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Energy requirements for nitrogen cooling systems of WBC units

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Whole-body cryotherapy (WBC) technique is based on supercooling patient's body to stimulate skin cold receptors at the depth of 0.15 mm from skin surface forming signal of maximum intensity at the temperature of -2°C . Heat removal by gas with the temperature of not more than -130°C allows localizing body supercooling zone at the depth of receptors. The research is made to estimate maximum intensity of heat removal and necessary power consumption. It allows determining requirements for power supply of WBC units that is crucial for efficiency and safety of WBC. The research is carried out by the mathematical models of WBC object (human body surface) and a unit of volume for WBC zone (patient's cabin). Implementation of WBC technique is shown to require removing 3.8 kW of heat from patient's body surface. Taking into account total refrigerating capacity the cryostatting system for single-seated WBC cabin has to remove as less as 6.4 kW of heat from the temperature level of -130°C . Therefore, a refrigerator of 47 kW power or nitrogen cooling system with refrigerating medium consumption of 0.025 kg/s or 4.45 kg per procedure is necessary. The use of nitrogen cooling for WBC zone results is compact and mobile single-seated WBC units. Owing to high competitive advantages single-seated units for WBC are widely used in the world, they being used in Russian clinical practice for more than 20 years.

Keywords: WBC, supercooling, heat load.

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Энергетические требования к системам азотного охлаждения установок для WBC

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Технология whole-body cryotherapy (WBC) основана на переохлаждения поверхности тела пациента для стимуляции холодовых рецепторов кожи, которые расположены на расстоянии 0,15 мм от поверхности кожи и формируют сигналы максимальной интенсивности при температуре -2°C . Отвод теплоты газом с температурой не выше -130°C позволяет локализовать зону переохлаждения тела на уровне залегания рецепторов. Исследование выполнено для оценки оптимальной интенсивности отвода теплоты и сопутствующих затрат энергии. Исследование позволяет определить требования по энерговооруженности установок для WBC, которая определяет эффективность и безопасность технологии WBC. Исследование выполнено на математических моделях объекта WBC (оболочки тела человека) и единицы объема зоны WBC (кабины пациента). Показано, что для реализации технологии WBC необходимо отводить теплоту с поверхности тела пациента 3,8 кВт. С учетом прочих затрат холодопроизводительности, система криостатирования одноместной WBC кабины должна отводить не менее 6,4 кВт теплоты с температурного уровня -130°C . Это может обеспечить рефрижератор с мощностью привода 47 кВт или азотная система охлаждения с расходом криоагента 0,025 кг/с или 4,45 кг на процедуру. Использование азотного охлаждения зоны WBC обеспечивает компактность и мобильность одноместных устройств для WBC. Благодаря высоким конкурентным преимуществам одноместные установки для WBC получили широкое распространение в мире, практика их клинического применения в России насчитывает более 20 лет.

Ключевые слова: WBC, переохлаждение, тепловая нагрузка.

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Introduction

In the papers concerning the methods of whole-body cryotherapy (WBC) clinical effects of the procedure are paid main attention to [1, 2, 3]. The issues of procedure method choice, the temperature of cooling gas, and cooling exposition are discussed much less often [4, 5]. The technological task of WBC technology — supercooling of patient’s body surface to subterminal temperature — is not paid attention as well. It is supercooling of the body surface in the cold receptors area that provides stimulating effect on central nervous system (CNS) of the body. The intensity and duration of the effect is crucial for the positive influence of WBC. The most obvious and controllable effect of WBC is the time of analgetic effect or effective time (ET WBC) [6]. The research carried out at ITMO University allows estimating the dependency between decreasing the temperature of patient’s body surface and ET WBC value. The conditions of hypothermal safety for patients are determined. An optimal gas temperature in WBC zone is found out by numerical experiment.

However, the exploitation of WBC units proves that insufficient power of cooling system is the main issue for the systems in use [7]. It is true for the units with nitrogen cooling system where nominal consumption of liquid nitrogen do not stabilize the temperature in WBC zone. A greater power insufficiency is observed in nitrogen-free cooling systems where vapor refrigeration cycles are used to remove heat. Electrical power in these refrigerators is 5–10 times less than it is necessary to remove heat load at the air temperature claim in WBC zone [8]. Low power of cooling system does not allow for modern multi-seater WBC units to maintain temperature at –170° C as the original Japanese unit, in which cryotherapeutic effect was observed for the first time, does [9, 10].

