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The Role of Thermoelectricity in Biological Research and Medical Applications

The article considers the use of thermoelectric phenomena, namely, the Peltier and Seebeck effects and devices based on them, as a highly effective tool for solving current problems in the field of life sciences. Considerable attention is paid to the advantages of thermoelectric cooling, heating and highly sensitive thermometry due to the absence of moving parts, as well as due to the high accuracy of temperature maintenance and compactness of the devices.

Keywords: thermoelectricity, biology, medicine.

Introduction

The use of electronic devices in biology and medicine is closely related to the need for precise temperature control of biological samples, reaction media, and local microenvironment, as one of the key physical parameters that determine the course of biochemical and physiological processes. In addition to temperature control of biological objects, an important aspect is also the thermal regime of the electronic equipment itself: overheating of electronic components can lead to drift of measured signals, reduced sensor accuracy, and instability of

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device operation, which is especially critical for highly sensitive biomedical systems. Even slight deviations from the optimal temperature range can distort the results of polymerase chain reaction (PCR), inhibit the growth of cell cultures, or disrupt the stability of biological drugs, including vaccines. Traditional thermoregulation systems, such as compressor refrigeration units or the use of cryogenic agents, are characterized by significant dimensions, energy consumption, and limited suitability for integration into portable and autonomous medical devices. In this regard, thermoelectric technologies are attracting particular attention.

Thermoelectric modules are compact solid-state devices without moving parts and working fluids, capable of providing direct conversion of electrical energy into a temperature gradient and vice versa. Their operation is based on the Peltier effect, which allows for both cooling and heating with high precision temperature control without the use of compressor systems, cryogenic agents or liquid circuits. Due to this, thermoelectric modules are widely used in thermal stabilization systems of modern laboratory equipment, in particular PCR amplifiers, as well as in compact systems for storing and transporting biological materials.

The Seebeck effect opens up possibilities for creating autonomous energy sources that can use the temperature gradient between the human body and the environment. Such approaches are being considered for powering wearable sensor systems, in particular ECG, EEG and blood pressure monitoring devices, as well as as a promising component of implanted medical devices. In parallel, thermoelectric technologies are used in precise thermal control systems of laboratory equipment and are being investigated in the context of local therapeutic effects, in particular for stimulating reparative processes in tissues. Although most of these solutions are at the experimental research stage, they are considered a promising direction for reducing the dependence of medical systems on traditional energy sources. In fundamental biophysical research, thermoelectric phenomena are studied at the molecular level, in particular in organic structures and DNA, to analyze the mechanisms of charge transfer and energy conversion. The obtained data form the theoretical basis for the development of biocompatible sensor platforms and autonomous thermoelectric systems.

Of particular interest is the use of thermoelectric systems in minimally invasive technologies, where local controlled cooling or heating can be used to influence biological tissues. Although cryogenic methods currently dominate high-power clinical procedures, in particular cryoablation, thermoelectric approaches are considered as a potential alternative or complement, especially in the context of miniaturization and increased precision of instruments. Computer simulation and optimization of working tools for cryodestruction of oncological tumors allow to accurately predict the area of tissue necrosis, which minimizes damage to healthy cells and increases the efficiency of cyclic temperature exposure. In medical practice, thermoelectric technologies are also used in non-invasive monitoring systems. In particular, heat flow sensors, characterized by extremely high sensitivity compared to other known thermometers, allow to assess local metabolic processes and blood flow through the skin, forming the basis for the analysis of physiological parameters in real time. Such approaches facilitate the transition from qualitative observation to objective monitoring of the patient's

condition. The use of multi-stage thermoelectric coolers allows achieving ultra-low temperatures necessary for cardiac ablation in the treatment of arrhythmias.

Thus, thermoelectricity forms a promising interdisciplinary direction at the intersection of physics, materials science, and medicine, providing new opportunities for precise control of thermal processes, autonomous energy supply, and the development of intelligent medical systems.

1. Key areas of research and practical applications

1. *Molecular thermoelectricity*. Research into thermoelectric effects in individual molecules and molecular contacts (including DNA) to study charge transfer mechanisms and determine dominant carriers (electrons or holes), as opposed to bulk materials.

2. *Organic semiconductors*. Research of thermoelectric transfer in organic crystals using quantum modeling to assess the influence of thermal fluctuations and increase the thermoelectric coefficient.

3. *Laboratory tests and diagnostics*. Thermoelectric devices (TEDs) are widely used in molecular biology for precise temperature control, particularly in PCR, where they provide rapid and reproducible changes in the temperatures required for DNA amplification. Peltier-effect elements are used in refrigeration and thermostabilization systems for storing biological samples at low temperatures, although cryogenic methods are usually used for deep cryopreservation.

