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NON-IONIZING RADIATION

# Research of the Biomedical Effects of Electromagnetic Field in Russia over 130 Years: Main Stages of Advances in Scientific Knowledge

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**Abstract**—We have analyzed the key stages of advances in the scientific history of research into the biomedical effects of electromagnetic field (EMF) in Russia over 130 years and proved the continuity of this scientific knowledge and its passage from one generation of scientists to the next due to scientific schools, systematic research, and national scientific coordination. The article focuses mainly on the period in which planned EMF health research was formed, the basic methodological principles were founded, and scientific principles were established for understanding the nature of the biological effects of EMF and their impact on health. The basic concepts on the part of Russian scientists about the mechanism underlying the biological effects of EMF and principles of their hygienic regulation are summarized.

**Keywords:** electromagnetic field, biological effect, nonionizing radiation, radiobiology, hygiene, nervous system, radio frequencies, Russia, history of science

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Research into the biological effects of electromagnetism in Russian spans more than a century. However, until now, there have been no attempts to generalize the scientific history of advances in this area of research or to analyze the consistent development of scientific knowledge, the role of key research laboratories, and the continuity of scientific schools of electromagnetic biology, radiobiology, and hygiene involving nonionizing radiation. This authors make such an attempt, admitting the difficulties of the format and space limitations of the journal. An important motive for writing the article was the sense of responsibility of preserving the scientific achievements of our predecessors and teachers and understanding of the need to convey the prehistory to new generations, which makes it possible to assess the efforts of Russian researchers into the biomedical effects of electromagnetism, whose studies have undoubtedly advanced and influenced the directions of global research.

Speaking of the history of research into the biomedical effects of electromagnetism, we should note the fundamental difference between electromagnetic field (EMF) and other physical factors of the environment: EMF is a special type of matter through which electrically charged particles interact with each other [1]. The emphasis on special type of matter (the nature of which is not completely clear to modern science) requires separating EMF from other physical factors with which humans interact, both in terms of its biotopic significance and the complexity of studying this factor.

Reports by scientists from the Imperial Medical-Surgical (Military Medical) Academy on the biomedical effects of electromagnetism and electricity have been known since 1840 (P.D. Shipulinskii and I.I. Kabat). Russian authors of scientific research in the mid-19th century were familiar with how magnetism and electricity worked at a distance, as well as with methods of inducing currents using electromagnets; however, they did not apply "remote" effect, since they saw no advantages to it. They studied the physiological role of bioelectricity in the nervous system and "electricity as form of stimulus to the nervous system."

At the end of the 19th century, research into the biomedical effects of electromagnetism became a logical continuation in studying the role of electricity in the body and its significance in functioning of the nervous system. Research into electromagnetism in its modern sense became possible after studies by Maxwell (1865) and Hertz (1888), which laid the foundation for practical electrodynamics and engineering

solutions for electrophysical devices to generate alternating EMFs. The consistent creation of EMF theory and development of technical tools and their introduction into industry, everyday life, and medicine were of primary importance for physiology's transition from electricity to electromagnetism.

Starting in 1895, Professor of the Imperial Kharkiv University V.Ya. Danilevskii and his student, Dr. S.I. Kostin were the first in the Russian Empire to study the biomedical effects of electromagnetism in its classical understanding, almost simultaneously with the invention of A.S. Popov's practical radio: the basic schematics of the Danilevskii/Kostin and Popov devices for generating alternating EMF were extremely similar [2–4].

Kostin was the first scientist in the Russian Empire to defend an "electromagnetic" dissertation in physiology in May 25, 1898, Old Style: "On the Doctrine of the Physiological Effect of Electric Field on the Motor Nerve" [5].

A.S. Popov's large family directly influenced the first studies of the biomedical effects of electromagnetism in the late 19th–early 20th centuries: this was an informal association of medical doctors, physiologists, and electrophysicists working together. Popov personally designed high-frequency sources for personnel at the Imperial Military Medical Academy almost simultaneously with the development of his own equipment. Professional and family ties contributed to the defense of the first medical and biological dissertation in the Russian Empire on the direct effect of EMF on humans (P.I. Izhevskii, Imperial Military Medical Academy, 1900) and the first dissertation in medicine at the Imperial Tomsk University on remote physiological effects of electricity (N.S. Spasskii, 1901), in which the degree candidate and his supervisors (Profs. V.N. Velikii and F.Ya. Kapustin) questioned the "energy" theory of the physiological effect of "high-frequency" EMF by the French scientist d'Arsonval, which dominated in Europe in the last decade of the 19th century [6, 7].

