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USING THE PELTIER EFFECT FOR INTRAVASCULAR COOLING OF DONOR ORGANS

Yaroslav Zabilo
yarzab55@gmail.com
Vladyslav Shlykov
v.shlykov@kpi.ua
Svitlana Vovianko
sivovianko@gmail.com
Department of Biomedical Engineering
National Technical University of Ukraine
“Igor Sikorsky Kyiv Polytechnic Institute”
Kyiv, Ukraine

Abstract *– This work is devoted to the problem of perfusion preservation of donor organs under conditions of controlled cooling. For the purpose of cooling is promising to use the Peltier effect. In particular, the Peltier effect is one method of cooling that can be used to preserve and transport organs from donors to recipients. One of the advantages of using the Peltier effect is that this method does not require the use of additional liquid coolers, which allows you to avoid potential problems related to contamination of organs or disruption of their structure. In addition, cooling by means of the Peltier effect is quite efficient and can be controlled by changing the electric current. A separate problem is the development of the design of the intravascular cooling system to preserve the viability of the organ intended for transplantation, taking into account its characteristics. The developed insulated container with cooling system has good thermal insulation. To evaluate the efficiency of the cooling system, the calculation of cooling losses was carried out. According to the performed calculations, for cooling the solution with which the donor organ is perfused, it is advisable to use Peltier elements, that possible to develop a compact and inexpensive system for viability of donor organs. The use of such a system increases the viability of transplants, reduces the probability of ischemic and ischemic-reperfusion injuries accompanying the process of donor organs preservation.*

Key words *– peltier effect, transplantation, transportation of donor organs, organ viability, cooling system, Peltier element, temperature stabilization.*

I. INTRODUCTION

Organ transplantation, unlike blood transfusion, is a serious surgical intervention with the use of drugs to suppress the immune system (immunosuppressant’s, including corticosteroids) and the possibility of infection or rejection of the transplanted organ. Tissues and organs obtained from living donors are more preferable because they are usually healthier. Stem cells (from bone marrow, umbilical cord blood, or venous blood) and kidneys are tissues that are most often taken from living donors. Living donors can provide only part of the liver, lung or pancreas. Some organs, for example, the heart, cannot be obtained from a living donor. Organs obtained from living donors are usually transplanted within a few minutes after removal. Donor organs outside the body remain viable only for a few hours. Other organs can remain viable for several days if they are placed in the cold. The main limitations of the viability of transplants received from donors with extended criteria are ischemic and ischemic-reperfusion injuries accompanying the process of organ removal and preservation [1]. These damages also weaken the recovery potential of such organs, which already have lifelong degenerative changes associated with the patient's age (interstitial fibrosis, glomerulosclerosis, atherosclerotic damage to arterioles) and preceded the death of the patient. The main problem of transplantology (contradiction between the need for transplants and the number of performed operations) is the problem of a sufficient number of optimal donor organs, which can be solved by using means of mechanical life support in the organs and organ complexes from deceased person [2]. Extracorporeal technologies (heart-lung bypass machine) make it possible to eliminate the problem of the vulnerability of donor organs to ischemic damage, which cannot be solved by traditional approaches. In practice, there is a need for development and implementation of systems for perfusion preservation and restoration of viability of donor organs. This work is devoted to the problem of perfusion preservation of donor organs under conditions of controlled cooling.

II. OBJECTIVE OF STUDY

The purpose of the work is increasing the results of transplants due to reliable support of the viability of donor organs at the stage of transportation.