4. *Incubation and storage*. TEDs provide stable, vibration-free temperature control for incubators and portable medical refrigerators, which is essential for transporting sensitive biological products.

5. *Biological monitoring with autonomous power supply*. Thermoelectric generators (TEGs) can use the temperature gradient between the human body and the environment to partially power research and sensor systems. Mobile research sensors: flexible TEGs convert skin heat into electricity, reducing battery dependence while continuously monitoring vital signs (including heart rate, oxygen saturation, and body temperature). The use of TEGs in implanted devices (pacemakers, neurostimulators) is considered a promising direction, but is currently at the stage of experimental research. A potential source of energy for such TEGs is the temperature difference between deep tissues and the skin surface.

6. *New therapeutic applications*. Wound healing: Recent publications report the development of thermoelectric hydrogels that accelerate tissue regeneration by enhancing endogenous electric fields, which promotes cell migration and angiogenesis. In oncology, thermoelectric approaches are being investigated in the context of localized hyperthermia and the effects on the tumor microenvironment, in particular through the control of electrical and thermal gradients. Antimicrobial therapy: Thermoelectric materials are used to induce local reactions, including the generation of reactive oxygen species, to inhibit the growth of microorganisms.

7. *Space and extreme environment exploration*: thermoelectric technologies are used in NASA's space biology experiments, in particular in systems for maintaining controlled

temperature conditions for living organisms. The use of Peltier modules provides compactness, the absence of moving parts, and low noise, which is important for operation in confined and autonomous environments, including space missions [1].

It is advisable to present the main areas of application of thermoelectricity in biology and medicine in the form of a flowchart (Fig. 1).

