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DAMAGE AND NECROSIS OF BIOLOGICAL TISSUES UNDER THE ACTION OF LOW AND HIGH TEMPERATURES

Abstract: The experiment for determining intensity of heating and cooling the skin, fat, muscle and bone tissues was implemented in the article. The damage depth of the biological tissues from time of the action of the low and high temperatures was determined. The dependencies of the degree of damage and the fraction of the necrotic biological tissue from the value of the operating temperature were built.

Key words: the biological tissue, the temperature, the damaged tissue indicator, the fraction of the necrotic tissue.

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Introduction

The biological tissue is the single system of the cells and their derivatives that have the common development, the structure and functionality. The organism interaction with the external environment, the need to adapt to the conditions of existence led to occurrence of the several types of the biological tissues with the certain functional properties.

The skin is the body integument and consists of three layers: the epidermis (the layer thickness is minimum), the dermis (the layer thickness is maximum) and the subcutaneous fat (the layer thickness is more or less than the dermis layer or the layer absence). The skin thickness on the various body area can vary in the range from 2 to 11.5 mm. The skin anatomy is presented in the Fig. 1.

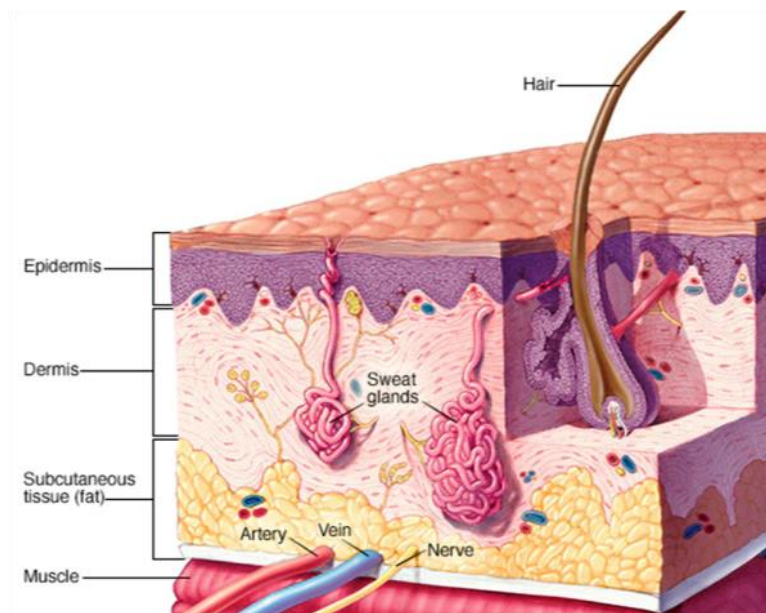


Figure 1 – The skin anatomy [1].

The muscle tissue is the elongated cells that have the ability to contract. There are the smooth and striated muscle tissues. The each muscle tissue differs in the length, the cell nuclearity, and purpose.

The bone tissue is the connective tissue. The bone tissue consists of the bone cells, the intercellular organic matrix of the bone and the main mineralized intercellular substance. This tissue in the human body is presented by the rough fibrous and lamellar types. The bone tissue performs the supporting function in the body.

The normal human body temperature is 36.6 °C. Protective mechanisms are activated when increasing or decreasing the body temperature. The biological tissues are subjected to heating or cooling, which leads to burns or frostbites of varying severity [2-8]. Burns and frostbites are classified into four degrees depending on the value and the action time of the temperature. Lesion of the upper layer of the epithelium (the tissue edema appears) is characteristic of the first degree. Lesion disappears completely after the few days. The epithelium is affected to the malpighian layer with the blisters formation filled with transparent content in the second degree. Lesion disappears completely in two weeks. Lesion of all layers of the epidermis and the dermis with the death of the surface layers of the tissues and the scars

formation is observed in the third degree of thermal burn or frostbite. The death (necrosis) [9] of all soft tissues and the partial bone damage occur in the fourth degree. The biological tissues do not regenerate.

The diagnostics of thermal injuries can be performed humanely using the computer modeling. The temperature and time ranges that do not cause burns and frostbites of the second and higher degrees can be determined by the action on the models of the biological tissues of the temperature loads of different intensity. Thus, the experimental information about the degree of damage of the number of the human biological tissues in the conditions of the action of the low and high temperatures will be obtained.

