COLD PENETRATION OF THE FOURTH-LAYER TISSUE MODEL IN THE WHOLE BODY CRYOTHERAPY CONDITIONS

A. Cholewka, Z. Drzazga, W. Borgieł, M. Kurpas

A. Chełkowski Institute of Physics, Department of Medical Physics, University of Silesia,Uniwersytecka 4, 40-007 Katowice, Poland

E-Mail Address: armand@post.pl

Abstract:
The *in-vitro* studies of cold penetration of the fourth-layer tissue model in the whole body cryotherapy conditions were performed. The special measurement system for study was constructed. The temperature plots as a function of time as well as depth of tissue model during cooling and returning back to the room temperature was recorded. Moreover the computing simulations were performed basing on Fourier heat equation. Comparison of the experimental with numerical results indicates quite well qualitative agreement. The cooling temperature and the thermal properties of model tissues markedly influenced the heat transport. The Fourier equation can be useful in description of the cold penetration of the studied tissue model.

Introduction

Cold treatment was known even in antiquity. Modern cryotherapy is not only local but also whole body cryotherapy where patient is influenced by very low temperature (~ -120˚C) in the special room called cryogenic chamber [1]. The cold transport through the skin into the internal tissues can cause many different biochemical and physiological reactions of organism.

There are many medical applications of cryotherapy such as: inflammatory states of spinal vertebrae joints, degeneration and inflammatory states of joints (*monoarthritis* and *oligoarthritis*) and *periarthritis.* Good effects in the cold treatment of rheumatism, low back pain diseases, *sclerosis multiplex* and *osteoporisis* [1, 2, 3].

The explanation of cold influence on living organisms requires knowledge of temperature changes in the tissues.

The aim of the present work was to study the cold penetration of the fourth-layer tissue model in the whole body cryotherapy conditions experimentally as well as theoretically using the Fourier heat transport equation analyses [4, 5].

Materials and Methods

The experimental studies were performed for the fourth-layer tissue model made from materials, which had thermal properties similar to biological tissues. Model consisted of four concentric layers: 1) rubber – imitated skin, 2) animal fat, 3) jelly – imitated muscle 4) tekstolite – imitated bone. The model was cooled up to low temperature (-30, -90 and -120˚C) in the special cooling chamber in 210 s time to create the conditions in whole body cryotherapy. The temperature was measured by using of the 4-wire resistor sensors as a function of time in the various depths (d_i where i = 3, 8, 13 and 30 mm) of the mode. The simplified scheme of the used measurement system is presented in Figure 1.

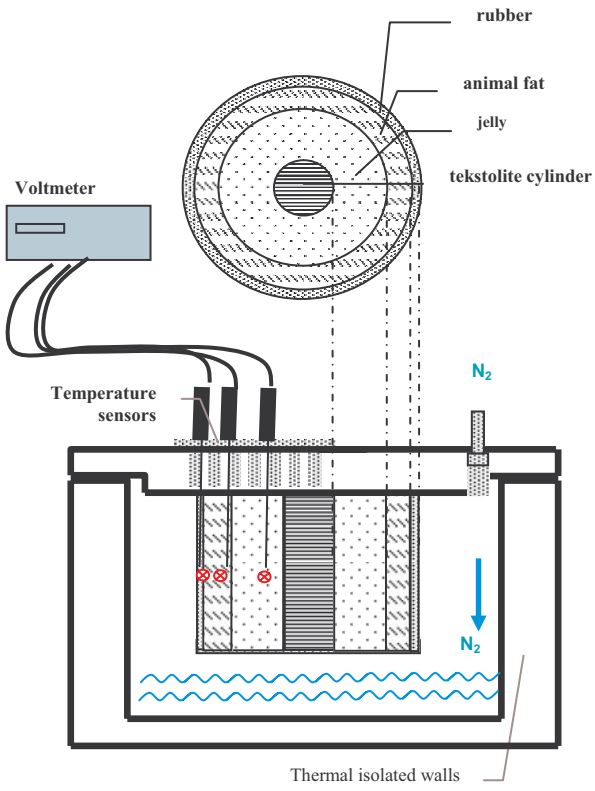

Figure 1: Scheme of the measurement system.

Moreover the computing simulation was performed (see chapter Computing Simulation).

The written program made possible the presentation of the temperature change in real time.

Results

The temperature plots as a function of time for fourth layer tissue model treated by cold impact are pre-

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sented in Figure 2 and 3. During cooling of tissue model the temperature drastically drops especially in the external layer and after taking out of chamber the temperature increases up to the room temperature (after about two hours). According to expectation the biggest temperature changes are observed in the external layer of tissue model. It follows from comparison of Figure 2 and 3 that the cold penetration is dependent on the magnitude of minus temperature in cooling chamber. It was obtained that decrease of temperature (ΔT) in the 3 mm depth was about 17°C, 27,7°C and 37,3°C for cooling chamber temperature $T_{cooling}$ = -30, –90 and -120 ˚C, respectively.

