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BIOMEDICAL ASPECTS OF ELECTRO-MAGNETIC WAVE INTERACTION WITH THE ORGANISM

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This tutorial is based on a lecture course prepared by the authors for the Master's programme in Medical Physics. A primary aim of this tutorial is to examine the key stages in the evolution of theoretical and experimental research into the effects of low-intensity millimetre-wave electromagnetic radiation on biological systems of differing organisational complexity, including living organisms.

This tutorial was developed as part of the TPU Innovation Educational Programme in the field of Nuclear Power Engineering, Nuclear Fuel Cycle, Safe Handling of Radioactive Waste and Spent Nuclear Fuel, Ensuring Safety and Counter-Terrorism, and is intended for senior undergraduate, Master's, and postgraduate students studying physics and biomedical subjects.

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INTRODUCTION

0.1. Relevance of studying the biological effects of electromagnetic radiation

Technological advancement in many of its manifestations is associated with the utilisation of electromagnetic fields or their generation as a by-product. The total power output from sources of electromagnetic fields is constantly increasing, and the parameters of electromagnetic radiation are becoming more diverse, such that people, and the ecosystem as a whole, are exposed to electromagnetic signals with increasing intensity and unusual, previously unencountered, characteristics. This impact can quite reasonably be termed electromagnetic pollution of the environment. The average intensity of this electromagnetic background is extremely low, but in some localities and at certain times it is significant, particularly for personnel servicing various communication systems, location systems, and technological installations. The inevitability of exposure to electromagnetic radiation, with its potentially adverse consequences, compels us to assess the danger that various types of this physical factor pose to human health. Several studies have found a link between the duration of exposure to electromagnetic waves and the development of various diseases. For example, the review by L. Vershaeva [1] indicates an increased frequency of leukaemia and the occurrence of malignant tumours of the central nervous system in children exposed to electromagnetic radiation. The possibility of free radical formation under the influence of electromagnetic fields is also emphasised, leading to genome disruptions, even DNA strand breaks.

In the work of J. I. Trosko [2] discusses three possible mechanisms by which electromagnetic waves may influence the status of an organism's genetic system and, ultimately, the state of human health: 1) cell killing (cytotoxicosis); 2) genetic or chromosomal mutations; 3) alteration of genetic information expression during transcription (blocking or unblocking various loci of the genome during reading) at the translational (stabilisation or destabilisation of genetic messages) and post-translational (alteration of the gene product – protein) levels. These effects could potentially lead to a variety of diseases. This latter mechanism, unlike the two preceding ones, is irreversible, characterised by threshold behaviour and diverse biochemical pathways, and requires repeated exposure to electromagnetic radiation for the effect to manifest. Ultimately, as an epigenetic factor, electromagnetic waves induce one of the following four effects in the cell: alteration of growth and proliferation; disturbances in cell differentiation; programmed cell death (apoptosis); adaptive responses of differentiated cells.

The reviews by J.R. Goldsmith and Yu. Utylajnen [3, 4] discuss the risks to humans from various devices, including domestic appliances . Four factors are indicated as influencing health status from these devices: 1) disturbances in haematological indices; 2) changes in leukocyte chromosomes; 3) an increased frequency of adverse births; 4) a greater prevalence of cancerous diseases.
A number of epidemiological studies have investigated the correlation between electromagnetic radiation and specific diseases. S. Zmigalsky analysed the relationship between the incidence of oncological diseases and the level of exposure to electromagnetic radiation [5]. The frequency of these diseases was found to be 119 per 100,000 individuals for personnel servicing installations with elevated levels of electromagnetic radiation, compared to 57 per 100,000 for the general population. For young individuals with malignant tumours of the haematopoietic and lymphatic systems, the greatest difference between exposed and unexposed groups is noted in cases of leukaemia and lymphoma, conditions associated with immunocompetent cells.

Many people have personal computers. Although these devices are declared to be completely harmless, they emit electromagnetic radiation. It has been noted that this radiation contributes to mutagenic effects, disrupts the function of the stomach and glands, and impairs memory [6]. Electromagnetic radiation from mobile telephones affects the central nervous system, the eyes, and the gonads [6]. Furthermore, it affects the dysfunction of the cardiovascular, haematopoietic, and immune systems, and disrupts metabolic processes.