Danilevskii and Kostin experimentally proved that EMF is a stimulus to the nervous system, with the total energy balance of the body remaining unchanged. Prof. Danilevskii laid the foundations for the approach to using EMF of the radio frequency range as a stimulus to the nervous system. The most important result of his research is the identification of the leading role of nervous tissue in the formation of a response to alternating electric and EMF. A "nerve" was experimentally shown to be a target for EMF, regardless of frequency: the nervous tissue "responds" directly; the excitability of the nerve changes under the influence of EMF and generally increases "signficantly." The con-

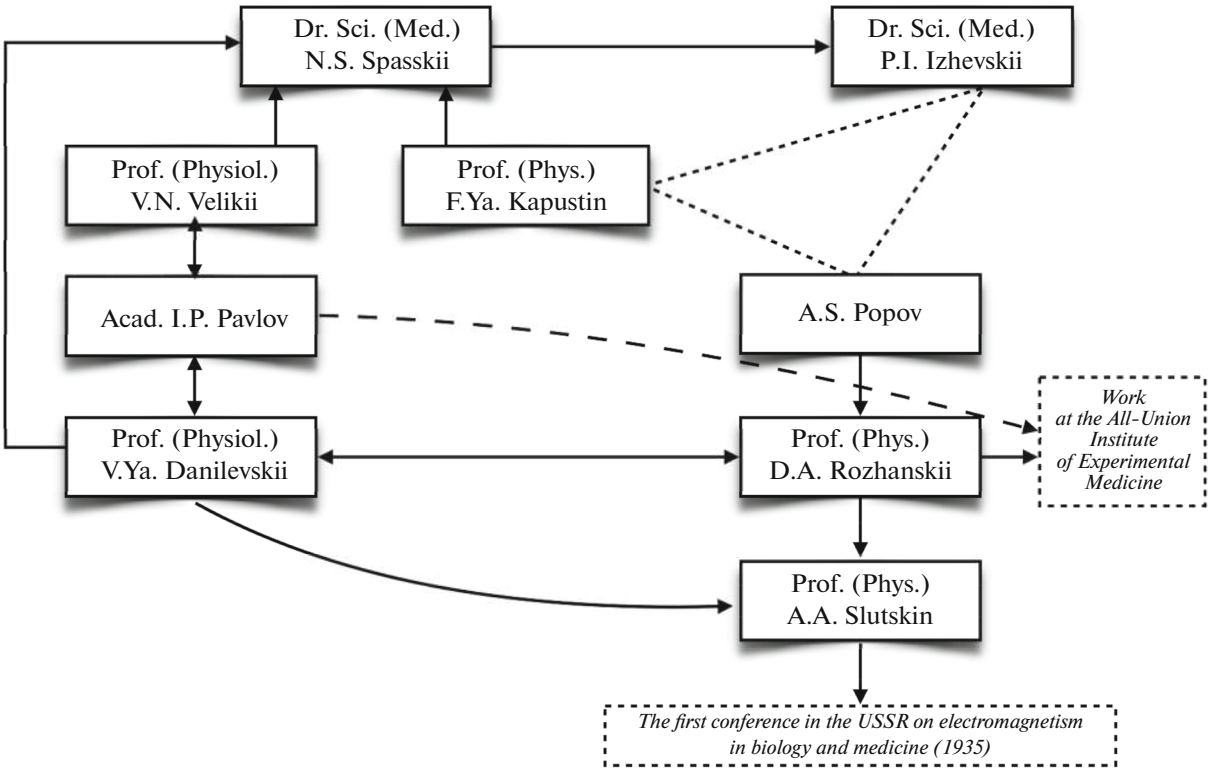



**Fig. 1.** Scientific contacts and continuity of the first researchers of biomedical effects of electromagnetism in the Russian Empire [6].

clusion about the primacy of the nervous system's response to "remote electricity" was supported by Russian academicians V.M. Bekhterev and I.P. Pavlov.

Danilevskii's data quickly entered scientific circulation and were used by Academician I.R. Tarkhanov to explain the contradictions in his X-ray experiments. Tarkhanov revealed that the excitability of the central nervous system decreased under the influence of X-rays emitted by a Crookes tube. However, he observed intense muscle contraction during irradiation of a neuromuscular slide from a frog, which contradicted his own data on the decrease in excitability under the influence of X-rays. Tarkhanov (1897) wrote: "Clearly, the phenomena I studied in this research using a Crookes tube are very similar to the phenomena recently indicated by Prof. Danilevskii on the remote effect of dark discharges of a Ruhmkorff spiral on a neuromuscular slide from a frog. The only difference is that I had a Crookes tube in the secondary spiral circuit of the Ruhmkorff spiral, near which I grouped all my experiments, while Prof. Danilevskii simply used the poles of the secondary spiral of the Ruhmkorff spiral" [8]. This observation had significant consequences for radiology, since Tarkhanov later used a screen in accordance with Danilevskii's method, to eliminate the stimulating effect of the pulsed EMF of the coil. As a result, screening the electric field of the X-ray machine was introduced into practice. Radiobiologists forgot about the effect of the pulsed electric field of the X-ray machine on the central nervous system until the 1950s, when Tarkhanov's case was repeated during experiments at the Institute of Biophysics of the USSR Ministry of Health under the supervision of Academician M.N. Livanov [9].

In 1933, Academician A.A. Ukhtomskii proposed continuing research on the physiological stimulus as a fundamental property of electromagnetism. Ukhtomskii wrote: "Physiology and electrophysiology have until now been built... on concepts that sound archaic...; it will be an urgent matter to reconsider the provisions of electrophysiology in terms of the new electromagnetic physics and field theory. The primary problem will be to reconsider the theory of physiological stimulus in terms of field theory. One of the first foundation stones in the upcoming work was laid by Danilevskii with his research on the remote physiological effect of electrical voltages" [10]. This set the main development vector of planned scientific research into the biomedical effects of electromagnetism, which determined its outlook for the years that followed.

From the 1930s to 1992, research into the biomedical effects of electromagnetism in the USSR was carried out under planned topics at the All-Union level.

