Technical sciences

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HISTORY AND PERSPECTIVES OF ELECTROTHERAPY DEVELOPMENT

Electrotherapy, or electrotherapy, is currently understood as a group of physiotherapeutic methods based on the controlled use of electromagnetic factors (direct, pulsed, and alternating currents, electric and magnetic fields, electromagnetic fields of induction and radiation) on the human body for therapeutic purposes[1]. It should be noted that among the various methods of therapeutic intervention using physical factors, electrotherapy plays a predominant role, accounting for 70 % of all procedures performed[2]. In particular, electromagnetic energy (EME) is widely used for health restoration, the alleviation of the consequences of illness or surgery (rehabilitation), prevention of diseases (prophylaxis), and even the restoration of normal well-being and productivity in individuals who have experienced physical or nervous fatigue (recreation).

The use of electromagnetic energy has a deep-rooted history, dating back to ancient times when people began to utilize the electrical properties of amber and electric fish discharges to treat paralysis, nervous disorders, and rheumatic pain. During the time of the Roman emperors Tiberius and Claudius (beginning of our era), the ancient Roman physician Scribonius Largus applied electric stingrays to the heads of patients to treat migraines and used electric fish for foot baths to alleviate gout.

1 Bogolyubov, V.M., Ponomarenko, H.M. (1999). General physiotherapy.

2 Syvolap, V.D., Kalensky, V.Kh. (2014). Physiotherapy. URL: http://dspace.zsmu.edu.ua/bitstream/123456789/2244/1/SyvolapVD14_Fizioter.pdf (20.08.2023).

In medieval Europe, electric discharges from stingrays were not employed, as they were considered to be associated with magic. However, Islamic scholars adopted the ideas of ancient authors regarding the therapeutic use of skates. Persian scientist, who known in the West as Avicenna, recommended treating headaches and melancholia with electric stingray discharges in his work "The Canon of Medicine" (circa 1025 AD). In Europe, interest in electric stingrays was rekindled during the Renaissance period (14th-16th centuries), and their study eventually contributed to the discovery of sources of electric current. Descriptions of attempts to use atmospheric electricity for therapeutic purposes can be found in the works of English physicist and physician William Gilbert (1544–1603) and Benjamin Franklin (1706–1790).

In the second half of the 18th century, with the advent of the Leyden jar (the first electrical capacitor, invented by Dutch scientist Pieter van Musschenbroek and his student Cuneus in 1745 in Leiden) and later the galvanic cell (a chemical source of electric current proposed by Alessandro Volta in 1800), electricity began to be widely applied in medicine. Medications and patients were electrified, and regardless of the results, reports of "undoubtedly positive effects" were written. Many "healers" emerged, persuading that they possessed exceptionally powerful electrical influence and could therefore heal the sick. Even "treatment methods" were developed, according to which paralyzed individuals needed to be charged with "positive" electricity for healing, while the mentally ill required "negative" electricity.

Unfortunately, despite the significant accumulated experience and successful empirical attempts to apply electric energy, a metaphysical approach predominated, based on intuition, logic, and sometimes bordering on mysticism, charlatanism, and ignorance.

The aim of this article is to conduct a retrospective analysis of main events that have contributed to the establishment of electrotherapy and to identify the most promising directions for its future development.

Presentation of the main material. The catalyst for the scientifically grounded use of electromagnetic energy (EME) for therapeutic purposes is commonly attributed to the experiments of the Italian scientist Luigi Galvani (1737–1798). In his initial experiment, he observed the contraction of the calf muscle of a frog when a bimetallic (Fe/Cu) forceps was applied to the sciatic nerve. Continuing his experiments, Galvani concluded that electrical charges were generated due to some life processes in the frog's leg, as physicists at that time (including Galvani himself) believed that metals could only conduct electricity and could not produce an electric current. Asserting that he had discovered a new form of electricity, Galvani cited electric fish as an example.

While studying electric fish (one of which is even named after him today as the "Galvani torpedo"), Galvani became convinced that if skates could generate electricity, then the muscles of any other animal must also produce it. In his treatise, the Bolognese professor emphasized that he considered the electricity generated during friction, as well as atmospheric and skate electricity, to be similar to the "animal electricity" he had discovered. In 1791, L. Galvani published "Treatise on the Forces of Electricity in Muscle Motion," in which he described the presence of electric current in animal muscles. The book generated significant interest among physicists and physicians.

In the midst of the triumph of galvanism, an article by Professor of Physics at the University of Pavia, Alessandro Volta (1745–1827), appeared in the Italian "Physico-Medical Journal". He claimed that there was no need to postulate the existence of a specific 'animal electricity' to explain Luigi Galvani's experiments. It had nothing to do with the hapless frog or its severed leg. Galvani unwittingly brought two different metals into contact, which generated an electrical force, and the frog merely served as a conductor.

Naturally, Luigi Galvani couldn't let this assertion go unanswered. In front of witnesses, he dissected frogs with an iron knife, placing them on an iron stand, and connected the muscle and nerve with a wire made of the same metal. However, the legs still twitched, which, in Galvani's opinion, confirmed the presence of an electricity source in the animal.

Alessandro Volta argued that even a single piece of wire couldn't be considered perfectly homogeneous because it could contain impurities. He demonstrated electricity generated entirely without the involvement of animals, using only dissimilar metals. Volta dubbed it "metallic electricity".

The world of physicists divided into two camps. Some supported Luigi Galvani and were called galvanists, while others adhered to Alessandro Volta's views. It's difficult to say how this dispute in the 18th century would have ended if Luigi Galvani had not exited the scene (he died on December 4, 1798). The longstanding dispute was resolved – both participants were correct, and they are now recognized as the founders of the study of electricity. Luigi Galvani's experiments with 'animal electricity' laid the foundation for a new scientific field at the time – electrophysiology, and the method of applying direct electric current for therapeutic purposes is called galvanization.

At the time when Galvani was still conducting experiments with frog legs, Andrei Timofeyevich Bolotov (1738-1833) had already established an electrotherapeutic clinic and claimed to successfully treat almost all known diseases at that time.

Despite the delayed arrival of the trendy European craze for electromedicine (a precursor to modern electrotherapy) in the Russian Empire, it immediately assumed a serious form, marking the birth of a new branch of medicine. A significant role in this was played by Bolotov A.T. At the intersection of two interests – electricity and medicine – Andrei Timofeyevich began to create a new science, simultaneously advancing both theory and practice. The theoretical part was formulated by him in several works published throughout the 1790s, such as "History of My Electrification and Treatment of Various Diseases Therewith", "A Brief Electric Therapeutics", and others. The culmination of his work on electromedicine was released by Bolotov in 1803, titled 'Brief and Experimental Remarks on Electricity and the Ability of Electric Machines to Aid in Various Diseases.' In this book, the scientist detailed the construction of his electric instruments, their operating principles, and provided comprehensive instructions for the application of electricity in various medical cases.

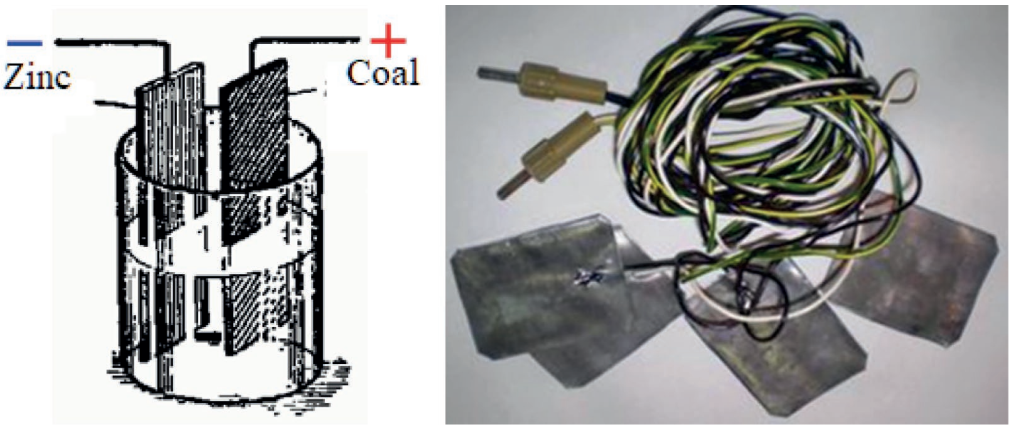
In his clinic, Andrei Timofeyevich proposed to treat colds, rheumatism, heart diseases, digestive system disorders, paralysis, contractures, nervous and psychological disorders, and more. Describing the results of his medical practice using electrical charges, the scientist spoke of the cure of more than 1500 individuals over a period of two and a half years, 'not only from various minor... ailments but many times from the most severe, longstanding, advanced, and even the rarest, extraordinary diseases, which had resisted all other remedies and even the skilled practices of physicians.'

Bolotov simplified the design of electrostatic machines and Leyden jars to the maximum. According to the scientist, this allowed for the production of miraculous electrical devices everywhere, even in the most primitive workshops, and provided assistance to both the rich and the poor. In one of the machines described by Bolotov, the charge passed through a metal comb to a conductor, which was a simple iron rod, and reached a Leyden jar made from a beer glass and flattened lead, "the kind in which tea is imported from China". From the Leyden jar, the electrical charge was directed to the patient through a wire with a goose feather at the end. This instrument was used, for example, for the treatment of coughs and ear infections.

Bolotov's unique developments, while generating interest among scientists and physicians, did not achieve the widespread adoption he had hoped for. By the beginning of the 19th century, the excitement around the new panacea began to wane. The public had expected miracles from electromedicine, but they did not always occur, and when they did, they were within the bounds of possibility.

When A.T. Bolotov established his electrotherapeutic clinic and wrote works on electricity, the understanding of the nature of electricity was still quite limited. The primary principle that guided the use of electricity in the treatment of various diseases in Europe at the time was that weak tissues should be stimulated, while excessive tension should be subdued. Obviously, in the majority of cases, treatment was not effective. Nevertheless, attempts to utilize electrical energy for therapeutic purposes persisted.

For a considerable period, galvanic batteries composed of galvanic cells or accumulators were considered the best sources of current for galvanization procedures (Fig. 1). The main advantage of such sources at the time was seen in the absence of voltage and current pulsations (unlike electrical machines).



a *b*

Figure 1. Galvanic cell and lead electrodes for galvanization procedures

The most suitable elements for galvanic batteries were those consisting of carbon and zinc immersed in a solution of vitriol. Both lead-acid and alkali accumulators were used. To obtain the required voltage (from 30 to 70 V), the battery regulated the number of galvanic cells or accumulators, which were connected in series. The application of current to the patient's body was carried out using pliable tin or lead electrodes, which were connected to the current source through specialized wires. The thickness of the electrodes typically ranged from 0.25 to 0.5 mm, and their shape and surface area depended on the area being subjected to electrization. The procedure for galvanization involved placing unpainted cotton fabric pads between the electrodes and the patient's body, which were moistened with water.

In 1802, V. Rossi first used direct electric current to introduce mercury salts into the body of a patient with syphilis, which were widely used at the time to treat this disease. To conduct such a procedure, a pad under one of the electrodes was moistened with an aqueous solution of mercury salts, which dissociated into ions and hydrophilic complexes. Under the influence of the external electric field, the ions of mercury salts moved towards the opposite pole, penetrating deep into the tissues and exerting a therapeutic effect. Essentially, these procedures marked the beginning of a new method – medicinal electrophoresis. Thus, a slight modification in the technique of galvanization procedures led to the creation of a new electrotherapeutic method – medicinal electrophoresis.