Noise radiation can significantly impact the vital functions of the human organism, particularly in the millimetre wave range [7]. It is within this range that water most intensely absorbs electromagnetic radiation. The water content of human skin is approximately 60%. Consequently, millimetre waves are almost entirely absorbed within a skin layer 0.7–1 mm thick and do not reach the internal organs. The human organism comprises approximately 10^{15} cells, which generate electromagnetic fields in the millimetre wave range. A human being in a healthy and diseased state exhibits differing amplitude-frequency responses. This means that any pathology is, primarily, a pathology of the cell. External millimetre-wave electromagnetic radiation, for example that generated using IMPATT diodes [8], stimulates the organism's endogenous radiation within this range in a diseased individual. The spectral density of noise radiation varies between different IMPATT diodes, although they all have an approximately similar level, of the order of 10^{-19} W/Hz. Each individual generates their own electromagnetic radiation at specific frequencies, at which background noise may influence the human organism.

All these data indicate the need to develop new sanitary regulations specifying safe levels of anthropogenic electromagnetic radiation. Particular attention should be paid to radiation sources such as television receivers, radio stations, mobile telephones, power lines, radio communication systems, television broadcasting, radio navigation equipment, radar systems, electric transport, and domestic and office equipment [9].

One of the primary reasons for the lack of such sanitary standards is the insufficient research into the biological effects of electromagnetic radiation, particularly their dependence on radiation parameters and exposure conditions. To determine demonstrably safe levels of electromagnetic radiation, it is necessary to investigate thoroughly the biological effects at low intensities of the incident waves. However, the very existence of biological effects from low-intensity electromagnetic fields is currently a subject of discussion. Despite the findings of numerous experimental studies, some physicists dispute the possibility that electromagnetic quanta in the frequency range $10^{8}...10^{11}$ Hz can induce conformational transitions in biomacromolecules, because the quantum energy $h\nu$ is significantly less than the thermal energy of the medium kT. For example, Yu.I. Kolchugin [10] estimated the specific absorption rate of electromagnetic radiation in biological tissues using macroscopic electrodynamics. It was found that energy absorption cannot exceed $kT/10$ at non-thermal incident wave intensity levels. The following energy accumulation mechanisms were considered: 1) a multi-photon process; 2) direct impact of the electric field on ions; 3) cooperative effects and/or coherent excitations. It was found that these mechanisms are ineffective in terms of transforming wave energy into the internal energy of the system. It follows that non-thermal biological effects are not possible in the microwave frequency range of the applied electromagnetic radiation.

All conclusions regarding the impossibility of non-thermal effects of electromagnetic radiation on biological objects are predicated on the assertion that an effective mechanism for accumulating sufficient energy to overcome the potential barrier between conformational states has not been identified. This situation arises because a number of physical characteristics of the interaction between biosystems and electromagnetic radiation are not considered.

Firstly, a characteristic of biological macromolecules is that their primary structure is formed as a chain of subunits, each exhibiting internal oscillatory movements with corresponding natural frequencies, and connected to each other by dissipative, but crucially, non-elastic bonds. When such a system interacts with an electromagnetic wave, an oscillatory mode (type of oscillation) may be excited in a biomacromolecule; the energy of this oscillation type will not then be redistributed to other types [11]. This mechanism facilitates the accumulation of energy, sufficient for a conformational transition, within a specific type of internal oscillation in a biomacromolecule. This mechanism can be interpreted in a slightly different manner: such an interaction enables the concentration of energy from numerous unsynchronised internal oscillations within a biomacromolecule into a single type of oscillatory motion, synchronised by the external electromagnetic field.

The second characteristic of the interaction between biological systems and electromagnetic radiation is related to the wavelength of the electromagnetic wave. Opponents of non-thermal biological effects induced by microwave electromagnetic waves posit a low probability of multi-photon processes. From a thermodynamic perspective, this holds true for the Wien region in the theory of equilibrium (thermal) radiation, where the average number of photons per mode with a specific frequency cannot exceed one. The microwave range pertains to the Rayleigh-Jeans region, where the average number of photons □ □> 1. In this case, the thermodynamic limit of the efficiency of transformation of external radiation energy into Helmholtz free energy will equal 1 within a certain interval of absorbed power [12]. Within this interval, the energy of the external electromagnetic field is most efficiently transformed into the energy of internal oscillations, which are ordered within the system by external influence, including multiphoton processes. This conclusion is consistent with the hypothesis of Bose-Einstein condensation within the structure of biological membranes [13]. A similar approach has been used when considering the influence of electromagnetic fields on chemical processes in membranes during signal transduction [14].