III. ANALYSIS AND STATEMENT OF THE PROBLEM

Organ transplantation is a major surgical intervention with the use of drugs to suppress the immune system and the possibility of infection, rejection of the transplanted organ, and the occurrence of other serious complications, including death [3]. Some organs, such as the heart, cannot be obtained from a living donor, so the problem of their delivery to the recipient arises. For the transportation of donor organs, preservation is used, which is mainly provided by hypothermia, under which conditions the metabolic activity of tissues decreases, reserves of adenosine triphosphate (ATP) are preserved, and the formation of free radicals in the reperfusion phase is prevented [4]. To reduce damage to isolated organs and tissues removed from the donor's body, three main preservation methods are used:

– normothermic perfusion – maintenance of metabolic processes at the initial (optimal) level due to continuous delivery to the organs of oxygen and nutrients in conditions of normothermia [5];

– hypothermic perfusion and static conservation – maintenance of exchange processes at a reduced level due to cooling to subzero temperatures [6];

– freezing at negative temperatures (cryopreservation) is the most complete, reversible cessation of metabolic processes in cells [7].

The choice of method and specific method of preservation of organs and tissues is determined by their structure, intensity of metabolism and performed function [8]. It is believed that perfusion systems with pulsatile supply of perfusate allow not only to improve the functioning of transplants in the early and remote post-transplantation periods, but also to increase the number of donor organs suitable for transplantation due to their post-ischemic rehabilitation during perfusion [9].

For the purpose of cooling, devices of various complexity are used, the functioning of which is based on a number of physical phenomena. It is promising to use the Peltier effect [10], which is implemented in the corresponding elements.

The technical characteristics of the TEC1-12706 elements available on the market make it possible to develop a compact and inexpensive system that should ensure cooling of the donor organ with constant circulation to a temperature of 4–6°C and maintaining this mode for 8 hours. The advantage of the Peltier element is its small size, the absence of any moving parts, as well as gases and liquids. When changing the direction of the current, both cooling and heating are possible – this makes it possible to thermostat at an ambient temperature both above and below the thermostating temperature [11]. The main problem in the construction of Peltier elements with high efficiency is that the free electrons in the substance are simultaneously carriers of both electric current and heat. This is due to the fact that in addition to Peltier heat, Joule heat is always released, which partially covers the cooling effect. On the other hand, with the same amount of heat released as a result of the Peltier effect on one contact and absorbed on another, the temperature difference between the contacts will be greater, the smaller the heat transfer from the hot end of the conductor to the cold, that is, the smaller the coefficient of thermal conductivity [12]. The material for the Peltier element must have two mutually exclusive properties at the same time - it conducts electric current well, but it conducts heat poorly, otherwise the temperature effects will be leveled.

IV. SYSTEM OF PRESERVATION DONOR ORGANS

The system of preservation donor organs is implemented on the basis of a thermally insulated box and Peltier cooling elements to maintain a constant cooling temperature [13].

To improve the system of preservation donor organs [13], the operation of the thermoelectric cooling element TEC1 with a capacity of 60 W (Peltier element) was investigated depending on various conditions (voltage, presence of heat dissipation, presence of liquid in the heat exchanger). Cooling was carried out using an aluminum radiator, which was in contact with the entire area of the hot side of the TEC1 element and the computer cooler attached to it.

Figure 1 shows an experimental cooling system, as a heat exchanger – an aluminum water block 4×4×1 cm with a wall thickness of 1 mm.

As a simulation of the organ, there is a 150 ml container with water, which is placed in the middle of the container, which is covered with a 1 cm thick foam insulation layer for cold preservation.

The main elements of the system are a pump, a cooler, a Peltier element, as well as a thermostat that automatically controls the temperature. A transformer and a diode bridge are needed to rectify the current from the mains. Under ideal conditions, the battery should be used.

Table 1 and table 2 show the effect of using a heat exchanger with a volume of 16 cm^3 in a circulation system with a pump with a capacity of 300 ml/min.