The first outcome of scientific research into the therapeutic effects of low-intensity direct electric current was the publication of "Reports on Galvanic Experiments" by the academician of the Medico-Surgical Academy, Vasily Vladimirovich Petrov, in 1803. He created the world's first high-voltage current source (Petrov's battery) and conducted research on its effects on living organisms among other experiments. As a result, V. V. Petrov discovered the narcotic effect of electricity. Over the years, electroanesthesia became firmly established in medical practice.

The appearance of a source of periodic current pulses (medical magneto) made it possible to establish the nature of tissue excitability and its fundamental laws. This enabled B. de Duchenne and R. Erb to experimentally substantiate the methods of nerve electrostimulation and determine the location of 'motor points' in the human body. The physical foundations and physiological regularities of the action of pulsed currents were summarized by I. F. Tsion in the book 'Foundations of Electrotherapy,' which was awarded the Golden Medal of the Paris Academy of Sciences in 1870.

Discoveries in the fields of physics, chemistry, and mathematics led to the formation of physicians' scientific worldview on a solid foundation of exact sciences. Using electromagnetic factors, they sought to investigate the therapeutic effects based on the analysis of the patient's organism's responses.

In 1864, J Maxwell created the theory of the electromagnetic field, according to which electric and magnetic fields exist as interrelated components of a unified whole – the electromagnetic field, any changes in which should generate electromagnetic waves propagating in a dielectric medium at a finite speed. This theory, from a unified perspective, explained the results of all previous research in the field of electrodynamics and served as the basis for the development of scientifically based methods of therapeutic use of the electromagnetic field.

In 1882, J. Wimshurst's invention of the electrostatic machine contributed to the development of a method for the therapeutic application of the electric field, which subsequently became known as "Franklinization" (named after Benjamin Franklin, an American politician and scientist). In 1891, N. Tesla created an electric generator of high-frequency oscillations, and in the same year, French researcher Jacques-Arsène d'Arsonval demonstrated the absence of excitation effects on biological tissues with high-frequency currents and successfully applied them for tissue heating, laying the foundation for high-frequency electrotherapy. Today, one of the methods of electrotherapy is named d'Arsonvalization in his honor.

With the advent of artificial light sources, active research into their therapeutic effects began. In 1807, W. Herschel demonstrated the chemical effects of ultraviolet radiation, and in the second half of the 19th century, the bactericidal effects of short-wave ultraviolet radiation were discovered. In 1903, Niels Ryberg Finsen became the first Danish laureate of the Nobel Prize in Physiology and Medicine, "in recognition of his contribution to the treatment of diseases – especially ordinary (tubercular) lupus – with concentrated light radiation, which opened up new broad horizons for medical science".

In 1816, A. Döbereiner at the University of Bern quantitatively determined the thermal effect of infrared radiation. Further research showed that photo-biological reactions when exposed to electromagnetic radiation on the human body are determined by the absorption of photon energy, which increases as the wavelength decreases. The nature of the interaction of optical radiation with biological tissues depends on its penetrating ability. In general, the depth of penetration of optical radiation of the specified range into human skin increases when transitioning from ultraviolet to infrared radiation. Today, the combination of all methods of using electromagnetic radiation in the specified range for therapeutic purposes is referred to as phototherapy.

In 1895, W. C. Röntgen discovered electromagnetic radiation that occupies the spectral region between ultraviolet and gamma radiation within wavelength ranges from 10^{-7} to 10^{-12} meters. X-rays or X-rays immediately interested medical experts due to their strong penetrating power. By 1919, X-ray tubes had gained wide acceptance and were used not only in diagnostic devices but also in therapeutic equipment in medical practice.

Today, X-ray therapy is one of the types of radiation therapy undergoing its fifth stage of development. This stage is characterized by the cooperation of specialists from various fields, combining physical, diagnostic, technical, radiobiological, and clinical approaches to the treatment of each patient. Special devices with X-ray emitters, which generate short-wave (hard) X-ray radiation, are used for radiation therapy procedures. The application of this method is based on the destructive action of radiation on the cells of malignant tumors, causing mutations that lead to cell death[3]. The penetrating ability of X-ray radiation increases with the increase in radiation energy, which, in turn, depends on the voltage across the X-ray tube.

Depending on the energy of X-ray radiation (in X-ray therapy, radiation energy ranging from 10 to 250 keV, corresponding to wavelengths of 0.12–0.05 nm, is used), X-ray therapy can be divided into three groups:

short-focus or close-distance X-ray therapy with radiation energy from 10 to 60 keV (0.12–0.021 nm) is used for irradiation at short distances (up to 6–7.5 cm) and for treating relatively superficial skin and mucous membrane lesions.

deep or far-distance X-ray therapy with radiation energy from 100 to 250 keV (0.012-0.005 nm) is used for irradiation at distances of 30 to 60 cm for deeply located pathological lesions. medium-distance X-ray therapy is mainly used for non-tumor diseases.

The 20th century marked the most productive period of electrotherapy development. Ideas, inventions, and discoveries in the field of biophysics and physiology provided a solid scientific foundation for the formulation of theoretical concepts of electrotherapy and played an exceptional role in understanding the mechanisms of the therapeutic effects of electromagnetic energy factors[4]. Another contributing factor to the successful development of electrotherapy was the achievements in electrical engineering and electronics[5].

A. E. Shcherbak experimentally proved the involvement of the autonomic nervous system in the mechanisms of the therapeutic effects of physical factors. Based on his concept of “vegatoreflex therapy”, methods of segmental-metameric zone galvanization were developed.

Extremely effective for the treatment of patients were ultrahigh-frequency electric fields obtained in 1926 by E. Shlihake, which led to the method of UHF

3 Kipenskyi, A.V. (2018). X-ray radiation for diagnosis and treatment. Bulletin of National Technical University “KhPI”. NTU “KhPI”, 4 (1280), 93–100.

4 Larin, A.A., Kipenskyi, A.V. (2021). History of electrical engineering. Madrid Printing House, 2021. 263 p.

5 Sokol, E.I., Ivashko, A.V., Kachanov, P.A. (2019). Electronics, automation, computer science – people and inventions: teaching. Manual. NTU “KhPI”, 2019. 226 p.

therapy, and high-frequency magnetic fields obtained in 1927 by M. Kovarshik, which led to the method of inductothermy. In the 1930s, research was conducted on the therapeutic effects of aeroions (electrically charged gas molecules) obtained by ionizing the air under the influence of a high-voltage electric field (the method of aeroionotherapy). In 1937, our compatriots A. N. Obrosov and I. A. Abrikosov described the action of diadynamic currents (pulse currents with a sinusoidal front and an exponential decay with a frequency of 50 or 100 Hz) on the human nervous-muscular apparatus in medical practice for the first time. At that time, the first prototypes of devices were created, but their use did not receive much support. It was only from 1946 that the diadynamic therapy method gained widespread acceptance when French dentist P. Bernar established the analgesic effect of diadynamic currents.

In 1943, G. M. Frank experimentally substantiated the effectiveness of ultraviolet irradiation for sanitizing infected wounds and relieving pain in the wounded and sick. A. V. Rakhmanov revealed the effect of activating the differentiation and growth of connective tissue under the influence of an ultrahigh-frequency electromagnetic field.

Significant achievements in electrotherapy in the post-war years are associated with the name of A. N. Obrosov. He was the first to quantitatively describe the neurostimulating effect of sinusoidal modulated currents (carrier frequency 5 kHz, modulation frequency range 10–150 Hz), which was later used by his student V. G. Yasnogorodsky in the method of amplipulse therapy (currently, frequency ranges have been expanded to 2–10 kHz for carrier frequencies and 1–150 Hz for modulation frequencies). At various times, A. N. Obrosov theoretically and experimentally substantiated the methods of decimeter wave therapy (DMW therapy), centimeter wave therapy (CMW therapy), and pulse ultrahigh-frequency therapy (UHF therapy).

In 1960, American physicist Theodore Maiman created the first laser, a generator of highly directional electromagnetic radiation in the optical range. By 1962, a laser using an artificial ruby crystal was applied in the United States for the treatment of retinal disorders. In the mid-1960s, similar lasers were successfully used in Soviet clinics to treat patients with retinal detachment by precise "spot-welding." Laser treatment for glaucoma was conducted using laser pulses to create a channel for aqueous humor drainage in the anterior chamber of the eye, thereby stabilizing intraocular pressure. Laser photocoagulation was utilized to treat choroidal melanoma. From 1965 onwards, the Ukrainian Cancer Institute initiated a broad study into the biological and anti-tumor effects of laser radiation. In the same year, the first publications on laser applications in dermatology emerged.

Low-energy laser radiation began to be used in surgery for preoperative preparation and postoperative therapy starting from the late 1960s, in dentistry from 1970, and in cardiovascular surgery from 1974. In 1974, the Ministry of Health issued permission for the mass production and application of the first laser therapy device. This event can be considered the inception of laser therapy as an independent medical discipline.

In the mid-1970s, it was discovered that the therapeutic effect of laser radiation could be enhanced when combined with the simultaneous application of a constant magnetic field to the irradiated area. This laid the foundation for developing methods of combined laser therapy with other forms of energy used in physiotherapy. The first publications on the use of low-intensity helium-neon lasers for laser therapy in ophthalmology date back to 1978.

In gynecology, practical application of lasers began with the use of laser radiation on reflexogenic zones and acupuncture points in patients with chronic inflammatory processes in the uterine appendages. In 1978, the development of the method for intravascular laser blood irradiation using optical fibers commenced. In 1981, a group of Soviet scientists was awarded the State Prize in the field of science and technology for creating, developing, and implementing new laser surgical tools and new laser surgical methods for abdominal, purulent, and plastic surgery. By 1985, laser therapy found new applications in clinical practice for treating malignant neoplasms. Low-energy laser radiation could alter the properties of drugs injected parenterally and have a static effect on tumor tissues. This method became known as photodynamic therapy.

In the latter half of the 20th century, more detailed insights into the nature of pathological processes affecting the entire body emerged, alongside the discovery of hormones and cerebral opioid systems. These findings formed the basis for developing original methods to influence the body through electromagnetic factors via the brain. In 1949, A. A. Gilyarovskiy and N. M. Liventsev proposed the method of electrosonotherapy. In 1970, L. Limoj justified transcranial electroanalgesia. In 1984, V. M. Bogolyubov introduced transcranial UHF therapy into medical practice.

Numerous experimental studies conducted by the Belarusian therapist V. S. Ulashchik demonstrated that the use of pulsed currents for medicinal electrophoresis procedures allows for the penetration of medicinal drugs to greater depths. As a result of these experiments, the book "New Methods and Techniques of Physical Therapy" was published in 1986, describing and justifying new methods such as diadynamophoresis, amplipulsephoresis (in the unipolar generation mode), fluctuophoresis (unipolar current), and electrophonophoresis[6].