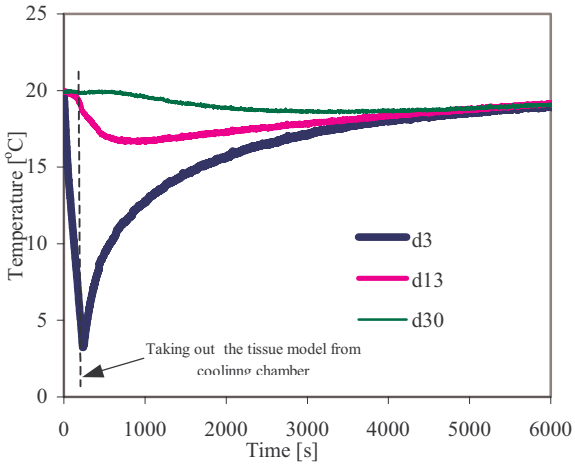

Figure 2: The temperature for the depths: 3 mm (d3), 13 mm (d13) and 30 mm (d30) versus time [s] of the model tissue. Temperature of the cooling chamber was established and equal to –30˚C.

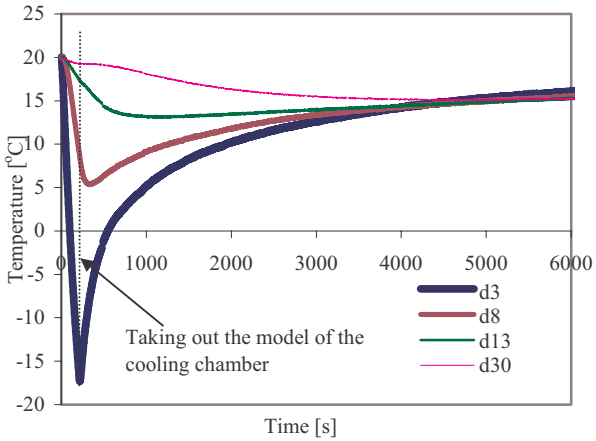

Figure 3: The temperature for the depths: 3 (d3), 8 (d8), 13 (d13) and 30 mm (d30) versus time [s] for the tissue model when cooling chamber temperature was –120˚C.

Cooling of the internal layers is markedly smaller and delayed in time what is in detail presented in Figure 4 and 5. The time to be up to minimum temperature rises nearly exponentially with depth of tissue model and depends on the cooling temperature. Moreover the time delay increases with depth and decreases with cooling temperature. The observed time delay reveals the temperature relaxation process occurring in the tissue model.

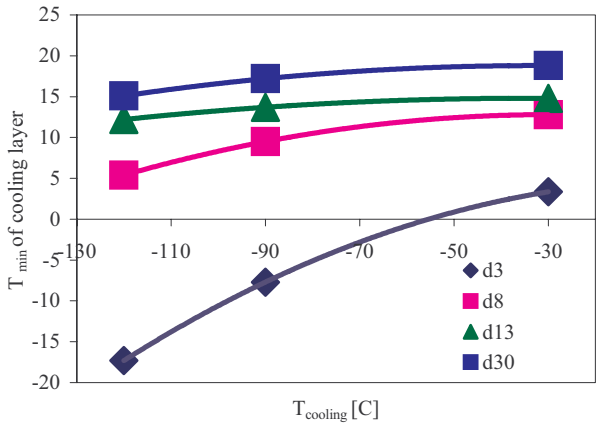

Figure 4: Minimal temperature as a function of depth of the tissue model cooled in temperature –30 °C, -90 °C and – 120 °C, respectively.

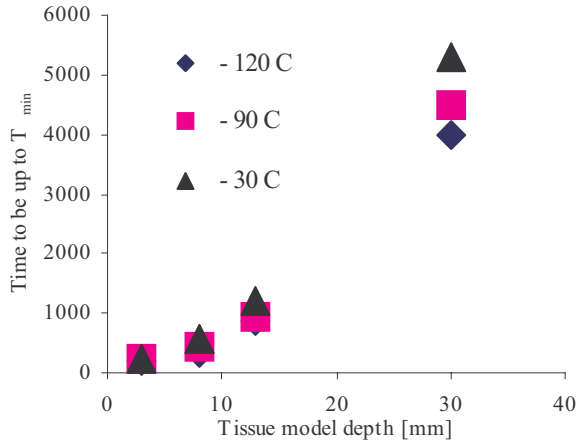

Figure 5: Time to be up to minimum temperature during cooling in chamber with temperature –30 °C, -90 °C and – 120 °C, respectively.

