

MODEL OF LOW TEMPERATURE DISTRIBUTION

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ABSTRACT

This paper deals with heat distribution in human tissues. The Bioheat equation is used for modelling of heat transfer in tissues. Software application Cryomodel is described in this paper. The Cryomodel is realized in Matlab software for simulation of cryosurgery operation. Simulation is realized in 3D space of tissue. The Cryomodel contains many adjustable parameters like: Temperature and diameter of cryoprobe and properties of tissue. The Cryomodel considers four layers of tissue. Layers of epidermis, dermis, subcutaneous fat and muscle for example. This software application should be a good planning tool for doctors in practise.

1. INTRODUCTION

1.1. BASIC ANATOMY OF USED TISSUES AND PHYSICAL PROPERTIES OF HUMAN TISSUES

It is necessary to know structure of used tissues for simulation of heat distribution in tissues during the cryosurgery. Skin model is used in this case. Each layer of skin is shown on figure Figure 1 and described below.

Top layer is called Epidermis. The epidermis is the outer layer of skin. The thickness of the epidermis varies in different types of skin. It is the thinnest on the eyelids at 0.05 mm and the thickest on the palms and soles at 1.5 mm. [8]

Middle layer is called Dermis. The dermis also varies in thickness depending on the location of the skin. It is 0.3 mm on the eyelid and 3.0 mm on the back. [8]

The subcutaneous tissue is a layer of fat and connective tissue that houses larger blood vessels and nerves. This layer is important for regulation of temperature of the skin itself and the body. The size of this layer varies throughout the body and from person to person. [8]

All types of tissues can be described with thermo physical properties. Thermo physical properties of human tissues are included in table Tabulka 1. These properties of human tissues are very individual and depend on temperature and hydration. Some papers deals with phase transition temperature range in tissues. It means that $-8\text{ }^{\circ}\text{C}$ to $-1\text{ }^{\circ}\text{C}$ is the boundary of completely frozen region. Y. Rabin shows that physical properties of soft tissues are dependent on temperature boundaries for example. It is shown on the first two lines of table Tabulka 1. It is hard to acquire Temperature dependent properties of tissues. [1], [5]

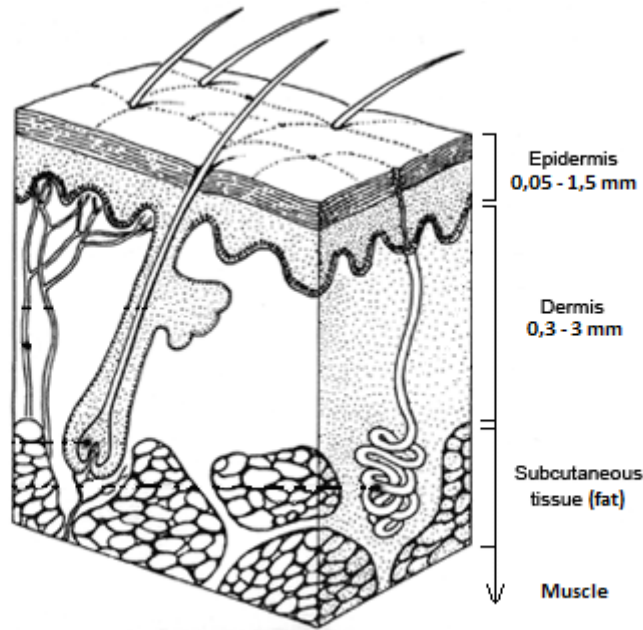


Figure 1: Anatomy of skin tissues. [7]

Tissues	ρ [kg/m ³]	C [J/(kg.°C)]	k [W/(m.°C)]	w_b [l/(s.kg)]	q_{met} [W/kg]	reference
soft tissues T > -1°C	1040	3600	0.50	0.01075	32.50	[1], [6]
soft tissues T < -1°C	1040	1800	2.00	0.01075	32.50	[1], [6]
grey matter	1040	3684	0.57	0.01014	9.70	[6]
white matter	1040	3611	0.50	0.00438	9.70	[6]
fat	920	2493	0.24	0.00042	0.15	[6]
muscle	1045	3580	0.50	0.00044	0.67	[6]
epidermis	1200	3600	0.26	0.00000	0.00	[6]
dermis	1200	3600	0.52	0.00141	0.17	[6]
subkut. Fat	1000	3060	0.21	0.00104	0.01	[6]
blood	1060	3780	0.51	0.16667	0.00	[6]

Tabulka 1: Thermo physical properties of human tissues.