The reason for the insufficient power of cooling systems for WBC units is the faulty estimating heat emission from the patient’s body, poor design of the procedure cabins, and erroneous choice of the technique for heat removal from cooling gas to refrigerating medium.

Insufficient power of cooling systems is the main reason for low treatment efficiency of most modern WBC units. The temperature in WBC zone is unstable. In the presence of patients the temperature rises by 30–50 K. The units cryostatted by vapor refrigeration cycles needs 8–10 min to regain temperature in the main cabin after each procedure [7, 11].

To solve the above issues one should provide proper insight into the real cooling system heat load in WBC zone, and to determine a refrigerator power or liquid nitrogen consumption corresponding to the heat load.

Thermophysical processes in WBC systems

WBC procedures are based on quick supercooling of patient’s body surface due to heat removal to cryogenic gas. At ITMO University thermophysical theory of WBC has been

developed, and an optimum degree and rate of skin surface supercooling has been determined [6]. To meet the efficiency requirements for WBC procedures one should remove great amount of heat form patient’s body surface for a limited time. To perform this task cryostatting system of WBC unit has to exhibit refrigeration capacity at the temperature level not exceeding –130° C [6].

Heat emission from patient’s body surface and cooling system heat load proved to be much higher than it was expected by most manufacturers of WBC units.

1. Thermal processes in patient’s body surface during WBC procedure

According to thermophysical theory of WBC an intensive heat removal is necessary to decrease the temperature of patient’s body surface (BS) to subterminal level $t_s \rightarrow -2^\circ\text{C}$. Decreasing BS temperature (T_s) results in irritation of skin cold receptors. The intensity of stimulating action (ISA) on cold receptors increases hyperbolically as the temperature nears to the terminal one ($t_{term} = -2.5^\circ\text{C}$).

$$I_{sa} = \frac{1200}{(T_s - T_{term})^2}, \tag{1}$$

where T_s, T_{term} are the BS temperature and the terminal temperature K correspondingly

Hyperbolical dependence between BS temperature and ISA value is that supercooling of BS to the temperatures above 275 K (2.0 °C) irritates cold receptors negligibly. At $T_s=275$ K the value of ISA is only 60. Cooling to $T_s=271$ K (–2.0 °C) gives 80 times ISA increase [7, 8, 11].

The amount of heat transferred from BS to cooling gas has been determined from calorific capacity of the body for the long time. An average calorific capacity of the body at moderate physical activity is 100 W/m² [10]. Taking into account average BS area nominal heat flow form human body is 160 W. Under the conditions of maximum physical activity the calorific capacity may increase significantly. For example, while swimming body generates up to 700 W of heat. The analysis of energy indicators for WBC units in use demonstrates that heat capacity of patients body was estimated at 300 W on average when designing [7].

During WBC procedures the heat from supercooling BS tissues gives the main heat load. Epithelium, fat tissue, and muscles are of high density ρ , moisture content ϕ , thermal capacity c , and thermal conductivity λ (Table 1). These physical properties of BS tissues determine their thermal inertia [11]. Specific calorific power of metabolism for particular tissues q_{met} influences BS temperature to a certain extent. Metabolism heat generates distributed heat sources preventing supercooling in WBC object.

Heat removal from BS is carried out due to convection of cooling gas

Table 1

Thermophysical properties of BS tissues [7]

Structure	$\rho, \text{kg/m}^3$	$\phi, \%$	$c, \text{J}/(\text{kg}\cdot\text{K})$	$\lambda, \text{W}/(\text{m}\cdot\text{K})$	$q_{met}, \text{W/kg}$
Epithelium	1093	72,0	3600	0,35	10,06
Muscles	1041	80,0	3458	0,475	6,99
Fat tissue	916	20	2250	0,21	—

$$q_{s-1} = \alpha(T_s - T_1); \quad Q_{s-1} = \int_{\tau=0}^{\tau=\tau_{\max}} q_{s-1} \partial\tau, \quad (2)$$

where α — heat transfer coefficient at natural gas convection, W/ (m²·K);

T_s, T_1 — the temperatures of BS and cooling gas K correspondingly.

Surface temperature decreasing results in an additional heat intake by heat transfer from BS internal sections:

$$q_\lambda = -\frac{\lambda(T_s - T_1)}{\Delta E}, \quad (3)$$

where Δx — the interval of surface division into conditional sectors, m.