Computing Simulation

Moreover the computer simulation of heat transport for the studied fourth-layer tissue cylinder model was performed. Fourier heat equation (1) was used in the numerical analysis.

$$r\frac{\partial T}{\partial t} = \alpha\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) \qquad (1)$$

where:
r – radius,
T=T(r, t) – temperature function,
$\alpha = \frac{k}{\rho c_w}$ – thermal diffusivity,
k – thermal conductivity,
ρ – density,
c_w – specific heat

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The special program was written for analyse of the evolution of temperature within a finite, three-dimensional, not homogeneous continuum, with no internal sources of heat, subjected to some different initial and boundary conditions. Only the solutions in the stability range were taking into consideration [6].

The numerical analyses were performed for three variously determinate temperature of model surface: temperature of tissue model surface was taking into calculation $T_{cooling}$ equal the cooling temperature in chamber – method I, contact temperature according to formula (2)

$$T_c = \frac{b_1 T_1 + b_2 T_2}{b_1 + b_2} \qquad (2)$$

where:

b_1 and b_2 – contact coefficients characterizing touching surfaces with temperature T_1 and T_2, respectively

– method II and including into calculations the fifth layer - surrounding cooling air where transfer heat was taking into account also – method III.

Simulations were done using three methods described above for the similar conditions as *in-vitro* studies. The results are presented in Figure 6 –10 which will be discussed below.

Discussion

Numerically simulated results on the temperature T(r, t) as a function of time basing on the Fourier equation (1) are in qualitative agreement with the experimental ones. The results not depend of course on methods, which were used to simulate the surface of the model.

Figures 6 - 7 show the results of our calculation on T(r, t) versus time t due to cold impact. One can see that within method I in which was assumed that the temperature of the surface of the tissue model is fixed and equal to chamber temperature, the simulation curves differ from experimental. Method II, which used the contact temperature, described by (2) gives much better fits to experimental measurements when compared to the method I. However by the introducing into calculation the fifth layer - surrounding cooling air (method III) the most reliable description of experiment (Figure 9 and 10) is obtained. It is due to the fact that the heat transfer occurs inside as well as outside of the tissue model.

It is interesting to check an influence of thermal coefficients α, k, ρ, c_w characterising individual tissue of model on the temperature response due to cold impact. Table 1 presents maximum, minimum and mean values thermal diffusivity coefficients found in literature [7,8], which were applied in the computing simulations. It follows from Figure 8 that thermal diffusivity which changes from maximum to minimum value influences markedly the calculated results

Of course the biggest differences appear in the vicinity of curves minimum.

Moreover it was obtained that the change of layer thickness in the range about 10% does not give significant change in time dependence of temperature.

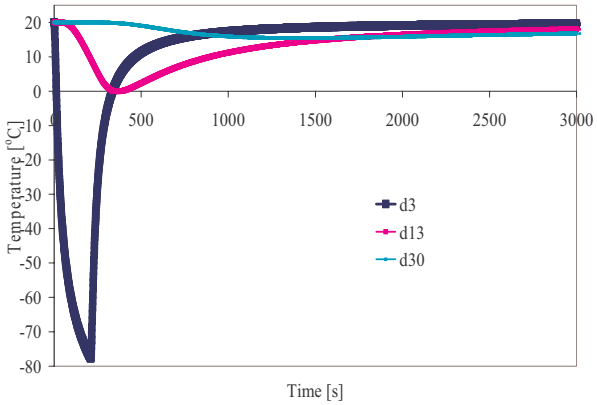

Figure 6: The temperature plots computed by method I for 3 (d3), 13 (d13) and 30 mm (d30) depth in tissue model due to cooling at –120˚C (using α_{mean}).

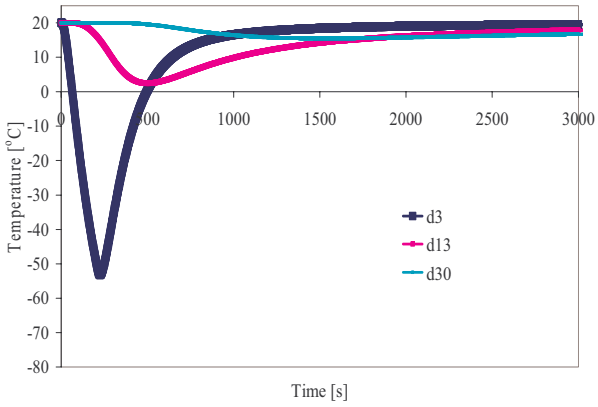

Figure 7: The temperature plots computed by method II for 3 (d3), 13 (d13) and 30 mm (d30) depth in tissue model due to cooling at –120˚C (using α_{mean}).

