Numerical analysis of the heat flux density of the whole-body cryotherapy (WBC) object coming from the skin

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Abstract. In technologies of cryotherapeutic effects, the main attention is paid to the choice of temperature of cryogenic gas. At the same time, along with the gas temperature, other process parameters are also essential: the gas velocity, the dimensions and spatial orientation of the biological cooling object, the humidity and gas velocity, etc. To develop the technique and technology of general cryotherapy, generalizing research is needed that can form the theoretical basis for the production and design of cryotherapy equipment. The most general results can be obtained by studying the effect that cooling has on a biological object with different intensities of heat removal along the length of the biological object. The work will conduct a chilled analysis of heat flux losses from the surface of the skin of a biological object with a slight change in the geometry of cryosauna during the whole-body cryotherapy process (WBC). To implement these tasks, a software package using the finite element method will be used. To describe the biological object with internal heat release, these biological heat equations were solved using the Penns approximation. The results of this work will help to give recommendations to cryosauna manufacturers to optimize the design of the cryotherapy unit, which in turn will help to increase the effectiveness of cryotherapy.

1. Introduction

Now, whole body cryotherapy (WBC) is used to treat and prevent a few diseases, such as dermatological, rheumatological, neurological, respiratory, cardiovascular diseases [1-5]. Unfortunately, at present, the WBC method has not gained wide popularity, although it is promising not only for medical needs, but also for services, beauty salons, etc. From a medical point of view, WBC is not yet included in generally accepted clinical methods and this is due to a small theoretical basis for the effect of the cooling effect on the body and the lack of control over the procedure. Only experimental data obtained on commercial equipment is not enough to introduce cryotherapy into wide medical practice, which is one of the main criteria of low popularity in the medical field. If we consider the use of WBC in the service sector, the main reasons for the lack of mass demand for cryotherapy are the high cost of the procedures, the bias of patients about the dangers of cryogenic temperatures, the unsatisfactory implementation of the procedure (lack of accurate temperature control on the skin surface, uneven distribution of heat flux over the height, etc. d.). The existing cryosauna is classified by the number of simultaneously accommodated patients (individual and group), as well as
by the cooling mechanism (generating cold in a refrigeration machine with vapor compression or using cryogenic gas - liquid nitrogen). Group installations, such as ARCTIC (Poland), Crio Space Cabin (Germany), KGT LLC Krio Kholod (Ukraine), have shown their unpopularity and inefficiency due to the high cost of equipment and installation, high consumption of cooling medium or consumption of electric refrigeration power machine, significant heat gain. Thus, individual installations are more promising for modernization, due to their small size, efficiency, mobility, etc. A large number of such plants have been designed, for example, such as: KAEKT-01 “Kryon” (Russia), Icequeen, Cryomed-20/150-01, etc., but the cost and ease of operation directly depends on the supply of nitrogen and other thermal and economic factors. It should be borne in mind that it is possible to increase the efficiency of the procedure by lowering the temperature of the cooling gas around the patient, by increasing the gas supply rate and changing the geometry of the nozzle in the cryosauna. However, it must be understood that in the cryosauna the heat exchange conditions are formed between the cooling gas and the patient, which are close to natural convection and safety conditions cannot be neglected, and the fact that the gas flow distribution directly affects the uneven temperature distribution along the height of the cryosauna.

With a local transition of the temperature barrier of -2.5 °C, the probability of a significant frostbite of the object being studied appears [6-7]. There are various proposals for improving heat transfer in compliance with safe conditions, namely, maintaining the temperature at 12 °C> T (body surface temperature) > -2.5 °C, cooling rate dT/dτ> 0.01 °C/s [8] and limiting the duration of the procedure, the case of maximum risk in an experimental study on patients will only lead to the absence of a positive effect. The experimental determination of the temperature field distribution from the skin of the object during the WBC process is difficult, since in a single cabin the temperature decreases once to –130 °C at a rate of 8 °C/s [6]. During fluctuations, serial temperature sensors can give incorrect readings due to their own thermal inertia.

2. Experimental setup WBC
In numerical analysis, in this case, the most difficult moment is the description of the processes of heat transfer by the coolant (hemodynamic mechanism of the thermoregulation system). More often in such works, the thermoregulation system is not considered, to simplify the task and calculations. To solve this problem, in this work, additional terms, Q_{bio}, are added to the general heat equation, which characterizes the heat release of biological tissues through blood density, specific heat of blood at constant pressure, blood perfusion rate, arterial blood temperature, and metabolic heat source. Using computer simulation, we reproduce the WBC process with some assumptions; the results correlate with experimental data. The Bioheat module was used to mathematically describe biological tissues [9]. The module is used to simulate heat transfer in biological tissue and considers the following heat sources: blood perfusion and metabolism, which are included in the classical heat transfer equation in the form of Q_{bio} [10].

The model used the average density of these substances: nitrogen = 1.18 kg/m³, epithelium = 1093 kg/m³, fat layer = 916 kg/m³ and muscle layer = 1041 kg/m³. The model also considered heat sources from blood perfusion and metabolism: arterial blood temperature - 310.15 K, blood density - 1060 kg/m³, blood heat capacity - 4200 J/(kg·K), blood perfusion - 0.003 1/s, metabolic heat source 7277 W/m³ [8].

In this paper, assumptions will be introduced to describe biological processes, and the biological heat equation will be solved using the Penn approximation. The Penn approximation is described in more detail in [11]. This approximation is used to simulate heat transfer in biological tissue, considering heat sources from blood perfusion and metabolism in the classical heat transfer equation.

