Heat transfer between human and fluid under extreme conditions of partial body cryotherapy

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Abstract. This paper is aimed to study the cooling gas, cryocabin and skin temperature distributions to clear the partial body cryotherapy dosing. First, an experiment was performed in an empty cabin. It showed the effect of heat flow from the cabin walls to the cooling gas, as well as the distribution of gas temperature in the cabin without the human heat load. Second, an experiment was conducted with a volunteer. It showed the influence of the human heat load on the gas temperature, as well as the relationship between the skin surface temperature and the cooling gas temperature. Also, after the cooling gas supply is stopped, the dynamics of gas in the cabin, the cabin walls and the patient's skin rewarming are considered. Data on the actual temperatures during cryotherapy may help correct current empiricism of cryotherapy protocols.

1. Introduction
Cryotherapy (partial or whole body) – short-term cooling of the human body surface (except for the parts most sensitive to cold, covered with protective clothes). When the patient's head and neck are in normal ambient conditions, this cryoexposure is called partial body cryotherapy (PBC) [1]. However, even in this case, more than half of the patient's body surface is subjected to cryotherapy. The typical duration of exposure is 3 minutes. The aim is to perform skin cooling, lowering the body surface temperature to the minimum safe values, and to achieve a non-specific decrease in the temperature of other biological tissues (fat, muscle, as well as receptors of the nervous system and capillaries of the cardiovascular system), followed by a subsequent response. The patient's body surface temperature can decrease to 0...5 °С. As a cooling fluid, air (or nitrogen-air mixture) is used with an inlet temperature up to -190 °С. Today, PBC is an empirical physical therapy method. PBC causes both local effects (positive effects on joints, skin, etc.) and general effects (training of the nervous and cardiovascular systems) [1].

The lack of a quality standard for cryotherapy equipment leads to the fact that different cabins and chambers provide different and frequently unknown temperature of the gas near a patient [1]. Savic et al. [2] showed that actual temperature in the cryocabin is different from the one reported by the manufacturer. Beaumont et al. [3] also showed that the gas temperature throughout the cabin is much higher than expected. Polidori, et al. [4] noted that more experimental approaches are needed to define the actual temperature that the skin and gas reaches during cryotherapy and then to replace the current empiricism of the cryotherapy protocols. During cryoexposure, this temperature is not constant. On the way to the patient, it rises and has a gradient in height [5]. Exposure time and expected inlet gas temperature of particular cabin or chamber do not fully describe the effect of the procedure. Therefore, cryotherapy often has the low correlation between the desired and the actual effects. To improve dosing it is possible to obtain objective data on the actual gas, cryocabin and skin temperature during
cryoexposure, as well as their correlation. An objective thermal analysis and further comparison of different cryotherapy variants [4] may provide a basis for finding the most appropriate exposure parameters required to achieve the desired effects and in the future to form a quality standard for cryotherapy.

This paper is aimed to study the gas, skin and cryocabin temperature distributions to clear the cryoexposure dosing. For this used one of the most common types of cryocabins for partial body cryotherapy.

2. Materials and methods

The experimental installation consists of three parts: the gas preparation unit, the cryocabin and the data acquisition system. The gas preparation unit is used from the widespread type of liquid nitrogen cryosauna. One of the most famous manufacturer of this type is Krion (Russia). This system is regulated by on-off law. The gas preparation unit had the following settings. When the temperature at the inlet to the cabin reaches -190°C the flow rate of the mixture is 0.03 kg/s. The inlet gas temperature gradually increases. When the gas is heated to -160°C, the gas flow rate increases to 0.06 kg/s. At a base flow rate (0.03 kg/s) the inlet gas velocity is about 2.7 m/sec (45 cm²), outlet one is 2.5 m/sec (48 cm²). This supply method is related to the design features of this gas preparation unit, which contains a vapor generator with periodic filling of liquid nitrogen.