In Ukraine, until 1992, the Ministry of Health purchased medical equipment from over 300 supplier factories, with 65 % of them located in Russia and only 19 % in Ukraine. Under these conditions, domestic industry could only meet 13–15 % of Ukraine's medical equipment needs in terms of product range and 20 % in terms of volume[7]. To improve the state of medical equipment in Ukraine, two State Programs for the Development of Medical Equipment were implemented from 1992, following Cabinet of Ministers resolutions. The execution of these programs led to the creation of new medical equipment that had not been previously manufactured in Ukraine. However, the level of domestic medical equipment supply increased only to 30–35 %.

Starting in 2002, several projects of a Comprehensive Program for the Development of the Medical Industry in Ukraine were prepared to supply institutions in the domestic healthcare system with medical equipment. Initially, for the years 2004–2010, then for 2006–2010, and later for 2008–2012. In 2008, the Cabinet of Ministers of Ukraine, by Resolution No. 968 of November 5, 2008, approved the State Target Scientific and Technical Program for the Development of Medical Equipment Production for 2009-2013. However, funds for the implementation of this program were never allocated, and consequently, the medical industry did not receive the development it deserved. In 2011, Resolution No. 968 ceased its effect, pursuant to Cabinet of Ministers Resolution No. 704 of June 22, 2011.

All of these factors led to a highly unsatisfactory state of medical equipment in Ukraine by 2005. Much of the equipment was physically worn out, morally outdated, and required systematic replacement[8]. For physiotherapeutic devices, this indicator was even higher, exceeding 90 %[9]. Some domestically produced physiotherapeutic devices from the 1960s and 1970s are still in use to this day (Fig. 2).

6 Ulaschyk, V.S. (1986). New methods and techniques of physical therapy. 175 p.

7 Devko, V. (2001). Medical technology of Ukraine. Development of branch of medical industry. Medical market. Business supplement to journals of Medical Institute of Ukraine "Medicine of Ukraine". Kyiv, 3, 3–8.

8 The concept of the state targeted scientific and technical program for the development of the medical industry of Ukraine for 2006-2010 : Medical market. Business supplement to the journals of the Medical Institute of Ukraine "Medicine of Ukraine". (2005). Autumn. 2-4.

9 Korobov, A.M. (2005). About concept of domestic industry development of medical equipment (Letter to President of Ukraine V.A. Yushchenko). Application of lasers in medicine and biology. Materials XXIV International. science and practice conf. 7–14.

At the end of the 20th century, a new direction in physiotherapy emerged – photobiomodulation therapy, based on the use of narrowband LED light of different colors[10]. Another name for this approach, LED therapy, was proposed by scientists from Kharkiv[11]. Each component of light possesses specific therapeutic effects and can be applied for the optimal treatment of various pathologies. The application of red, green, and blue LED optical radiation has been extensively studied. However, other spectra within the visible range also find applications in medical practice.

Therefore, the development of electrotherapy in the 20th century was closely tied to the advancements in scientific and technological progress, the creation of new sources of electromagnetic energy, and novel electrotherapeutic devices.

The current state of electrotherapy. Today, all electrotherapy methods and corresponding technical equipment for conducting procedures are conventionally grouped based on the part of the electromagnetic spectrum used.

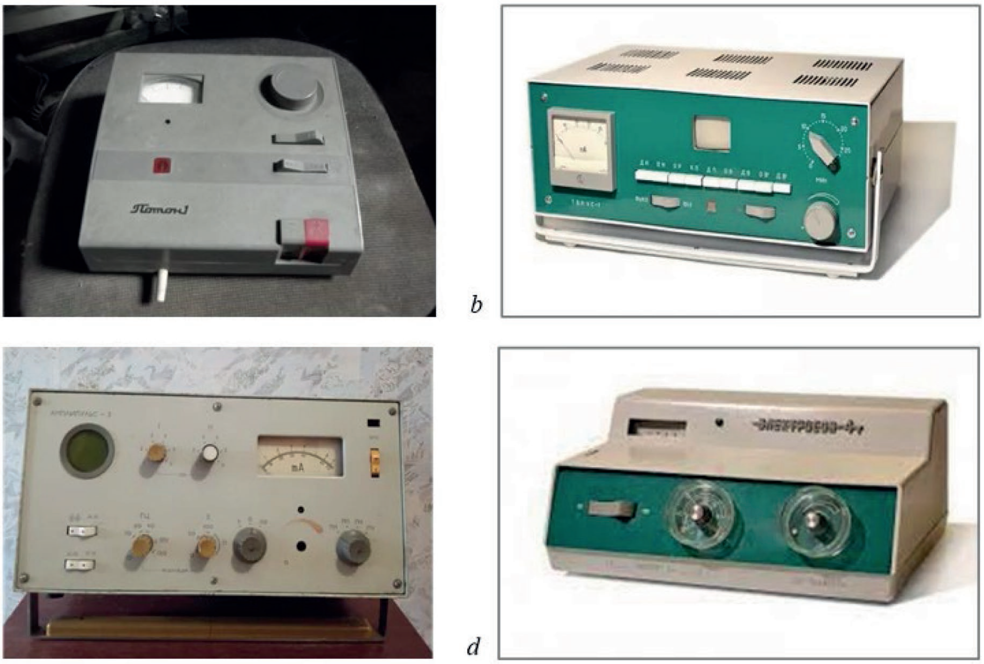


Figure 2. Domestic electrotherapy devices produced in the 1960s and 1970s:
Flow 1 – for galvanization and medicinal electrophoresis (a);
Tonous 1 – for diadynamotherapy (b);
Amplipulse 3 – for therapy with sinusoidal modulated currents (c);
Electrosound 4 – for electrosonotherapy (d).

10 Bilovol, A.M., Tkachenko, S.G., Tatuzyan, E.H. (2017). Physiotherapy in cosmetology. KhNMU. 116 p.

11 Tondiy, L.D., Tondiy, O.L., Zakrevska, E.L. (2012). Light, color: therapy from lamp, laser and diode light sources. S.A.M. LLC. 168 p.

In accordance with the International Radio Regulations, this spectrum includes the following ranges: low-frequency (LF), medium-frequency (MF), high-frequency (HF), infrared (IR), visible (V), ultraviolet (UV), and X-ray (X) (Tab. 1).

Table 1.

Spectra of electromagnetic vibrations used in electrotherapy

Part of the emission spectrum, wavelength range and frequency band	Electrotherapy methods, wavelength range or frequency band
LF: 10^8–10^3 m; 3–3·10^5 Hz	***Pulse magnetic therapy*** 0,16–0,66 Hz. ***Diadynamic therapy*** 50 и 100 Hz. ***Electrosleep therapy*** 5–160 Hz. ***Short pulse electroanalgesia*** 2–400 Hz. ***Low frequency magnetic therapy*** 0,125–1000 Hz. ***Electropuncture*** before 1 kHz. ***Fluctuarization*** 0,1–2 kHz. ***Transcranial electroanalgesia*** 60–2000 Hz. ***Interference therapy*** 3–5 kHz. ***Amplipulsetherapy*** 2–10 kHz (carrier frequency). ***Ultratonotherapy*** 22±1,6 kHz. ***Local darsonvalization*** 110 kHz.
MF: 10^2–10^{-3} m; 3·10^6–3·10^{11} Hz	***Ultrahigh frequency therapy*** 27,12±0,16 MHz and 40,68±0,02 MHz. **High frequency magnetic therapy** 13,56 МГц, 27,12 МГц, 40,68 МГц. ***Decimeter wave therapy*** 460±4,6 MHz. ***Centimeter wave therapy*** 2375 MHz and 2450±50 MHz. ***Extreme High Frequency Therapy*** 42,194±0,01 GHz and 53,534±0,01 GHz.
HF: 10^{-3}– 7,6·10^{-7} m; 3·10^{11}–3,95·10^{14} Hz	***Infrared irradiation method*** 780–1400 nm.
V: 7,6·10^{-7}–4·10^{-7} m; 3,95·10^{14}–7,5·10^{14} Hz	***Chromotherapy*** 380–780 nm
UV: 4·10^{-7}–1,8·10^{-7} m; 7,5·10^{14}–1,7·10^{14} Hz	***Long-wave ultraviolet irradiation*** 320–400 nm. ***Mid-wave ultraviolet irradiation*** 280–320 nm. ***Short-wave ultraviolet irradiation*** 180–280 nm.
X: 10^{-7} – 10^{-12} m; 3·10^{15} – 3·10^{20} Hz	***Short-focus or near-distance radiotherapy*** 0,12–0,021 nm. ***Deep or long-distance radiotherapy*** 0,012–0,005 nm. ***Mid-distance radiotherapy.***

The first developed device was named ANET-50 GT (Fig. 3) and was designed for galvanization and drug electrophoresis procedures, the techniques of which have long been known, well-documented, and approved by relevant authorities.

Figure 3. Low-frequency electrotherapeutic device ANET-50 GT

The distinctive feature of this device was that it allowed for both constant (galvanic) current and pulsed current with a frequency adjustable in the range of 1 to 99 Hz[12]. This made it possible to perform pulsed electrophoresis procedures and use the device to achieve trophic and stimulating effects on tissues within the range of pulse frequencies from 1 to 20 Hz. The application of pulsed currents with a frequency of 80-100 Hz induces an analgesic effect by blocking pain impulses in the gelatinous substance of the spinal cord (gate control of pain) and stimulating the humoral antinociceptive system represented in the body by endorphins and enkephalins[13].

The generation of control pulses to stabilize the device's output current and modulate it was carried out using digital pulse converters (DPC) with frequency-pulse conversion law (FPC) and width-pulse conversion law (WPC). The general principle of forming pulse sequences is explained by the diagram shown in Fig. 4, a, and the temporal diagrams of the formation process (Fig. 4, b-e). Upon receiving a signal corresponding to the logical one level at the S-input of DPC with FPC, the converter begins counting down a previously recorded number N_1. This count is performed by decrementing the number by one with each clock pulse u_{CP}, which occurs at intervals of T_{CP} (Fig. 4, b-c). When the condition $N_1 \leq 0$

12 Sokol, E.I., Kipenskyi, A.V., Korol, E.I. (2006). Expanding the functional capabilities of electronic medical device for galvanization and medicinal electrophoresis. Technical electrodynamics. IED of NASU, 7, 107–110.

13 Kipenskyi, A.V., Kubyshkina, N.I., Korol, E.I. (2012). Functional possibilities of electrotherapeutic apparatus and its quality improvement due to improvement of software and mathematical support. Applied radio electronics. AN PRE, Khnure, 3(11). 354–360.

is met, a signal appears at the output of DPC with FPC, setting the RS-trigger into a single condition (Fig. 4, d). The signal from the trigger's output is applied to the C-input of the DPC with WPC, and counting down the number N_2 begins in the converter (Fig. 4, b, e). Upon completion of the N_2 count, the trigger is reset to zero (Fig. 4, d). The output signal of the RS-trigger is the output signal of the pulse generator u_{OUT}. In this case, the period of occurrence of the output pulses will be determined by the expression

$$T_{OUT} = N_1 \cdot T_{CP}, \quad (1)$$

and their duration

$$T_{OUT} = N_2 \cdot T_{CP}, \quad (2)$$

Thus, by varying the values of N_1 and N_2, it is possible to adjust the average value of the output current (the device uses the width-pulse modulation method with subsequent filtering for this purpose) and provide its modulation to deliver pulsed current therapy to the patient. The implementation of DPC can be achieved at both the hardware and software levels.