During the 1930s, the All-Union Institute of Experimental Medicine (VIEM), Military Medical Academy, and Ukrainian Institute of Experimental Medicine played a key role. It was at the All-Union Institute of Experimental Medicine where A.A. Slutskin founded the Department of Biophysics in 1933 with the direct support of Academician Danilevskii, which largely determined its continuity with the research achievements of the Russian Empire, including their transfer to VIEM. The studies by D.A. Rozhanskii and his students, Slutskin and M. Shternberg, led to the creation of decimeter-range and ultra-high-frequency (UHF) magnetrons. Subsequently, Rozhanskii continued research and development in the biological effects of EMF at the Leningrad Branch of VIEM together with G.L. Frenkel', as well as at the Scientific Research Institute of Inorganic Materials, where the developments of his Kharkiv students in microwave generation were being used. Students of Danilevskii and Popov in the USSR commenced research into the biomedical effects of electromagnetism on a large scientific scale [11, 12]. In 1935, the First All-Union Conference "Ultrashort Waves in Medicine and Biology" was held in Kharkiv, chaired Slutskin [13].

In December 1935, the Third All-Union Congress of Physiotherapists was held in Kharkiv, where more than half the reports were devoted to issues of using electromagnetism. One of the important decisions was to recognize studies with ultra-high-frequency (UHF) EMF sources as a hazardous profession, and the maximum permissible level (MPL) of radio frequency EMF (10 $\mu W/cm^2$) was recommended for the first time [14, 15]. Although the MPL was advisory and the scope of application was limited to physiotherapeutic and research installations for EMF generation, according to the materials currently available to us, this was the first specification of the hygienic standard for EMF collegially approved by the Russian scientific community.

Prof. A.V. Lebedinskii believed that the tradition of studying the influence of external factors on the body at the Department of Physiology of the Military Medical Academy (MMA) had been established by Tarkhanov, which "found its development in the cycles of studies by the department, devoted to analyzing the effect of ionizing radiation, radiant energy, ultrashort electromagnetic waves, altered conditions of a gas medium, and many other factors on the body." On the recommendation of I.P. Pavlov, materials from Danilevskii's studies, highly valued by I.P. Pavlov, were used in department's curriculum [16].

From 1933, the Department of Physiology of the Military Medical Academy of the Red Army began work in the field of biophysics, mainly electrophysiology and radiobiology. Head of the department, Prof. L.A. Orbeli, wrote: "In Tsarist Russia, studies of a biophysical nature were shoved to the background, largely

due to the technical and industrial backwardness of our country. At present, there are the makings of a strong shift towards development of biophysical topics, partly in connection with defense requirements and partly as a result of rapid industrial development" [17].

At the Department of Physiology of the Military Medical Academy, the electrophysical properties of tissues were studied (Lebedinskii and A.I. Bronshtein) and the theory of the origin of bioelectric phenomena was developed (Lebedinskii, A.S. Mozzhukhin, and I.A. Peimer), based on the ideas of I.M. Sechenov and V.Yu. Chagovets about the formation of electrical energy in living tissues through energy released during metabolism. There were studies of the effect of high-voltage currents (including induced currents) of industrial frequency (L.A. Orbeli and M.P. Brestkin). However, most papers studied the biomedical effects of ultrahigh frequencies and high-frequency (HF) and ultrashort waves (D.Ya. Glezer, A.V. Tonkikh, N.V. Bekauri, and A.V. Lebedinskii) [18–28].

Together with the Military Medical Academy, planned research into the biomedical effects of electromagnetism was conducted from 1934 at the Leningrad Branch of the All-Union Institute of Experimental Medicine by the physicobiological and physicotechnical departments, including a special-purpose laboratory that worked together with the Electrophysical Institute of the People's Commissariat of Heavy Industry (Rozhanskii).

The team of 28 persons at VIEM set the primary task of predicting a biomedical effect depending on the "dosage" of the EMF: constructing a dose–effect relationship suitable for practical application. In this regard, methods for assessing incident and absorbed electromagnetic energy were developed, including computational modeling using the bioelectrophysical characteristics of bodily tissues. Thus began methodically precise studies of the effect of EMF in the very-high-frequency (VHF) and HF ranges. In 1937, head of the Department of Physics and Biology of VIEM, Dr. Frenkel' wrote that, based on his own experimental material, "two extremely important features" of the EMF of radio frequencies were revealed: phasing and aftereffect. In the period until 1940, the dose–effect relationships for ineffective to lethal effects were obtained at VIEM for the VHF and HF ranges known at that time; a biophysical description of the mechanisms at the systemic and whole-body level was presented and bioelectrical phenomena in the cellular membrane and near-membrane region of cells were recognized as the predominant mechanism [29–31].

By the mid-1930s, data had been acquired on the development of morbidity among workers with sources of EMFs of radio frequencies, primarily radio operators, then among those working with generators, primarily physicists at the Physics Institute of Leningrad State University (LSU) and employees of VIEM, as well as physiotherapists. B.V. Likhterman was the first to carry out clinical and physiological examinations of employees of the Physics Institute of LSU who worked with EMF generators. A number of functional shifts were identified, which primarily include an increase in body temperature when working with generators, with a general disruption of the thermoregulation function; at the same time, there was usually no correlation of headaches and fatigue with changes in body temperature [22].