0.2. Characteristics of Ultra-High Frequency and Extremely High Frequency Electromagnetic Radiation

Observations to date indicate that the biological effects of electromagnetic radiation are dependent on the parameters of the applied fields. One of the most crucial parameters is radiation intensity. Intensity can be assessed by either the incident power flux density or the electric field strength of the electromagnetic field. The magnitude of the intensity dictates the nature of the biological effect, which may be thermal or non-thermal. The defining criterion for this distinction is the temperature of the bio-object under electromagnetic wave irradiation.

If the temperature increase due to irradiation is no more than 0.1 K, the intensity level is deemed non-thermal, and the electromagnetic radiation is classified as low-intensity in this instance.

In practice, it is convenient to use the incident radiation characteristic, specifically: incident power flux density. Let us estimate the non-thermal level of this parameter, using the example of a mouse. To do this, let us refer to Fig. 0.1, which schematically illustrates a mouse irradiated by an incident power flux with a density of P_{fall}.

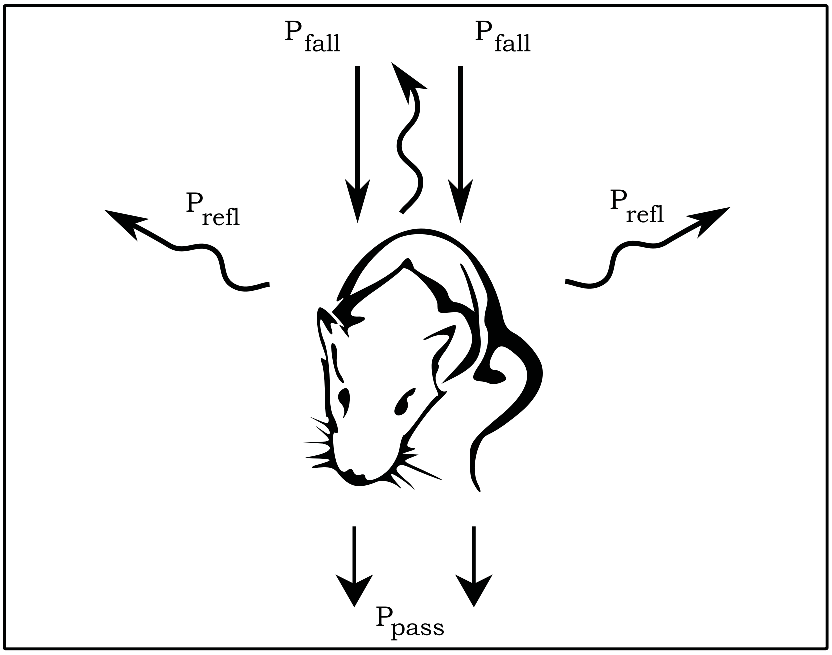

Fig. *0.1.* Diagram of animal irradiation with electromagnetic radi-

ation. A portion of the incident power may pass through the mouse. The power flux density after passing through the animal will be P_{pass}. A proportion of the incident power will be reflected from the mouse's body due to the difference in permittivity between air and biological tissues. The reflected power flux density is indicated in Fig. 0.1 as P_{refl}; however, the numerical value of this parameter varies depending on the angle of reflection. As the measurement of P_{pass} and, particularly, P $_{refl}$ presents considerable technical difficulties, typically only the incident power flux density P_{fall} is measured during the experiment. In this regard, it is expedient to limit ourselves to estimating the lower threshold of the non-thermal level of electromagnetic radiation, assuming that all incident power is absorbed by the animal's body.

