

ABSTRACT

Dissertation by Assylbekova Lyaida Ramazankyzy for the degree of Doctor of Philosophy (PhD) in the specialty «8D07105 - Biomedical Engineering» on the topic «Development of thermoelectric cooling devices based on the Peltier element for local exposure in medicine»

Relevance of the research topic. Thermoelectric cooling is currently widely used in many areas of modern technology. Specifically, it is used in electronics, quantum optics, high-frequency technology, autonomous and renewable energy sources, measuring instruments, and household appliances. The main advantages of the thermoelectric method are high reliability, compactness, ease of control, and speed of operation.

In recent years, this method has also begun to find its place in medicine. Specifically, it has begun to be used to prevent alopecia (hair loss), a side effect of cancer treatment. According to the Ministry of Health of the Republic of Kazakhstan, approximately 40,000 new cancer cases are registered in our country annually, and more than 230,000 patients are registered with dispensaries. These figures demonstrate the widespread nature of the problem.



Figure 1 – Dynamics of Cancer Patients and New Cases in Kazakhstan for 2020-2025

As shown in Figure 1, according to the Ministry of Health of the Republic of Kazakhstan, there has been a steady increase in the number of cancer patients in recent years: from 190,159 in 2020 to 231,019 in 2025, an increase of more than 21%. Moreover, approximately 40,000 new cases are diagnosed annually, indicating the high prevalence of cancer and the ongoing risk of further increases in incidence [1].

Hair loss can negatively impact patients' self-image, social life, and motivation for treatment. Hair loss can be scarring or non-scarring. In the former case, causes include neoplasms (tumors) of the skin and its appendages; physical and chemical exposures leading to skin scarring; and scalp infections (bacterial, fungal, viral). Non-scarring alopecia in cancer patients is caused by the suppressive effects of medications and ionizing

radiation on dividing hair follicle cells. Both types require treatment. Currently, medications (androgen metabolism inhibitors, growth factor stimulants, hormonal and non-hormonal antiandrogen drugs, glucocorticosteroids, antimetabolites and immunosuppressants, platelet-rich plasma, mesotherapy), surgical (autotransplantation of hair follicles from areas where hair growth and quality are not impaired), and physiotherapeutic methods (darsonvalization, PUVA therapy, galvanization, electrophoresis, light therapy, local cooling, and cryomassage) are used to prevent alopecia. Among these, a method based on cooling the scalp using special cooling helmets deserves special attention. The use of these technical means for treating alopecia in cancer patients in most cases significantly accelerates scalp regrowth. Other advantages of local scalp cooling in this regard include hypoallergenicity, safety and comfort of the procedure, and the ability to control temperature.

Therefore, scalp cooling during chemotherapy is one of the most effective methods for preventing alopecia. By reducing local skin temperature, this method slows scalp blood circulation, reducing the effects of medications on hair follicles. According to research, the effectiveness of scalp cooling depends on the type of chemotherapy, the patient's physiological characteristics, and the technical characteristics of the device used. For example, hair preservation rates with anthracycline-based chemotherapy are approximately 40%, with taxanes, over 70%, and with gemcitabine monotherapy, this figure can reach 100%.

Currently, scalp temperature reduction is technically achieved through the use of fan units, liquid cooling systems, and vapor-compression refrigeration units with appropriate devices for controlling their operating modes. The disadvantages of this type of equipment are, in the first case, the impossibility of cooling the surface of the head below the ambient temperature and low efficiency, noise produced during operation; in the second case, the mandatory presence of a compressor for pumping liquid, the impossibility of ensuring an accurate dosage of thermal exposure; in the third case, bulkiness and complexity of technological implementation.

Under these conditions, the use of devices using standard Peltier thermoelectric modules (Peltier thermocouples) as a cooling source for reducing scalp temperature is promising. These devices are characterized by high operational reliability, compact dimensions, excellent environmental friendliness, quiet operation, and a long service life.

It should be noted that there is currently a significant lack of research in this area related to cooling device hardware and optimization of their characteristics for specific operating conditions. This circumstance underscores the relevance of conducting a dissertation research project related to the development and study of a thermoelectric device (TED) designed to reduce scalp temperature to prevent alopecia in cancer patients, capable of being used in both hospital and field settings.

Furthermore, thermoelectric cooling devices have the potential to find wide application not only in oncology but also in other fields. For example, they are used to reduce pain from migraines and neuralgia, in rehabilitation processes after surgery and traumatic brain injuries, in sports medicine for rapid recovery after intense physical

activity, and in cosmetology to strengthen hair and improve scalp condition. Furthermore, they can be used as protective devices against heat stress for professionals working in high-temperature conditions, firefighters, and military personnel.

All of the above clearly demonstrates the scientific, medical, and social significance of this topic. Therefore, the use of thermoelectric cooling systems for medical purposes, namely, to improve the quality of life of cancer patients, is a relevant and promising area of research.

