R.R. Kobylianskyi[1,2], I.A. Moskalyk[1]

[1]Institute of Thermoelectricity of the NAS and MES of Ukraine, 1 Nauky str., Chernivtsi, 58029, Ukraine;
[2]Yu. Fedkovych Chernivtsi National University, 2, Kotsyubinsky str., Chernivtsi, 58012, Ukraine.

R.R. Kobylianskyi

I.A. Moskalyk

THE PROSPECTS OF USING THERMOELECTRICITY FOR HUMAN HEAD CRYOTHERAPY

The paper presents the analysis of current status of using human brain cooling in medical practice. The operating principle of currently available devices for brain hypothermia, their advantages and shortcomings are briefly described. The prospects of using thermoelectricity for human head cooling are determined.
Key words: *thermoelectricity, human head cooling, local hypothermia, brain hypoxia.*

Introduction

General characterization of the problem. Brain hypoxia is one of the relevant problems in medical practice [1 – 8]. It is present at cerebrovascular accidents, shock states, acute cardiovascular insufficiency, complete atrioventricular heart block, head injuries, carbon monoxide poisoning and asphyxia of different origin. Brain hypoxia can be a complication of cardiac surgery and vascular procedures, as well as in the early postoperative period. It is accompanied by various neurologic syndromes and mental disorders.

With oxygen starvation for more than 3 – 4 minutes rehabilitation of brain activity becomes impossible. However, it is known that local hypothermia of brain reduces its oxygen requirement, increases resistance to hypoxia, as well as reduces or even removes the danger of temporary brain ischemia, thus increasing permissible duration of oxygen starvation [9 – 10]. Thus, for instance, cooling by as low as 5°C increases brain lifetime by several times. Hypothermia is recommended with various head injuries, cardiac surgeries, as well as in the postoperative period – with hypoxic brain edemas, intoxication and central nervous system injuries.

Generally, the existing equipment for human head cooling includes large-size stationary devices based on compressor refrigerating units. Though in recent times devices based on thermoelectric cooling become available which, despite obvious advantages, have not found widespread application.

Therefore, *the purpose of the work* is to determine the prospects of using thermoelectricity for human head cooling.

Effect of cooling on human brain activity

Low temperatures as one of the physical factors of influence on human organism with a curative purpose are widely used in medical practice as a method for reducing organism reaction to surgical intervention, prevention of severe hypoxia progression and increasing brain resistance to oxygen starvation. Craniocerebral hypothermia method is used for complex treatment of various hypoxic and posthypoxic states. For instance, with craniocerebral injuries, when disturbed cerebral circulation and gas exchange result in brain edema, craniocerebral hypothermia offers the opportunity to prevent increase in intracranial pressure and brain edema by head cooling to temperature 30°C.

The methods for therapeutic hypothermia in emergency medicine are based on the following principles of heat removal: external cooling of large body areas, cooling of organ cavities (stomach, rectum), extracorporal and intravenous blood cooling. Of special note is craniocerebral hypothermia method (brain cooling through head skin cover with a view to improve its resistance to oxygen starvation). There are the following types of craniocerebral hypothermia: moderate hypothermia 37 – 35°C (characterized by adaptation of organism to cooling and development of compensatory functions aimed at preservation of thermoregulation), medium hypothermia 34 –30°C (characterized by instability of organism functions and increased generation of heat) and deep hypothermia 29 – 24 °C (minimization of vital organism functions – some acquired reflexes disappear, peripheral nerve conductivity, pulmonary ventilation and O_2 utilization by organism tissues are reduced, moreover, heartbeat rhythm is also reduced by 64 % and blood pressure is decreased).

Besides, craniocerebral hypothermia is an efficient method for increasing biological tissue resistance to oxygen starvation, as long as in this case there is neurovisceral system block. With craniocerebral hypothermia the temperature of the head is reduced 2 – 3 times quicker than with a general cooling of the body. The advantages of this method include quick onset of neurovisceral block that cannot be achieved in time by means of medicines. A moderate depth of craniocerebral hypothermia is achieved in 20 – 25 minutes at rectal temperature 37 – 35°C. With a deep craniocerebral hypothermia that comes in 25 – 30 minutes, rectal temperature reaches 30 – 24°C, and cerebral temperature – 25°C. Moderate craniocerebral hypothermia is an unstable cooling phase, whereas with a deep hypothermia the changes in the organs and tissues are stabilized. Thus, at the stage of a deep craniocerebral hypothermia arterial blood pressure is reduced to 51.5%, minute volume of blood is as low as 59.5%, arterial blood pressure and blood flow in liver are halved.