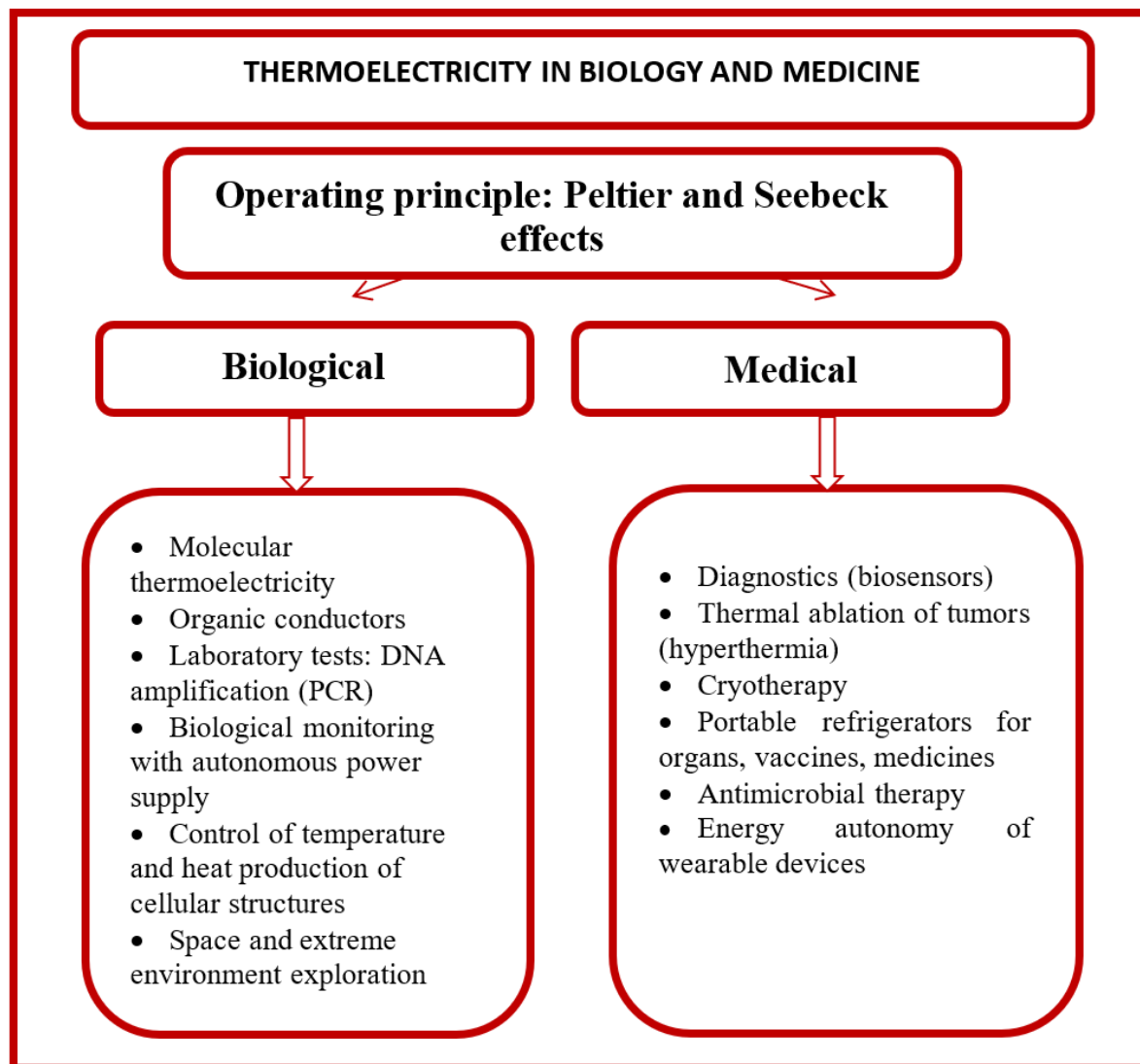


Fig. 1. Flowchart of the main practical applications of thermoelectricity in biology and medicine

2. Biological Seebeck effect

In general physics, the Seebeck effect is the occurrence of an electric voltage (thermoelectromotive force) in a closed circuit consisting of different conductors, in the presence of a temperature difference between their contacts. In a biological context, the Seebeck effect is defined as the ability of biological structures (tissues, cell membranes, or macromolecules) to convert a temperature gradient directly into an electric potential. That is, the biological Seebeck effect is a phenomenon that occurs when temperature gradients in living

organisms or biomaterials cause the migration of ions (ionic Seebeck effect) or the flow of electrons, generating an electric potential from thermal energy. The biological manifestations of the Seebeck effect are primarily associated with ion transport and temperature-dependent processes in living systems. Similar principles of thermoelectric conversion are also used in wearable devices, the power of which is provided by generating electricity from the body's temperature gradient.

Unlike metals, in biological systems, water-containing polymers such as collagen, keratin, melanin, or complex lipid membranes act as conductors. Regarding the type of conductivity, it should be noted that in biological systems the effect is often ionic or protonic, rather than purely electronic. The temperature difference causes ions or protons to migrate from a hot area to a cold area, creating a charge distribution. Some organisms use this effect as part of their thermoreception system (sensing heat).

Studies show that the Seebeck effect may play a key role in the functioning of specific organs and tissues. In particular, it is believed that such receptors may use thermoelectric signals for navigation or hunting. For example, the ampullae of Lorenzini are unique electroreceptor organs in the form of tiny pores located on the head and body of cartilaginous fish (sharks, rays, chimaeras) and filled with a jelly-like substance, allowing predators to detect weak electric fields generated by prey, enemies or used for navigation in the ocean [2]

Understanding the biological Seebeck effect underlies the development of organic electronics and biosensors (see Table 1):

Table 1

Area	Practical significance
Bionic prostheses	Creating "artificial skin" that senses heat through thermoelectric signals just like human skin.
Body energy	Development of implants powered by the temperature difference between internal organs and the surrounding environment.
Medical diagnostics	Study of abnormal electric fields in tissues (e.g. tumors) that have a different thermal profile.

Collagen has the properties of a natural thermoelectric material. Even a slight temperature difference between the inner layers of the skin and its surface can generate microcurrents that affect tissue regeneration [3].

Let us consider the thermoelectric properties of collagen. While in metals current is created by free electrons, in collagen this process is much more complex and is based on its unique molecular structure. Collagen is a fibrillar protein, the molecules of which are twisted into dense triple helices. These helices have a high degree of order, which makes them similar to crystals. Collagen molecules possess a permanent dipole moment because they are electrically polar. Each collagen molecule is surrounded by a hydration shell of water molecules, with hydrogen bonds between them and the hydrophilic groups of amino acids.

Water forms a hydration shell around the triple helix, stabilizing its structure, providing flexibility and strength to the fibers, and retaining moisture in the tissues.

When a temperature gradient occurs (one side of the tissue is warmer than the other), the Seebeck effect occurs. There are two processes underlying this.

1. Ion diffusion: The hydrated collagen matrix contains mobile electrolyte ions (Na^+ , K^+ , Cl^- , Ca^{2+}) that can diffuse under the influence of a temperature gradient. Heat makes them move faster. Due to the difference in kinetic energy, the ions accumulate at the end with a lower temperature, creating a potential difference.
2. The Grotthuss mechanism is a specific way in which protons (H^+) move along the chains of water molecules surrounding collagen. The protons literally “jump” from one water molecule to another. However, it is believed that this is not one specific transition of a proton from one molecule to another, but that the jump of a proton to one molecule leads to the jump of another proton from that molecule. The direction of this movement is determined by the temperature gradient.

