The study of thermal processes of the skin of the object of the whole-body cryotherapy (WBC) using numerical analysis

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Abstract. The work investigated the thermophysical processes occurring in the cryoanuna during cryotherapeutic effects on the human body. Experimental studies in the field of the whole-body cryotherapy (WBC) are complex, since studies are necessary in such a wide range of environmental parameters as phase state, temperature, heat flux density, gas flow velocity in the cryosauna. One of the solutions to this problem is the development of computer models of the processes of heat transfer of a biological object in a cryoanuna, allowing a wide range of studies to be carried out without human experiments. In this paper, we analyze a modification of the design of a cryochamber with a biological object. In this work, several types of computer models will be created, the models of which vary depending on the geometry of the wall of the cryoanuna chamber from 90 to 85 degrees. The paper will show how much it is necessary to pay attention to the geometry of the cryoanuna and work on the modification of the geometry. This work shows that when the geometry of the wall of the cryoanuna was changed, it turned out that it smoothed the temperature distribution along the length of the object, which, in turn, will positively affect further research in this area. The results can be applied to optimize the supply of cryogenic gas in saunas, further geometry modernization, as well as to increase the efficiency and safety of the WBC process.

1. Introduction

Whole body cryotherapy (WBC) is the process of cooling a biological object under investigation to low temperatures in a special unit (cryoanuna). Under ideal conditions, in order to achieve the theoretical maximum cryotherapeutic effect, the temperature of the skin of the studied biological object should be cooled to a temperature of 270.5 K. With a local transition of the temperature barrier of 270.5 K, the probability of significant frostbite of the investigated biological object appears [1-3].

The application of this WBC procedure is diverse: from the treatment of a number of diseases associated with general effects on the body, the immune and endocrine systems, to the prevention of organism restoration in both athletes and ordinary people [4-6]. With inflammatory processes in the patient’s body, the WBC procedure allows one to reduce the temperature of the inflamed tissue and limit inflammation, which favorably affects the overall treatment [7-9].

The experimental determination of the temperature field of the human body during WBC is extremely time-consuming and often fraught with the danger of local frostbite. In the literature, the most common and generally accepted approach for the numerical study of this class of problems is the use of thermal conductivity models of a system of multi-element multilayer cylindrical shells. Most of
the work concerns the stationary formulation of problems, the use of fixed thermophysical parameters of the layers, as well as a limited range of environmental parameters. Moreover, such important features of thermophysical processes as the influence of internal heat sources and convective heat transfer between different layers and elements of the system, temperature, pressure and gas flow rate in the cryosauna are not considered in the literature. At the same time, taking these factors into account allows one to obtain more accurate and reliable results for further design and optimization of cryosauna elements.

In this paper, when modeling the cryotherapy process, additional equations were used that describe the internal heat sources, which made it possible to more accurately describe the cryotherapy process. The reliability of the results obtained is determined by a comparative analysis of the calculated data with the experimental and calculated data known in the literature, as well as testing of software models. Thus, the obtained estimate of the heat flux density is consistent with the data obtained in [1].

In this paper, we consider the influence of geometric factors, such as: the angle of the chamber wall \( n = 3,4,5 \) °; \( m = 3,4,5 \) °) and the shape of the chamber (round and conical). These changes in geometry will affect the temperature of the body surface at a given point and the temperature heterogeneity along the length of the biological object. To collect information about the dynamics of the temperature field and control the heat flux in the volume of the cryosauna, as well as on the surface of the object, both at this point and along the entire length of the object before and after WBC, the process, as during the process, can be obtained using computer simulation (finite element method), which is a safe method and a fairly reliable way to conduct an experiment.

2. Experimental setup WBC

Numerical analysis was carried out using the finite element method in a software package. Figure 1 schematically shows the different forms of the cryosauna. To simulate the work of WBC, conditional separation of the object into internal organs and muscles is used - “muscle layer - 0”, fat layer - “fat tissue - 1”, body integumentary tissues - “epithelium - 2”, cryogenic gas - 3, cryosauna - 4, cryosauna wall - 5, protective clothing for legs - 6.