We shall estimate for an exposure duration of 30 minutes, neglecting heat exchange between the animal's body and the surrounding environment. Furthermore, we shall assume that the specific heat capacity of the animal's body is 3 kJ/(kg.K), given that biological tissues are composed of approximately 75% water on average [15]. For a mouse with a body mass of approximately 20 g, the energy absorbed should not exceed 6 J, provided the body temperature increase Δt is 0.1 K.

$$Q = cm\Delta T = 6 \text{ Дж}.$$

To satisfy this condition, with an exposure time t_{exp} = 30 min and a mouse body projection area S_m = 10 cm^2, the incident power flux density must be equal to:

$$P_{fall} \approx \frac{Q}{S_m t_{\exp}} \approx \frac{6[\text{Дж}]}{10[\text{см}^2]\cdot 1{,}8\cdot 10^{3}[\text{с}]} \approx 3{,}3\cdot 10^{-4}\,\frac{\text{Вт}}{\text{см}^2} \approx 330\,\frac{\text{мВт}}{\text{см}^2}.$$

For humans, this value is approximately five times greater, as the mass/projection area ratio is 10 g/cm ^{2} for a human body, compared to 2 g/cm ^{2} for a mouse. When considering the body's heat exchange with the environment, and the fact that some of the incident power is reflected by the body rather than passing through it, the threshold value must be increased. It is understood that these estimates are valid for frequencies at which virtually the entire body is involved in the absorption of incident waves. Specific measurements have shown that, in the microwave range , the temperature of a human body increases by 0.1 K with an incident power flux density of approximately 5 mW/cm ^{2} after a 30-minute exposure . It is also necessary to consider how this threshold depends on the exposure duration. The shorter the exposure duration, the higher the threshold for non-thermal effects of electromagnetic radiation.

The frequency of electromagnetic radiation is another important parameter, as non-thermal bioeffects are resonant. However, this value is only meaningful with continuous or long-pulse exposure at a fixed carrier frequency. The latter case is characterised by the duration of the pulses τ_{imp} being significantly greater than the period of oscillations T:
$\tau_{imp} << T = 1/f$. In this case, the spectrum of the amplitude-modulated radiation closely approximates the spectrum of the output signal from real generators operating at a fixed frequency in continuous wave mode.

With amplitude or frequency modulation, resonant interaction between biological objects and the applied radiation occurs with a specific periodicity, determined by the repetition rate of the modulating pulses. This repetition frequency also has biological significance, as it may be close to or a multiple of the frequency of electrical activity rhythms in the central nervous system.

In many cases, such as frequency modulation, amplitude modulation with short pulse durations, and noise exposure, it is more meaningful to refer to the frequency spectrum or frequency band of electromagnetic radiation, rather than the carrier frequency. A quantitative characteristic of the exposure intensity in this case, in addition to the integral power density of the incident radiation, is the spectral density of the radiation. This parameter is a measure of the power of the radiation incident on a particular frequency interval: $\Delta P / \Delta f$.

Finally, it is pertinent to consider separately the frequency spectrum of ultrashort pulses, otherwise known as ultra-wideband signals . This is addressed in the following paragraph.

0.3. Frequency Characteristics of Biologically Significant Electromagnetic Radiation

First, let us consider the frequency ranges used in medicine for therapeutic or diagnostic purposes. A diagram illustrating the current state of research in this area is shown in Fig. 0.2. The frequency ranges of electromagnetic waves generated by common household appliances are also shown, indicating a significant intensity of anthropogenic radiation. Furthermore, the diagram employs radio engineering terminology, typically used by manufacturers of generating and transmitting equipment.