Additionally, in the ANET-50 GT device, in coordination with the medical collaborator, the possibility of applying pulsed currents with automatically changing frequencies, known as scanning modes, was provided. There were a total of six such modes, in each of which the impulses frequency varies from f_{Imin} to f_{Imax} or, conversely, according to some predetermined law.

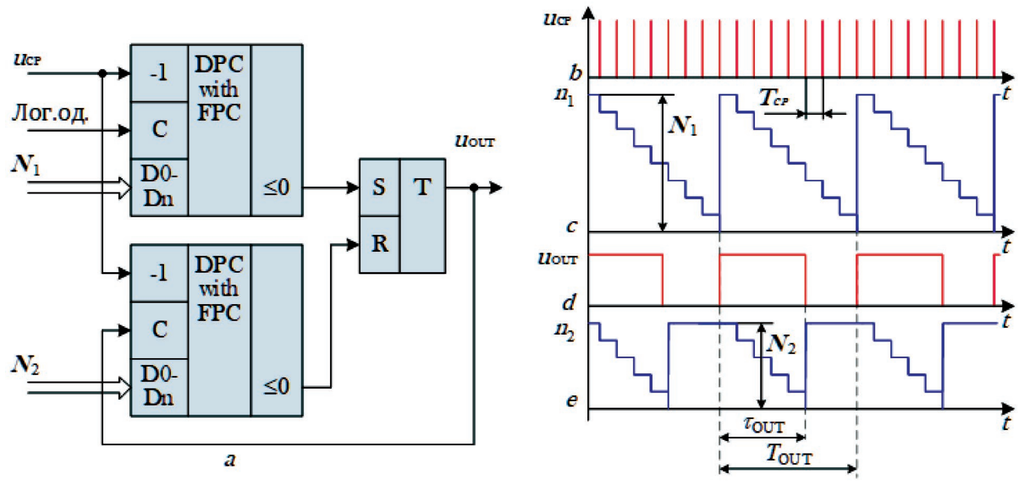


Figure 4. Scheme and timing diagrams for the formation of control pulses

For first scanning mode (on device indicator – C1), the impulses frequency f_{I1} of the output current automatically changes from 1 to 10 Hz following a sawtooth pattern with an ascending slope (Fig. 5, a).

In second scanning mode (C2), the pulse frequency f_{I2} of the output current changes from 1 to 10 Hz and back to 1 Hz following a triangular pattern (Fig. 5, b).

The third scanning mode (C3) features the pulse frequency f_{I3} of the output current changing from 10 to 1 Hz according to the sawtooth law with decreasing (Fig 5, c).

In fourth scanning mode (C4), the pulse frequency f_{I4} of the output current changes from 10 to 100 Hz in a sawtooth pattern with an ascending slope (Fig. 5, d).

The fifth scanning mode (C5) involves the pulse frequency f_{I5} of the device's output current changing from 10 to 100 Hz and back to 10 Hz following a triangular pattern (Fig. 5, e).

When selecting the sixth scanning mode (C6) of the device, the frequency f_{I6} of its output current will change from 100 to 10 Hz in a sawtooth pattern with a descending slope (Fig. 5, f).

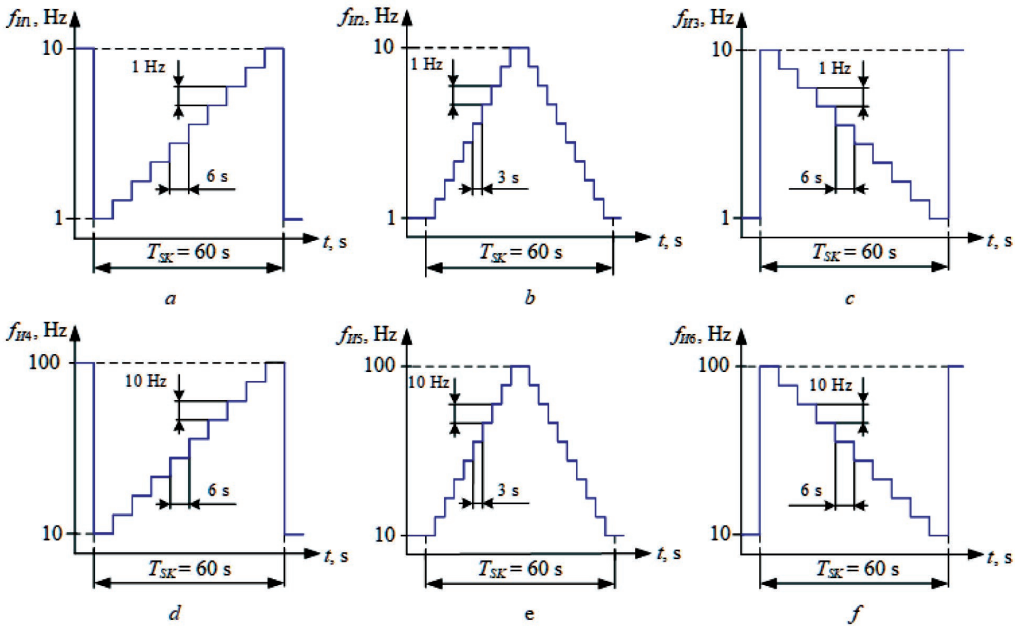


Figure 5. Change in pulse repetition rate over time when the ANET-50 GT device operates in scanning modes

In first and fourth scanning modes, the change in the repetition rate of current pulses within the scanning period is determined by the expression

$$f_{I1(4)}(t) = \Delta f_{I1(4)} \left(1 + \left[\frac{t}{\Delta t_{1(4)}} \right] \right), \quad (3)$$

and in third and sixth scanning modes, the expression for changing pulse repetition rate will have the form

$$f_{I3(6)}(t) = \Delta f_{I3(6)}\left(10 - \left[\frac{t}{\Delta t_{3(6)}}\right]\right), \tag{4}$$

where Δf_{Ii} – discreteness of changes in pulse repetition rate: in first and third scanning modes $\Delta f_{I1(3)}$ = 1 Hz, in fourth and sixth scanning modes $\Delta f_{I4(6)}$ = 10 Hz;

t – current time within the scan period T_{SC};

Δt_i – time interval for the formation of a constant value of pulse repetition rate, which in first, third, fourth and sixth scanning modes is 6 s;

$\left[\frac{t}{\Delta t}\right]$ – integer part of the quotient from division.

In second and fifth scanning modes, the change in repetition rate of current pulses within the scanning period is determined by the expression

$$f_{I2(5)}(t) = \begin{cases} \Delta f_{I2(5)}\left(1 + \left[\frac{t}{\Delta t_{2(5)}}\right]\right) \text{ at } 0 \le t < \frac{T_{SK}}{2}; \\ \Delta f_{I2(5)}\left(10 - \left[\frac{t - 0{,}5T_{SK}}{\Delta t_{2(5)}}\right]\right) \text{ at } \frac{T_{SK}}{2} \le t < T_{SK}, \end{cases} \tag{5}$$

where Δf_{Ii} – discreteness of changes in pulse repetition rate: in second scanning mode Δf_{I2} = 1 Hz; in fifth scanning mode Δf_{I5} = 10 Hz;

Δt_i – time interval for formation of a constant value of pulse repetition rate, which in second and fifth scanning modes is equal to 3 s;

T_{SK} – scanning period.

In all scanning modes, the scanning period T_{SK} is equal to 60 s, and the average current value will be equal to half the amplitude value of the output pulses of device.

Scanning modes C1 and C3 (Fig. 5, *a*, *c*) do not allow tissues to adapt and given the low-frequency nature of the impact, be used in subacute and chronic processes in order to enhance metabolic and trophic manifestations. A more gentle option for these cases is C2 (Fig. 5, *b*).

The use of scanning modes C4 and C6 (Fig. 5, d, f) is most rational for acute pain manifestations. However, as in the previous case, the most gentle current is the scanning mode C5 (Fig. 5, d)[14].

In the process of medical testing of ANET-50 GT device, specialists from the Department of Physiotherapy and Balneology of Kharkov Medical Academy of

14 Kipenskyi, A.V., Kubyshkina, N.I., Korol, E.I. (2012). Functional possibilities of electrotherapeutic apparatus and its quality improvement due to improvement of software and mathematical support. Applied radio electronics. AN PRE, Khnure, 3(11). 354–360.

Postgraduate Education proposed adding three modes to stimulate human neuromuscular system. In any of the stimulation modes, the patient is exposed to series of current pulses i(t) with amplitude I_m and frequency f_I = 100 Hz during time intervals τ_C (with a duty cycle of two) which alternate with pauses lasting τ_L (Fig. 6).

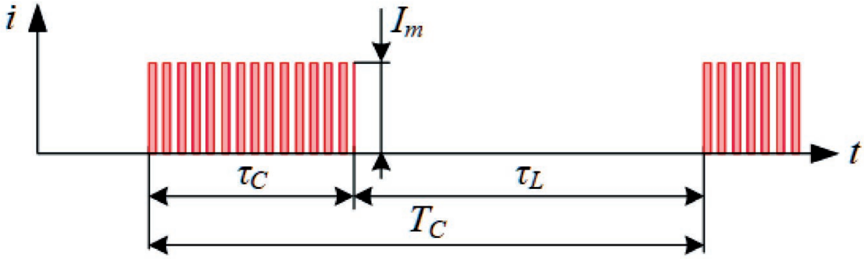


Figure 6. Output current of the ANET-50 GT device in stimulation modes

When selecting first stimulation mode (P1 on device indicator), duration of pulse series is 4 s, and pause between series is 6 s. In second stimulation mode (P2), the duration of pulse series is 2 s, and pause duration is 3 s. In third mode (P3) τ_C = 1 c, τ_L = 2 c. The P1 stimulation mode is recommended to be used for deep lesions of nerves and muscles, the P2 mode for moderate ones, and the P3 mode allows you to stimulate healthy but weakened muscles (if they have been immobilized for a long time, in the absence of proper load, etc.). In all stimulation modes, the duration of the pause is 1.5-2 times longer than the duration of the series of current pulses, which is more physiological and allows (during the pause) the muscle to rest and restore its metabolism[15].

The change in the output current of the device in any stimulation mode can be determined by the expression

$$i(t) = \begin{cases} I_m \ \text{in} \ \ 0 \le t < T_{OUT}/2, \ \text{if} \ \ 0 \le t < \tau_C; \\ 0 \ \ \text{in} \ \ T_{OUT}/2 \le t < T_{OUT}, \ \text{if} \ \ 0 \le t < \tau_C; \\ 0, \qquad\qquad\qquad\qquad \text{if} \ \ \tau_C \le t < T_C, \end{cases} \qquad (6)$$

where T_C – repetition period of series of current pulses

$T_C = \tau_C + \tau_L$.

The average value of the output current (including pauses) in the stimulation mode will be determined by the expression

$$I_{AVG} = 0{,}5 I_m \tau_C / T_C \qquad (7)$$

and for the first and second stimulation modes it will be 0.2 I_m, and for the third – 0.167 I_m.

15 Kipenskyi, A.V., Kubyshkina, N.I., Korol, E.I. (2012). Functional possibilities of electrotherapeutic apparatus and its quality improvement due to improvement of software and mathematical support. Applied radio electronics. AN PRE, Khnure, 3(11). 354–360.