Materials and methods

The action of the low and high temperatures on the biological tissues was implemented by the computer modeling in the *Comsol Multiphysics* software [10]. Four models of the studied biological tissues (the skin, the fat, the muscle and the bone) were built in the two-dimensional view. The two-dimensional view of the biological tissue models is presented in the Fig. 2.

The thicknesses of the biological tissues models correspond to the thicknesses of the real biological tissues located in the breast area of the adult.

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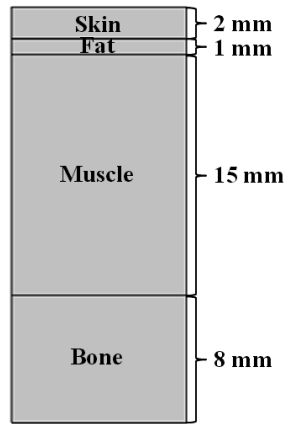


Figure 2 – The thicknesses of the two-dimensional models of the biological tissues.

The heat transfer calculation from the external source to the biological tissues models was carried out in the *Bioheat Transfer* module: the consistent stabilization – the streamline and crosswind diffusions; the shape function for the damaged tissue

indicators – the discontinuous Lagrange; the temperature discretization – quadratic. The properties of the real biological tissues were set for all models. The properties of the studied biological tissues are presented in the table 1.

Table 1. The properties of the studied biological tissues.

Properties	Materials			
	Skin	Fat	Muscle	Bone
Heat capacity at constant pressure, J/(kg·°C)	3445	2300	3360	1300
Density, kg/m ³	1109	911	1090	1908
Thermal conductivity, W/(m·°C)	0.45	0.2	0.5	0.3
Frequency factor, 1/s	4.575 ⁷²	4.43 ¹⁶	-	-
Activation energy, J/mol	4.71 ⁵	1.3 ⁵	-	-

The initial temperature of all biological tissues was 36.6 °C. The various low and high temperatures affected the outer surface of the skin model. The low temperatures were varied in the range of 0...-60 °C, the high temperatures were varied in the range of 40...100

°C. The step of changing the low and high temperatures in the calculation was ±10 °C. Time of the temperatures action was 60 s. The initial conditions for the calculation of heat transfer in the biological tissues are presented in the Fig. 3.



Figure 3 – The initial conditions of heat transfer.

The calculation of heat transfer in the biological tissues was performed based on the formulas (1-5)

$$d_z \rho C_p \frac{\partial T}{\partial t} + d_z \rho C_p u \cdot \nabla T + \nabla \cdot q = d_z Q + q_0 + d_z Q_{bio} \quad (1)$$

$$q = -d_z k \nabla T \quad (2)$$

$$Q_{bio} = \rho_b C_b \omega_b (T_b - T) + Q_{met} \quad (3)$$

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where d_z is the domain thickness in the out-of-plane direction; ρ is density of the biological tissues; C_p is heat capacity of the biological tissues; T is the temperature; t is time; u is the velocity field; ∇T is the temperature gradient; $\nabla \cdot q$ is the divergence of the heat flux vector; Q is the heat source; q_0 is inward heat flux, normal to the boundary; Q_{bio} is the perfusion and metabolic heat source; q is the heat flux vector; k is thermal conductivity; ρ_b is density of blood; C_b is specific heat of blood; ω_b is the blood perfusion rate; T_b is the arterial blood temperature; Q_{met} is the metabolic heat source.

$$-n \cdot q = 0 \quad (4)$$

where n is the normal vector on the boundary.

$$T = T_0 \quad (5)$$

where T_0 is the prescribed temperature on the boundary.

The each model was divided into the finite elements. The small size of the finite element will allow to get the most accurate results of the computer calculation. The statistics of dividing the models into the finite elements is presented by the following parameters: the sequence type – the physics-controlled mesh; the element size – extremely fine; the triangular elements – 10956; the edge elements – 417; the vertex elements – 10; the minimum element quality – 0.7588; the average element quality – 0.9898; the element area ratio – 0.1901; the mesh area – 286 mm². The quality of dividing the two-dimensional models of the biological tissues is presented in the Fig. 4.