Collagen is also pyroelectric. Pyroelectricity is a general property of living organisms [4, 5]. This means that when the temperature changes, its internal electrical polarization changes. That is: the temperature increases $\rightarrow$ the molecular helix expands slightly or vibrates, the distance between the charges inside the protein changes, a free electrical charge appears on the surface of the fiber.

Microcurrents arising from the Seebeck effect in collagen act as biofeedback, namely: tissue regeneration occurs because electric fields direct cells (fibroblasts) to the site of damage, and bone adaptation occurs because thermoelectric and piezoelectric effects help bone tissue determine where to strengthen the structure under the influence of loads or temperature changes.

A comparison of the characteristics of collagen and metals is given in Table 2.

Table 2

Characteristic	Metal thermocouple	Collagen (Biomaterial)
Charge carrier	Electrons	Protons (H^+) and ions
Seebeck coefficient	Low ($\mu\text{V/K}$)	High (mV/K) — due to ionic nature
Environment	Vacuum or solid	Hydrated (aqueous) environment

It should be noted that biological thermoelectric coefficients (Seebeck coefficient) are often significantly higher than those of metals due to the high mobility of ions in hydrated media and range from 1.2 mV/K to 2.5 mV/K. The Seebeck coefficient for collagen is not a constant: for dry collagen $\alpha = 0$, since ionic conductivity disappears.

Thus, the Seebeck effect serves to generate energy to power implanted devices, wearable sensors, and non-volatile sensors that are part of the real-time remote monitoring system for the patient's condition.

The paper [6] discusses TEGs that use the Seebeck effect to convert body heat into electricity, powering self-contained medical devices such as implants and monitors.

3. Peltier effect

Thermoregulation and control using the Peltier effect is used to create precise temperature regimes, which is critical for biological processes:

- Diagnostics (PCR): rapid cyclic heating and cooling of DNA samples in thermal cyclers [7, 8].
- Cryotherapy and surgery: local cooling of tissues to reduce inflammation or spot freezing (cryodestruction) of neoplasms [9].
- Transport of biomaterials: maintaining a stable temperature for containers with organs, blood or vaccines [10].
- Laboratory studies: temperature control of microfluidic chips (lab-on-a-chip) [11]. In this article, the authors investigate the problem of precision linear cooling of microfluidic chips using thermoelectric coolers operating on the Peltier effect. Precise temperature control is critical for biomedical analyses such as nucleic acid amplification and cell cryopreservation. With the developed method, it was possible to achieve stable linear cooling from +25.2 °C to –19.7 °C at a rate of 24 to 41 °C/min. The linearity index exceeded 0.998.
- Physiotherapy. The developed thermoelectric device using Peltier modules allows for the implementation of new iontophoresis modes with controlled temperature, opening up prospects for increasing the effectiveness of physiotherapy procedures and developing new medical technologies [12].

The use of thermoelectricity in PCR diagnostics is perhaps the most successful commercial application of the Peltier effect in biology to date. The devices used to perform PCR diagnostics are called amplifiers or thermal cyclers.

The role of TEM in PCR is very important. PCR is a DNA copying process that requires multiple (30–40 times) repetition of a cycle of three different temperatures. TEM is ideal for this because it can change the temperature from hot to cold in a matter of seconds simply by changing the polarity of the current.

Let us present a diagram of the PCR cycle using a Peltier module (Table 3)

Table 3

Cycle stage	Temperature	The role of Peltier module	In-vitro process
1. Denaturation	~ 94–98 °C	TEM operates at maximum heating.	The DNA double helix breaks into two strands.
2. Annealing	~ 50–65 °C	TEM instantly cools the unit.	Primers "stick" to the desired sections of DNA.
3. Elongation	~ 72 °C	TEM maintains a stable temperature.	The enzyme completes the new DNA strand.

When amplifying DNA in modern thermal cyclers, it is the Peltier effect that allows the device to quickly change the temperature of the reaction mixture, which is critically important for passing through the stages of denaturation, primer annealing and elongation. The system is

based on TEMs - semiconductor devices, the operation of which is based on the phenomenon of heat release or absorption when an electric current passes through the contact of two different conductors, which provides:

- Reversibility. If the direction of the current is reversed, the hot and cold sides of the module swap places. This allows the same element to both heat and cool the aluminium block with the tubes.
- Speed up to 10°C per second. Thanks to Peltier elements, high temperature change rates (ramp rates) are achieved, which significantly reduces analysis time.
- Accuracy. Thanks to electronic current control, the thermal cyclers can maintain temperature with an accuracy of 0.05 °C.
- Multi-zone capability. Multiple Peltier modules can be installed in a single device. This allows for the creation of a temperature gradient – a situation where different parts of a single sample plate have different temperatures, which is useful for test optimization.