It is important to note that the ANET-50 GT device utilized microprocessor technology for its control system. This allowed for an expansion of its functional capabilities primarily through software enhancements without complicating the hardware components.

Another distinctive feature of the ANET-50 GT device, which facilitates the improvement of electrotherapy techniques, is the ability to perform procedures using two, three, or four electrodes, conveniently color-coded as red (R), yellow (Y), green (G), and black (B). Each electrode can be connected to the plus (+) or minus (-) terminals of the current regulator (CR) of device. Some of possible electrode connection options to human body are illustrated in Fig. 7. In each of depicted cases, the polarity of current regulator can be reversed. The dashed lines indicate the directions of currents in patient's body.

No less important is presence of a self-diagnostic system in the apparatus, which allows[16]:

- completely eliminate the possibility of exposing the patient to unregulated current intensity;
- ensure that procedures with two, three or four electrodes are conducted strictly in accordance with the chosen methodology;
- expedite the process of identifying and resolving emergencies and discrepancies in the apparatus's operation.

All of this increases the reliability of the apparatus, thus ensuring a higher quality of procedures and contributing to patients' faster recovery.

Thus, the creation of an apparatus with extensive functionality that goes beyond the requirements for devices used in galvanization and medicinal electrophoresis procedures has led to the development of new electrotherapy techniques using scanning modes (C1-C6) and stimulation modes (P1-P3).

The successful testing and medical evaluation of the low-frequency electrotherapy apparatus ANET-50 GT resulted in the approval by the State Service for Medicines and Medical Devices for the use of the apparatus in medical practice (Certificate of State Registration No. 6309/2007). Additionally, the ANET-50 GT apparatus received a Certificate of Compliance with Standards and Technical Conditions No. 879461, Series VB, registered on July 23, 2007, in the Register under No. UA1.007.0096514-07, allowing for serial production of the apparatus[17].

16 Kipenskyi, A.V., Kubyshkina, N.I., Korol, E.I. (2007). Algorithms of self-diagnosis of the apparatus for galvanization and medicinal electrophoresis. Applied radio electronics. AN PRE, Khnure, 1(6). 86–95.

17 Kipenskyi, A.V., Kubyshkina, N.I., Korol, E.I. (2015). Electronic medical equipment. Developments of Department "Industrial and Biomedical Electronics" NTU "KhPI": Monograph. Golden Pages. 264 p.

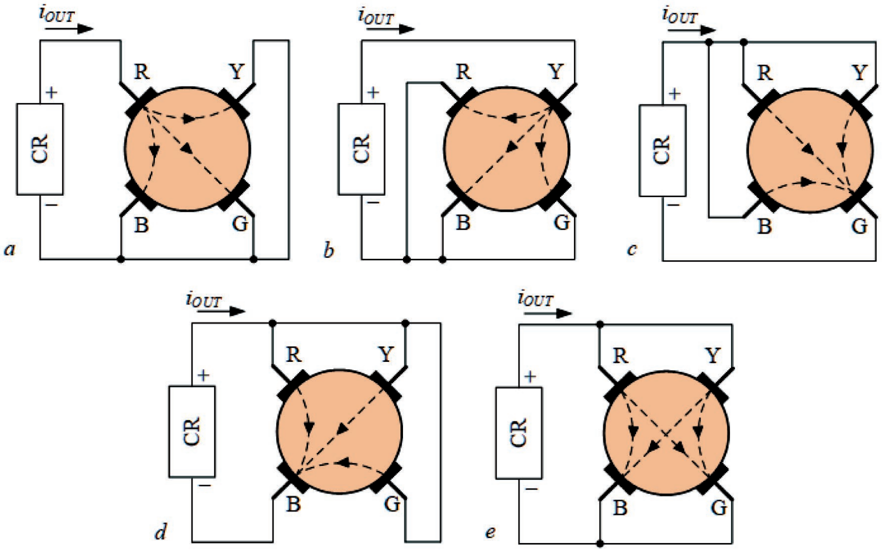


Figure 7. Directions of currents in the patient's body during operation of the ANET-50 GT device with four electrodes

The excellent performance of the ANET-50 GT apparatus justified the need for its further improvement. In this regard, the developers from the Radmir company of AO NIIIRI and the NTU "KhPI" took different paths.

The Radmir company introduced the ANET-50 M (multifunctional) apparatus, as shown in Fig. 8[18]. ANET-50 M generates multiple types of currents, allowing it to be used not only for galvanization and medicinal electrophoresis procedures but also for diadynamotherapy, amplipulsetherapy, fluctuorization, and short-pulse electroanalgesia.

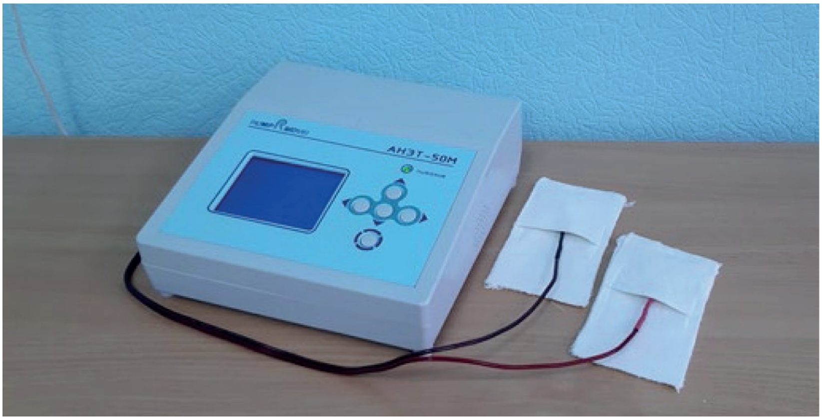


Figure 8. Low-frequency electrotherapeutic device ANET-50 M

18 Kypenskyi, A.V., Vereshchak, V.A., Smotrov, I.V. (2019). Physiotherapy apparatus of new generation. East European Journal of Internal and Family Medicine. "FACT", 1. 114–123.

When performing galvanization and medicinal electrophoresis procedures using direct current in the apparatus, there are options for stabilizing the output voltage (in the range of 0 to 110 V) or stabilizing the output current (in the range of 0 to 80 mA) with a load resistance of 500 ohms. The current stabilization mode is especially relevant considering that the resistance of the body area being exposed to direct electrical current can change significantly (up to 40 %) during the procedure[19].

For diadynamotherapy procedures, the ANET-50M apparatus generates diadynamic currents. These currents consist of sequences of pulses with a sinusoidal front and an exponential decay, occurring at a frequency of 50 Hz (single half-period current) or 100 Hz (two half-period current, Fig. 9), as well as various combinations of them, involving changes in amplitude and alternating with pauses. In total, the ANET-50M apparatus generates seven primary types of diadynamic currents, each having a wide range of therapeutic effects due to their different frequency spectra[20].

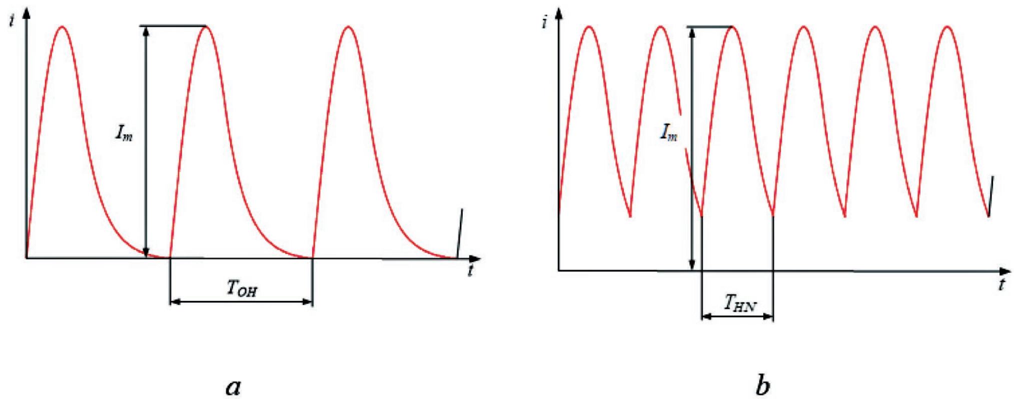


Figure 9. Diagrams of half-wave (a) and full-wave (b) diadynamic currents

The ANET-50M apparatus also provides extensive capabilities for conducting amplipulse therapy procedures, a method in which specific areas of the patient's body are exposed to the influence of sinusoidal modulated currents (SMC). These currents consist of harmonic oscillations with varying amplitudes, obtained by modulating the carrier oscillations at a frequency of $f_H = 1/T_N$ with modulating oscillations at a frequency of $f_M = 1/T_{OUT}$ (Fig. 10).

19 Kipenskyi, A.V., Gura, Yu.M., Kubyshkina, N.I. (2010). The results of study of changes in resistance of interelectrode area during medical electrophoresis procedures. Technical electrodynamics. IED of NASU, 1. 251–255.

20 Kipenskyi, A.V., Dotsenko, M.E. (2009). Therapeutic properties of diadynamic currents and their harmonic composition. Radiotechnique. KhNURE, 158. 152–161.

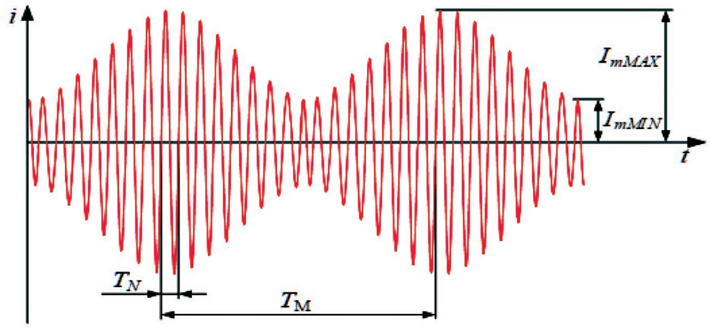


Figure. 10. Sinusoidal modulated current diagram

Using the ANET-50M apparatus, the carrier frequency can be set within a range from 2000 Hz to 10000 Hz (in steps of 1000 Hz), while the modulating frequency can be chosen from a series of discrete values: 1, 2, 3, 4, 5, 10, 15, 25, 50, 100, and 150 Hz. The amplitude modulation coefficient, denoted as k_{AM} and typically calculated as:

$$k_{AM} = \frac{U_{mMAX} - U_{mMIN}}{U_{mMAX} + U_{mMIN}} \cdot 100\ \%\ , \qquad (8)$$

Where U_{mMAX} and U_{mMIN} –maximum and minimum amplitude values of modulated signal (Fig. 10) can be selected from the range: 0, 25, 50, 75, 100 and 125 % (in the latter case, there are pauses between series of modulated oscillations).

In total, the ANET-50 M device generates five types of sinusoidal modulated currents.

To carry out fluctuarization procedures, a method in which individual areas of the patient's body are exposed to fluctuating currents (currents with a noise spectrum), the ANET-50M device provides the ability to use three types of currents:

– bipolar symmetrical (Fig. 11, a);
– bipolar asymmetrical (mainly negative polarity, Fig. 11, b);
– monopolar (Fig. 11, c).