Note that during the first minutes of brain oxygen starvation thousands of cells die away, that can lead to irreversible changes, so it is important to minimize mass death of human brain cells. It is done due to local hypothermia of human head that brings about suppression of metabolic processes, reduction of oxygen consumption and increase of resistance to hypoxia. In medical practice it has been established that optimal temperature of cold carrier (water, air) that contacts the surface of human head is +2°C. Lower temperatures are dangerous for human organism because of frostbite of skin cover. In so doing, the temperature of patient' body is measured at several points (inside acoustic meatus at the level of ear drum, in nasal pharynx, esophagus and rectum). The temperature inside acoustic meatus at the level of ear drum corresponds to the temperature of cerebral cortex at the depth of 25 mm from the inner scull cap. Cooling continues till the temperature in rectum becomes at least equal to 33 – 32°C, in esophagus – 32 – 31°C. After craniocerebral hypothermia it is recommended to actively warm the patient to temperature not higher than 35°C, further warming of the patient should be gradual [1 – 10].

Currently available devices for human head cooling

So far, more than ten experimental devices have been developed for human brain hypothermia through external skin cover or upper air passages [17 – 30]. Such devices are based on refrigeration apparatus (generally compressor type) for cold carrier cooling and a hydraulic system that assures forced circulation of cold carrier through cryoapplicator. As cold carrier, the majority of devices employ water at a temperature of +5 °C. Control of cooling modes of such devices is done by regulation of cold carrier circulation rate through cryoapplicator on achievement of given level of temperature reduction of the biological tissue of cooled area.

It should be noted that surface heat removal at local hypothermia is mainly due to thermal conductivity and must be more energetic than own thermal production of human organism. In so doing, it is necessary to overcome heat inleak from the organism thermal centre which requires rather long cooling period.

There are known developments of devices whose operating principle lies in human brain cooling through upper air passages (Figs. 1 – 5) [29 – 36]. Such devices comprise catheters that are inserted into patient's nostrils into which cooled normal saline is poured or cooled air is blown. However, the main disadvantage of such devices is impossibility of their use with craniocerebral injuries, nasal bone fractures and respiratory diseases, which restricts considerably the areas of their application.

There are also developments of devices for human head cooling through the external skin cover (Figs. 6 – 12) [17 - 23]. These devices include cooling helmet for human head and refrigerating unit for cold carrier (air, water, alcohol solution, etc). However, it should be noted that up to now there is no experimental proof of human brain temperature reduction to the necessary temperature +30 ÷ 32°C with the aid of the above developments.

In the overwhelming majority of cases the existing equipment for human head cooling through the external skin cover includes large-size stationary devices based on compressor cooling units. Only 2 developments of devices are known that are based on thermoelectric cooling [26 – 28]: thermoelectric device in the form of a helmet for human head cooling (Fig. 11) and Olympic Cool-cap thermoelectric system for cooling of newborns (Fig. 12).

Thermoelectric device for human head cooling is made in the form of a motorcycle helmet (Fig. 11). Cooling helmet comprises 120 thermoelements connected thermally in parallel and electrically in series. Refrigerating capacity of this device is 200 W, but the main disadvantage of such development is large weight of cooling helmet - 9 kg, creating certain discomfort during use of this device in medical practice. Moreover, this device is a mere development, and no data is available on its medical test.

Unlike previous development, Olympic Cool-cap thermoelectric system for cooling of newborns [24, 25] (Fig. 12) is mass-produced and used in medical practice for prevention or considerable reduction of neurological disorders related to hypoxic ischemic encephalopathy of newborns. The device cooling helmet is composed of a cap (having a network of channels with water circulating from cooling device), cap holder and external insulation cap. The device assures a regular and controlled cooling of newborn child head to +32 °C. To maintain the necessary temperature of cooling helmet, the external cap is thermally isolated and copper foil clad [26, 27]. The minus side of this device is its large weight-size parameters, namely cooling unit dimensions are (132 × 44 × 57) cm, and its weight – 52 kg.

However, today there are no analogous thermoelectric devices for brain cooling of adults. Thus, in order to develop up-to-date portable devices for brain cooling of adults, it is necessary to determine the prospects of using thermoelectricity for human brain cooling.