Even moderate BS supercooling results in sharp increase of heat supply by thermal conductivity. At the interval $\Delta x = 0.5 \cdot 10^{-3}$ m surface temperature decrease by 1 K results in heat supply by thermal conductivity with the power $q_\lambda = 700$ Вт/м². The task performance of WBC is to supercool surface by 34 K, from 305 (32 °C) to 271 K (-2 °C). Therefore, it is necessary to remove 650 kJ of heat accumulated in BS tissues from BS.

The heat emission is due to supercooling of deeper BS layers along with the surface [12, 13]. It is proved by the graphs of tissue temperature changes across the BS thickness both in the beginning and in the end of WBC procedure (Fig. 1). With distance from the surface the degree of BS tissue supercooling decreases (Δt_i) from the maximum of 34 °C at $X=0$ to 0.3 °C $\Delta X=15$ mm. Lowering the temperature of every BS segment is accompanied by accumulated heat emission

$$Q_{Ai} = \Delta T_i \Delta x \rho_i c_i. \quad (4)$$

The total amount of the heat emitted due to supercooling of tissue is the sum of the heat emitted from the elementary BS segments:

$$Q_A = \sum_{i=0}^{30} \Delta T_i \Delta x \rho_i c_i. \quad (5)$$

When the temperature of BS changes according to the graph presented in Fig. 1 456 kJ/m² of heat accumulated

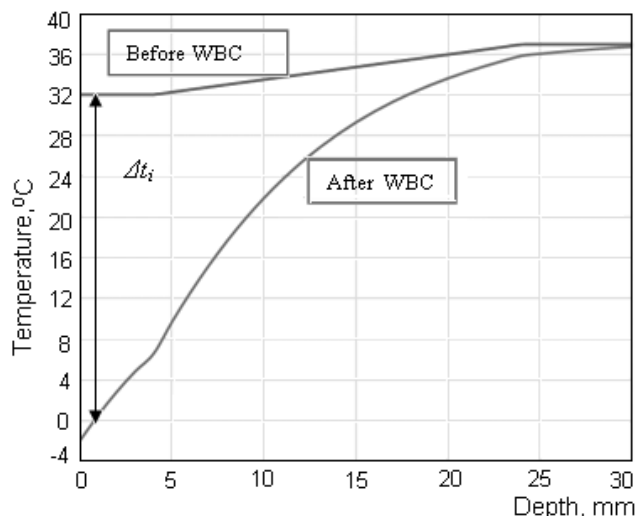


Fig. 1. The temperature distribution across patient's body surface before and after WBC procedure

by BS tissues is emitted for the procedure. 476 kJ/m² of heat is removed from BS. The difference between the heat removed from BS and the temperature of BS tissue supercooling is the heat emitted due to metabolism in the patient's body

$$Q_{met} = Q_{s-1} - Q_A. \quad (6)$$

BS heat balance allows estimating heat gain from different sources. Epithelium supercooling heat gives the main part of heat load on CS (280 kJ/m² or 59%). Heat of supercooling of subcutaneous tissue — 171 kJ/m² (35%). Supercooling of muscles gives only 6 kJ/m² (1.4%). Metabolism heat gives only 20 kJ/m² (4.6%) [13].

Monitoring body surface temperature after WBC procedures in multi-seated units shows that, due to high level of rated temperature in the main cabin, cryogenic gas is not able to remove the proper amount of heat from an object [14, 15]. In all cases the measured temperature of skin surface after the procedure was more than 10° C. It is much higher value than it is recommended according the WBC process modeling [6]. If these requirements are not met the current research' [16] not proving the effects described by the developer in [9] is due to the fact these requirements are not met.

A small amount of heat gained from metabolism allows substantiating exploitation advantages of WBC technique. Firstly, body protection form supercooling is achieved not due to the system of thermoregulation, but due to thermal inertia of BS tissues. Therefore, WBC procedures are suitable for patients of every age and training level. Secondly, patient's system of thermoregulation is by no means necessary to be adjusted to thermal loads during WBC procedures, so there is no reason "to train" patient's body before the short-time procedures. The treatment can be started immediately stat from minimal exposition of 120 sec [7].

The heat of supercooling and the heat of metabolism should be removed form BS for a limited time. An allowable WBC exposition is not more than 200 sec. Known time of cooling allows estimating the power of heat flow power from patient's body surface to cryogenic gas

$$q_{s-1} = \frac{Q_{s-1}}{\tau_{\max}}. \quad (7)$$

An average density of heat flow form BS is 2.38 kW/m² or 3.8 kW per patient. It is approximately 10 times higher the values used in calculation for actual WBC units. It should be also noted that along with the heat coming from patient's body the system of cryostatting should compensate heat gain from other sources.