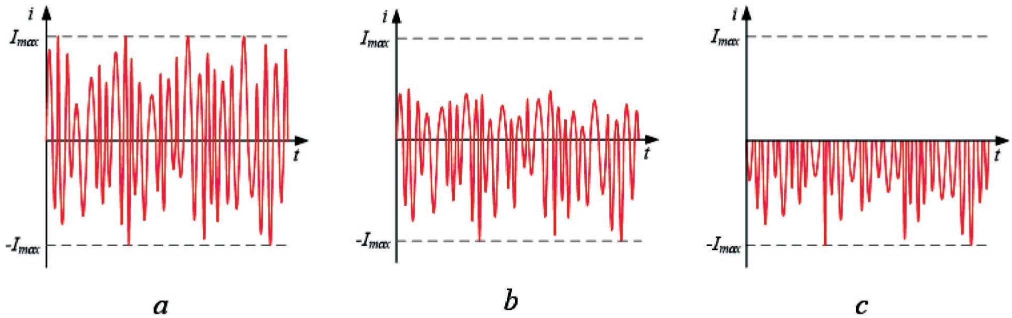


Figure 11. Fluctuating current diagrams

The feature of the action of fluctuating currents lies in the fact that disordered variation of electrical current parameters prevents the occurrence of summation and adaptation processes in tissues that typically occur with rhythmic exposure to identical pulse types or harmonic oscillations.

Another method of electrotherapy that can be implemented using the ANET-50M apparatus is short-pulse electroanalgesia (transcutaneous electroneurostimulation). This method of electrotherapy involves the application of short current pulses to a painful area of the body with a pulse frequency ranging from 1 to 150 Hz. For short-pulse electroanalgesia, pulses of various shapes are used:

- Monopolar rectangular pulses with an amplitude of I_m, duration of τ_I, and a repetition period of T_{OUT} (Fig. 12, a);
- Monopolar triangular pulses with an amplitude of I_m, duration of τ_I (at the level of I_m /2), and a repetition period of T_{OUT} (Fig. 12, b);
- Monopolar rectangular pulses with an amplitude of I_m, duration of τ_I, and a repetition period of T_{OUT} in the form of series with a duration of τ_I alternating with pauses of duration τ_L (Fig. 12, c);
- Bipolar rectangular pulses with equal amplitude values ($I_m = |-I_m|$) and durations of the positive and negative parts of the pulse ($\tau_{I+} = \tau_{I-}$) (Fig. 12, d);
- Bipolar triangular pulses with equal amplitude values ($I_m = |-I_m|$) and durations of the positive and negative parts of the pulse (at the level of I_m/2) (Fig. 12, e);
- Bipolar asymmetric pulses with a positive rectangular part and a negative triangular part (Fig. 12, f).

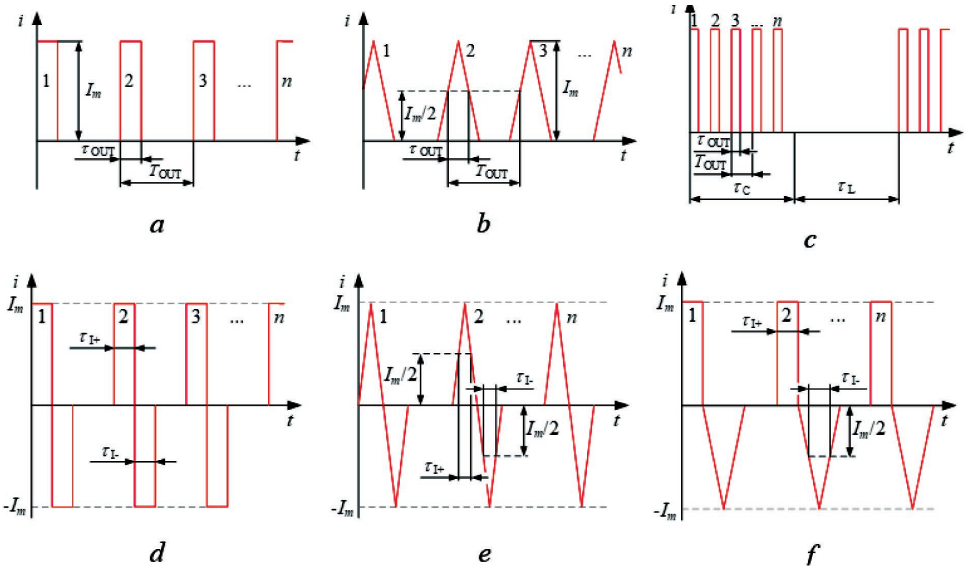


Figure. 12. Current diagrams for short-pulse electroanalgesia

Therefore, the improvement of electrotherapy techniques using the ANET-50M apparatus is possible thanks to extended ranges for adjusting the parameters of exposure (especially in amplipulsetherapy) and the ability to sequentially use different types of current in a single procedure.

In the treatment of certain diseases, depending on their severity, it is advisable to use various types of electromagnetic energy (EME)[21]. This aspect became pivotal in further enhancing the ANET apparatus in the Laboratory of Biomedical Electronics at the National Technical University "KhPI." As a result of this modernization, a multifunctional electrotherapeutic apparatus, the ANET-50 EME for Electrotherapy, Magnetotherapy, and Phototherapy, was developed (Fig. 13)[22].

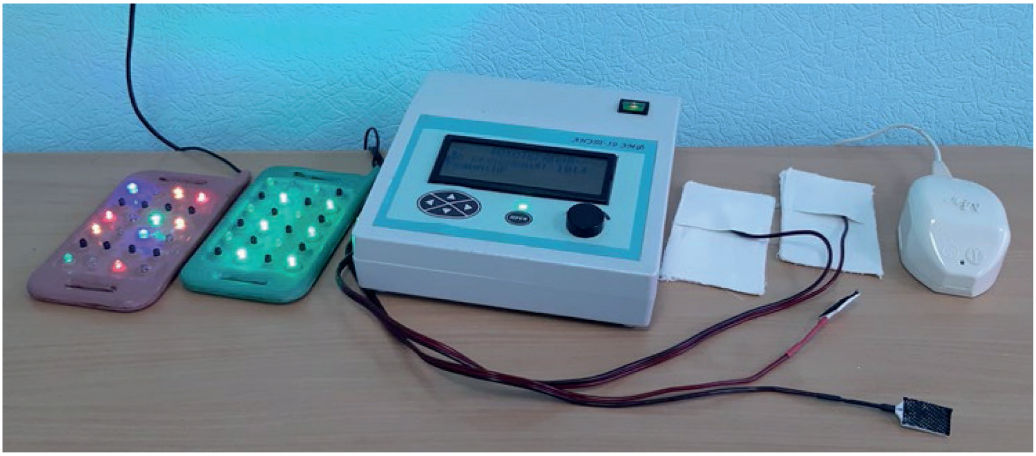


Figure 13. Low-frequency electrotherapeutic device ANET-50 EMF

The ANET-50 EME apparatus incorporates all the functional capabilities of the ANET-50 GT apparatus and adds new functions, both for regulating exposure parameters and the types of exposures themselves.

Specifically, for conducting diadynamic therapy procedures, nine types of diadynamic currents were additionally provided, displaying the current pulse amplitude and average values during pulse series intervals on the apparatus's display. The inclusion of diadynamic currents in the ANET apparatus was motivated by their myoneurostimulating, analgesic, vasodilatory, and trophostimulating effects. This enables effective use of diadynamic therapy for treating diseases of the peripheral nervous system, cardiovascular system, gastrointestinal tract, musculoskeletal injuries, and several other conditions.

21 Vasylieva-Linetska, L.Ya., Tondiy, L.D., Kas, I.V., Zamyatina, O.I. (2014). Clinical effectiveness of the use of multifunctional ANET devices and the Korobov photonic matrix in the complex treatment of patients with dorsalgia. Bulletin of the National Technical University "KhPI". NTU "KhPI", 36(1079). 39–43.

22 Kipenskyi, A.V., Korol, E.I., Tyaglov, A.P. (2014). Multifunctional physiotherapeutic apparatus ANET-50 EMF. Materials XXXXI of International Science-Pract. conf. "Application of lasers in medicine and biology". 145–149.

To perform magnetotherapy procedures, the apparatus features a current control block for the inductor-electromagnet (the experimental model used the electromagnet of the MAG-30-4 apparatus). This allowed for the application of magnetotherapy procedures with a continuous and interrupted mode for both variable (sinusoidal) and pulsed (single half-period rectification) magnetic fields at a frequency of 50 Hz. Low-frequency magnetic fields have vasodilatory, catabolic, lymphatic drainage, trophostimulating, hypocoagulatory, and hypotensive effects. Indications for low-frequency magnetotherapy include heart diseases, cardiovascular system disorders, peripheral nervous system conditions, consequences of closed head injuries, inflammatory diseases of internal organs, bone fractures, arthrosis and arthritis, slow-healing suppurative wounds, burns, keloid scars.

To conduct phototherapy procedures, the apparatus was designed to utilize devices from the Scientific and Production Medical and Biological Corporation "Laser and Health," such as the photon matrices "Barva-Flex," photon probes "Barva-GPU," laser massager "Barva-LMK," and others, with a power supply voltage of 14–15 V and a current consumption not exceeding 200 mA. Regardless of the selected emitter, the apparatus enables its operation in several modes: continuous emission mode, pulsed emission mode (with the ability to adjust the modulation frequency of the EMR from 1 to 100 Hz with a pulse duty cycle of two), and six scanning modes (by the frequency of electromagnetic radiation modulation), similar to the scanning modes (C1–C6) during current pulse exposure (Fig. 5). The rationale for creating different scanning modes is based on the distinctions in their effects: sedative (C1, C4); tonic (C3, C6); normalizing (C2, C5).

The experience with four electrodes led to an intriguing idea for the development of an apparatus for conducting transcranial pulsed electrotherapy procedures. This is why the capabilities of this method, which involves influencing the central nervous system (CNS) with various low-frequency, low-intensity pulse currents, were incorporated into one of the modifications of the ANET apparatus[23]. Further advancement of transcranial pulsed electrotherapy was envisioned by the experts at the Institute of Neurology, Psychiatry, and Narcology of the National Academy of Medical Sciences of Ukraine (medical collaborators). They aimed to create an apparatus with extensive functional capabilities, enabling not only the implementation of procedures using all known methods but also the

23 Sokol, E.I., Kypenskyi, A.V., Kulichenko, V.V. (2007). Transcerebral electrotherapy. Problems and prospects. IED of NASU, 2. 18–122.

development of new methods and techniques for applying pulse electric currents to the human brain.

Based on the analysis of various methods for transcranial intervention, primary electrode placement techniques were established (FR – facial right; FL – facial left; BL – back left; RR – rear right), and potential polarity options were determined for applying electric currents to various areas of the human brain.

To facilitate these various methods of applying pulsed electric currents to the human brain, a functional apparatus schematic (Fig. 14) with a microprocessor-based pulse control system (MBPCS) and an electronic switch was proposed.

Regulation of the frequency and duration of pulses in each channel of the device is provided using a digital digital insulator with a chip and a digital digital insulator with a pulsed pulse. Control of all CIP, regulated pulsed current sources with an additional constant component (PPC1 and PPC2) and switch switches S11–S18 (first channel) and S21–S28 (second channel) is provided by a computing unit (CU). The switch keys allow you to connect any pole of any current source to any of the four electrodes. The current regulators of each channel provide independent regulation and stabilization of the amplitude ImOUT of rectangular pulses and the level of IDPS of the additional constant component (ACC) (Fig. 15).