Table 1. Study of the functioning of Peltier elements

Work time, min	Temperature, °C
10	10.6
20	9.8
30	9.5
40	9.2
50	9.0
60	9.0

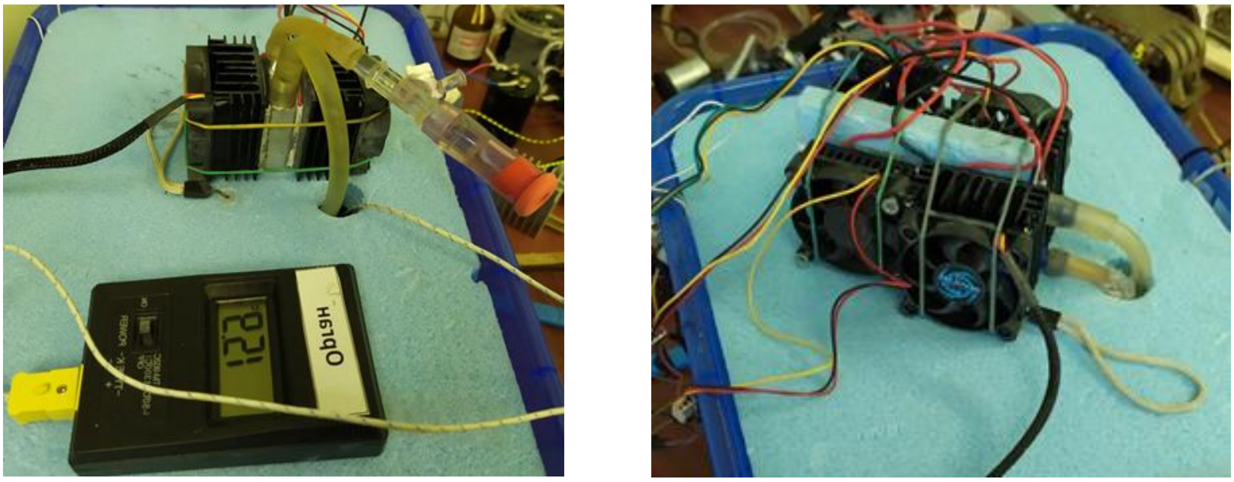
Four Peltier elements, 2 pairs connected in series, are complete with radiators (160 cm^2 each) and coolers.

Table 2. Productivity of circulation system with a pump

Productivity is reduced, %	up to 200 ml/min
70	9.0
80	8.9
90	8.8

The supply voltage is 7 V for each element separately, 14 V for a pair. The initial temperature is 20°C.

Therefore, the technical characteristics of the Peltier elements make it possible to develop a compact system with the maintenance of a constant cooling temperature 9°C – 10°C.



a) b)

Figure 1. – Isolated system with a water block 4x4x1cm:
a) Peltier elements for isolated system; b) Water box for isolated system

V. CALCULATION OF COLD LOSSES

To evaluate the efficiency of the cooling system, the calculation of cooling losses was carried out.

Let's find the value of cold losses for tubes 20 cm long:

$$Q_{\text{ТР}} = L \cdot q = 0.2 \cdot q \qquad (1.1)$$

where L – length of tubes, m; q – heat losses per meter in one hour, W/m.

Let's calculate the heat loss per meter in one hour:

$$q = K \cdot 3.14 \cdot (t_{\text{с}} - t_{\text{в}}) \qquad (1.2)$$

where K is the linear heat transfer coefficient, W/m· °C; $t_{\text{с}}$ – ambient temperature; $t_{\text{в}}$ – water temperature, °C.

Let's calculate the linear heat transfer coefficient:

$$K = \frac{1}{\left(\frac{1}{2\lambda}\right) \cdot ln\left(\frac{d_{\text{з}}}{d_{\text{в}}}\right)} \qquad (1.3)$$

where λ – coefficient of thermal conductivity of the material; $d_{\text{з}}$ – outer diameter of the tube; $d_{\text{в}}$ – inner diameter of the tube.