1.2. MATH

The Bioheat equation was formulated by Henry Pennes in 1948. This fundamental equation is used without serious changes till now. The Bioheat equation is extended equation of heat transfer. All types of heat transfer equations are partial differential equation (PDE) of parabolic type. The Bioheat equation is shown below:

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \rho_b w_b C_b (T_b - T) + \rho \dot{q}_{met} \quad (1)$$

where ρ is density of tissue [kg/m³], C is specific heat capacity [J/(kg.°C)], T is temperature [°C], t is time [s], k is thermal conduction [W/(m.°C)], b is blood, w_b is blood perfusion [l/(s.kg)] and q_{met} is metabolic heat generation rate [W/kg].

It is necessary to rewrite the Bioheat equation into following expression. This equation is expressed by explicit method using a forward difference at time p and a second-order central difference .

$$T_{i,j,k}^{p+1} = \frac{\Delta t}{\rho C_{i,j,k} + \rho_b w_b C_b \Delta t} \cdot \frac{k}{(\Delta x)^2} \left(T_{i+1,j,k}^p + T_{i-1,j,k}^p + T_{i,j+1,k}^p + T_{i,j-1,k}^p + T_{i,j,k+1}^p + T_{i,j,k-1}^p - 6T_{i,j,k}^p \right) + \frac{\Delta t(\rho_b w_b C_b T_b + \rho q_{met}) + T_{i,j,k}^p \rho C_{i,j,k}}{\rho C_{i,j,k} + \rho_b w_b C_b \Delta t} \quad (2)$$

where p is time level, i, j and k are calculated grid points, Δt is time [s], Δx is edge of voxel [m]. [1], [3], [4]

2. SOFTWARE APPLICATION CRYOMODEL

2.1. ALGORITHM

The Cryomodel application solves Bioheat equation for whole 3D matrixes of temperature distribution simultaneously. 3D matrixes of temperature distribution are expressed as sum of shifted matrixes. This procedure is faster than progressive solution voxel by voxel. Whole process is repeated for n iteration. Main part of source code is shown below. It is shifting of T matrixes.

```
Txp = padarray(T(1:Xdim-1, :, :), [1 0 0], 'replicate', 'pre');
Txz = padarray(T(2:Xdim, :, :), [1 0 0], 'replicate', 'post');
Typ = padarray(T(:, 1:Ydim-1, :), [0 1 0], 'replicate', 'pre');
Tyz = padarray(T(:, 2:Ydim, :), [0 1 0], 'replicate', 'post');
Tzp = padarray(T(:, :, 1:Zdim-1), [0 0 1], 'replicate', 'pre');
Tzz = padarray(T(:, :, 2:Zdim), [0 0 1], 'replicate', 'post');

T = konst1.*(Txp + Txz + Typ + Tyz + Tzp + Tzz - 6*T) + konst2;
```

2.2. RUNNING APPLICATION

The Cryomodel application is able to solve a distribution of low temperatures in different human tissues. The temperature distribution is realized only for 3D space. Minimal dimension of edge of 3D space is limited by diameter of cryoprobe. This application counts with frozen and unfrozen regions also. It means that properties of tissues are depended on state (frozen/ unfrozen). This threshold is between -1°C and -8°C. The lower boundary is used in this study. Practical consequences of used frozen/ unfrozen condition are following: Frozen regions have higher thermal conduction and lower specific heat capacity than unfrozen regions therefore cooling rate and depth of penetration of low temperature are better for frozen state regions. This finding is fundamental. The Cryomodel considers four layers of tissue. Setup of layer 4 is used for whole 3D matrix if the popup menu "Layer" is set on "4". It is possible to set up many parameters of simulation. The main parameters are: Temperature and diameter of cryoprobe, dimensions of 3D matrix and layers, properties of simulation (time step, edge of voxel, threshold and time of during the simulation) and tissues. [1], [2]