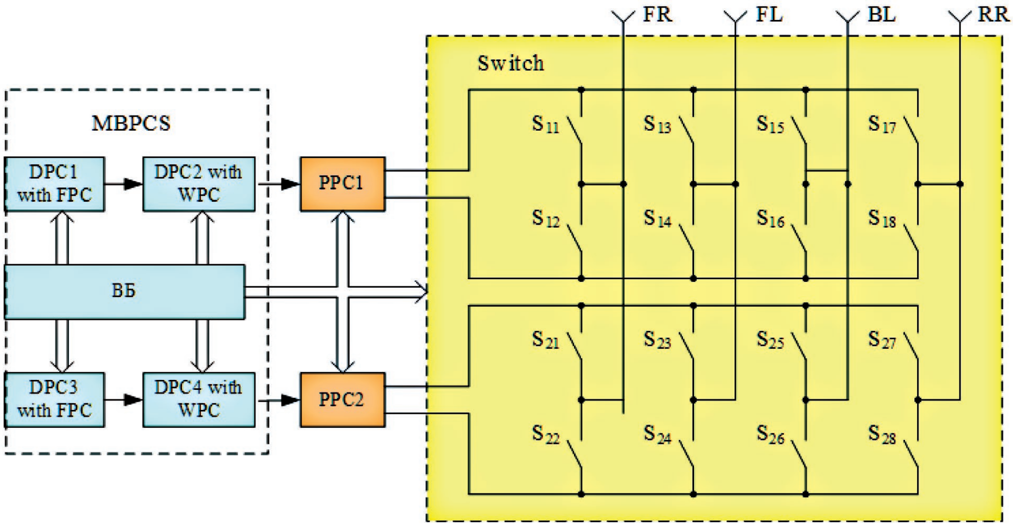


Figure 14. Functional diagram of device for transcerebral pulsed electrotherapy

The ability to select any polarity for RT for any of the electrodes has allowed for the formulation of several unique variations of transcranial intervention.

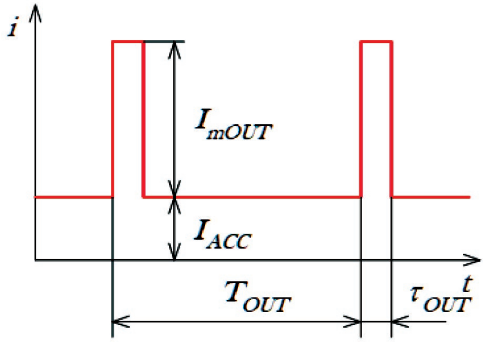


Figure 15. Sequence of rectangular pulses with ACC

1. Asymmetrical Intervention. The polarity of one electrode is set to positive (for example, LR), while all the others are set to negative (it is also possible to establish the opposite polarity). Any of the four electrodes can be chosen to have a polarity different from the others. In this configuration, the intervention will concentrate in the area of the LR electrode (as shown in gray in Fig. 16, a).

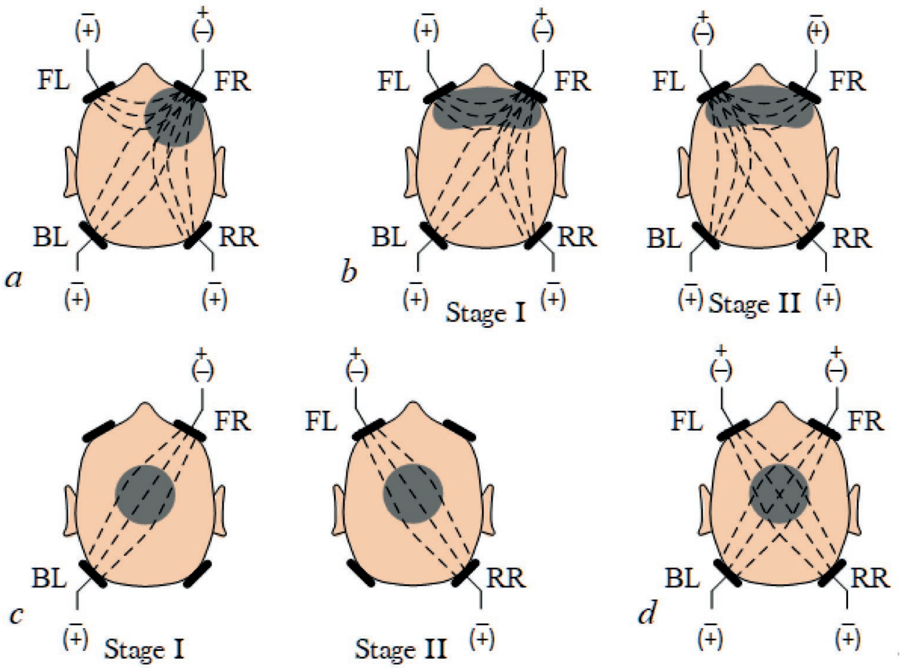


Figure 16. Options for transcerebral exposure

2. Displaced-extended impact. The impact is carried out in two stages (the minimum duration of each stage here and further in the text is equal to the pulse repetition period T_{OUT} (Fig. 15)). At first stage, the polarity of one electrode is set to positive (for example, FR), and all others are set to negative (it is also possible to

set the opposite polarity). At the second stage, the polarity of the other electrode is set to positive (for example, FL), and all others are set to negative. Instead of the FR and FL electrodes, which alternately have polarity, any other pair of electrodes can be selected. Under the specified operating modes of the current sources and the considered option for connecting the electrodes, the impact will be concentrated in the area of the FR and FL electrodes (shown gray in Fig. 16, b).

3. Alternate diagonal impact. The impact is carried out in two stages. At the first stage, the polarity of one electrode (for example, FR) is set to positive, and the diagonal electrode (respectively, BL) is set to negative (it is also possible to set the opposite polarity). At the second stage, the polarity of the other electrode (for example, FL) is set to positive, and the polarity of the corresponding diagonal electrode (RR) is set to negative. In this case, diagonal pairs of electrodes are connected to current sources alternately. Under the indicated operating modes of current sources and the considered option for connecting electrodes, the impact will be concentrated in the area of intersection of current paths (the central part of the brain, shown gray in Fig. 16, c).

4. Total diagonal impact. The impact is carried out by two pairs of diagonally placed electrodes. The initial polarity of the electrodes is chosen arbitrarily and, if necessary, can be changed during the procedure. Each pair of diagonal electrodes is connected to its own current source. Under the indicated operating modes of the current sources and the considered option for connecting the electrodes, the impact will be concentrated to an even greater extent than in the previous case in the central part of the brain (shown in gray in Fig. 16, d).

From the examples considered, it is clear that the use of two adjustable sources of pulsed current and the improvement of the algorithm of the device's operation made it possible to significantly expand the possibilities of transcerebral influence. It is obvious that the introduction of such a device into medical practice will make it possible to develop new methods of transcerebral pulsed electrotherapy.

Promising directions of electrotherapy. Among the promising areas of electrotherapy, we note the following.

An analysis of various electrotherapeutic devices shows that the undisputed leaders are multifunctional devices that allow procedures to be carried out using various methods and techniques[24]. To implement such devices, it is most advisable to use universal low-frequency electrical signal generators[25]. The principle of

24 Sokol, E.I., Kypenskyi, A.V., Vereshchak, V.A. (2006). Analysis of quality indicators of devices for amplipulse therapy. Technical electrodynamics. IED of NASU, 3. 123–130.

25 Kipenskyi, A.V., Korol, E.I. (2018) Theoretical substantiation of possibility of creating a universal low-frequency signal generator for electrotherapy. Bulletin of National Technical University "KhPI". NTU "KhPI", 26(1302). 86–94.

operation of such generators is the sequential transformation of a harmonic carrier signal by three modulators with different modulation laws (Fig. 17). In this case, to control each modulator, it turned out to be sufficient to generate modulating signals u_{M1}–u_{M3} with two or three stationary and transition sections[26].

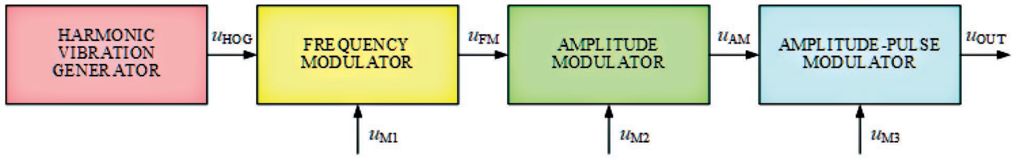


Figure 17. Signal shaping channel in a universal low-frequency generator

An example of a modulating signal with three stationary sections 1, 3, 5 and three transition sections 2, 4, 6 is shown in Fig. 18. This signal has two transition sections (2 and 4) – increasing and one (6th) – decreasing, and the voltage levels in the stationary sections correspond to –1 in the first section, 0 in the third section and +1 in the fifth section.

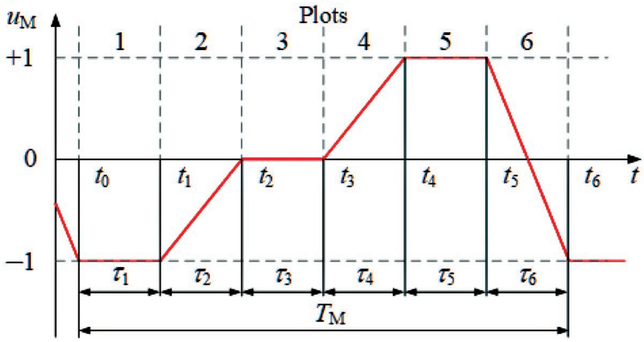


Figure 18. An example of a modulating signal

The considered modulating signal can be generally described by an expression of the form

$$u_M(t)=\begin{cases} U_{m1}, \quad \text{if} \quad t_0 < t \le t_1; \\ U_{m1}+\left(U_{m3}-U_{m1}\right)\dfrac{t-\tau_1}{\tau_2}, \quad \text{if} \quad t_1 < t \le t_2; \\ U_{m3}, \quad \text{если} \quad t_2 < t \le t_3; \\ U_{m3}+\left(U_{m5}-U_{m3}\right)\dfrac{t-\left(\tau_1+\tau_2+\tau_3\right)}{\tau_4}, \quad \text{if} \quad t_3 < t \le t_4; \\ U_{m5}, \quad \text{if} \quad t_4 < t \le t_5; \\ U_{m5}-\left(U_{m5}-U_{m1}\right)\dfrac{t-\left(\tau_1+\tau_2+\tau_3+\tau_4+\tau_5\right)}{\tau_6}, \quad \text{if} \quad t_5 < t \le t_6, \end{cases} \tag{9}$$

26 Kipenskyi, A.V., Korol, E.I., Prodchenko, N.S. (2019) Formation of modulating signals for controlling a universal low-frequency generator for physiotherapeutic purposes. Applied radio electronics. KhNURE, AN PRE, 1–2. 23–33.

where U_{m1}, $U_{mI.3}$ and $U_{mI.5}$ – voltage levels at the first, third and fifth stationary sections of the signal $u_{M.}(t)$.