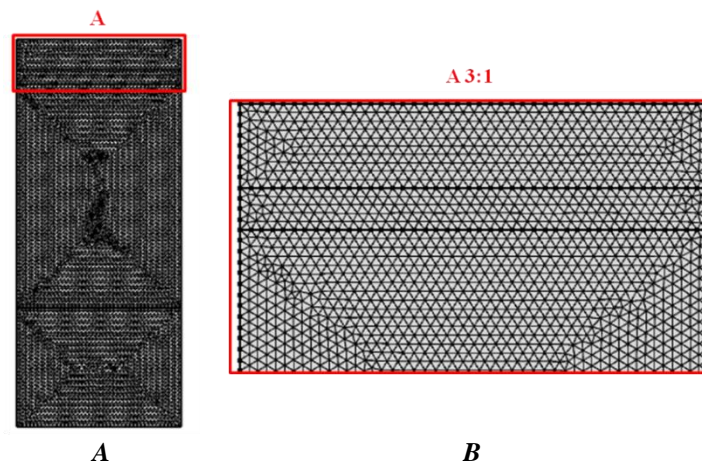


Figure 4 – The quality of dividing the models into the finite elements (A) and the detail section of the mesh (B).

The time-dependent solver configurations: **the absolute tolerance** the global method – slaced; the tolerance – 0.001; **time stepping** the method – BDF; the maximum BDF order – 2; the minimum BDF order – 1; the consistent initialization – the backward Euler; the error estimation – exclude algebraic; **direct** the solver – MUMPS; the factor in the error estimate – 400; **segregated** the termination technique – the tolerance; the maximum number of the iterations – 10; the tolerance factor – 1; **the method and the**

termination the nonlinear method – constant (Newton); the damping factor – 1; the Jacobian update – minimal; the termination technique – the iterations; the number of the iterations – 1.

Results and discussion

Intensity of the temperature distribution in the layers of the skin model is presented by the color surfaces in the Fig. 5.

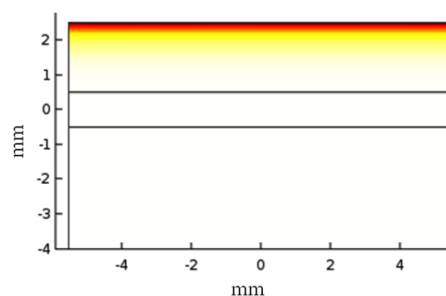


Figure 5 – The temperature contours on the skin model.

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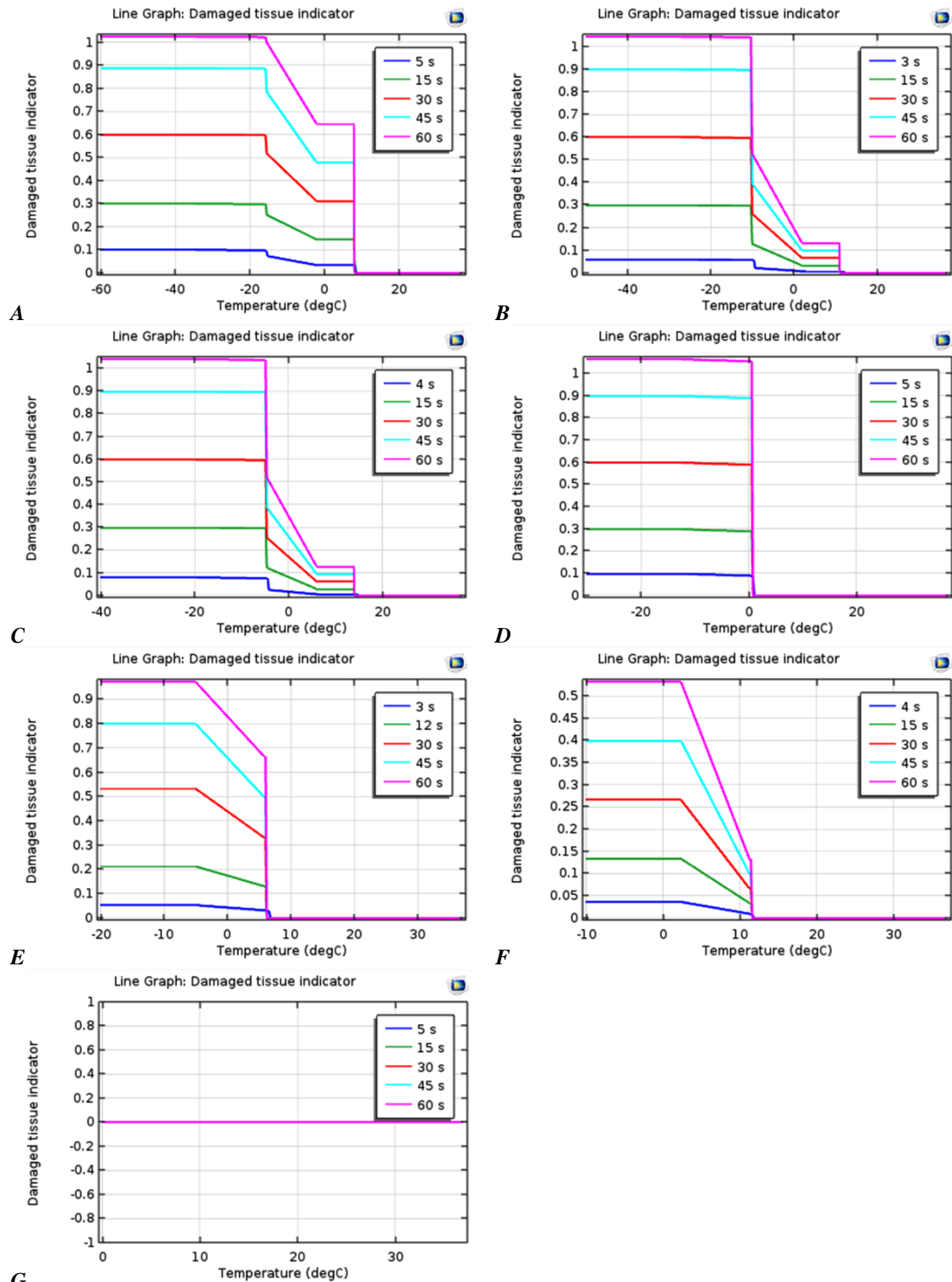