In a general monograph by VIEM (1937), the main symptoms of the harmful effects of radio frequencies primarily the involved the nervous system: weakness of memory, absent-mindedness, forgetfulness, nervousness, insomnia, and hand tremors. Headaches, increased fatigue, reproductive disorders (especially in women), and visual impairments were recorded. In 1935, for the first time in the USSR, the Leningrad Institute of Labor Protection began to conduct systematic hygienic studies of the working conditions involving VHF generators at VIEM. VIEM developed administrative and technical methods of protection, including shielding [33].

In 1939–1940, the Department of Physics and Biology at VIEM published four general collections on different aspects of the effect of ultrashort waves, including their impact on development and growth processes (including malignant tumors), blood and circulation, and infection and immunity, as well as the effect on microorganisms [34].

During World War II, Dr. Frenkel' and part of his former VIEM team worked at the Naval Medical Academy, where they developed issues of military electrical trauma caused by the use of electricity "for combat purposes." In addition, Frenkel' headed research that used VHF EMF sources for treating frostbite, for fever therapy, and for combating wound infections; his monograph *Electric Fever and Exchange Effects of a High-Frequency Field* (1945) remains a valuable practical guide to this day [35].

The experience of hospital therapeutic use of magnetic field in treating the wounded and sick during WWII was summarized in a monograph of scientists from the Molotov Medical Institute (Perm) *Biological and Therapeutic Effects of Magnetic Field and Strictly Periodic Vibration* (1948), which also contains important practical material [36].

A peculiarity of research into the biomedical effects of electromagnetism in the postrevolutionary period was fundamental consideration of the potential of electromagnetic radiation for military use, discussed in different forms by the Council of People's Commissars and leadership of the Red Army, starting with a

note by V.I. Lenin in 1921 (see p. 88 in [36]). To ultimately resolve the issue, on behalf of the Revolutionary Military Council of the USSR, the special-purpose laboratory of VIEM (A.M. Kugushev) provided biophysical support for the development of a VHF device for defense purposes from 1934, proposed by Academician A.F. Ioffe in 1932. This device was supposed to hit the enemy at a distance of 300–400 m. As is known, the "electromagnetic gun" was not created in the 1930s, and researchers were convinced that a military direction of bioelectromagnetism was futile; however, the technical developments were used in creating the first domestic radar [38, 39].

After the end of WWII, the advent of new technologies led to a large number of radio frequency generators and an increase in the number of people exposed to EMF, primarily in industrial settings, at research laboratories, and at the Ministry of Defense.

In 1946–1947, Prof. Kevork'yan and his group from the Institute of Occupational Hygiene and Occupational Diseases, USSR Academy of Medical Sciences, conducted a large-scale, long-term clinical and physiological examination of a group of persons (87 persons) working in the radiation zone of VHF pulse generators (wavelength 3–5 cm) [40, 41]. The peculiarities of the effects of pulse generators were identified for the first time, with a predominant effect on the autonomic nervous system; a conclusion was drawn about specific responses to radiation, determined by "functional damage to the brain." The general clinical pattern of chronic irradiation corresponded to the data obtained in the prewar period at VIEM. Prof. Kevork'yan presented a complete clinical picture of health problems caused by chronic radiofrequency exposure, gave recommendations for treatment, and described the recovery dynamics. In 1948, he proposed a schedule for medical examinations and the makeup of specialists, as well as contraindications to working with sources of radio frequency EMFs, which have not fundamentally changed to this day.

In the early 1950s, in connection with the introduction of radar stations in the navy, a scientific group was created at the Naval Medical Academy at the Department of Nervous Diseases, led by Corresponding Member of the USSR Academy of Medical Sciences A.V. Triumfov, to study the state of health of navy personnel under the EMF irradiation conditions of radar stations. In 1954, it transformed into a full-time research laboratory focused exclusively on "electromagnetic" issues. The problem of electromagnetic safety was solved in a comprehensive manner: hygienic, clinical, and physiological studies were supplemented by experimental ones in the fields of physiology, electrophysiology, biochemistry, engineering, and hygiene. After the Naval Medical Academy was merged with the MMA in 1959, the laboratory became an independent scientific unit at the order of the USSR Minister of Defense and its new staff was introduced.

Thus, research into the biological and medical effects of electromagnetism in Russia evolved over the first 50 years from pioneering scientists in the Russian Empire to planned work in the USSR and subsequent creation of specialized scientific units.

It should be noted that the question of whether there is a specific biological effect from low-intensity radiofrequency EMFs significant for physiology or only thermal impact can lead to significant effects that never disappeared from scientific discussions in the 1930s [34, 40, 42]. Advances in the "energy" or "thermal" direction of research was inextricably linked with the consideration of EMF as a stimulus when solving the problem of determining the dose–effect relationship from inactive to lethal levels.

In its integral form, the theory of the biomedical effects of electromagnetism had formed in the USSR by the 1960s; it can briefly be characterized as follows. When exposed to an EMF in the entire frequency range, it is impossible to oppose or mutually replace the thermal and nonthermal effect in the entire range of intensities. In any case, energy is absorbed in all tissues into which the electric component of the field penetrates; depending on the energy balance, one is dealing with the "thermal" effect. Regardless of energy, the EMF acts as a stimulus to the central nervous system (CNS); the response of the higher regions of the CNS is particularly significant in this case; the nature of the response depends on EMF parameters: the direction of the body's responses in the experiment can be the opposite, depending on the method of signal organization (continuous or pulse-modulated). The conclusion on the role of the CNS agreed with the ideas of Academician I.P. Pavlov about the role of the nervous system in the analysis and balance of all stimuli from the external and internal environment of the body.

