The cost of liquid nitrogen for WBC sessions

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Abstract. The first unit for the whole-body cryotherapy (WBC) used liquid nitrogen (LN). Liquid nitrogen has a low boiling point (-196 °C) and a high heat sink capacity (HSC). The HSC of LN is 260 kJ/kg at a temperature level of -130°C. Approximately 600 kJ of heat should be removed from the body surface of a patient during a WBC session. The average heat flux from the body surface makes up 3.4 kW. The use of liquid nitrogen makes it possible to remove heat without complicated equipment. Refusal to use LN is caused by the temperature in the WBC zone (-110 °C), This fact reduces the efficiency of WBC procedures. Cryoagent consumption is 5 times less than the demand in some units with LN coolings.

1. Introduction

The apparatus for the whole-body cryotherapy (WBC) is the most expensive type of the cryomedical equipment. High costs for the acquisition and operation of WBC units limit the availability of cryotherapy procedures for the public. In 1985, the approximate price of the first Japanese cryotherapy unit was $ 2 million. This was approximately 6 million dollars in 2018 [1]. The high cost of original equipment has become an insurmountable barrier for European consumers. Due to the high price of Japanese WBC units their purchase by European clinics was not even considered. Instead, European companies tried to make similar devices on their own. A lot of current WBC problems were initiated by this decision since European developers had only the superficial information about the device and the operating principle of the original equipment. As shown in the 21st century studies, the algorithm of the nitrogen cooling system of the units used by T.Yamauchi to implement the technology was not taken into account in the design. The change in the basic operating principles of the nitrogen cooling system (NCS) did not allow reproducing the temperature regime of the original WBC units. Thus, the European WBC devices resembled the original units but did not maintain the optimum temperature in the main treatment cabin.

In addition, the price of European WBC equipment remained too high. During operation of these units with NCS a lot of liquid nitrogen was consumed. The LN costs significantly increased the cost of procedures. The desire to reduce the operating costs and make the procedures more affordable resulted in appearance of cryotherapy units with “nitrogen-free cooling systems” (NFCS) in Europe in 1990 - 1995. The NFCS is based on refrigeration machines. The independence from LN supply has greatly simplified the operation of the WBC units. The operating costs have decreased significantly. However, the gas temperature in the main cabin does not drop below 170 K in the WBC units with the NFCS.
This is considerably higher than the air temperature in the original Japanese unit (100 K). The fact that the air temperature in the WBC zone has increased by a factor of 1.7 has fundamentally changed the effect of the procedure on a patient’s body. The effectiveness of the WBC procedures has become 10 times lower [2].

At the current stage of WBC development the NCS technology is the only workable version of heat removal from the WBC zone. To substantiate the advantages of nitrogen cooling systems, the operating principle of the original Japanese WBC unit is to be considered in detail.

2. Nitrogen cooling system of multi-seat WBC units
The NCS was used on the first units for the WBC procedures. These devices were designed to carry out WBC group procedures. There were from 5 to 10 patients at the same time in the cabin. The design of a multi-seat WBC unit is identical to the design of a cold room for long-term food storage. To maintain a cryogenic temperature level, liquid nitrogen was supplied to the heat exchangers of multi-site WBC units instead of freon. The use of the NCS made it possible to abandon energy-intensive equipment. The energy required to conduct the WBC procedures is expended in liquid nitrogen plants. To hold WBC exposure for one patient, it is necessary to remove about 600 kDj of heat within 3 minutes at a temperature level no higher than 140 K. Under such conditions the average heat flux from the patient body is 3.4 kWt. For removal of such heat flux at the temperature level of 140 K a refrigerator with an electric drive power of 13 kW is required. The use of LN eliminates the need for the WBC owner to connect the powerful cooling systems to the electric power network and to operate them. This is particularly relevant for the multi-seat WBC systems [3].

The multi-seat WBC units with the NCS provided first data on the therapeutic possibilities of cryotherapy. The information about the possibility of successful treatment of rheumatoid arthritis (RA) was of special interest to doctors. The WBC procedures relieved patients from pain and stiffness in joints for 6 hours. T. Yamauchi, the author of the WBC method, used up to three cryotherapy procedures per day to treat the RA. Thanks to the effect of the WBC procedure the patients could do remedial exercises which in turn provided RA treatment [4].