Figure 6 – The dependencies of the damaged tissue indicator from the long-term action of the low temperatures on the skin: A – at -60 °C; B – at -50 °C; C – at -40 °C; D – at -30 °C; E – at -20 °C; F – at -10 °C; G – at 0 °C.

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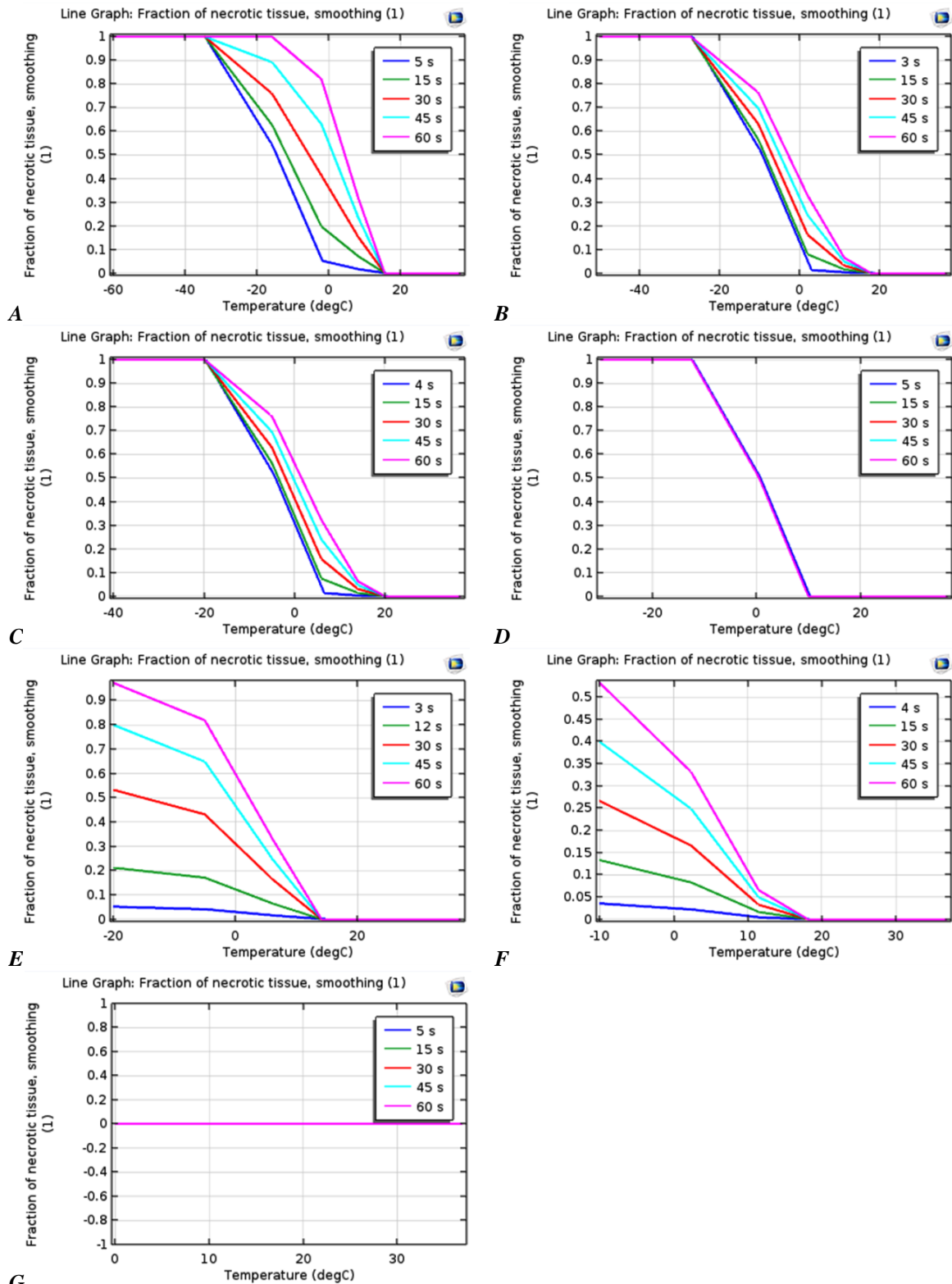