The principle of the hazardous effect indicator was determined: compensatory responses of the body, which can develop into a pathological process. This served as the basis for substantiating the first hygenic standards for persons working with radio frequency sources and for the military. It was maintained that the division of the transition of physiological compensation to pathology is very complex; this requires a study of integral indicators characterizing the general response of the body to the effect of EMF and functions sensitive to its impact.

In the 1960s, research into the biomedical effects of electromagnetism was coordinated scientifically on a national scale by the Scientific Council of the USSR Academy of Sciences on Cybernetics, as well as the Scientific Council on Problems of the Biosphere and

advisory groups of the USSR Academy of Medical Sciences. Accordingly, fundamental research was carried out mainly within the cybernetic approach, which considered the response of the CNS to a change in a parameter of the external environment as the perception of information. It was assumed that, if the response of the CNS and body to the "nonthermal" EMF level was proven, this could be called the "informational effect of EMF." The primary mechanism of perception was the main subject of research and discussion in the absence of data on specialized receptors and analyzers for the perception of EMF, including in the context of mechanisms of natural orientation and regulation of behavior. The information approach led to the consistent adoption of strict mandatory state MPLs of radio frequencies higher than 300 MHz (10 $\mu W/cm^2$ for workers and the military and 1 $\mu W/cm^2$ for the rest of the population) [43–45].

During this period, the topics of planned research were formed in the following areas: biophysical mechanisms; determination of intensity, metrology, and dosimetry and organization of irradiation conditions in an experiment; characteristics of the thermal effect of the EMF of radio frequencies, including microwaves; effect on the cardiovascular system, on the function of the digestive organs, on the endocrine system and metabolism, on the immune system, on the blood system, on the central nervous system and behavior, and on the reproductive system. The issues of the etiology and pathogenesis of functional and morphological changes were generalized. After 1962, discussions were initiated on the need to develop standards for conditions of local irradiation of the head, safety criteria, and control methods for multiple sources of microwave EMF [46–51].

In the 1960s, communication, radio, and television broadcasting systems, and technological electromagnetic systems were intensively developed. This created the need for EMF regulation on the behalf of the population and workers unrelated to the operation of EMF sources; it gave rise to research in the interests of public hygiene and confirmed the reliability of the MPLs for workers [49, 50, 52].

Based on long-term clinical observations, a new unit has been proposed: "radio wave disease," the clinical pattern of which is governed by changes in the functional state of the nervous and cardiovascular systems [53]. The occurrence of this disease was explained by prolonged exposure to microwave radiation with an intensity from tens of $\mu W/cm^2$ to several $mW/cm^2$.

The hygienic characteristics of irradiation conditions became the basis for both experimental planning and clinical epidemiology. Dosimetry was determined by a unified system of metrological support for measurements of electric and magnetic field strength and electromagnetic energy flux density, created at the All-Union Scientific Research Institute of Physicotechnical and Radiotechnical Measurements in the 1960s–1969s, including a system for the production of measuring instruments and their metrological support, antenna calibration, and verification of measuring instruments and primary and working standards [54]. This suggests the high reliability of the data on irradiation conditions.

The scientific coordination councils and advisory groups of the USSR Academy of Sciences and USSR Academy of Medical Sciences ensured planning of research and methodological guidance for studies performed in different laboratories of the country on certain topics. The first methodological guide, *Principles of Studying the Biological Effect of Radio Waves* (1974), which standardized the general principles of research organization for the country's laboratories, was published based on the results of discussions at the All-Union Symposium Principles and Criteria for Assessing the Biological Effect of Radio Waves, held at the Kirov Military Medical Academy in May 1973 [55].

Since 1978, the scientific coordination of basic research on how electromagnetism affects biological objects and improving the scientific basis for standardizing the effect of this factor on humans and biological objects was entrusted to the United Section of Electromagnetic Biology within the Scientific Councils of the USSR Academy of Sciences on Problems of Biological Physics and Radiation Biology. The coordination plan "Physical Environment" became the basis for state discretionary funding of most of the research. In 1983, within the United Section, the next research problems were defined actually for the last planning period, including study of the mechanisms underlying the effect at different levels of biological integration; assessment of the significance of the observed changes and their classification as responses of perception or adaptive–compensatory and pathological responses with an analysis of the lifetime of the resulting changes; the search for general patterns of the effect of the physical parameters of EMF; determination of the threshold parameters of EMF for biological responses of varying significance; and study of the physical fields of biological objects.