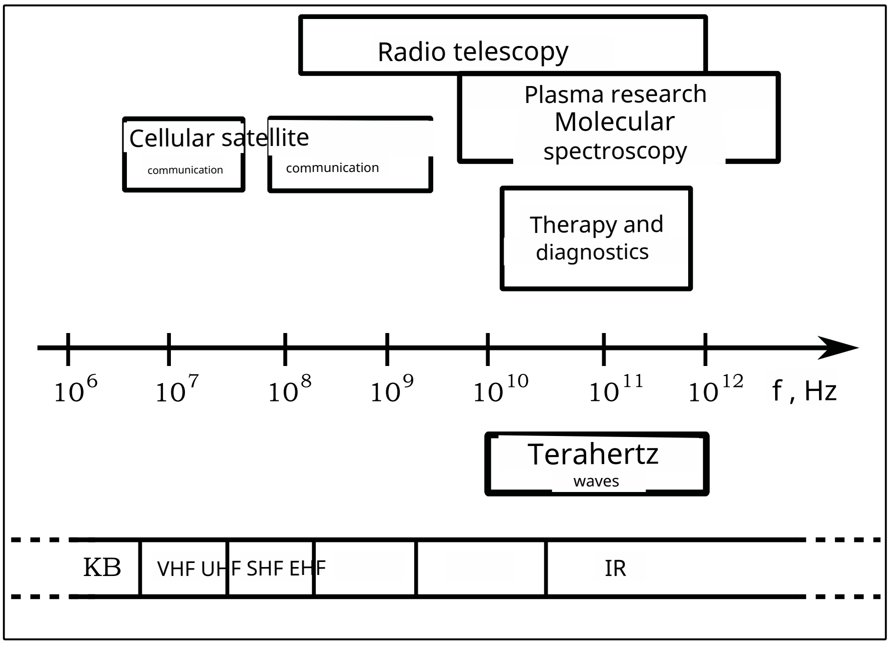

Fig. 0.2. Radio engineering frequency scale

Fig. 0.2 shows that there are no gaps in the radio engineering scale, and the term 'terahertz waves' is not included in this system. Physicists use a slightly different scale. This scale progresses sequentially through metre, decimetre, centimetre, millimetre, and submillimetre waves, followed by far- and near-infrared light, the visible spectrum, near- and far-ultraviolet, and X-ray and gamma ranges. This scale also lacks a space for 'terahertz waves'.

Conversely, the prefixes kilo, mega, giga, and tera represent multipliers of 10^3, 10^6, 10^9, and 10^{12}, respectively. Therefore, 'terahertz waves' should correspond to frequencies from 10^3 to 10^6 GHz, that is, an interval covering a portion of submillimetre waves, the infrared range, and part of the visible spectrum. In reality, this term refers to the range from 100 to 100,000 GHz. What is the reason for this?

There are two reasons for the emergence of this term. On the one hand, although there is no gap in the aforementioned scales, there was a gap in the exploitation of frequency ranges. Mastering the frequency range requires three components: oscillation generators, developed waveguide systems, and diagnostic equipment. Since the era of Hertz and Popov, radio engineers have developed this technology, consistently progressing up the frequency scale and reaching the beginning of the submillimetre range by the end of the last century. Conversely, optics has developed from the visible range into the ultraviolet and infrared regions. Due to these historical reasons, the frequency range ascribed to 'terahertz waves' has only begun to be explored in recent years.

The second reason is that this range has proven to be of great interest in terms of its applications, particularly in medicine. It exhibits the most advantageous properties of the adjacent wavebands. Like radio waves, it penetrates materials that are opaque to visible light (excluding metals). However, waves in this range can be focused like light, and the principles of geometric optics can be applied to the construction of electrodynamic systems.

References for this chapter

1. Verschaeve L. Can non ionizing radiation induce cancer? // Cancer J. – 1995. – № 5. – P. 237–249.
2. Trosko J.E. Human health consequences of environmentally modulated gene expression: potential roles of ELF-EMF induced epigenetic versus mutagenetic mechanisms of disease // Bioelectromagnetics. – 2000. – № 21(5). – P. 402–406.