Traditional resistive heaters can only heat. Cooling in this case would be passive and slow. Since PCR requires dozens of heating-cooling cycles, without the Peltier effect, this process would take hours instead of minutes.

The use of thermoelectricity (Peltier modules) for the transport of biomaterials is a critically important niche in modern medicine, especially when it comes to the cold chain. This technology allows for the safe transport of organs for transplantation, vaccines, drugs, blood samples and stem cells. There are no vibrations in thermoelectric containers. This is critical for biological samples (e.g., eggs or complex proteins), where mechanical vibrations can damage the cellular structure. Peltier modules allow for temperature control to within 0.1 °C, which is not possible with ice or dry ice. The container can be inverted, shaken, or tilted – the thermoelectric element contains no liquid that can leak. During transportation, some biomaterials require not just cold but also strict adherence to specific temperatures (for example, +22 °C for platelets or +37 °C for certain cell cultures).

By simply reversing the polarity of the current, the container is transformed from a refrigerator to a thermostat. This is especially important when transporting in extreme conditions, such as in winter, to prevent samples from freezing [13,14,15,16].

The features of transport logistics are presented in the form of Table 4:

Table 4

Transportation object	Regime	Why thermoelectricity?
Organs for transplantation	+4 °C	Reliability and the ability to be powered from the on-board network of a car or helicopter.
Vaccines (last mile)	+2 до +8 °C	Lightness and portability for delivery to hard-to-reach areas.
Blood and its components	Stable	Accurate temperature maintenance prevents hemolysis (destruction of red blood cells).
Biochips and reagents	Cooling	Preventing enzyme degradation during delivery from the laboratory.

The use of thermoelectric refrigerators in the transportation of perishable agricultural products to maintain optimal temperature and humidity levels throughout the refrigeration chain, which is important for limiting physicochemical degradation and suppressing microbial growth so as not to significantly reduce quality and shelf life, is reported in [17].

Modern containers are becoming part of the “Internet of Medical Things” due to their autonomy, as TEGs are used to recharge the monitoring sensors inside the box, and they are also characterized by continuous recording of the temperature regime in the cloud [18]. If a failure occurs, the thermoelectric system instantly reacts with rapid cooling. The main disadvantage is the relatively low efficiency compared to large industrial refrigerators. However, in medicine, reliability and accuracy are much more important than energy efficiency, so thermoelectrics have no competitors here.

4. Molecular thermoelectricity and its practical significance

The fundamental limit of miniaturization of thermoelectric devices is the molecular level. The study [19] provided a complete characterization of thermoelectric transport in individual molecules, opening the way to the creation of next-generation biosensors. For the first time, it was possible to fully characterize thermoelectric properties, namely the Seebeck coefficient and the conductivity of an individual molecule. Such systems will be able to convert biochemical thermal gradients inside cells into digital signals, which in the future will allow monitoring of life processes at the level of individual molecular interactions. The authors prove that at the molecular level, thermoelectric efficiency can be much higher due to quantum phenomena. In medicine, this may lead to the creation of “smart drugs” or nanorobots that are powered directly by thermal fluctuations in the cell.

The work [20] focuses on the most significant biomolecule – DNA – and is a cornerstone for understanding how biological information can be linked to a thermoelectric signal. The authors proved that the Seebeck coefficient in a DNA molecule depends on its sequence (the ratio of G-C and A-T pairs). This opens up a serious prospect in terms of using thermoelectric sensors for DNA sequencing or detecting genetic mutations without complex optical labels. It is also shown how the thermoelectric signal varies depending on the length of the chain. In medicine, this can be used to determine the degree of DNA degradation or analyze fragments of viral genomes. The article explains the mechanisms of charge transfer through DNA, which is critical for the development of biochips that are powered by body heat and simultaneously analyze the patient's genetic material.

The complex physics of thermoelectricity is linked to the real work of a molecular biologist in [21]. The author explains that the thermal cycler is the heart of modern molecular biology and its operation directly depends on the accuracy of the TEM. Thermoelectric technology is indispensable for ensuring the temperature regime on which all modern genetic expertise is based.