Obtaining a modulating three-level signal of the desired shape can be achieved by varying the durations of stationary and transition sections. The duration of each of the stationary (τ_1, τ_3 and τ_5) and transitional (τ_2, τ_4 and τ_6) sections can vary in the range from 0 to T_M, where T_M is the modulation period, but the T_M condition must always be $T_M = \tau_1 + \tau_2 + \tau_3 + \tau_4 + \tau_5 + \tau_6$. In practice, it is more convenient to set the duration values of sections in relative units, as a certain part of the T_M modulation period.

Additional possibilities for generating modulating signals appear if the transition from one stationary state to another is carried out according to some nonlinear law[27]. Expressions for some nonlinear laws are given in Tab. 2 (numbers of expressions in table correspond to the numbers of curves in Fig. 19). This technique makes it possible to generate a modulating signal even in the form of harmonic oscillations[28].

Table 2.

Basic laws of changing the modulating signal as a function of control signal

Growing transition section		Decreasing transition section	
1	$U_{MOD} = \sqrt{1-(u_C-1)^2}$	1	$U_{MOD} = \sqrt{1-u_C^2}$
2	$U_{MOD} = 2u_C - \sin^2\left(\frac{\pi}{2}u_C\right)$	2	$U_{MOD} = 2 + 2u_C - \cos^2\left(\frac{\pi}{2}u_C\right)$
3	$U_{MOD} = u_C$	3	$U_{MOD} = 1 - u_C$
4	$U_{MOD} = \sin^2\left(\frac{\pi}{2}u_C\right)$	4	$U_{MOD} = \cos^2\left(\frac{\pi}{2}u_C\right)$
5	$U_{MOD} = 1-\sqrt{1-u_C^2}$	5	$U_{MOD} = 1-\sqrt{1-(u_C-1)^2}$

27 Kipenskyi, A.V., Korol, E.I. (2017). Modulation of parameters of physiotherapeutic effects. Materials of 1st international science and technology conf. "Actual problems of automation and instrument engineering". FOP Mezina V. 53-54.

28 Kipenskyi, A.V., Korol, E.I. (2018) Theoretical substantiation of possibility of creating a universal low-frequency signal generator for electrotherapy. Bulletin of National Technical University "KhPI". NTU "KhPI", 26(1302). 86–94.

The process of sequential modulation of the harmonic carrier signal u_{HOG} is shown in Fig. 20.

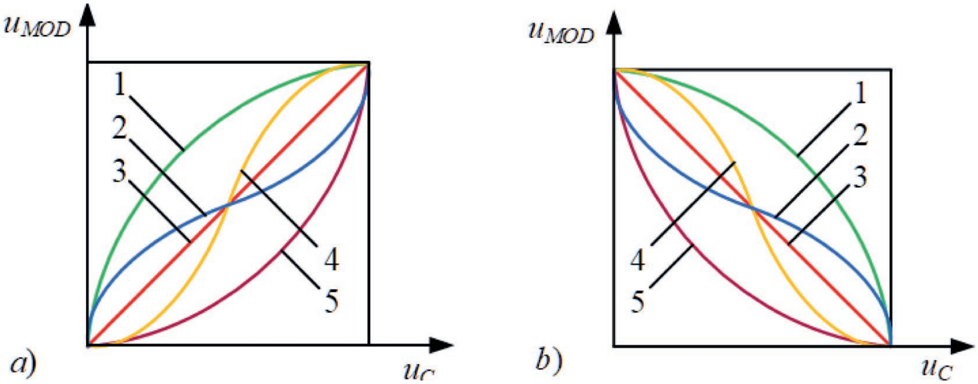


Figure 19. Nonlinear laws of modulating signal change

The output signal u_{HOG} of the harmonic oscillation generator (HOG), which is characterized by the amplitude U_{mHOG} and frequency f_{HOG}, is described by expression (Fig. 20, a)

$$u_{HOG}(t) = U_{mHOG}\cos(2\pi f_{HOG}t) \quad (10)$$

The frequency modulator, under the influence of the first modulating signal u_{M1}, provides frequency modulation of the HOG signal. In this case, the output signal of the frequency modulator will correspond to the expression

$$u_{FM}(t) = U_{mHOG}\cos(2k_{FM}\pi f_{HOG}t), \quad (11)$$

where k_{FM} – frequency modulation coefficient, the value of which is a function of the first modulating signal

$$k_{FM} = k_1 u_{M1}, \quad (12)$$

where k_1 – unit matching coefficient, and u_{M1} can vary from 0 to +1. (Fig. 20, b). It is obvious that when u_{M1} = 0 at the output of the frequency modulator a constant signal with a level U_{mHOG}.

The amplitude modulator, under the influence of the second modulating signal, provides amplitude modulation of the output signal of the frequency modulator (Fig. 20, c) in accordance with the expression

$$u_{AM}(t) = F(u_2)\cdot U_{mHOG}\cos(2k_{FM}\pi f_{HOG}t), \quad (13)$$

where $F(u_2)$ – conversion function of the second modulating signal u_{M2}, which can vary in the range from – 1 V to + 1 V. In the example under consideration, the second modulating signal varied according to the expression

$$u_M(t) = 1 + k_{AM}\sin 2\pi f_M t, \quad (14)$$

where k_{AM} – amplitude modulation coefficient.

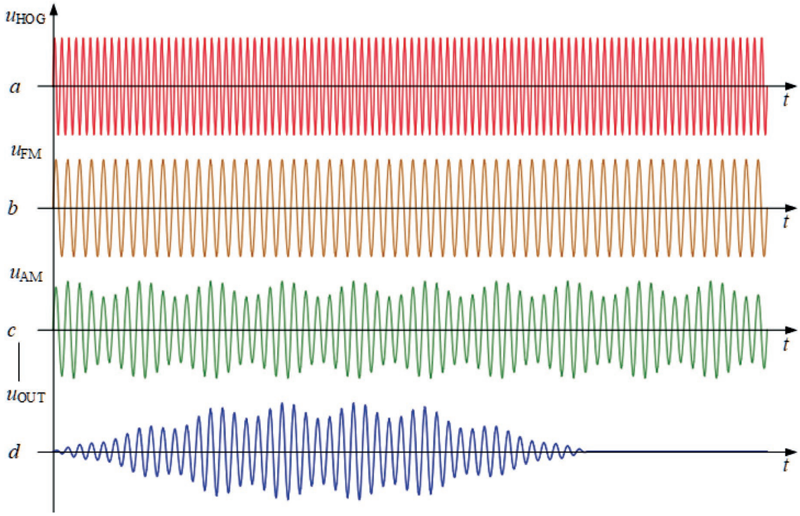


Figure 20. Signal diagrams in a universal low-frequency oscillator

The third modulating signal has a trapezoidal shape and is applied to the amplitude-pulse modulator's modulation input. The result of such modulation is shown in Fig. 20, d. The obtained signal is similar to the sinusoidal modulated current in the second mode of operation; however, it differs from the mentioned current in that the amplitude of the oscillations gradually increases at the beginning of the series and decreases at the end of the series (this approach can be justified in some cases).

It is worth noting that the modulation of the original harmonic signal in all cases was carried out at the software level.

One of the distinctive features of electrotherapeutic devices with universal low-frequency signal generators is that they can not only generate all the signals already used in electrotherapy but also adjust their amplitude-frequency-temporal parameters in wide ranges and generate entirely new signals. This undoubtedly contribute to the emergence of new methods and techniques.

Another advantage of devices with such generators is the possibility of automatically adjusting the intervention parameters in response to the body's reactions, which should enhance the effectiveness of therapeutic electromagnetic energy applications. All of this justifies the transition from simple (although multifunctional) devices to intelligent electrotherapeutic systems (IETS) with full biocontrol.

The essence of such control is that the parameters of the electromagnetic energy (EME) applied to a person for therapeutic purposes should automatically change based on the changes in the person's physiological parameters during the relevant procedures. In this case, all types of EME are considered: current, electric field, magnetic field, electromagnetic fields, and radiation.

The construction of IETS should be based on personal computers 1 or specialized microcontrollers (Fig. 21). In this case, IETS should simultaneously perform the functions of a diagnostic device and an electrotherapeutic apparatus. The doctor uses the keyboard and monitor (the signal input and data entry signal U_1) to set the type and amplitude-frequency-temporal parameters of the EME and enter the patient's anthropological data. Based on all the set parameters and entered data, the AC voltage from the power supply network U_C is converted into the supply voltage u_2 for the executive organ 3 in the control unit 2. This organ converts the supplied voltage into electromagnetic energy with the specified parameters.

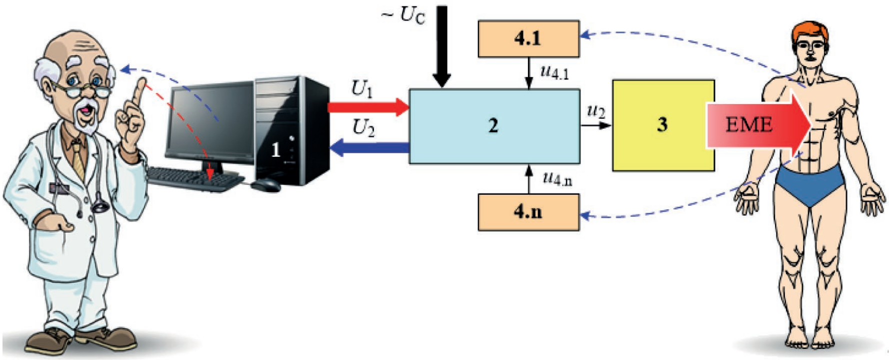


Figure 21. Block diagram of an intelligent electrotherapeutic system with full biocontrol

During the procedure, information about the changes in the patient's physiological parameters, characterizing the patient's condition, is received by the IETS control unit from the outputs of sensors 4.1–4.n in the form of signals $u_{4.1}$–$u_{4.n}$. The control unit processes this information, digitizes it, and generates a data stream U_2 for the personal computer 1.

Conclusions. In summary, when certain changes in the physiological parameter values (the body's response to the intervention) occur, the computer makes a decision to automatically adjust the EME parameters, which is displayed on the monitor.

The most challenging task in implementing IETS is determining a functional relationship between the parameters of the applied electromagnetic energy (EME) and the patient's physiological indicators that would ensure maximum therapeutic efficacy. One approach to establishing such a connection may involve a principle of sequential approximation in modifying intervention parameters in response to biological feedback[29]. A specific case of biocontrol is bio-synchronization, which involves synchronizing changes in EME parameters with a patient's endogenous biorhythms[30].

It should also be noted that genetic algorithms and neural networks can be quite effective tools for achieving full biocontrol, made possible through the use of microprocessor technology in IETS implementation.

An important question when developing IETS is the selection of the physiological indicators themselves or various combinations of them. Among other indicators, particular attention should be given to bioelectric potentials, as they reflect the subtlest changes in the functioning of the body's organs and tissues.

Furthermore, the choice of indicators that need to be monitored during the procedure may be determined by the purpose of electrotherapy itself, as a means to reconfigure the pathological process toward normalization. It is entirely possible that by monitoring the state of the pathological process (not only using functional diagnostic methods), it may be possible to optimize the therapeutic intervention.

Therefore, one of the most promising directions in electrotherapy today is the development of IETS with full biocontrol, as they have the potential to not only enhance the quality of treatment but also open up unique opportunities for creating new and improving existing therapeutic methods and techniques.

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