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) [12]. 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. This model is a multi-layer and multi-element model, where each part of the body is represented as a calculated element with the corresponding number and type of layers (Figure 1).

Figure 1. The simplified scheme used in the calculation (index number: 0 — internal organs and muscles, 1 — fat layer, 2 — epithelium, 3 — cryogenic gas (medium), 4 — cryosauna chamber).

3. Equations

3.1. Heat Transfer in Solids

General heat equation for solids 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:

$$\mathbf{q} = -\kappa \nabla T,$$

(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:

$$Q_{bio} = \rho_b \cdot C_{p,b} \cdot \Delta \alpha_b (T_b - T) + Q_{met},$$

(4)

where $\rho_b$ – blood density [13], $C_{p,b}$ – specific heat of blood at constant pressure, $\omega_b$ - blood perfusion rate [14], $T_b$ - arterial blood temperature, $Q_{met}$ - metabolic heat source.
3.2. Heat equation for a liquid.

The general heat equation for a liquid (in a gas $N_2$):

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} + \rho \cdot C_p \cdot \mathbf{u} \cdot \nabla T + (\nabla \cdot \mathbf{q}) = Q,$$

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

(a) Turbulent flow of the $k$-$\varepsilon$ model.

General equation:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot \left[ -\rho \mathbf{I} + \left( \mu + \mu_t \right) \nabla \mathbf{u} + \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) \right] + \mathbf{F},$$

$$\rho \nabla \cdot (\mathbf{u}) = 0.$$  

Turbulent viscosity is modeled as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon},$$

where $C_\mu$ is a model constant.

The transport equation for $k$ reads:

$$\rho \frac{\partial k}{\partial t} + \rho \mathbf{u} \cdot \nabla k = \nabla \left[ (\mu + \mu_t) \nabla k \right] + P_k - \rho \varepsilon,$$

where the production term is:

$$P_k = \mu_t \left[ \nabla \mathbf{u} : \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) - \frac{2}{3} (\nabla \cdot \mathbf{u})^2 \right] - \frac{2}{3} \rho k^2 \nabla \cdot \mathbf{u}.$$  

The transport equation for $\varepsilon$ reads:

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho \mathbf{u} \cdot \nabla \varepsilon = \nabla \left[ \left( \mu + \mu_t \right) \nabla \varepsilon \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} P_k - C_{\varepsilon 2} \rho \varepsilon \frac{\varepsilon^2}{k},$$

where $\mathbf{u}$ is the velocity, $\mu T$ is the eddy viscosity;

$$P_k = \mu_t \left[ \nabla \mathbf{u} : \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) \right].$$

The model constants in Equation (10), Equation (11), and Equation (13) are determined from experimental data [15].

4. The study results obtained using numerical analysis

Reflection of bioenergetic processes in the human body is the heat flux from the surface of the skin of a biological object [8]. To simulate thermal processes when changing the geometric parameters of the cryosauna wall, it is also necessary to analyze the change in the heat flux of the biological object WBC coming from the integumentary tissues. The heat flux will also be analyzed in height, since it is necessary to consider local heat losses. The heat flux emanating from the surface of a biological object during the WBC process, which varies with time, is shown in Figure 1 with a time step of 20 seconds, from 0 to 200 seconds.
Figure 2. The dependence of the change in heat flux density on the length of the object 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.

In Figure 2 it is seen that the largest heat loss occurs in a period of 160 seconds. In the future, we consider in more detail this period when changing the geometry of the chamber wall. In Figure 3 there is a graph of the heat flux of a biological object emanating from integumentary tissues.

Figure 3. The dependence of the change in heat flux density on the length of the object WBC. 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. Conclusion
In this paper, the reliability of the results obtained is determined using a comparative analysis of the calculated data with the experimental results, which are described in earlier works. Thus, the obtained estimate of the heat flux density is consistent with the data obtained in [6]. The value of the heat flux density allows us to estimate the duration of the effective exposure, that is, the time during which the analgesic effect of WBC is maintained. According to the method proposed in [7], the analgesic effect of WBC was evaluated for the case considered in this article. With an average calculated heat flux = 4 kW/m², the WBC analgesic effect will last 4 hours. Figure 3 shows a graph that has a maximum in the middle region, where the heat flux density locally increases to 4.85 kW/m². Such intense heat transfer can lead to local frostbite.
An increase in the heat flux density from the surface of a WBC biological object from 1.0 to 3.0 kW/m$^2$ is accompanied by an increase from 0.25 to 6, i.e., almost 25 times. Moreover, the main growth is observed in the range from 0.5 to 4.5 kW/m$^2$. The calculated values of the effective heat flux do not exceed 0.5 h., therefore it is necessary to modernize the design of the cryochamber to evenly remove the heat flux from the surface of the biological object at a level of from 3.5 to 4 kW/m$^2$. The different nature of the curve in different areas located to the right and left of the maximum indicates that an increase in the heat flux density leads to qualitative changes in the processes occurring in the layers of the WBC biological object. In order to obtain a high cryotherapeutic effect and compliance with patient safety requirements, it is necessary to ensure intensive and uniform heat removal from the body surface along the length of the WBC object. In this case, the only safe way to transfer heat from the surface of the housing to the heat receiver of the cooling system is gas convection. For this reason, it is necessary to use cryogenic temperatures to remove heat flux with a high density. Also, when designing real systems, it should be borne in mind that the average area of the entire human body is 1.5 m$^2$. The system of the cryotherapeutic complex should provide heat removal on average about 4 kW/m$^2$ per patient, and heat removal should be carried out at a temperature of no higher than 140 K. Determining the power requirements for cryotherapy complexes will protect the medical equipment market from low-quality WBC equipment.

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

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