Today the multi-site WBC units with the NCS are used only in Poland. Most of the multi-site units are cooled with the NFCS. The refusal to use the NCS took place for economic reasons. The use of the NFCS led to a sharp increase in the air temperatures in the WBC zone which fundamentally changed the cold air effect on the patient’s body. The recent research of the WBC with the NFCS does not show a lot of positive WBC effects described when using the units with the NCS. Thus, the WBC method is discredited.

The NCS is widely used for the WBC procedures in single units. These units were developed in Russia at the end of the twentieth century. The single WBC units with the NCS are known under the “cryosauna” trade name. The NCS is the basis for the competitive and therapeutic benefits of the cryosaunas.

Twenty-year clinical application of the cryosaunas has shown that their therapeutic effectiveness is similar to that of the original Japanese units. This is related to the high heat dissipation capacity of the NCS. The current WBC units with the NCS made in Poland are 2 to 2.5 times less effective as compared to the original Japanese units. This loss of efficiency is connected with modification of the operating principle of the NCS and inadequate consumption of LN.

With the similar operating principle of the NCS the WBC technology of the cryosaunas differs significantly from that of the multi-seat devices. It is useful to determine these differences for further development of the WBC technology.
2.1. Cooling system for Japanese WBC units

Published works about the Japanese WBC units operating mode contain conflicting information concerning the temperature in the main low-temperature chamber.

There are different data on the temperature in the publications: -186°C (87 K), -175°C (98 K) and -160°C (113 K) [5]. This uncertainty confuses the issue of the temperature conditions of the device. Taking into account the complex algorithm of the device, it is unclear at which procedural stage the temperature is measured. An inaccurate description of the temperature conditions has caused the errors in the assessment of the main factor of cryotherapy – the gas temperature in the WBC zone. Cryogenics specialists suppose that it is impossible to maintain the temperature of 87 K in the treatment cabin. The surface temperature of the cooling coil of the heat exchanger should be at least 10 K lower than the air temperature (77 K). However, the surface temperature of the heat exchanger shall be not less than 82 K to prevent air condensation on the heat exchanger surface. When designing the European cryotherapy systems, the nominal air temperature in the WBC zone was assumed to be -160°C (113 K). This decision led to a number of negative effects which significantly reduced the effectiveness of the WBC units manufactured in Germany and Poland.

A universal mathematical model of the WBC unit was developed at ITMO University which allowed simulating the full cycle of operation of the multi-site WBC unit with the NCS. It is found that the air temperature in the main (low-temperature) cabin of the WBC device can be reduced to the level of 85-87 K. The reduction can be achieved using the minimum thermal load on the heat exchanger with the NCS. The minimum thermal load is observed when patients are absent [6].

![Diagram of temperature conditions](image)

**Figure 1.** Temperature conditions of the main cabin of the Japanese unit for the WBC in the absence of patients and in the presence of patients.

The figure (Figure 1) explains the operating principle of the NCS under changing conditions of the thermal load. Cold air I is located inside the insulated cabin II. Heat flow with a density of \( q_{at} = 20 \) W/m\(^2\) penetrates from the atmosphere through the thermal insulation of the cabin II. Considering the standard dimensions of the multi-cabins for the WBC (2x2x2 m), no more than 500 W of heat penetrates through all walls of the cabin II. This heat warms up the air I. Natural convection arises in the cabin. Air movement transfers heat supplied from the atmosphere to the surface of the heat exchanger IV. The heat exchanger IV consists of a large number of metal plates cooled by pipes passed through them. Liquid nitrogen is inside the pipes. The LN boiling point depends on the pressure in the heat exchanger pipes.
To ensure that the air does not condense on the heat exchanger plates IV, the temperature of the plates shall be higher than the air condensation temperature $T_{\text{HE}}>T_{\text{AI}} = 81$ K. To fulfill this condition, the nitrogen vapour pressure in the pipes of the heat exchanger IV is to be more than 0.05 MPa. The boiling point of nitrogen is $T'_{\text{LN}} > 81$ K. The surface area of the heat exchanger IV is calculated taking into account the maximum thermal load which increases 20-30 times in the presence of the patients. With a low thermal load, the air temperature drops to the values close to the surface temperature of the heat exchanger IV which tends to equilibrate with LN boiling in the pipes $T_{AI} \rightarrow T_{\text{HE}} \rightarrow T'_{\text{LN}} > 81$ K. Under such conditions, the air temperature inside the main cabin of the multi-seat WBC unit can drop to 85 - 87 K. The operation of these devices starts with a cooling mode which takes 2-3 hours. During this mode the NCS cools down the cabin walls II. At the end of the cooling mode the air temperature reaches its minimum value and the temperature of the inner surface of the cabin walls is close to the air temperature $T_S \rightarrow T_{AI} \rightarrow T_{\text{HE}} > 81$ K. After completion of the cooling process the unit goes into the procedural mode in which the thermal load on the NCS depends on the presence of the patients in the cabin. As a rule, the duration of patients’ stay in the cabin does not exceed 50% of the total duration of the procedural cycle. The thermal load is reduced and the NCS restores its temperature equilibrium reached in the cooling mode.