2. Sources of heat load for cooling system of WBC unit

Heat removed from patient's body is an effective load for cryostatting system. Along with effective load there are always the sources of heat which are not connected with therapeutical effect. Total heat load on CS is the sum of useful Q_{s-1} and useless Q_{us} load:

$$Q_{ful} = Q_{s-1} + Q_{us}. \quad (8)$$

Useless heat load is a combination of the heat coming through thermal insulation Q_{iz} and the heat transferred by gas flows into WBC zone Q_{komw} . The biggest amount of warmer gas comes to WBC zone through the doors. Cabin door are opened twice during the procedure: for patient's entrance and exit. In single-seated cryo saunas an atmospheric air comes through the opened doors. It should be replaced by nitrogen vapors in the beginning of the procedure. The total amount of heat coming by atmospheric air for one procedure into 1 m³ of single-cabin volume is

$$Q_{komw} = \rho_1 c_{komw} (T_{komw} - T_1), \quad (9)$$

where ρ_1 — density of cooling gas at nominal temperature of WBC zone, kg/m³; T_1 — nominal temperature of WBC zone, K; c_{komw} — heat capacity of gas coming into WBC zone, J/(kg·K); T_{komw} — temperature of gas coming into WBC zone, K.

Convective heat gain into the cabin and airlock cumber of multi-seated WBC unit is calculated in an analogous way. Atmospheric air fills the airlock cumber at the patients' entrance and exit to capacity. A relative warm air form lock-chamber (LC) ($t_{LC} = -60$ °C) comes into main chamber (MC), where it is mixed with a cooler air ($-130 \leq t_{MC} \leq -110$ °C) in the ratio of 1/1. Following the mixing air temperature in LC and MC reaches the average temperature level

$$\begin{aligned} \bar{t} &= 0,5(T_{MC} + T_{LC}); \\ -95 \leq \bar{t} &\leq -85 \text{ }^\circ\text{C}. \end{aligned} \quad (10)$$

Due to temperature increase air density in the main cabin decreases by 0.5 kg/m³. After closing the transfer hatch the temperature in MC decreases gradually to nominal level, and air density increases. To maintain normal pressure level additional 0.5 kg/m³ of air should be supplied to the volume. This air comes into MC from LC and adds additional heat. One opening of the transfer hatch between MC and LC results in additional 116 kJ/m³ of heat comes into MC volume with gas flow from LC. As for one procedure the doors between LC and WC are opened twice convection heat gain into MC is 232 kJ/m³ [7]. For one procedure LC filing is repeated twice, 256 kJ/m³ coming into LC volume. Specific heat gain by convection in single-seated cabin is 365 kJ/m³.

Heat comes from thermal insulation of LC and MC. The influence of heat flow through insulation in multi-seated and single-seated unit differs significantly. Multi-seated cabin has a precooling stage of 2–3 hours. At this stage cooling of thermal insulation takes place. During the procedures only the heat transferred by thermal conductivity comes from insulation (47 kJ/m³).

Single-seated unit has no mode of insulation cooling. After each procedure single-seated cabin is filled with atmospheric air, therefore, in the beginning of the procedure the temperature of inner surface equals the temperature of ambient air. During the procedure internal surface of the insulation is refrigerated to the temperature close to the nominal temperature of WBC zone. A great amount of heat accumulated by insulation is released during this process. Negative effect of the insulation is even more pronounced due to by the fact that the volume of single-seated cabin is less than 0.5 m³. In the cabins of small volume the specific surface

of setting is 6.5 m²/m³ compared to only 2.4 m²/m³ for multi-seated cabins. Due to the combined effect of the all above factors specific heat gain form the wall of single-seated unit is 10 times as much as in multi-seated unit (Table 2).

Table 2
Heat gain for one procedure in WBC zone of single and multi-seated unit (kJ/m³)

Sources of heat	Single-seated unit	Multi-seated unit
Convection heat supply	364	488
Heat from patients body surface	1460	279
Heat from or thermal cooling of WBC zone	493	47
TOTAL	2317	814

In Table 2 the values of specific heat gain from patient's body surface are given. In single-seated cabin the gain of specific heat from patient's body surface is five times more. It results from the high compactness of patient's positioning in a cabin. One patient takes 0.5 m³ of single-seated cabin volume. In multi-seated units one patient takes up to 2 m³ of LC and MC volume. Specific heat gain form patient's body surface in single-seated units is 5.2 times as much as in multi-seated ones [7].