![Figure 1. Schematic image: a – modified form; b – standard form.](image)

In standard form, the geometric dimensions are equal (Figure 1b): gas supply hole \( l_{\text{out}} = 75 \) mm, \( h_{\text{out}} = 160 \) mm), cryogenic gas outlet hole \( l_{\text{in}} = 75 \) mm, \( h_{\text{in}} = 160 \) mm), free surface through which gas is discharged into the surrounding medium \( d_{\text{out}} = 700 \) mm), camera body \( l_{\text{ch}} = 1000 \) mm, \( h_{\text{ch}} = 1500 \) mm), wall \( l_{w} = 400 \) mm, \( h_{w} = 500 \) mm), subcutaneous layer of the WBC object, internal fabric of the WBC object, the inner cavity of the chamber, filled gas mixture \( d_{g} = 800 \) mm, \( h_{g} = 1400 \) mm) [2].
In a modified form, the angle of the wall of the cryosauna chamber changed from 90° to 90° - n (0 < n < 5) and the camera angle from 90° to 90° - m (0 < m < 5). The values of the dimensions of the cryosauna chamber body changed depending on the given angle.

The simulation was carried out in the time interval from 0 to 250 seconds, the intensive supply of cryogenic gas was from 0 to 180 seconds, the model was considered unsteady. The computer model used the parameters of the cryocamera "Kryon" (Russia). In this work, the circulatory system works in conjunction with a thermoregulation system and transfers heat from internal organs to the surface of the body.

3. Equations

3.1. Heat Transfer in Solids

For any selected elementary volume, it is assumed that the heat transfer process is stationary at each current point in time (∂τ). The heat transfer process is determined by the values of the effective coefficient of thermal conductivity (κ), specific heat (C) and density (ρ). The specific heat and density vary slightly inside the element; therefore, they are considered permanent.

General heat equation for solids is used in our calculations:

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \nabla T + \nabla \cdot \mathbf{q} = Q.
\] (1)

The heat flux density:

\[
\mathbf{q} = -\kappa \cdot \nabla T,
\] (2)

where \(\kappa\) – a coefficient of thermal conductivity.

The Bioheat Equation:

\[
\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot \mathbf{q} = Q + Q_{bio} + Q_{ext},
\] (3)

where \(Q_{bio}\) is the heat release of biological tissues:

\[
Q_{bio} = \rho_b \cdot C_{p,b} \cdot \omega_b (T_b - T) + Q_{met},
\] (4)

where \(\rho_b\) – blood density [10], \(C_{p,b}\) – specific heat of blood at constant pressure, \(\omega_b\) - blood perfusion rate [11], \(T_b\) - arterial blood temperature, \(Q_{met}\) - metabolic heat source.

Spatial heat source: \(Q_{ext}\) describes heat generation from an external source:

\[
Q_{ext} = H_{ab} (r,t)[T_{ab} (r,t) - T(r,t)] +
+ H_{vb} (r,t)[T_{vb} (r,t) - T(r,t)],
\] (5)

where \(H_{ab}\) – coefficient for heat transfer between tissue and arterial blood per unit volume of tissue [W/(m³·K)], \(H_{vb}\) - coefficient for heat transfer between tissue and venous blood per unit volume of tissue [W/(m³·K)], subscript: b - blood, ab - arterial blood, and vb - venous blood.

We made assumptions, the heat dissipation \(Q_{ext}\) can be neglected, since we set \(H_{ab}\) and \(H_{vb}\) to be zero [12].

3.2. Heat equation for a liquid

The general heat equation for a liquid (in a gas N₂):
\[ \rho \cdot C_p \cdot \frac{\partial T}{\partial t} + \rho \cdot C_p \cdot \mathbf{u} \cdot \nabla T + (\nabla \cdot \mathbf{q}) = Q, \]  

(6)

where \( \rho \) - density, \( C_p \) - heat capacity, \( T \) - absolute temperature, \( t \) – time, \( \mathbf{u} \) - velocity vector, \( \mathbf{q} \) - heat flux, \( Q \) - heat sources.

The heat flux density:

\[ \mathbf{q} = -\kappa \cdot \nabla T, \]  

(7)

where \( \kappa \) – a coefficient of thermal conductivity.

4. Materials

All properties of materials were taken isotropic in the calculations of this model. The data on thermal conductivity and heat capacity of the epithelium, fat layer, muscle layer used in the model are presented as dependences on temperature and are shown in [13].