To accurately predict the efficiency of molecular thermoelectricity, it is necessary to account for the interaction of the electronic subsystem with vibrational degrees of freedom. In [22], thermoelectric transport is considered through the prism of the Marcus theory. Based on

the Marcus formalism, it is shown that the reorganization energy of the medium is a key parameter that determines the thermoelectric response of molecular compounds. This provides a mathematical apparatus for interpreting the anomalously high values of the Seebeck coefficient in biomolecules and allows optimizing the design of molecular thermoelectric interfaces for nanomedicine. The results of the work are important for understanding how charge is transferred in biological molecules, where the cross-interaction between electrons and vibrations of the medium (polarization) plays an important role. Most models consider the molecule as a simple conductor. The Marcus theory better describes charge transfer in soft molecular systems (such as proteins or DNA), where electron transfer is accompanied by reorganization of the environment. It is also analyzed how the energy of reorganization of the environment affects the thermoelectric figure of merit. This provides a theoretical basis for the development of biosensors operating in liquid (aqueous) environments of the body. It is considered how thermoelectric characteristics change with large temperature gradients at the molecular level, which is important for understanding processes in "hot spots" of cells or during cryosurgical interventions

The fundamental principles of thermoelectric devices at the nanoscale are systematized in detail in [23]. The authors prove that molecular tunneling junctions open up unique opportunities for manipulating charge and heat flows, which significantly surpasses the capabilities of traditional bulk semiconductors. This confirms the strategic prospects of using molecular thermoelectrics for the development of intelligent biomedical systems capable of high-precision diagnostics at the cellular and subcellular levels. Effective implementation of molecular thermoelectrics in biomedicine requires precise methods for measuring thermophysical parameters at the level of single contacts. As noted in [24], modern methods for characterizing molecular transitions allow not only to estimate the Seebeck coefficient, but also to analyze in detail the thermal conductivity, which is a crucial factor for ensuring the thermal stability of biointegrated nanosystems.

The transition from individual molecular contacts to scalable systems is provided by the use of self-assembled monolayers (SAMs). Works [25, 26] demonstrate that the use of benzothieno-benzothiophenes and organometallic complexes allows for effective control of the electronic structure of the junctions. This opens the way to the creation of high-performance molecular thermoelectric films that combine nanoscale quantum efficiency with the mechanical stability required for biomedical applications, such as active shells for the surface of neuroprostheses and autonomous sensor platforms, ensuring a uniform response over the entire contact area.

In [27], the authors demonstrate how the incorporation of ruthenium or iron atoms into molecular junctions allows for control of the arrangement of energy levels (HOMO-LUMO). In medicine, this makes it possible to design sensors with a tuned sensitivity to specific biochemical reactions accompanied by the release of heat. Metal-organic complexes are often more stable in changing environments than pure organics. This is critical for medical implants that must operate for years in the aggressive liquid environment of the body. Due to their specific electronic structure, these complexes can exhibit higher values of the Seebeck

coefficient, which makes them promising for powering microscopic nerve stimulators or drug delivery systems. [28] explores one of the most challenging problems in nanotechnology: how to transmit energy and signals across long molecular chains without significant loss. Typically, at the molecular scale, efficiency decreases with distance. The authors have found ways to maintain a thermoelectric signal even in long molecules, which is critical for creating biosensors that can penetrate cell membranes. The study shows how the structure of the molecule allows energy to be avoided. This is important for the reliability of medical sensors. The molecular wires described in the article have a unique property: they are composed of organic compounds (most often carbon-based), which makes them chemical relatives of our own tissues. Unlike metals, which can oxidize or cause chronic inflammation, such molecules can literally integrate into the cell membrane.

In [29], the authors show that adding several metal centers (nuclei) to a molecule acts as an amplifier. This allows the HOMO (highest occupied molecular orbital) level of the molecule to approach the Fermi level of the electrode, which dramatically increases the thermoelectric efficiency. The production of complex molecules is important for obtaining a high Seebeck coefficient, which in turn provides sufficient power for autonomous devices even from the body's own heat.

5. Wearable devices and patches. Ionic thermoelectricity

Smart Patches are flexible sensors for monitoring ECG, glucose and temperature. The works [30,31] describe new generation semiconductors that are not only efficient but also have mechanical properties similar to human tissues (softness, elasticity). The use of thermoelectricity in targeted drug delivery and intelligent wound dressings is shown.

In the context of thermoelectrics and modern biomedical technologies, medical patches are intelligent wearable devices that attach directly to the patient's skin. They look like a regular adhesive bandage, but contain complex microelectronics inside.

Let us highlight three main functions of such patches.