By the end of the 1980s, the main research of biomedical effects of electromagnetism, radiobiology, and hygiene of nonionizing radiation was carried out in a coordinated manner in scientific institutions of the USSR, where special scientific divisions (laboratories and departments) were created: Institute of Biophysics of the USSR Ministry of Health, Military Medical Academy and Institute of Aviation and Space Medicine of the USSR Ministry of Defense, Marzeev Research Institute of General and Communal Hygiene (Kiev), Kharkiv Research Institute of Occu-

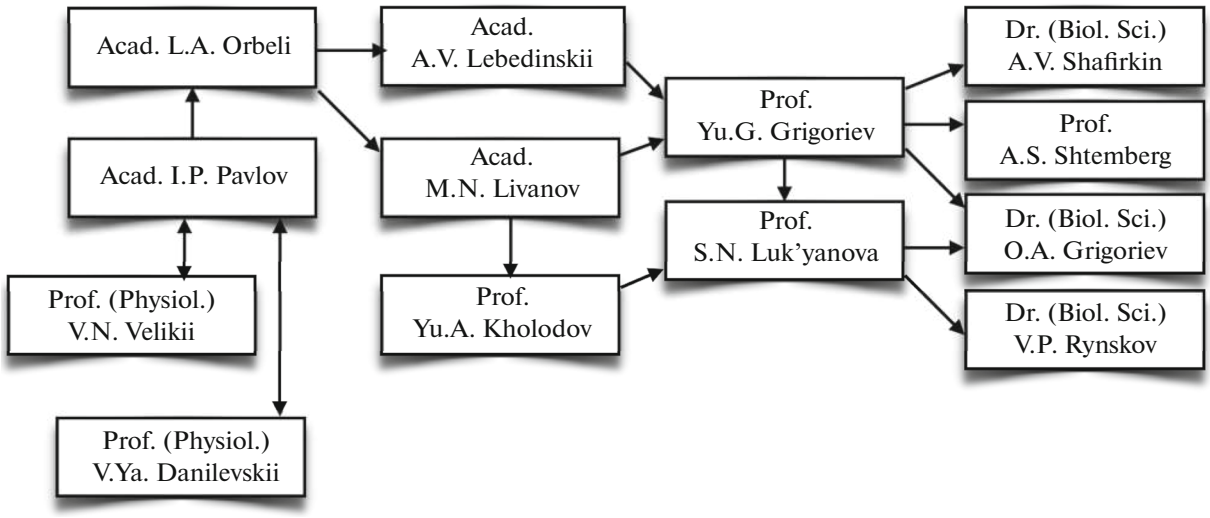



**Fig. 2.** Genealogical branch of the scientific school of researchers of biomedical effects of electromagnetism through the Institute of Biophysics of the USSR Ministry of Health.

pational Hygiene and Occupational Diseases of the Ministry of Health of the Ukrainian SSR, Leningrad Research Institute of Occupational Hygiene and Occupational Diseases of the RSFSR Ministry of Health, Research Institute of Occupational Hygiene and Occupational Diseases of the USSR Academy of Medical Sciences, Tomsk University, Institute of Medical Radiology of the USSR Academy of Medical Sciences, Institute of Biophysics, and Institute of Biomedical Problems of the USSR Academy of Sciences [43, 56].

Despite the aim for coordination in electromagnetic biology, radiobiology, and hygiene of nonionizing radiation, the medical–hygienic and biological directions of research into the biomedical effects of electromagnetism were not codeveloped in the 1970s and 1980s [57, 58]. By order of the Council of Ministers of the USSR, the "Plan for Scientific Research Aimed at Developing Hygienic and Technical Measures Associated with the Placement of Transmitting Radio and Television and Radar Stations" was developed and approved by the Council of Ministers in 1984 for the period up to 2004 [43]. The task was to ensure the balance of scientifically sound sanitary and epidemiological requirements for the conditions of the Soviet population's contact with EMF sources and trends in industrial and technological development. Hygienicists were faced with the need to substantiate specific MPL values under limited time conditions due to plans for the development of industry and communications [57, 58]. Of decisive importance were mathematical and experimental modeling of the experiment and development of mathematical prediction methods in determining the MPL based on limited experimental data [59, 60]. The unsolved problem of the mechanism was bypassed by considering the human body in experiment as a "black box" and defining the methodology as a cybernetic approach [43, 61, 63, 64]. It was assumed that the effect of EMF was manifested at the following levels: subcellular and cellular, organs and systems, and the body as a whole; sensitivity to electromagnetic energy increases with increasing body complexity. Academician M.G. Shandala substantiated the concept of an optimum EMF environment: excessive EMF values and artificial isolation from the natural set of electromagnetism factors have an adverse effect on the body [58, 62]. In his opinion, it is very difficult to accurately determine the significance of the consequences of EMF exposure to the body, often due to the complex interaction between electromagnetic energy and human health and lack of knowledge about the factor and mechanisms of its impact.

In the second half of the 1980s, a set of research results on the biomedical effects of electromagnetism was implemented in a system for sanitary regulation of EMF sources for the population and workers, which covered all the principles of generation known at that time, from electrostatics and continuous magnetic fields to modulated radio frequencies. This made it possible to create the world's most advanced system for managing electromagnetism as an environmental factor [43, 56, 62, 64, 65].