The thermal equilibrium of the cabin is disturbed at the moment of patient II entry (Fig. 1). The warm air from the intermediate chamber ($T_{AI} = 210$ K) penetrates through the open doors of the cabin when the patients enter. As a result of air movement in the main cabin, the average temperature is set $T_{AI} \approx 148$ K.

Owing to the high temperature difference between skin and air ($\Delta T_{\text{SK-AI}} \approx 150$ K) a significant amount of heat is released from the surface of the patients' bodies. The heat intake from one patient is more than 3 kW. Due to the penetration of the warmer air from the pre-chamber and the heat supply from the patients' bodies the air temperature in the main cabin and the heat load on the heat exchanger IV are sharply increased. There is a reserve of liquid nitrogen in the heat exchanger pipes which maintains a constant temperature of the metal pipes. Owing to this the temperature of the heat exchanger plates IV does not rise significantly and the temperature difference between the heat transfer plates and air increases to $\Delta T_{\text{AI-HE}} \approx 75$ K. With such temperature gradient, the intensity of heat removal from the air in the cabin increases 20 to 30 times which results in gradual lowering of the temperature. The thermal equilibrium can be established within 30-60 s at the sufficiently large area of the heat transfer surface of the heat sink surface. This process is somewhat facilitated by the fact that the temperature of the cabin walls III is lower than the air temperature at this stage. In the empty cabin the air temperature is about 87 K, so the inner surface of the walls has a temperature lower than 95 K. The heat transfer to the surface of the heat exchanger IV and the cabin walls III reduces the air temperature from 150 K to 100 K [7].

The air temperature in the main cabin of the WBC unit is set at 87 K when the cabin is empty and at 100 K when the patients are in the cabin. The algorithm of the air temperature change in the WBC zone of Japanese units can be reproduced in practice, so the doubts about the reliability of the air temperature data in the zone given by T. Yamauchi are unreasonable.

Due to the fact that the air temperature reaches a minimum permissible level in the empty cabin, it is possible to compensate for the sharp increase of the thermal load at the moment when the patients enter the cabin. The heat exchanger pipes IV are constantly filled with liquid nitrogen, so the increase of the thermal load is compensated by intensive boiling of the cryoagent.

The use of the NCS in the first WBC units was critical for achievement of the therapeutic effect. Due to the large heat removal capacity the NCS compensated for all design and manufacturing imperfections of the multi-site WBC systems.
The thoughtless reconstruction of the nitrogen cooling systems has led to deterioration of European multi-seat systems.

2.2. European multi-seat units with NCS for WBC

In the design of the European units with the NCS the nominal temperature in the WBC zone was assumed to be -160°C (≈ 115 K), i.e. above the temperature level in the Japanese units at the time of the procedure. The increased nominal temperature has significantly changed the operating principle of the NCS. To maintain the air temperature at 115 K in the empty cabin, LN should be fed into the heat exchanger IV in portions. The heat transfer from the air to liquid nitrogen is carried out only in some part of the heat exchanger IV. It ensures thermal equilibrium at a given temperature level. LN supply is controlled by the temperature control system (TCS) which was unavailable in the Japanese units. When LN is fed in portions the heat exchanger pipes are periodically cooled to a level of 81 K. Pipe cooling leads to cooling of the heat exchanger plates and to the increased removal of heat from the air in the cabin. The air temperature drops below 115 K and the TCS stops supplying LN to the heat exchanger. In the empty cabin, when the heat input to the heat exchanger IV is small, LN is virtually not supplied. As a consequence, the temperature of the plates and pipes of the heat exchanger tends to the nominal air temperature. The temperature difference between the inner surface of the pipes and boiling LN can exceed 16 K [8].