3. Juutilainen J., Seze de R. Biological effects of amplitude-modulated radiofrequency radiation // Scand. J. Work, Environ. and Health. – 1998. – № 4. – P. 245–254.
4. Goldsmith J.R. Epidemiological studies of radio-frequency radiation: Current status and areas of concern // Sci. Total Environ. – 1996. – № 1. – P. 3–8.
5. Szmigielski S. Cancer morbidity in subjects occupationally exposed to high frequency (radiofrequency and microwave) electromagnetic radiation // Sci. Total Environ. – 1996. – № 1. – P. 9–17.
6. Malenko, O.G., and Tupitsyna, T.V. 'The effect of radiation from video monitors on the human organism.' Reports of the XXXIV and XXXV Scientific and Technical Conferences of the Khabarovsk Technical University. – Khabarovsk, 1966. – p. 96.
7. Burov, A.L., Kolchugin, Yu.I., and Paltsev, Yu.P. 'Ecological aspects of electromagnetic radiation from mobile communication system stations.' Occupational Safety and Industrial Ecology, 1966, no. 9, pp. 17–19.
8. Medical application of noise radiation of INPATT diode / Ya. Savenko [et al.] // AmerEM 2000. – Report 1-2-2. – P. 30.
9. Grigoryev Yu. G. Man in electromagnetic field (present situation, expected effects and danger estimate) // Radiation biology and radioecology. – 1997. – № 4. – P. 690–702.
10. Kolchugin Yu.I. On the issue of sanitary standards for electromagnetic radiation in the range of 300–3000 MHz // Occupational Safety and Industrial Ecology. – 1996. – No. 9. – P. 20–23.
11. Pickard W.F., Moros E.G. Energy deposition processes in biological tissue: nonthermal biohazards seem unlikely in the ultra-high frequency range // Bioelectromagnetics. – 2001. – № 22(2). – P. 97–105.
12. Karnaukhov A.V., Ponomarev V.O. Dissipative resonance – a novel class of physical phenomena. Some approaches to analytical description // Biomedical Engineering and Electronics. – 2001. – No. 8. – P. 23–31.
13. Chukova Yu.P. Discovery of non-thermal resonant effects of millimetre-wave electromagnetic radiation – the genesis of a new biophysics // Proceedings of the X All-Russian Symposium «Millimetre Waves in Medicine and Biology». – M., 1995. – P. 132–136.
14. Frohlich H. The Biological Effects of Mikrowaves and Related Questions // Advances in Electronics and Electron Physics. – 1980. – № 53. – P. 85–110, 143–152.
15. Neumann F. Digression on chemical electromagnetic field effects in membrane signal transduction – cooperativity paradigm of the acetylcholine receptor // Biochemistry. – 2000. – № 52(1). – P. 43–49.

1. INFLUENCE OF ELECTROMAGNETIC RADIATION ON BIOLOGICAL OBJECTS OF VARYING LEVELS OF ORGANISATION

The previous chapter presented arguments suggesting that the very possibility of biological effects from electromagnetic radiation with a frequency of 10^{11} or lower is contingent on the existence of a primary reception of electromagnetic waves; that is, whether there is a physical mechanism by which biological structures interact with an electromagnetic field of non-thermal intensity, resulting in a change to the functional activity of these structures. In this regard, it is important to understand what may occur during such interaction at the microscopic level. This chapter will examine the effects of electromagnetic radiation at the molecular and cellular levels.

1.1 Proteins as potential receptors of electromagnetic radiation

Analysing the results of studies on the effects of electromagnetic radiation on biological objects at various levels of organisation, it is readily apparent that most, if not all, effects can be explained by changes in the functional activity of proteins.
This applies to transport proteins and enzymes that determine biochemical processes, as well as biomacromolecules embedded in membranes. The structure of protein molecules allows for multiple conformational states. The functional activity of a protein molecule is largely dependent on which of these conformational states it adopts.

Transitions between conformational states in protein molecules occur continuously, but their dynamics and direction are determined by the conditions of the environment surrounding the protein molecule. One such external factor is electromagnetic radiation, which may shift the dynamic equilibrium in one direction or another. The potential for biological molecules to accumulate sufficient energy to overcome the potential barrier between conformational states is linked to the excitation of acoustic oscillations within biological structures. A key condition for this accumulation process to occur is the dissipative nature of the bonds between internal oscillators, a role that may be fulfilled by the side groups of amino acid residues in the protein chain, or by polar water molecules in the hydration shell of the protein molecule. An example of such a protein chain is shown in Fig. 1.1.