The data from Table 2 allow estimating energy efficiency of multi-seated and single-seated units by calculating thermal coefficient of efficiency (TCE)

$$\eta_H = \frac{Q_{s-1}}{Q_{fil}}. \quad (11)$$

TCE for single-seated unit is 0.63, and the one for multi-seated unit is 0.34. Contrary to common belief single-seated units are nearly twice as more economical as the multi-seated unit.

3. Energy consumption to remove heat load from WBC zone

The power of heat flow to be removed form WBC zone is defined from the formula

$$q_{fil} = \frac{N \cdot F_s \cdot Q_{s-1}}{\tau \cdot \eta_H}, \quad (12)$$

where N — the number pf patients in a cabin; F_s — average area of patients body surface, m²; τ — procedure time, s.

For the simplicity we can take $N=1$, $F_s=1.6$ m², $\tau=180$ s. Then, taking into account TCE values, the power of heat flow in multi-seated unit is 11.8 kW, in single- seated 6.4 kW [7].

This heat load should be removed from the temperature level of -130 °C. When the temperature decreases, the energy for heat load removal increases. The ratio of removed power to the electrical energy consumption is referred to as coefficient of performance

$$\varepsilon = q_{fil} / n_e. \quad (13)$$

At the temperature level of -130 °C $\varepsilon=0.25$, that means the power of the cooling system has to be for times as many as the power of the heat load. In single-seated unit a cooling system of 26 kW power is necessary, and for multi-seated unit

the electric power per patient is 47 kW. For five-seated unit a refrigerator of 235 kW power is necessary.

The above results explain why the systems with nitrogen cooling are so popular. At the temperature level of $-130\text{ }^{\circ}\text{C}$ cooling capacity of liquid nitrogen (LN) is $q_{LN}=260\text{ kJ/kg}$. Liquid nitrogen consumption in NCS is defined from the equation

$$g_{LN} = \frac{q_{ful}}{q_{LN}}. \quad (14)$$

For single-seated cabin nitrogen consumption in NCS is 0.025 kg/s or 4.45 kg per procedure. In five-seated unit design LN consumption is 0.025 kg/s or 41 kg per procedure. Such an expenditure of LN can be put into practice, at the same time refrigerators of 47 and 235 kW power require additional costs to connect them to power line [7, 8].

The above values of power or refrigerating medium consumption are much higher than the ones stated by manufacturers, only CRYON single-seated cryo sauna being the exception. In the latter LN consumption pre procedure is 4.5 kg. The power consumption values of the other manufacturers' units is far less than the design ones. The certificate of KR-2005 five-seated unit (Creator Company, Poland) declares that LN consumption per 10 procedures is 100 kg [10]. Insufficient refrigerating medium consumption in NCS is not enough for cryostatting MC at the nominal temperature level; when the patients enter MC the air temperature increases more than by $60\text{ }^{\circ}\text{C}$ and have no time to reach nominal value to the end of the procedure.

The situation with NFCS units is even worse in terms of power supply. Zimmer Midizin Systeme five-seated unit (Zimmer GmbH, Germany) consumes 14 kW of electricity in the main procedural mode. The unit maintains the temperature of $-110\text{ }^{\circ}\text{C}$ only. At such a temperature level coefficient of performance is 0.37, so 14 kW of electric power allows removing 5.2 kW of heat load. In addition, the unit allows only five procedures of three min. per hours, which means the real NFCS load is 0.25 form continuous operation conditions. Taking everything into consideration, NFCS heat removing capacity at the temperature level of $-110\text{ }^{\circ}\text{C}$ increases to 21 kW. However, power shortage is more than 50% under all assumptions [7].

Conclusion

The above analysis of energy and refrigerating medium consumption for WBC procedures demonstrates that for WBC to work in an efficient way it is necessary for power supply of CS to meet the technological heat load.

Calculated NFCS electric power for single-seated cryo saunas is 26 kW. In multi-seated systems 47 kW of for every patient should be provided.

Taking in to account the values obtained the production of effective WBC units with the use of NFCS is unprofitable. Refrigerators with such a power are too expensive, and high-qualified technical personal is required to connect them to electric power grid.

Single-seated cryo saunas with NCS should consume at least 4.5 kg of liquid nitrogen per patient. In multi-seated systems the nitrogen consumption per patient is as less as 8.1

kg, refrigerating medium consumption in precooling mode being not taken into account in calculations.

As insufficient refrigerating medium supply therapeutic reduces effect of WBC procedures it is inadmissible to economize on liquid nitrogen.

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