Results can be saved and loaded. Check box "Set threshold" enables to see the region of killed cells (temperature below -13°C [2]) only. User can select slice position (x means, that x = position of slider and y, z are from 1 to x dimension, z dimension). Button "Show C.R." shows cooling rates in defined depths 1, 2, ..., 9 mm. Condition of cooling rate about $200^{\circ}\text{C}/\text{min}$ is necessary for good freezing process during the cryosurgery. The Cryomodel application is shown below on Figure 2 and cooling rates are shown on Figure 3. [1], [2]

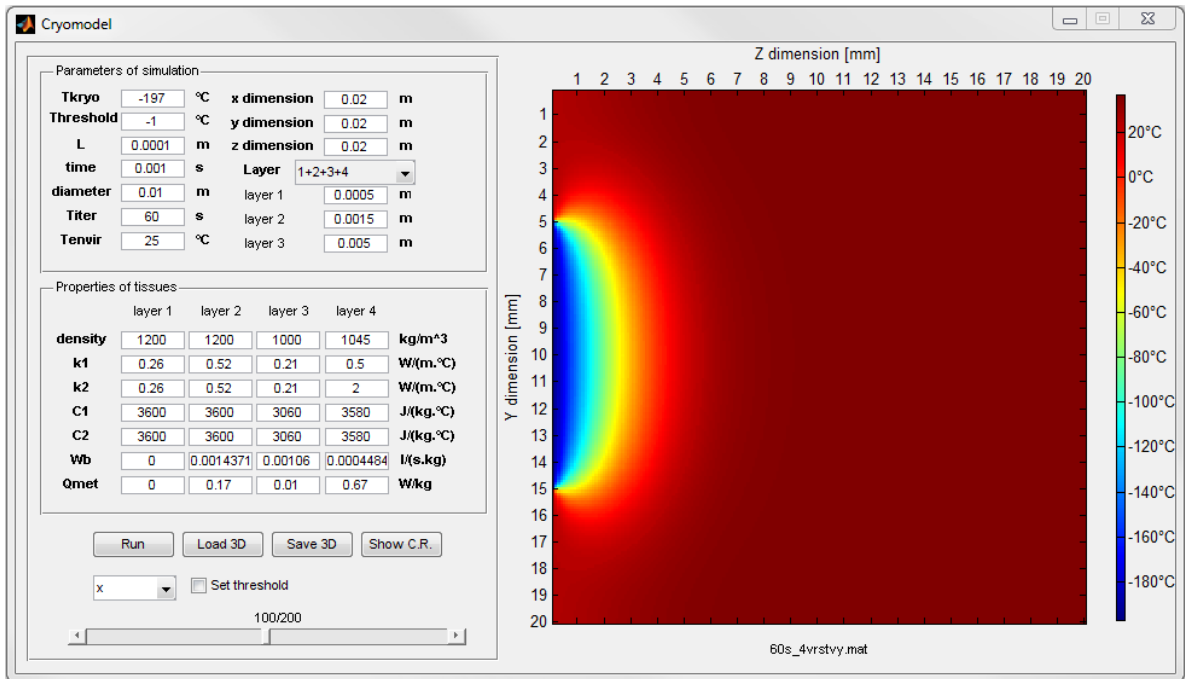


Figure 2: The interface of software application Cryomodel.