The coefficient of thermal conductivity of silicone is about 0.135 W/m·°C. The outer and inner diameters of the tubes are equal to: 0.005 and 0.004 m, respectively. Substituting the values into formula 1.3, we get:

$$K = \frac{1}{\left(\frac{1}{2 \cdot 0.135}\right) \cdot ln\left(\frac{0{,}005}{0{,}004}\right)} = 12.2 \text{ W/m·°C}$$

For the calculation, we will take the temperature of the external environment 18°C, and internal 8°C. Substituting the values into formula 1.2, we get:

$$q = 12.2 \cdot 3.14 \cdot (18 - 8) = 383 \text{ W/m}.$$

Then, substituting the value in formula 1.1, we get:

$$Q_{\text{ТР}} = 0.2 \cdot 383 = 76.6 \text{ W}.$$

The flow of thermal energy through the walls of the tubes of exchanger is 1.27 J per second, i.e. 1.27 W.

We will calculate cold losses for a plastic heat exchanger 5×12×6 cm and a volume of 360 cm^3:

$$Q_{\text{к}} = k \cdot S\,(t_{\text{з}} - t_{\text{в}}) \qquad (1.4)$$

where k – linear heat transfer coefficient, W/m·°C; $t_{\text{з}}$ – ambient temperature; $t_{\text{в}}$ – the temperature of the internal environment, °C.

Let's calculate the linear heat transfer coefficient for a plastic heat exchanger:

$$k = \frac{1}{\frac{d}{\lambda_{\text{п}}} + \frac{1}{\lambda_{\text{в}}} + \frac{1}{\lambda_{\text{з}}}} \qquad (1.5)$$

where $\lambda_{\text{п}}$ – thermal conductivity coefficient of polypropylene; $\lambda_{\text{в}}$ – coefficient of thermal conductivity from the internal environment to the body; $\lambda_{\text{з}}$ – coefficient of thermal conductivity from the case to the outside air.

The coefficient of thermal conductivity of polypropylene is approximately 0.2 W/m·°C. The thermal conductivity coefficient from the internal medium (water) to the body is equal to 0.6 W/m·°C. The thermal conductivity coefficient from the case to the outside air is equal to 0.3 W/m·°C. Substituting the value into formula 1.5, we get:

$$k = \frac{1}{\frac{0{,}001}{0{,}2} + \frac{1}{0{,}6} + \frac{1}{0{,}3}} = 0{,}2 \text{ W/m·°C.}$$

The total surface area of the heat exchanger with sides of 5×12×6 cm is 324 cm^2, but the surface area occupied by the Peltier elements has no cooling losses. Therefore, the surface area for calculation is equal to 260 cm^2 = 0.026 m^2. For the calculation, we will take the temperature of the external environment as 18°C, and the internal one as 8°C. Substituting the values into formula 1.4, we get:

$$Q_{\text{к}} = 0.2 \cdot 0.026\,(18 - 8) = 0.05 \text{ W.}$$

The level of thermal energy entering the heat exchanger depends on the heat removal by Peltier elements.

Let's calculate heat removal by Peltier elements from water in the heat exchanger:

$$Q_{\text{п}} = k \cdot S\,(t_{\text{в}} - t_{\text{п}}) \qquad (1.6)$$

where k – linear heat transfer coefficient, W/m·°C; S – area of Peltier elements, m^2; $t_{\text{п}}$ – the temperature of the cold surface of the Peltier element; $t_{\text{в}}$ –water temperature, °C.

The total area of the four Peltier elements is equal 64 cm^2 = 0.0064 m^2. Water circulates at a rate of 200 ml/min = 12 l/h. The linear heat transfer coefficient of flowing water is equal to $350 + 2100 \cdot \sqrt{12}$. Let's take the water temperature for calculation 18°C, and the temperature of the Peltier element -3°C. Substituting the value into formula 1.6, we get:

$$Q_{\text{п}} = (350 + 2100 \cdot \sqrt{12}) \cdot 0.0064 \cdot (21) = 1025 \text{ W.}$$

The $Q_{\text{п}}$ = 1025 W – heat extraction by Peltier elements.