1. Thermoelectric generator patches (TEG Patches) use the temperature difference between the skin (34–36 °C) and the environment to convert human body heat into electricity to power other sensors. Such a patch serves as a replacement for batteries in medical devices, and can continuously power a heart monitor or pedometer while the person is wearing it.
2. Diagnostic (sensor) patches not only collect energy, but also measure vital signs. They are used to monitor body temperature with high accuracy to detect inflammation, pulse, blood oxygen level or even sweat composition for glucose, lactate. Thanks to flexible materials, such patches perfectly repeat the skin relief, which provides a much more accurate signal than massive bracelets [32].
3. Therapeutic patches (Smart Bandages) are smart bandages that actively heal. The Peltier module inside the patch can locally heat the skin, which opens pores and accelerates the absorption of ointments or special heat-sensitive drugs. Controlled cooling or heating of the wound area helps reduce swelling or stimulate blood flow.

A comparison of a regular plaster and a medical patch is given in Table 5.

Table 5

Characteristic	Regular plaster	Thermoelectric patch
Material	Tissue / Polymer	Flexible semiconductors (organic/composite)
Energy	Absent	Seebeck effect (self-powering)
Function	Wound protection	Monitoring, therapy, data transfer via Bluetooth
Feedback	Passive	Active (responds to the patient's condition)

Ref. [33] discusses ionic thermoelectrics based on hydrogels. Hydrogels have mechanical properties very similar to human tissues, making them ideal for biomedical applications.

Unlike classic semiconductors, which rely on electrons, hydrogels rely on ions, which is much closer to how nerve impulses work in the human body. Hydrogels, the base of the patches, contain a high amount of water; they are soft, elastic, and adhere to the skin without irritation. This allows for the creation of patches that are virtually imperceptible to the patient. Furthermore, ionic thermoelectrics often exhibit a significantly higher Seebeck coefficient than metals, enabling efficient energy harvesting even with minimal temperature differences between the skin and the air.

A fundamental review systematizing knowledge about thermoelectric fibers, which serve as a transitional link between rigid modules and smart tissue, is [34]. This review serves as a bridge between fundamental materials science and applied medical patches. The authors examine various types of inorganic fibers (based on tellurides, selenides, and sulfides), allowing for the justification of the choice of a specific material for medical purposes. The article describes in detail technologies such as thermal drawing or coating, which are important for understanding the industrial scaling of medical sensor production. Much attention is paid to how these inorganic fibers can simultaneously serve as an energy source and a strain or temperature sensor. These hybrid structures, which combine the high thermoelectric efficiency of inorganic semiconductors with the flexibility of fibers, can also be used for integration into surgical gowns or smart bed linen for patients.

Ref. [35] creates a roadmap for the use of thermoelectric technologies in healthcare. In contrast to articles on individual materials, it systematizes all types of devices: from external patches to implantable TEGs. The authors honestly describe the challenges, such as the low temperature gradient of the human body and the need for high biocompatibility. The article offers a vision of how thermoelectrics will be integrated into personalized medicine and digital healthcare in the future.

Ref. [36] describes the creation of a thermoelectric fabric based on silver selenide Ag_2Se , which is manufactured without heating and is extremely elastic. Most thermoelectrics are brittle, but this material in the form of a fabric can be stretched, which is critical for constant contact with the skin on the joints or chest. The production method described in the article does not require high temperatures, which makes the technology cheaper and allows thermoelectric layers to be applied directly to textile fibers. Silver selenide Ag_2Se shows excellent results at room temperature and human body temperature, which makes it one of the best candidates for powering medical gadgets.

Ref. [37] is extremely important because it translates thermoelectricity from the role of a power source to the role of a sensor system for electronic skin. Ag₂Se-based films in this work are used not only for energy generation, but also as active sensors for electronic skin (e-skin). They are able to distinguish between touch, object temperature and even the approach of a warm object without contact. Thanks to the optimization of silver selenide films, the device is able to register minimal changes in heat flux, which in medicine can be used to monitor blood microcirculation or detect thermal anomalies of the skin. This opens the way to the creation of a new generation of prostheses that can not only function autonomously, but also provide the patient with feedback about the ambient temperature with high accuracy. That is, it can return the feeling of temperature to patients with prostheses.

Ref. [38] focuses on the engineering aspect – the creation of implantable TEGs, which is critical for autonomous powering of internal medical devices. The article solves a specific geometric and energy problem of thermoelectricity in the human body. For effective operation of TEGs, a large temperature difference is required. Since the temperature gradient in the human body is very small, the authors developed a design with long and thin “thermolegs”. This allows maximizing the temperature difference across the device even in the narrow space between tissues. The work is directly aimed at powering pacemakers, neurostimulators, and deep brain stimulation (DBS) systems, where battery replacement requires surgical intervention. The described methods allow for the creation of extremely compact devices that can be integrated into the biological environment without significant discomfort to the patient.