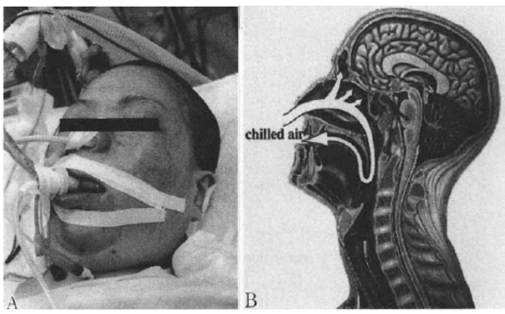

Fig.1. Device for human brain cooling through upper air passages (Japan) [29 - 31]

Fig.2. Quick hypothermia device (USA) [34]

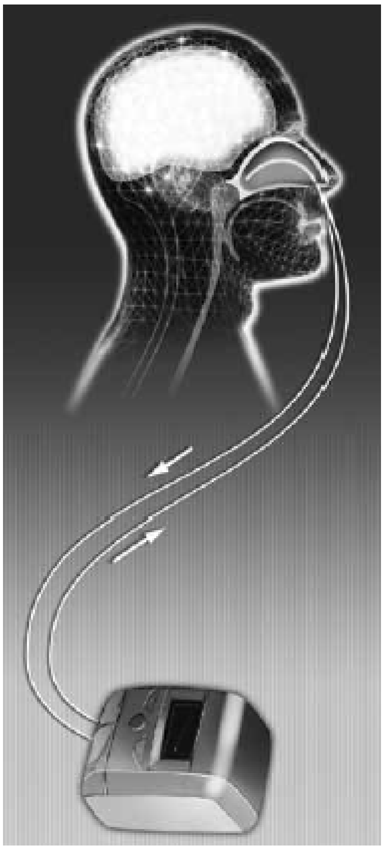

Fig.3. QuickCool intranasal system (Sweden) [35]

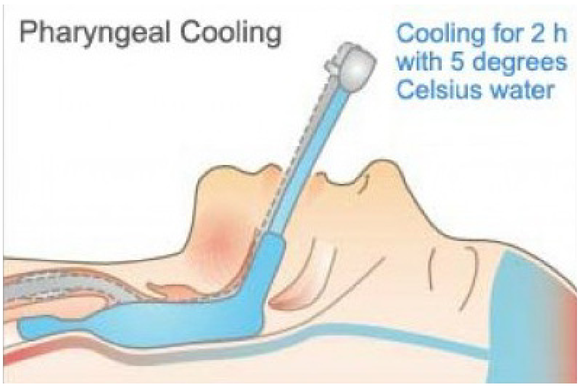

Fig.4. Pharyngeal cooling cuff (Japan) [36]

Fig.5. RhinoChill human brain hypothermia device (USA) [32, 33]

Fig.6. Curative hypothermia apparatus (Russia) [23]

Fig.7. "Kholod 2F" hypothermia device (Russia) [17 - 19]

Fig.8. Blanketrol- II craniocerebral cooling device (USA) [20]

Fig.9. CoolSystem cerebral hypothermia device for treatment of severe craniocerebral injuries [21]

Fig.10. Sovika GmbH Device for human head cooling (Germany) [22]

Fig.11. Helmet-shaped thermoelectric device for human head cooling (Turkey) [28]

Fig.12. Olympic Cool-cap thermoelectric system for cooling of newborns (USA) [26, 27]

Comparative analysis of currently available devices for head cooling is given in Table 1.

Table 1.

Comparative analysis of currently available devices for head cooling [17 – 36]

№	Device name	Weight, kg	Dimensions, cm	Power consumption, W	Refrigerating capacity, W	Manufacturing country	Note
Devices for human head cooling through upper air passages							
1.	Device for human brain cooling through upper air passages [29 – 31]	–	–	–	–	Japan	Development
2.	Quick hypothermia device [34]	–	–	–	–	USA	Development
3.	QuickCool intranasal system[35]	–	–	–	–	Sweden	Development
4.	Pharyngeal cooling cuff [36]	–	–	–	–	Japan	Development
5.	RhinoChill human brain hypothermia device [32, 33]	4.8	39×26×16	–	–	USA	Serial production
Devices for human head cooling through external skin cover							
6.	Curative hypothermia apparatus [23]	65	94 × 45 × 52	–	–	Russia	Development
7.	“Kholod 2F” hypothermia device [17 – 19]	–	–	–	–	Russia	Development
8.	Blanketrol- II craniocerebral cooling device [20]	67	43 × 43 × 95	–	–	USA	Serial production
9.	CoolSystem cerebral hypothermia device for treatment of severe craniocerebral injuries [21]	–	–	–	–	USA	Development
10.	Sovika GmbH human head cooling device [22]	–	–	–	–	Germany	Serial production
11.	Helmet-shaped thermoelectric device for human head cooling [28]	–	–	–	200	Turkey	Development
12.	Olympic Cool-cap thermoelectric system for cooling of newborns [26, 27]	52	132× 43× 57	500 – 700	–	USA	Serial production