In aluminum heat exchangers, the area of cold losses can be neglected, because almost their entire surface is occupied by Peltier elements, and the rest were completely insulated with polystyrene foam, which confirms the results of the research using a thermal imager.

According to the obtained results, it can be concluded that the operation of the Peltier elements completely covers all the cold losses of the tubes and the heat exchanger.

Research and analysis of the intravascular cooling system with a 4×4×1 cm heat exchanger with four Peltier elements was carried out using a FLIR i7 thermal imager for cold loss.

Characteristics of the FLIR thermal imager: IR image resolution: 176 × 220 pixels;

thermal sensitivity: 0.10°C; viewing angle/min. focal length: 50° × 38.6°; spectral range: from 8 to 14 μm; image refresh rate: 9 Hz; display: 2.0 inches (50.8 mm) TFT LCD; temperature range: from 10°C to 45°C.

The figure 2 shows a picture of a thermal imager, the sight of which is directed to the side of the heat exchanger. The temperature of the object is 10.9°C.

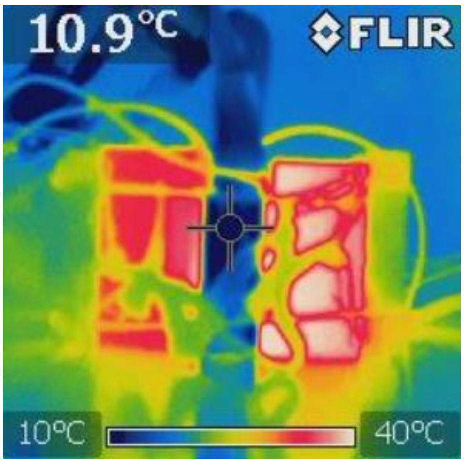


Figure 2 – Shot of the side of the heat exchanger

The figure 3 is a picture of the thermal imager, top view; the sight is directed at the radiator. The object temperature is 37.8°C.

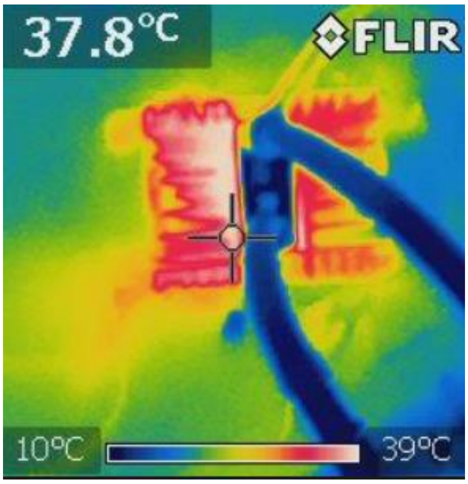


Figure 3 – Top view of the cooling system

The figure 4 shows a picture of the thermal imager, a side view, the sight is directed at the wall of the container insulated with 1 cm Styrofoam. The temperature of the object is 17.1°C.

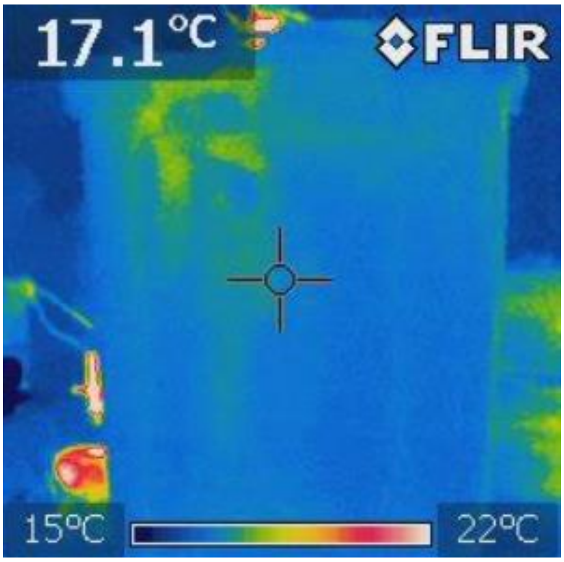


Figure 4 – Picture of the container wall

The Styrofoam-insulated container has good thermal insulation, as can be seen from Figure 6, as there are no red spots on it, which would indicate high temperature and heat loss. The hottest spots were the heat sink radiators and the pump motor housing.