6. The use of thermoelectricity in high-precision surgery, cryodestruction and thermoelectric diagnostics of heat flows

A special place in modern medical thermoelectricity is occupied by the development of instruments for minimally invasive surgery. The use of multi-stage thermoelectric coolers makes it possible to achieve the ultra-low temperatures necessary for cardiac ablation to treat arrhythmias [39].

Ref. [40] combines the systematization of modern thermal ablation methods with computer modeling, defines their clinical prospects, and outlines ways of integration with robotic and thermoelectric technologies for safer and more precise treatment of tumors and other pathologies.

Computer simulation and optimization of working tools for cryodestruction of cancer tumors allow for accurate prediction of the area of tissue necrosis, which minimizes damage to healthy cells and increases the effectiveness of cyclic temperature exposure [41, 42].

In addition to therapeutic effects, thermoelectricity offers unique methods for non-invasive diagnostics. Experimental studies of medical heat flow sensors demonstrate the possibility of monitoring metabolic rate and local blood flow through the skin [43]. In [44], the authors report important results for the application of thermoelectric cooling in medicine, especially for neurosurgery, dentistry, and microsurgical bone processing. The main medical problem is overheating of the bone during grinding, since significant local heat is generated during drilling or grinding of the skull bone. If the temperature exceeds approximately 47 °C

even for a short time, thermal necrosis of the bone tissue and damage to the periosteum can occur.

In [45], a new approach to the application of thermoelectric systems in medicine is proposed, which consists in using local controlled hypothermia for the treatment of glioblastoma. The authors investigated the thermal characteristics of ultrathin microwires designed to remove heat from tumor tissue to a thermoelectric cooler, and established their decisive role in ensuring an effective decrease in temperature to a cytostatic level. The scientific novelty of the work lies in the combination of thermoelectric cooling with implanted heat-conducting microstructures for minimally invasive effects on deeply located brain tumors. The results obtained open up prospects for the creation of new biomedical thermoelectric devices for local therapy of oncological diseases.

Ref. [46] is devoted to the concept of Selective Brain Cooling (SBC) - a local controlled decrease in brain temperature without systemic hypothermic effects on the whole body. This allows protecting neurons from damage during ischemia, trauma or after surgery and reduces the risk of systemic complications associated with general body cooling. It is shown that local brain cooling can be implemented through miniature thermoelectric modules that can be combined with soft robotic instruments, allowing simultaneous intervention and control of tissue temperature.

In summary, the role of thermoelectricity in biology and medicine at various levels of application is presented in the form of Table 6.

Table 6

Level	Object of research or application	Practical medical purpose
Molecular	Individual DNA strands and molecular wires.	Diagnostics: Highly sensitive screening for mutations and tumor markers (alternative to PCR).
Cellular	Nanosensors based on self-assembled monolayers (SAMs).	Monitoring: Tracking biochemical indicators (glucose, hormones) inside cells
Tissue	Peltier effect probes for local cooling.	Therapy: Neuromodulation (stopping epilepsy) and cryosurgery of pathological tissues.
Organ	Smart patches and capsules with temperature regulation.	Drug delivery: Precise release of drugs at the site of inflammation through heating.
System	Flexible thermoelectric generators (TEGs).	Autonomy: Powering implants (pacemakers) with the energy of human body heat.

Conclusions

Thermoelectric technologies demonstrate growing potential in biological research and biomedical applications, including precision thermal control systems, wearable sensor devices, autonomous energy sources, and innovative medical applications.

Analysis of current research indicates the development of biocompatible materials and miniaturized solutions that combine monitoring, local thermal effects, and partial power supply. Such approaches open up opportunities for creating integrated medical systems with increased autonomy.

At the same time, the practical implementation of thermoelectric technologies is limited by their relatively low energy efficiency and the need to ensure a stable temperature gradient, which is especially relevant for implanted devices.

Thus, further development of the industry is associated with improving materials, optimizing TEM designs, and integration with other biomedical technologies.

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Роль термоелектрики у біологічних дослідженнях і медичних застосуваннях

У статті розглядається використання термоелектричних явищ, а саме, ефектів Пельтьє та Зесбека і приладів на їх основі, як високоефективного інструменту для вирішення актуальних завдань у галузі природничих наук (Life Sciences). Значну увагу приділено перевагам термоелектричного охолодження, нагрівання та високочутливої теплометрії через відсутність рухомих частин, а також завдяки високій точності підтримання температури і компактності пристроїв.

Ключові слова: термоелектрика, біологія, медицина.