Against the socioeconomic turbulence of the 1990s, it is difficult to overestimate the important contribution of the Scientific Council of the Russian Academy of Sciences on Radiobiology and, in particular, Deputy Chairman of the Council, Prof. Yu.G. Grigoriev (who undertook personal colossal efforts to coordinate research and consolidate scientists in the absence of funding) to maintaining the sci-

entific heritage of nearly 100 years of research into the biomedical effects of electromagnetism in Russia. After 1995, a series of conferences on radiobiology and hygiene of nonionizing radiation were held under the auspices of the Scientific Council of the Russian Academy of Sciences on Radiobiology, including joint conferences with the World Health Organization and Russian National Committee for Protection against Nonionizing Radiation [65]. The conferences made it possible to organize the exchange of scientific data and outline the goals and objectives of research that met the conditions of fundamental changes in the conditions of the population and workers' contact with EMF sources, governed by the technological revolution of computerization and wireless data transmission.

In the 1990s, the basic set of sanitary standards was adapted to the conditions of new sources (computers and cellular communications) [43, 56, 62]. A theory allowing for the prediction of biomedical effects and their medical consequences for most radiation conditions was developed. One should note a number of generalizations made by colleagues in these years, including those developing the problem of the "dose" approach, which is the main one in the radiobiology of ionizing radiation, but problematic for the radiobiology of nonionizing radiation.

The data of radiobiological studies using complex irradiation modes suggest that microwave EMF with average EFD values $\leq$500 $\mu W/cm^2$ (in continuous mode or in pulses) should be considered as a stimulus to the central nervous system. Therefore, it is fair to apply the laws of physiology on biological strength, adaptive response, and ways to enhance the biological significance of a weak stimulus [67, 68].

The generalization of experimental data on quantitative indicators of microwave damage showed a peculiarity of the CNS response to pulsed microwave radiation according to estimates based on thresholds of equivalent biological reactions (e.g., extinction rate of conditioned reflexes, formation rate of avoidance response, etc.): pulsed irradiation is biologically 25–100 times more effective than continuous irradiation according to estimates by the average power in a pulse. The inverse relationship was also experimentally proven by epidemiological data: at an equal total irradiation power, pulse exposure leads to more severe biological and clinical consequences than for continuous irradiation [69].

Post-2000s, cellular communications became a mass product and the electromagnetic factor became significant for the population. According to fundamental concepts of the medical and biological effects of electromagnetism, predictions for a possible increase in morbidity due to exposure to EMF from cellular communications were substantiated from 2000 to 2008 according to fundamental concepts of the biomedical effects of electromagnetism based on changes in the conditions of the population's exposure and lack of scientific data on the consequences of irradiation of the brain under uncontrolled conditions in all population groups, including children: malignant neoplasms (including brain tumors and the auditory nerve), diseases and functional disorders of the nervous system (including triggering of epilepsy), and immunodeficiency-related diseases impaired [43].

According to current data, the Federal Statistics Agency Rosstat has recorded an increase in morbidity over 25 years for predicted disease groups in the population of adolescents aged 15–17 (malignant tumors, diseases of the nervous system, immunodefiency-related disorders, and diseases of the auditory and visual organs). Data from basic research, as well as assessment of the possible contribution of EMF from cellular communications to the increase in morbidity, performed by the IARC methodology, show that the dependence of increased morbidity on the effect of EMF indeed exists and is not a random coincidence. However, it is difficult to directly determine risk due to the uncertainty of dosimetry data, the absence of modern comparison groups, and incomplete concept of acceptable risk for mass cellular technology [70].

The correlation between the increase in morbidity and exposure to EMF of cellular communications equipment is a key question. Simultaneous exposure to EMF of different communication standards leads to different individual methods for organizing irradiation, which is significant for the biomedical effect and their further accumulation under repeat exposure; presumably, this indicates a path to compensatory responses and development of diseases. For new irradiation conditions, we have virtually no dosimetry information for either the near or far field. National software for an estimated prediction of incident and absorbed electromagnetic energy, including a national digital "electromagnetic" phantom (for children and adults), is required.

In 2011, the International Agency for Research on Cancer (IARC) assigned carcinogenic class 2B to radio frequency EMF; in 2019, it included the factor in the list of the highest priorities for revising the cancer classification taking into account new data; this decision was confirmed in March 2024. The "oxidative stress" mechanism was recognized for the first time as the main one for increasing the likelihood of neoplasms [71, 72]. In Russia, there are no data on "radio frequency EMF and neoplasms" taken into account by IARC, although the already known number of tumors recorded in the pediatric population allows for a case–control analysis.

In connection with the development of standards of fourth- through sixth-generation communications, the most important aspects are as follows: assessment of the effect on superficial tissues; the possibility of local brain damage due to the mechanism of absorption of "strong pulsed microwave radiation in the microsecond pulse range"; and the effect of pulsed signals on growth of melanomas.

Currently, the cause of the increase in morbidity due to exposure to EMF from cellular communications is a key question. However, it is hard to directly determine the risk owing to the uncertainty of dosimetry data and lack of development of the concept of acceptable risk for mass cellular communications technology. Taking into account the depth of development of the principles of EMF regulation and sufficient hygienic reserve coefficients, it should be assumed that the problem of the increase in morbidity due to the modern electromagnetic environment in Russia is governed by the shortcomings of the system of monitoring sources and their distribution (including from countries that follow the "thermal" principle of EMF limitation), rather than by the standards.

Studies by Russian scientists in monographs, key articles, and doctoral dissertations have formed the main body of knowledge in Russian about the biological effects of electromagnetism, radiobiology, and hygiene of nonionizing radiation.