Criocabin (Figure 1) is developed for this experiment. This is a hexagon with a external side of 560 mm and a height of 1600 mm. The diameter of the circle at the top is 600 mm. It is similar to cabins for partial body cryotherapy. The gas inlet and outlet are located at the level of the gas preparation unit supply ducts. During the procedure, the cold nitrogen-air mixture up to the shoulders surrounds the patient. The internal volume filled with gas and the patient is 1.15 m³. The cabin frame is made of high moisture resistance laminated plywood coated with phenolic film, 9 mm thick (density – 600 kg/m³, heat capacity – 1004 J/kg/K, thermal conductivity – 0.12 W/m/K). Then there is an air layer of 4 mm (density – 1.18 kg/m³, heat capacity – 2500 J/kg/K, thermal conductivity – 0.026 W/m/K). Next, thermal insulation (expanded polystyrene) with a thickness of 30 mm (density – 40 kg/m³, heat capacity – 1450 J/kg/K, thermal conductivity – 0.035 W/m/K). The cabin has a closed circuit, the cracks are glued.

The data acquisition system has ICP CON I-87k9 controllers. To measure the gas temperature, two types of sensors are installed. The first is the RTD RT100A resistance thermometer (Heraeus Sensor Technology): electrical resistance is 100 Ohm, material – platinum, temperature coefficient of electrical resistance is 0.00385 °C⁻¹, measuring range is from minus 196 to 150 °C, class A, type – thin film. Due to the lack of a protective housing, the sensor has a low-inertia. The second is a needle-type thermocouple Single-Point 1.5 Thermal Sensor (Galil Medical). Materials: thermocouples – copper-constantan, housing – stainless steel, inside there is a tip made of bronze. Each gas temperature measurement point contained both types of sensors. This is done to reduce the impact of measurement error. The instrumental measurement error is not more than ±2 °C. The thermal insulation temperature is measured only by thermocouples. The location of the measurement points is shown in figure 1b, the distance from the wall is 145 mm.

Also, a thermographic IR-camera Flir P640 was used and allowed the capture of high resolution thermographic images of skin temperature. Thermal sensitivity of the camera is 0.04 °C at 30 °C. Detector type is focal plane array (FPA) uncooled microbolometer 640x480 pixels. Spectral range is from 7.5 to 13 μm. Temperature ranges is from -40 °C to +500°C. Accuracy is ±2°C. Repeatability – 1% of the absolute temperature is not worse than 1 °C. Thermal imaging was completed from a distance of 3.1 m with the emissivity set to the 0.97. Air temperature is 24.3 °C, reflected temperature is 20 °C, relative humidity is 45%. Data from the camera was interpreted with commercially available software.

Two experiments were conducted. The first one presents data on gas and thermal insulation temperature in the absence of a human. Cooling time is 9 minutes. The second one presents the results of measurements of gas, thermal insulation temperature, as well as thermal images of the surface of the volunteer's body placed in the cabin. The duration of cooling is 3 minutes (at the same time, at about 150 seconds, the volunteer reported a characteristic skin tingling of the legs and back, which
indirectly indicates the local achievement of the target exposure temperature). The volunteer of the experiment was a man (age – 33, height – 177 cm, weight – 71 kg). During the exposure, volunteer wore briefs, gloves and felt boots. The exposure protocol contained acclimatization to room temperature, a thermogram before exposure, cryoexposure, a thermogram inside the cabin immediately after switching off the gas supply, a thermogram after exiting the cabin and for 15 minutes after.

![Human position](image1.png)
(a) Human position

![Location of temperature sensors](image2.png)
(b) Location of temperature sensors