Figure 7 – The dependencies of the fraction of the necrotic tissue from the long-term action of the low temperatures on the skin: A – at -60 °C; B – at -50 °C; C – at -40 °C; D – at -30 °C; E – at -20 °C; F – at -10 °C; G – at 0 °C.

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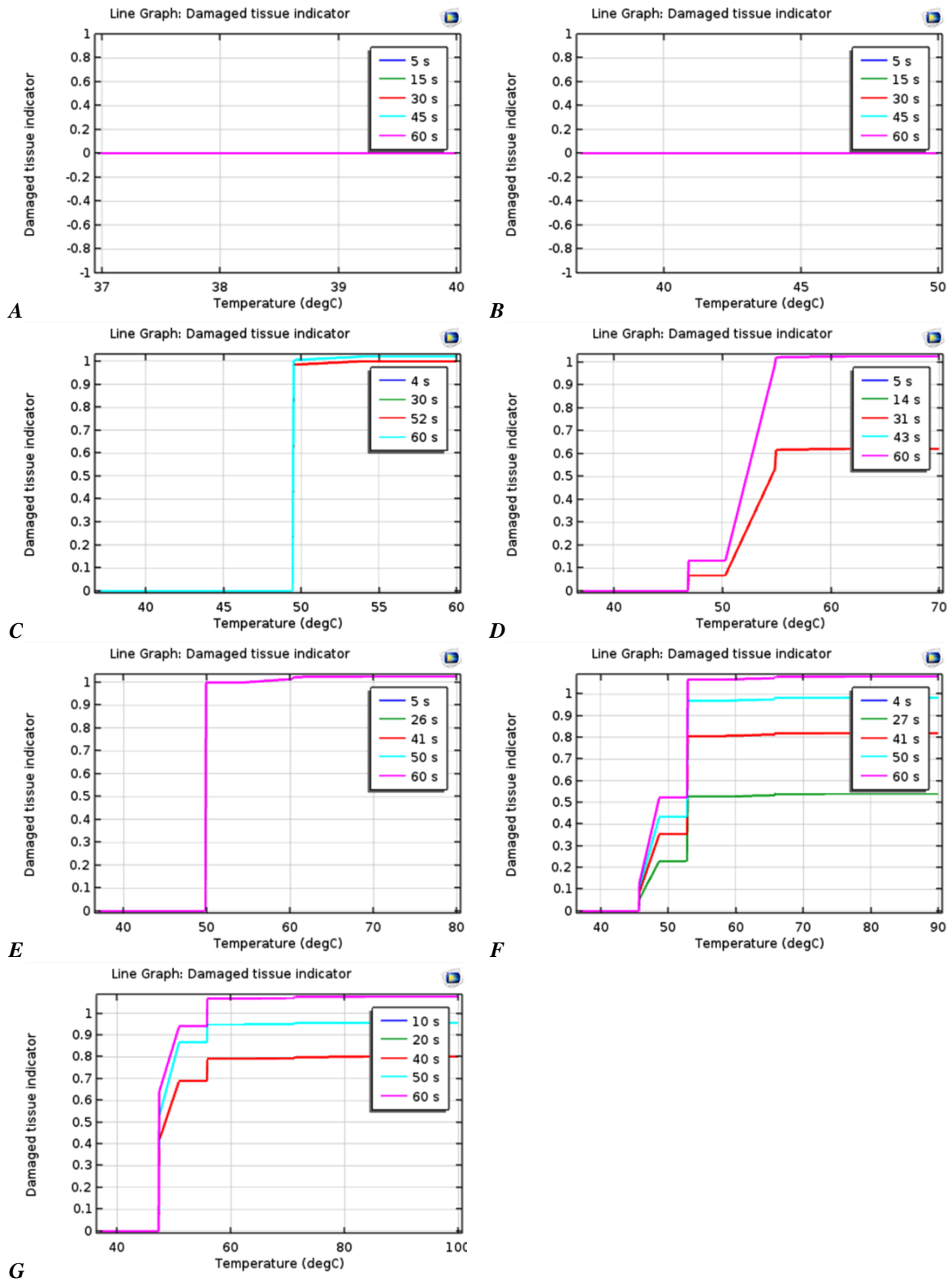