When the patients enter the cabin the air temperature sharply increases to 160 K. The TCS resumes the supply of LN to the heat exchanger. Due to the fact that the temperature of the heat exchanger pipes exceeds the boiling point of LN more than 16 K, cryoagent boiling goes to the ineffective "film" mode. A vapour layer is formed between LN and the inner surface of the pipe wall which poorly transfers heat. The efficiency of the heat transfer to LN is 10-20 times lower and the cryoagent has no time to evaporate in the heat exchanger pipes. A combination of the above-mentioned negative factors may result in the air temperature increase in spite of the supply of LN to the heat exchanger.

Due to the low-efficiency NCS operation with nitrogen control using the TCS, the air temperature does not fall below 160 K in the presence of the patients. The WBC procedure is performed at the air temperature 55 K higher than that in the original Japanese units. The inefficient boiling mode results in the large LN consumption which requires additional financial costs.

The shortcomings of the NCS operation described above led to the development in the 1990s of "nitrogen-free" cooling systems which could maintain the nominal temperature not exceeding 160 K. The NCS continued to use only in WBC units made in Poland where the nominal temperature was 170 K. Nowadays the researchers note that some WBC effects described by T. Yamauchi are reproduced with the Polish NCS units, while application of the units with the NFCS makes it possible to achieve the WBC efficiency comparable to that of hypothermic procedures [9].

2.3. Liquid nitrogen consumption estimation for multi-seat WBC units with NCS

Another reason for the low efficiency of the multi-site WBC units with the NCS is insufficient supply of the cryoagent. NCS developers underestimate the intensity of heat transfer from the patient's body surface. When calculating the LN consumption, only the heat is taken into account which a living organism produces by means of metabolic reactions. At a daily calorie intake of 3000 kcal the heat flow from the body to the environment is only 150 W. It appears from the NCS characteristics of the modern WBC units that the designers increase this value by half when evaluating the heat production by the patients. In fact the metabolic heat is less than 5% of the total heat release from the patient's body surface. The main heat supply is provided by heat capacity of skin. One patient emits up to 600 kJ of heat within 200 seconds, which creates a thermal load of 3 kW.

It is not hard to calculate that during the WBC 5 patients release 3000 kJ of heat to the treatment cabin volume. 15 kg of LN are required so that the NCS can compensate for this thermal load. In the
multi-seat WBC units the heat emission by the patients provides only 50% of the thermal load on the NCS, so each procedure requires 30 kg of LN. This condition is not satisfied in practice.

The Polish unit KR-2005N designed for 5 patients carries out 10 WBC procedures per hour. As reported by the manufacturer, the LN consumption is only 100 kg / h (10 kg per a procedure). Inadequate LN supply reduces the NCS efficiency. When the patients enter the cabin the temperature in the WBC zone rises by 40-50 K which reduce the procedure efficiency [10].

To restore the operating efficiency of the WBC units with the NCS, the LN consumption shall correspond to the heat load.

3. Conclusion

The multi-seat units are mostly used for the WBC procedures in Western Europe. In recent years a growing number of articles has been published claiming that the WBC provides no curative effects. The reason for these statements is that the WBC devices with the NFCS with a nominal temperature of not less than 160 K are used for the studies.

The researchers who apply the devices with the NCS find some WBC effects but the duration of such effects is 2 to 3 times lower than expected.

The reason for the low efficiency of the WBC units with the NCS is misuse of LN.

To restore the efficiency of the multi-seat WBC units, the NCS is to be used which maintains the air temperature of 90 K in the empty treatment cabin.

It is necessary to develop LN logistics technologies, to automate the cryoagent supply systems and to use large volume tanks for the cryoagent.

The use of the secondary sources of cooling capacity for cheap cryoagent production would be the right decision so as to reduce the costs for liquid nitrogen purchase.

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