**Figure 1.** Cryocabin.

3. Results & Discussion
The temperature of the cooling gas is shown in Figure 2. Only RTD PT100 sensors measurements are shown. Data received from thermocouples have a deviation from them of no more than 4 °C and a large temperature inertia. They are used to check the adequacy of measurements and to reduce the impact of random errors. The inlet gas temperature is the same in both experiments. Heating cycle of incoming cooling gas from -190 to -160 °C and subsequent cooling back to -190°C in the human experiment is 18% shorter. This is due to the fact that the heat load is higher and therefore the gas heats up faster. In the first experiment (without a human), the gas inside the cabin was divided into 2 parts: above and below the level of the inlet and outlet of the cooling gas. In steady mode, the gas temperature in the lower part was -126...-131 °C. The sensor with a temperature of about -140 °C was located near the cooling gas inlet. The sensors on top of the cabin had a higher temperature and a trend of increasing it to -110 °C. This is due to the fact that without a patient in the cabin, the amount of gas is excessive for its cooling and the gas circulation from the inlet to the outlet sucks the air out of the room. Cold gas slows down below the input and output levels, and at the outlet gas has an even more pronounced trend of temperature increase as the intensity of the heat load decreases (to -30 °C). Figure 2 also shows the rewarming of the gas in the cryocabin after the supply is turned off. In a second experiment (with a human), at the end of cryoexposure (at 180 seconds), the gas temperature was -92...-124 °C. It is higher than at the same moment without human heat load, but not significantly, because the total consumption of cooling gas is greater. Due to the heat load from the human, the cooling of the gas in the cryocabin is slower, and the rewarming of the gas is faster. But the general trends are the same. Since the experiment was started in a cryocabin at room temperature, it is possible to analytically adjust the duration of the experiment in order to compare the results of human cooling with the experiment with preliminary cabin cooling. If you need to cool the walls of the cryocabin, the total cooling time of the person needs more. However, even in this case, it will take at least 300 seconds to stabilize the gas in this cabin. For cabins with other dimensions stabilization time of the gas temperature under thermal load and its uniformity along the height may vary. In both cases, the final difference in gas temperature in the cryocabin and at the inlet of the cooling gas is
about 50 °C. Considered cryocabin has a large area of the walls than usual. Because of this, the total heat flow through the cabin walls may be higher, but there are no significant differences with [2, 5].

![Figure 2. Cooling gas temperature.](image)

Figure 3 shows the temperature of thermal insulation (the walls of the cryocabin) from the beginning of its cooling, to the moment of complete rewarming after the cooling gas supply is stopped (without opening the cryocabin door). Points 1-4 are located near the cooling gas outlet. The velocity of gas at the wall there is low. They show the average temperature of the thermal insulation during the cryoexposure performed without pre-cooling the cabin, which is usually carried out before the procedure with a person. After the pre-cooling, the starting point of the thermal insulation temperature will shift to the right. On the basis of lines 1-4 two conclusions can be drawn. First – to complete the cooling process of the cabin, it is necessary to supply cooling gas at least 5-10 minutes, which significantly increases the power consumption. With a shorter cooling time at the beginning of cryoexposure, thermal insulation significantly increases the temperature of the cooling gas inside the cabin, and thus changes the conditions for dosing. The second – when there is a pause between the pre-cooling and the start of the procedure equal to the time of pre-cooling, the effect of its disappears. This should be taken into account when planning the cryotherapy dose, as well as to increase the energy saving of PBC. Also, a person heats the cryocabin inside with thermal radiation. Then this heat flows to the cooling gas. In the second experiment, compared to cooling an empty cabin, the temperature after 180 seconds of cooling at point 1 was -32 °C (without a person was -39 °C), at point 2 it was 2,0 °C (without a person it was 1,1 °C). Therefore, this effect applies only to the inner half of the insulation. Points 5-8 are located near the inlet area of the cooling gas, which flows intensively around the insulation surface there. These are the minimum values of the thermal insulation temperature. To avoid excessive cooling of the cabin walls, it is necessary to avoid directing the inlet flow to the walls of the cryocabin. This will increase the energy saving of PBC.
Human body temperature is shown in Figures 4-6. Figure 4 (a, b) shows the results of measuring the surface temperature of the human body before cryotherapy (average temperature was 33.2 °C). The temperature at the end of the cryoexposure at 180 seconds (in the local region) is in Figure 5. The color shows the skin temperature (areas with a temperature up to 2.2 °C – control point Sp6). Black spots – hair (control point Sp7), self-adhesive gauze bandage, wires of temperature sensors, walls of a cryocabin. It shows areas with a temperature of less than 6.4 °C (including a section with a minimum temperature – 2.2 °C, control point Sp6) and warmer spots (control point Sp5). Colder areas of the skin were observed in areas of more gas velocity. In them, the volunteer felt the tingling sensation (lower back and front, legs). This correlation of sensations and temperature can be considered as the achievement of the target temperature. Frostbite of the skin and vascular spasm (temporary bleaching of the skin) were not observed. Figure 4 (c, d) shows the measurement results of surface temperature of the human body after cryoexposure (pause about 10 seconds between the end of the cooling gas supply and the front shot, back shot in another 5 seconds). They have (marked with dots) areas of lowest temperatures (all minimums are less than 9 °C). Therefore, during the time interval between the images of Figure 5 and Figure 4 (c, d), the most cooled parts partially warmed up. Since the cooling of biological tissue during PBC is shallow (due to the heat flow from body core and the low thermal conductivity of the fat layer – about 0.2 W/m/K), then at the beginning rewarming occurs quickly. Spots of minimal skin temperature immediately at the end of cryoexposure are expected to be larger. Thermograms were also made after cryotherapy (within 15 minutes). The obtained thermograms are consistent with [4, 6]. Based on the results obtained, a temperature history of cryoexposure was made (figure 6). The average skin surface temperature and its limit values are shown. However, it should be taken into account that the signal received by the thermal camera includes radiation not only from the external surface of the skin, but also from inside it. Therefore, the absolute surface temperature may differ (although no damage was detected, so it did not fall below the cryoscopic temperature). At the same time, the comparison of thermograms also shows the dynamics of changes in the object's temperature from the beginning to the end of cryotherapy.