Table 1: Maximal (max), minimal (min) and mean values of thermal diffusivity for chosen materials imitated natural tissues used in the numerical outline.

Item	Thermal diffusivity [mm²/s]		
	α_{mean}	α_{max}	α_{min}
Rubber - skin	0,14	0,19	0,093
Tekstolit - bone	0,14	0,168	0,113
Animal fat - fat	0,115	0,138	0,092
Jelly - muscle	0,135	0,145	0,127

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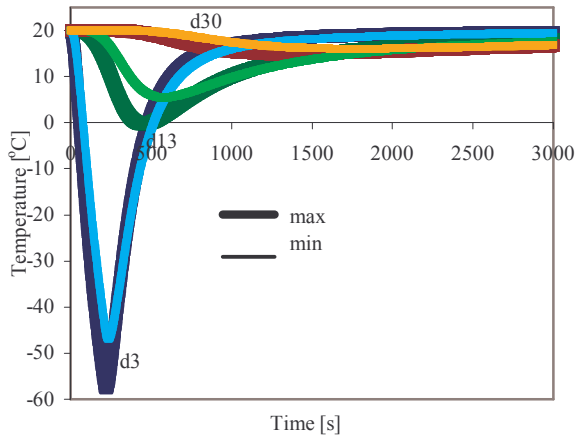

Figure 8: The temperature of the tissue against time calculated for maximal – max (α_{max}) and minimal – min (α_{min}) thermal diffusivity ($T_{cooling}$= -120°C).

Figures 9 and 10 illustrated the best fit of numerical data to the experimental curves obtained including into calculations the fifth layer being cool air surrounding the model and matching the thermal parameters in the range given in the Table 1. One can see that a good agreement between experimental and simulation curves especially for external layers (d3 and d8) occurs during cooling of tissue model (time of reaching minimum temperature and value of minimum temperature). However some discrepancies are seen for parts of curves in the time of return to thermodynamic equilibrium state. Probably it is caused by fact that in the theoretical outline the convection process was not taken into consideration.

This *in-vitro* preliminary study can be helpful in better understanding the thermal response of the skin and the body during whole body cryotherapy.

Deeper analysis is under consideration..

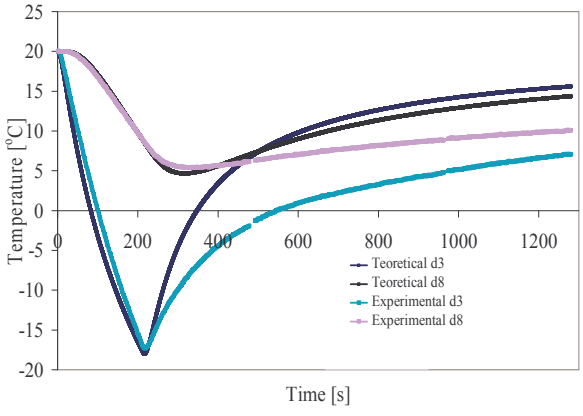

Figure 9: The best fit of experimental data and theoretical curves obtained for 3 (d3) and 8 (d8) mm depths in tissue model for cooling chamber temperature –120˚C.

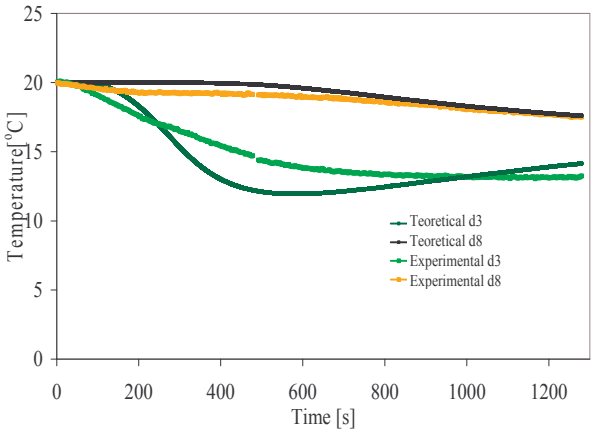

Figure 10: The best fit of experimental data and theoretical curves obtained for 13 (d3) and 30 (d30) mm depths in tissue model for cooling chamber temperature –120˚C.

Acknowledgements

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Conclusions

Fourier transport heat equation can be use for approximate description of the heat transport in multilayer tissue model. Comparison of experimental with numerical analysis indicates quite well qualitative agreement.

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