Stage of development of the research topic. The problem of alopecia caused by antitumor therapy has attracted the attention of researchers in the fields of medicine and biomedical engineering in recent decades. In particular, considerable attention has been paid to the development and improvement of methods for preventing hair loss, including localized scalp cooling. Local cooling is currently recognized as a non-drug method for reducing the risk of chemotherapy-induced alopecia by inhibiting hair follicle activity. Existing scalp cooling technologies primarily consist of liquid cooling systems and ventilation units. However, these technologies have several significant limitations: bulkiness, the need for stationary operating conditions, increased noise levels, insufficient temperature control accuracy, and the inconvenience of long-term use in clinical practice. Scientific and patent literature contains several publications devoted to the use of thermoelectric modules (Peltier elements) in medical cooling devices. These elements attract the attention of researchers due to their compact size, high reliability, quiet operation, and the ability to precisely regulate temperature. However, most existing developments are limited to laboratory prototypes that have not undergone clinical trials. Thus, despite certain scientific and technological advances in the field of cooling systems, the use of thermoelectric cap-type devices for localized scalp cooling remains an understudied area. This requires comprehensive scientific research aimed at the development, modeling, experimental testing and implementation of a new thermoelectric device with high precision, reliability and ease of use.

Object of the study is a specially designed thermoelectric device intended for the prevention of alopecia in cancer patients through localized scalp cooling.

The subject of this study is the thermal and electrical processes in a thermoelectric device for localized scalp cooling, as well as mathematical modeling and experimental analysis methods to improve the effectiveness and reliability of alopecia prevention in cancer patients.

The aim of this dissertation is to create a portable, specially designed thermoelectric cooling device for the prevention of alopecia in cancer patients through localized cooling, to develop a mathematical model of the device, and to study the electrical and thermal processes within it.

Research Objectives. Based on this objective, the following research objectives have been defined within the dissertation:

1. Critical analysis of existing methods and technical means based on the thermoelectric method of energy conversion in medicine, in particular, thermal effects.
2. Development of a mathematical model of a thermoelectric device for the

prevention of alopecia in cancer patients through localized cooling. 3. Conducting a numerical experiment using the developed mathematical model and analyzing the results.

4. Creating an experimental prototype (mock-up) of the device using computer-aided design methods based on the optimal solutions obtained during the mathematical modeling of the device and numerical experiments.

5. Conducting full-scale testing of the prototype of the cooling thermoelectric device on an experimental rig in accordance with the measurement methodology developed based on current regulatory documents and standards.

Research Methods. The dissertation's objectives were addressed using principles of a systems approach, mathematical modeling of heat transfer processes, elements of mathematical statistics, numerical methods for calculating systems of differential equations, automatic control theory, experimental studies, and computerized measurement data processing.

Scientific Novelty:

1. A method for localized scalp cooling based on a thermoelectric device has been developed. This method provides high-precision cooling of the cold surfaces of a thermoelectric module in the temperature range from 273 to 291.5 K (0-18.5°C), while heat is removed from the hot surfaces of the thermoelectric module using a liquid cooling system.

2. A mathematical model for studying the thermophysical processes occurring in the "head – thermoelectric device" system, characterized by the fact that it is based on the solution of a two-dimensional non-stationary heat conduction problem for a layered structure of complex shape, taking into account the presence of objects with different thermophysical parameters, heat exchange conditions at the boundaries of the second and third types of media, and the energy and geometric parameters of the thermoelectric modules.

3. The design of a thermoelectric device for the prevention of alopecia in cancer patients using local cooling, characterized by the fact that it consists of a cooling unit containing thermoelectric modules and a fan, a liquid cooling system used to remove heat from the heated surfaces of the thermoelectric modules, a control unit for the operation of the device, and a cap (helmet) worn on the patient's head.

The theoretical significance of this work lies in the creation of a mathematical model for studying the thermophysical processes occurring in the "head-thermoelectric device" system. This model is based on solving a two-dimensional, non-stationary heat conduction problem for a complex layered structure, taking into account the energy and geometric parameters of the thermoelectric modules.

Practical significance of this work:

- Development of design variants of a thermoelectric device for the prevention of alopecia in cancer patients using local cooling, which improves the reliability, effectiveness, and comfort of preventive measures;

- Implementation of research results in medical organizations and higher education institutions;

- Relevance of the practical application of the work's results, primarily in medical organizations and institutions;
- Recommendations for the practical application of thermoelectric devices.

Conclusions proposed for defense:

1. To prevent alopecia in cancer patients, it is advisable to use a local scalp cooling method based on a thermoelectric device, including a cooling unit containing thermoelectric modules and a fan, a water block for heat removal from the heated surfaces of the thermomodules, and a control unit that regulates the operation of the thermoelectric modules to ensure the required level of scalp cooling.

2. The mathematical model of a thermoelectric device for the prevention of alopecia in cancer patients using local cooling is based on the solution of a two-dimensional non-stationary heat conduction problem for a layered structure of complex shape, taking into account the presence of objects with different thermophysical parameters, heat exchange conditions at the boundaries of second- and third-order media, as well as the energy and geometric parameters of the thermoelectric module.

3. To cool the scalp using a thermoelectric device designed for a temperature range of 273 to 291.5 K (0-18.5°C), two standard DRIFT-0.8 thermoelectric modules manufactured by Krioterm LLC must be used. The characteristics of each module are as follows: power range from 20 to 80 W, average temperature difference between junctions of 50 K, power consumption from 100 to 500 W, current consumption from 3 to 11 A, and coefficient of performance ranging from 0.1 to 0.5.

The reliability of the results is ensured by the validity of the theoretical approaches used, the consistency of the mathematical modeling results with field experimental data, and the confirmation of the main conclusions of the study by publications in scientific journals.

Validation of the study results. Based on the results of the scientific research of the dissertation work, 6 scientific papers were published, including 2 articles in foreign publications included in the international citation database Scopus, 2 articles were published in scientific journals recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan, and 2 patents of the Republic of Kazakhstan for utility models were received.