On thermoelectric cooling efficiency

From the above analysis of works [17 – 36] it is seen that in the overwhelming majority of cases the existing equipment for human head cooling includes large-size stationary devices based on compressor refrigerating units. The average weight of such devices is 50 ÷ 70 kg with the volume of 0.2 ÷ 0.3 m^3, power consumption 500 – 700 W and refrigerating capacity nearly 200 W (Table 1). In so doing, the devices can be powered only from 110 ÷ 220 V of AC mains. This, in turn, restricts the use of such devices under non-stationary treatment conditions (for instance, in medical transport – automobiles, helicopters, airplanes, etc).

It can be easily verified that on the basis of thermoelectric cooling one can create a portable thermoelectric device for human head cooling that will have much lower weight-size characteristics as compared to existing analogs. To do this, we will perform simple calculation.

Let us consider a model of thermoelectric device for human head cooling (Fig. 13).

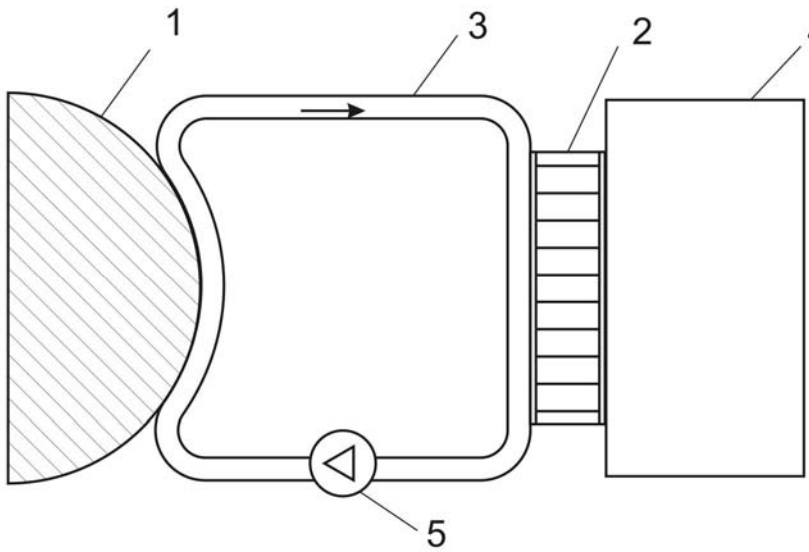

Fig.13. A model of thermoelectric device for human head cooling:
1 – human head, 2 – thermoelectric cooling system, 3 – liquid heat exchange system,
4 – liquid (or air) heat exchanger (радіатор), 5 – circulation pump.

From the medical requirements it is known [1 – 10] that minimum permissible temperature of human head surface is +2°C. The average ambient temperature in healthcare facilities, as a rule, is +20°C. Heat transfer from human head 1 to thermoelectric cooling system 2 is done by means of liquid heat exchange system 3. In so doing, heat transfer from thermoelectric cooling system 2 to environment can take place in two ways – liquid or air. For the best liquid heat exchangers temperature losses make 7 ÷ 8°C [41, 42], in the case of using the best air heat exchangers – 10 ÷ 20°C [41, 43]. With regard to losses, temperature difference on thermoelectric modules will be from $\Delta T \approx 30$°C with the use of both liquid heat exchange systems to $\Delta T \approx 45$°C with the use of liquid and air heat exchange systems. Best suited to this task are thermoelectric modules Altec - 011, specially developed by Institute of Thermoelectricity, that are characterized by increased value of maximum temperature difference [44]. Loading characteristics of such modules are given in Fig. 14.