This paper contains the results of single measurements in one of the modern types of cryocabins. They are obtained simultaneously and, therefore, show the relationship between the temperatures of the gas, the walls of the cryocabin and the human skin. In the future, it is necessary to increase the number of experiments with volunteers (various body mass indices, gender, age, etc.), to study the influence of the inlet, outlet of cooling gas and the size of the cabin on the skin temperature, to calculate the temperature distribution inside the biological tissue, and finally to optimize the conditions for supplying cooling gas in order to set the dose of cryotherapy in more detail and develop a standard for the quality of equipment.
4. Conclusion

In this paper, preliminary data on the dynamics and temperature distribution of the cooling gas, in the walls of the cryocabin, of the human skin during PBC are experimentally obtained. This information is expected to be useful for energy saving and improving the accuracy of PBC dosing. We hope that the information obtained will help to improve the quality of medical care using low temperatures.
Figure 5. Thermogram of human body inside the criocabin at 180 seconds of cryotherapy.

Figure 6. PBC temperature history.

5. References

[1] Bouzigon R, Grappe F, Ravier G, Dugue B 2016 Whole- and partial-body cryostimulation/cryotherapy: Current technologies and practical applications Journal of Thermal Biology 61 pp 67–81

[2] Savic M, Fonda B and Sarabon N 2013 Actual temperature during and thermal response after wholebody cryotherapy in cryo-cabin Journal of Thermal Biology 38 (4) pp 186–191

[3] Beaumont F, Taiar R, Bogard F, Murer S, Anger D, Bouchet B and Polidori G 2018 Partial body cryotherapy in confined cryosaunas: Effects of inherent thermal stratification Series on Biomechanics 32 (2) pp 12–17

[4] Polidori G, Taiar R, Legrand F, Beaumont F, Murer S, Bogard F and Boyer F C 2018 Infrared thermography for assessing skin temperature differences between Partial Body Cryotherapy and Whole Body Cryotherapy devices at −140 °C Infrared Physics and Technology 93 pp 158−161

[5] Leonov V P, Kolishkin L M, Voronov V A and Shakurov A V 2018 Experimental and computational study of the vertical axis temperature gradient of the liquid nitrogen individual cryo-cabin Refrigeration Science and Technology pp 91–96

[6] Costello J T, McInerney C D, Bleakley C M, Selfe J and Donnelly A E 2012 The use of thermal imaging in assessing skin temperature following cryotherapy: A review Journal of Thermal Biology 37 (2) pp 103–110

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