Figure 8 – The dependencies of the damaged tissue indicator from the long-term action of the high temperatures on the skin: A – at 40 °C; B – at 50 °C; C – at 60 °C; D – at 70 °C; E – at 80 °C; F – at 90 °C; G – at 100 °C.

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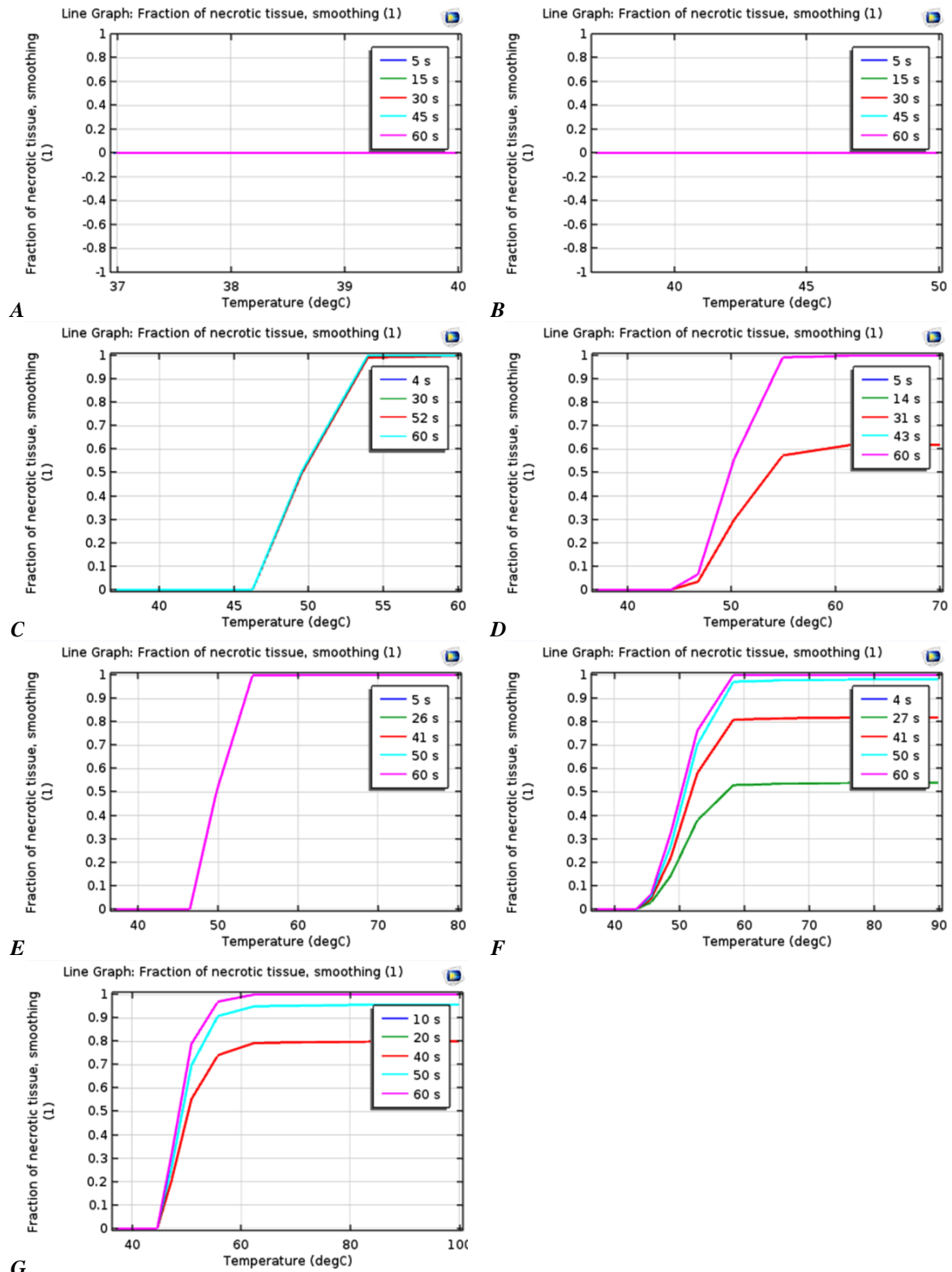


