the top than from the bottom part. The differences which appeared between the numerical solution and the thermography examination are caused by the necessary simplification of the FEM model, of course. Generally speaking, the results obtained using the FEM analysis have the satisfactory level of accuracy and reliability.

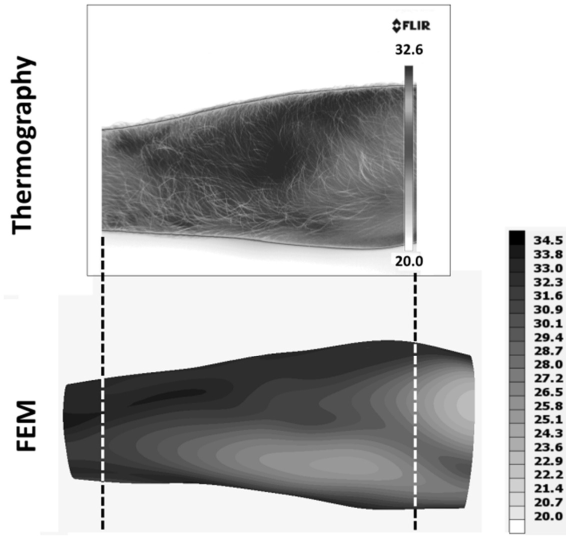

Fig. 7. Comparison of numerical solution and measurements

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