From Fig. 14 it is seen that at given temperature difference on thermoelectric module $\Delta T \approx 30 \div 45$°C with optimal electric current the refrigerating capacity of one module will be $Q \approx 20 \div 30$ W. Hence it appears that to assure the above mentioned refrigerating capacity of device 200 W, it is necessary to have 7 – 10 pcs thermoelectric modules. With regard to heat exchange system the volume of such device will make 10 – 15 liters, and weight is 5 – 7 kg.

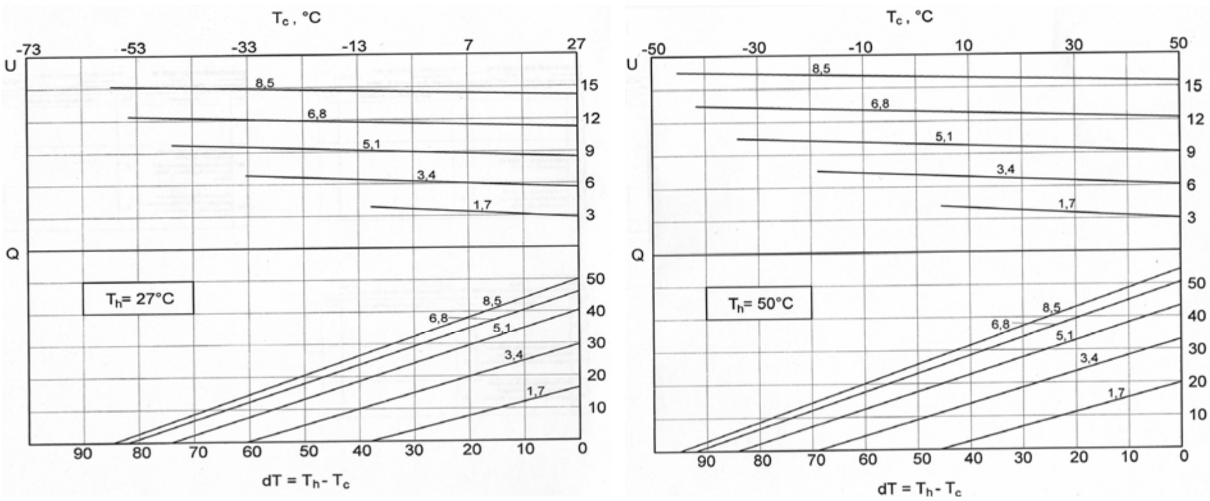

Fig.14. Load characteristics of thermoelectric modules Altec-011.

Moreover, thermoelectric cooling device can be easily adapted to power supply from the vehicle on-board mains 12 – 24 V DC. Thus, thermoelectric devices for human head cooling offer undeniable advantages over traditional compressor units (the weight and volume are 10 and 20 times lower, respectively, and power consumption is 2.5 – 3 times lower), providing the necessary refrigerating capacity 200 W.

When designing a device for human head cooling it is necessary to take into account the specific thermophysical processes in human organism. Investigations of human head cooling through external skin cover performed in [37 – 39] have shown that this method of human brain cooling is not efficient enough, since the temperature of near-surface brain layer is reduced only to +36°C. Besides, work [40] is known which demonstrates more efficient cooling of human brain (to +34°C) by cooling of neck in the area of passage of carotid arteries. It is evident that the use of both brain cooling methods will be most efficient. Therefore, for this purpose the device must comprise both head cooling helmet and neck cooling cuff.

The above analysis testifies that one can really create a portable thermoelectric device for human head cooling that will have lower weight and volume as compared to the existing analogs based on compressor refrigerating units. Such devices have a good potential for a wide practical use in medicine, which will increase the efficiency and quality of emergency medicine treatment in health care system.

Conclusions

1. Currently available devices for human head cooling (generally based on compressor refrigerating units) provide completely the necessary temperature conditions. However, large dimensions and high power consumption complicate their use under non-stationary treatment conditions (for instance, in medical transport – cars, helicopters, airplanes, etc).
2. It is established that one can really create a portable thermoelectric device for human head cooling that will have much lower weight-size characteristics (10 and 20 times lower weight and volume, respectively, as well as 2.5 – 3 times lower power consumption) as compared to the existing analogs based on compressor refrigerating units.
3. It is established that to increase the efficiency of human brain cooling, thermoelectric device must comprise both head cooling helmet and neck cooling cuff. Such devices can have a good outlook for emergency medicine (with blood strokes, heart attacks, cerebral circulation disorders, acute cardiovascular insufficiency, head injuries and human brain hypoxia).

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