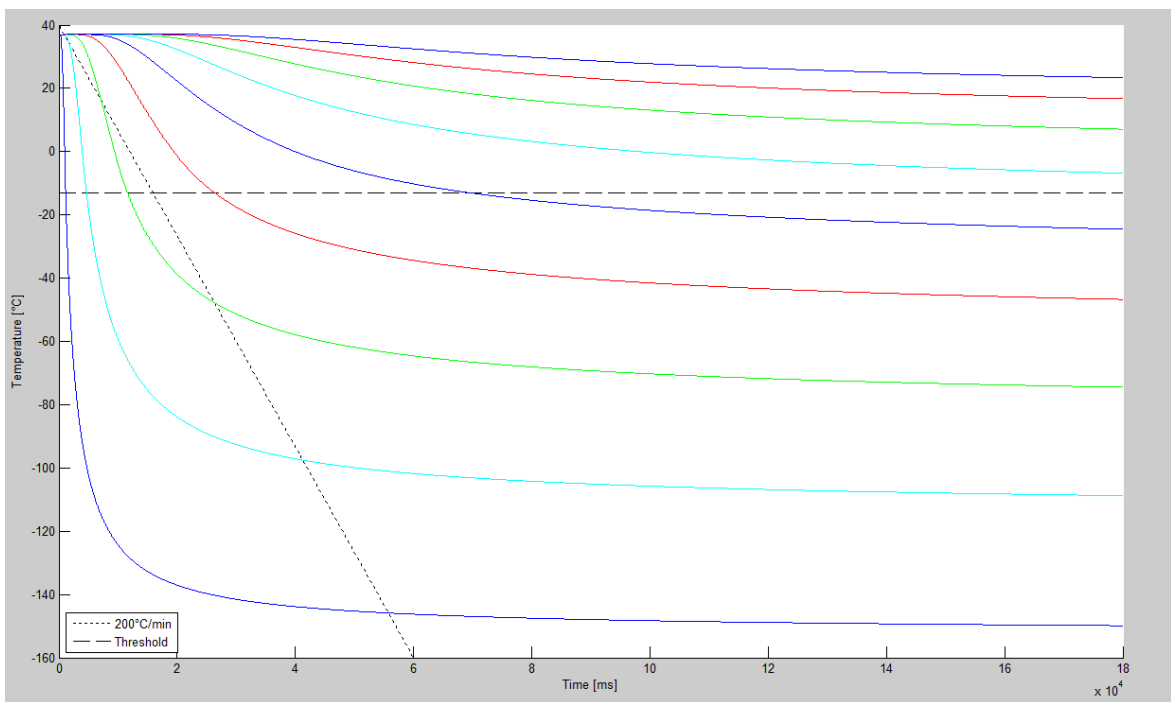


Figure 3: Cooling rates in depths.

3. CONSLUSION

This model study is based on finite differnce method and numerical solution of Bioheat equaion by Mr. Pennes (1948). The Cryomodel application has been tested for all properties of human tissue presented in table Tabulka 1. Cooling rates in defined depths are correct by [2] therefore we can suppose that results are corect. Results will be confronted with physical model in another part of this study. This model study will be extended about fully implicit numerical methods. [4]

REFERENCES

- [1] RABIN, Y., SHITZER, A. Numerical solution of the multidimensional freezing problem during cryosurgery. *Journal of biomechanical engineering* [online]. 1998, vol. 120 [cit. 2009-06-29], s. 32-37
- [2] ROZMAN, Jiří, et al. *Elektronické přístroje v lékařství*. 2006. vyd. Praha:Academia, 2006. 408 s. ISBN 80-200-1308-3
- [3] Finite difference method [online]. 2009, 22.06.2009 [cit. 2009-06-29]. Dostupný z WWW: <http://en.wikipedia.org/wiki/Finite_Difference_Method>.
- [4] POLANKA, M. *Technical Experiment Based Inverse Tasks in Mechanics* [s.l.], 2006. 141 s. Vedoucí dizertační práce Doc. Ing. Miroslav Raudenský, CSc.
- [5] AKAY, Metin. *Biomedical engineering: Volume 1 and 5*. Hoboken: John Wiley and Sons, 2006. ISBN-13: 978-0-471-24967-2
- [6] SCHMID, Gernot, et al. *Bestimmung der Expositionsverteilung von HF Feldern im menschlichen Körper, unter Berücksichtigung kleiner Strukturen und thermophysiologisch relevanter Parameter*. 2008. Bundesamtes fur Stratenschutz 38201 Salzgit-ter, Deutschland, 129 s. ARC-IT-0174
- [7] HABIF TP. *Clinical Dermatology: A Color Guide to Diagnosis and Therapy*. 2004. London: Mosby. 4th ed. (pp. 78, 816, 923–25).
- [8] BRANNON, Hether. *About.com : Dermatology* [online]. 2007-09-04 [cit. 2010-02-23]. *Skin Anatomy*. Dostupné z WWW: <<http://dermatology.about.com/cs/skinanatomy/a/anatomy.htm>>.