5. The study results obtained using numerical analysis

In this paper, we consider at what period of time a comparative analysis of future changes in the geometry of the cryosauna is necessary. Since, in this work, a biological object is placed in the cryosauna, and the biological object emits a significant amount of heat, which increases when the biological object is cooled, it is necessary to analyze and calculate the time interval, which has a significant effect during the WBC procedure. In this statement of the problem, it makes no sense to analyze all the modes, since we need to calculate the maximum cooled period of time, in all modes it will be one.

![Figure 2](image-url)

**Figure 2.** The distribution of skin surface temperature of the object length WBC. Time intervals: 1 – 0 s., 2 – 20 s., 3 – 40 s., 4 – 60 s., 5 – 80 s., 6 – 100 s., 7 – 120 s., 8 – 140 s., 9 – 160 s., 10 – 180 s., 11 – 200 s.

The main parameter showing the effectiveness of the WBC procedure will be temperature. Also, during the analysis, the dependences of the heat flux and the temperature of the internal tissues of the biological object will be considered. It is necessary to create a uniform temperature field along the length of the object by changing the angle of inclination of the walls of the cryosauna (changing the geometry) and varying the modes of supply of cryogenic gas into the cryosauna chamber. The temperature distribution of the surface of the skin from the length of the biological object over time is shown in Figure 2. As can be seen from Figure 2, the biological object is cooled as much as possible in a time interval of “10” (180 seconds). In the subsequent analysis, we will use this period of time as the most dangerous and significant.
In Figure 3, we will arrange the temperature curves at different angles of the angle of inclination of the cryosauna wall, which is done to more clearly consider the temperature curves and conduct a comparative analysis. To facilitate the reading of the simulation results, we will consider the curves in one cryogenic gas supply mode. Following the safety conditions, we cannot use the 3 mode that was described earlier, since in this mode there is a local frostbite of the biological object. For comparison with standard geometry, we will use 2 mode, 1 mode is too weak and will also be excluded from the analysis. Also, on this graph we will place the results at the standard angle of the chamber wall (the right angle is taken as the standard angle, see Figure 1).

In Figure 3, it can be seen that curve 5 extends beyond the boundary of curve 6 in the region of 0.9-1.1 m, which corresponds to the critical temperature; therefore, it follows that for standard geometry it is necessary to reduce the supply of cryogenic gas, since there is a danger in the region of 0.9-1.1 m frostbite of integumentary tissues of a biological object.

As can be seen from Figure 3, the effect of a slight change in the angle of the wall of the cryosauna by several degrees leads to a significant change in the temperature curve, which characterizes the temperature of the integumentary tissues of the biological object.

In Figure 3 we see that, in comparison with other curves, curve 4 is acceptable and at a given angle, the supply of cryogenic gas can be increased for more intensive cooling, which in turn will increase the efficiency of this procedure.

![Figure 3. Temperature dependence on the length of the object under study. Geometry: 1 – 5° angle (n, m - 5°), 2 – 4° angle (n, m - 4°), 3 – 3° angle (n, m - 3°), 4 – 2° angle (n, m - 2°), 5 – 0° angle (n, m - 0°), 6 – critical temperature line (270.5 K).](image)

6. Conclusion
In this article, several types of computer models were created, the model changed depending on the geometry, the geometry of the wall of the cryosauna chamber changed from 90 to 85 degrees. The created computer model allows one to estimate the thermal fields taking into account the internal heat source during and after the WBC process, as well as to study the effect of changes in the geometry of the cryosauna on such parameters as: velocity and temperature of the coolant, temperature of the integumentary tissues of the biological object, consider local frostbite and change the temperature regimes in depending on the results to increase the comfort and efficiency of the WBC process.

The work shows that it is necessary to pay attention to the geometry of the cryosauna and work on the modification of the geometry. It is shown that a change in the angle of inclination of the wall of the cryosauna chamber significantly affects the overall temperature field of a biological object. These experimental studies must be carried out with the participation of medical workers, since there is a high probability of obtaining local frostbite with an increase in the power of the cryosauna. This work
shows that when the geometry of the cryosauna wall was changed, it turned out that it smoothest the temperature distribution along the length of the object, which in turn will positively affect further research in this area. The results can be applied to optimize the supply of cryogenic gas in saunas, further geometry modernization, as well as to increase the efficiency and safety of the WBC process.

7. Conflict of interest
The authors declare that they have no conflict of interest on the content of this paper.

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