In the first half of the history of research, the most important contributions have come from V.Ya. Danilevskii, S.I. Kostin, I.A. Abrikosov, D.Ya. Glezer, K.P. Golysheva, P.I. Izhevskii, A.A. Kevork'yan, P.S. Kupalov, P.P. Lazarev, A.V. Lebedinsky, N.N. Livshits, B.V. Likhterman, N.N. Malov, A.N. Obrosov, D.A. Rozhanskii, G.M. Slavskii, N.S. Spasskii, F.M. Suponitskaya, A.A. Slutskin, I.R. Tarkhanov, V.V. Tatarinov, and G.L. Frenkel'.

The second half of the history is characterized by the system of organization of studies and training of scientific personnel in electromagnetic biology, radiobiology, and hygiene of nonionizing radiation, which makes it possible to differentiate three groups of doctors of biological and medical sciences:

(1) People who had a full course of specialization with the defense of candidate and doctoral dissertations on electromagnetic topics: Z.V. Gordon, O.A. Grigoriev, Yu.D. Dumanskii, G.I. Evtushenko, D.S. Ivanov, E.Sh. Ismailov, I.P. Los', S.N. Luk'yanova, G.G. Lysina, L.M. Merkulova, V.N. Nikitina, S.Yu. Perov, G.F. Plekhanov, V.G. Podkovkin, L.V. Pokhodzei, V.V. Rynskov, A.M. Serdyuk, V.S. Tikhonchuk, L.A. Tomashevskaya, Yu.A. Kholodov, and R.A. Chizhenkova.

(2) People who defended their doctoral dissertations on electromagnetic topics but had a primary specialization (candidate dissertation) on another topic: S.I. Alekseev, M.G. Baryshev, G.I. Vinogradov, Z.A. Vorontsova, N.N. Gavrish, T.V. Denisova, L.P. Zhavoronkov, V.A. Zhuravlev, N.P. Zalyubovskaya, T.V. Kalyada, N.N. Lebedeva, E.P. Lobkaeva, E.B. Lyskov, S.L. Malinovskaya, S.V. Nikogosyan, E.I. Obukhan, Yu.F. Perov, E.A. Pryakhin, N.B. Rubtsova, E.I. Sarapul'tseva, M.N. Sadchikova, A.G. Subbota, M.S. Tolgskaya, N.V. Tyagin, D.A. Cherenkov, B.A. Chukhlovin, A.A. Tsimbal, and M.I. Yakovleva.

(3) People who obtained scientific specialization in topics unrelated to electromagnetism and addressed the topic as mature scientists, which allowed them to make an important contribution to the scientific field with monographs and fundamentally significant scientific studies: I.G. Akoev, A.A. Antipov, Yu.G. Grigoriev, B.I. Davydov, A.P. Dubrov, Yu.B. Kudryashov, V.V. Lednev, O.P. Lomov, Yu.A. Osipov, Yu.P. Pal'tsev, V.G. Petin, I.R. Petrov, B.M. Savin, K.V. Sudakov, I.B. Ushakov, E.E. Fesenko, M.G. Shandala, A.V. Shafirkin, and A.S. Shtemberg.

## CONCLUSIONS

This review of the history of research of electromagnetic biology, radiobiology, and hygiene of nonionizing radiation in Russia cannot be considered exhaustive: the material accumulated over more than a century is vast. It does not include issues of applied research addressed by researchers of the biomedical effects of electromagnetism during that time: physiotherapy and clinical diagnostics, agriculture, including pest control and stimulation of plant growth; the influence on ecological systems, mitogenetic radiation, and the body's own EMF; solar–terrestrial electromagnetic coupling and problems of electromagnetic communication in nature; and anthropogenic electromagnetic pollution on the global natural background.

Continuity is evident in the evolution of scientific thought: analysis of the publications shows that many fundamental provisions on the biomedical effects of electromagnetism and their medical and environmental consequences were formulated before the 1960s, then confirmed in experiments, supplemented, and refined under different irradiation conditions in all frequency ranges from a constant EMF to EHF and modulated EMF. The fundamental results of planned research, which made it possible to predict effects, and the integration of electromagnetic topics into the system of radiobiology and hygiene made it possible to create a scientific theory and methodology for standardizing EMF in the 1970s–1980s. The continuity of knowledge is the main feature that indicates the continuous and consistent development of the scientific school in electromagnetic biology, radiobiology, and

hygiene of nonionizing radiation from the first researchers in the Russian Empire to our contemporaries, scientists of the Russian Federation, over the past 130 years.

In our opinion, when discussing the problems of EMF biomedical effects, it is necessary to take into account that the discussion about the nature of electromagnetism, its physical basis, and the existence of "ether" or an equivalent physical concept has never ceased. The relativity of ideas about the nature of the electromagnetic factor allows for the relativity of knowledge about its interaction with living objects, especially since knowledge about the living cannot be considered complete either.

The scientific school of research into the biomedical effects of electromagnetism has been going on in the Russian Empire, Soviet Union, and Russian Federation for 130 years and has deep roots in national science. The number of individual publications on the subject of radiobiology and hygiene of nonionizing radiation in Russian has long exceeded 10000, and the words of Prof. B.I. Davydov are currently becoming even more relevant: "a periodic systematization of the accumulated material, establishment of a unified terminology, and standardization of research methods and analysis of the resulting data are required."

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## ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any research involving human and animal subjects.

## CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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