Figure 9 – The dependencies of the fraction of the necrotic tissue from the long-term action of the high temperatures on the skin: A – at 40 °C; B – at 50 °C; C – at 60 °C; D – at 70 °C; E – at 80 °C; F – at 90 °C; G – at 100 °C.

The surface of the white color is the tissue temperature of 36.6 °C, the surface of the dark red color is the maximum temperature of the tissue.

Intensity of the color contours on the skin model is the same at the action of the low and high temperatures.

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The low and high temperatures of the skin are observed in all layers. The maximum temperature is determined in the surface layers of the skin, where contact occurs directly. The depth of intensive heating or cooling the surface layers of the skin is 0.5 mm. Heating or cooling by 15-20% of the initial temperature occur in the lower layers of the skin (bordering the subcutaneous fat). Increasing or decreasing the temperature are not observed in the middle layers of the skin. The other biological tissues are not subjected to heating or cooling. The second degree of severity is determined in accordance with the classification of burns and frostbites.

The dependencies of the damaged tissue indicator and the fraction of the necrotic tissue from the long-term action of the low and high temperatures are presented in the Figs. 6-9.

The range from zero to one is the values of the minimum and maximum degree of damage and the fraction of the necrotic tissue at the action of the low and high temperatures. Damage of the biological tissues does not occur in the temperatures range from 0 to 50 °C. The short-term action (up to 5 s) of the low temperatures of the various values leads to the skin damage up to 10%. Damage of the skin occurs at the temperature of 17 °C. Significant damage of the tissue is already observed at the temperature action of -20 °C for 60 s. The skin is damaged by 30, 60 and 90% at 15, 30 and 45 s of the temperatures action in the range from -30 to -60 °C, respectively. The values of the fraction of the necrotic tissue correspond to the values of the degree of damage at the action of the low temperatures. Necrosis develops at the temperature of the biological tissue, which is 8-9 °C higher than the temperature at which damage occurs.

The damaged tissue indicator and the fraction of the necrotic tissue at the action of the high temperatures were obtained in the range of 30-60 s. Damage occurs at the biological tissue temperature of 46 °C or higher. The action of the temperature of 60 °C for 60 s leads to significant damage of the surface layers of the human skin. Significant damage is calculated at the skin temperature of 50 °C (from 0 to 100%) in the conditions of the long-term action of the external temperatures of 60 and 80 °C. Partial damage of the skin to significant on the different temperature ranges occurs in other cases. The values of the fraction of the necrotic tissue correspond to the values of the degree of damage at the action of the high temperatures. Changing the fraction of necrosis (from the undamaged to dead biological tissue) occurs when increasing the temperature of the tissue by at least 7°C.

Conclusion

The action of the low and high temperatures for 60 s is accompanied by the skin damage to the entire depth to the subcutaneous fat. The surface layers of the skin are not damaged during experimental time in the action range of the external temperatures from 0 to 50 °C. The values of the damaged tissue indicator and the fraction of the necrotic biological tissue at the corresponding operating external temperatures are the same. However, changes of the damaged tissue indicator and the fraction of the necrotic tissue occur for the various functions (especially in the phase of active lesion). The temperatures action below -20 °C and above 60 °C for 60 s leads to significant damage and necrosis of the human skin layers.

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