The coldest points are the tube part of the pump and the body of the insulated container. The use of a thermal imager makes it possible to detect with high accuracy the places of intensive heat exchange in the system to improve the thermal insulation of volumes containing cooled liquid. Conversely, identified areas of intense heating may require additional heat removal measures.

VI. CONCLUSIONS

Existing methods of preservation of donor organs involve the use of systems of various complexities that ensure long-term support of the viability of transplants. The optimal technology for transporting donor organs over long distances is constant hypothermic perfusion in various variants. According to the performed calculations, for cooling the solution with which the donor organ is perfused, it is advisable to use Peltier elements, the technical characteristics of which make it possible to develop a compact and inexpensive system. The use of a thermal controller in the created system with optimal power supply of 4 elements in the experiment ensures hypothermic perfusion of the donor organ and maintaining the temperature at a stable level.

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ORCID ID and author contribution.

0000-0002-0424-3021 (A, D) Yaroslav Zabilo

0000-0001-8836-4658 (C, F) Vladyslav Shlykov

0000-0002-6889-3197 (B, E) Svitlana Vovianko

A - conception and design of the work, B - analysis of medical care standards and treatment protocols, C- algorithm design, D - writing the article, E- critical review, F- final approval of the article.

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ВИКОРИСТАННЯ ЕФЕКТУ ПЕЛЬТЬЄ ДЛЯ ВНУТРІШНЬОСУДИННОГО ОХОЛОДЖЕННЯ ДОНОРСЬКИХ ОРГАНІВ

Забіло Ярослав Сергійович
yarzab55@gmail.com
Шликов Владислав Валентинович
v.shlykov@kpi.ua
Вовянко Світлана Ігорівна
sivovianko@gmail.com
Кафедра біомедичної інженерії
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»
м. Київ, Україна

Реферат *– Дана робота присвячена проблемі збереження перфузії донорських органів в умовах контрольованого охолодження. З метою охолодження перспективним є використання ефекту Пельтьє. Зокрема, розглянуто застосування ефекту Пельтьє, який є одним із методів охолодження, що дає змогу використовувати його для збереження та транспортування донорських органів до реципієнтів. Однією з переваг використання ефекту Пельтьє є те, що цей метод охолодження не потребує використання додаткових рідинних охолоджувачів, що дозволяє уникнути потенційних проблем, пов'язаних із забрудненням органів або порушенням їх структури. Крім того, охолодження за допомогою ефекту Пельтьє є досить ефективним і цим процесом можна керувати шляхом зміни електричного струму. Окремою проблемою є розробка конструкції системи внутрішньосудинного охолодження для збереження життєздатності органу, який призначено для трансплантації, з урахуванням його особливостей. Розроблений теплоізоляційний контейнер із системою охолодження має хорошу теплоізоляцію. Для оцінки ефективності системи охолодження було проведено розрахунок втрат охолодження. Згідно з проведеними розрахунками, для охолодження розчину, яким здійснюється перфузія донорського органу, доцільно використовувати елементи Пельтьє, що дає змогу розробити ефективну, компактну та недорогу систему забезпечення життєздатності донорських органів. Застосування такої системи підвищує життєздатність трансплантатів, знижує ймовірність ішемічних та ішемічно-реперфузійних ушкоджень, що супроводжують процес збереження донорських органів.*

Ключові слова: *ефект Пельтьє, трансплантація, транспортування донорських органів, життєздатність органів, система охолодження, елемент Пельтьє, температурна стабілізація.*