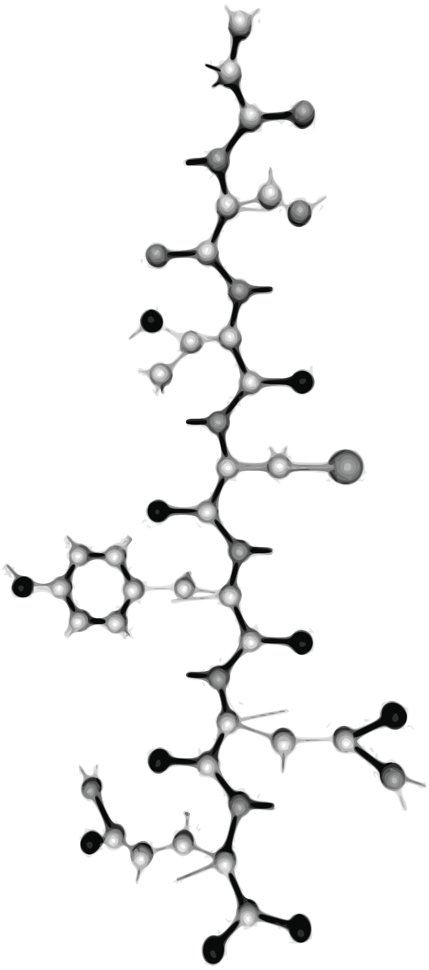

Fig. 1.1. Primary structure of the protein molecule

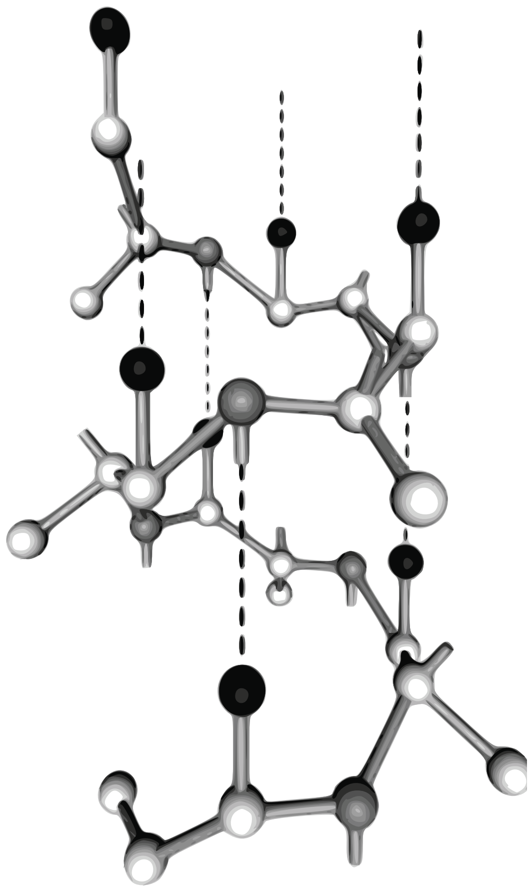

Fig. 1.2. Secondary structure of the protein molecule

Electrical charges or dipoles in these oscillators interact with the electrical component of the incident electromagnetic wave. This interaction can induce oscillations in individual constituents of the protein chain. Dissipative coupling between oscillators ensures synchronisation of these oscillations, resulting in an increased amplitude even with low-intensity stimulating electromagnetic radiation [1]. To a certain extent, it can be stated that the external influence does not supply the energy required for the conformational transition, but rather organises the energy of the biomolecule's internal oscillations for this purpose through their synchronisation.

A substantial increase in the amplitude of a specific type of internal oscillations results in a conformational transition within the protein molecule. Synchronisation occurs when the excitation frequency is close to , or a multiple of, the natural frequency of the oscillatory system. Given that the side groups of the protein molecule have different lengths, masses and bonding systems (Fig. 1.2), the spectrum of natural frequencies , and consequently interaction frequencies, will be broad.

A similar model of interaction between biological systems and electromagnetic radiation was described by A.R. Karimov [2]. A linear chain of monomers connected by dipole-dipole interaction was considered. Nucleotide pairs containing nitrogenous bases of DNA, or peptide residues in a protein chain, can act as monomers. Interaction with the electrical component of the electromagnetic field will induce oscillations in monomers via dipoles.

The matrix algebra solution for forced oscillations demonstrates the existence of resonant frequencies at which the effect of the electromagnetic wave on the protein molecule is maximised.

The haemoglobin molecule provides a convenient model for experimental studies of the interaction of electromagnetic radiation with protein molecules. In one of the early experiments [3], Mössbauer spectroscopy was used to study the fast dynamics of the rabbit haemoglobin molecule with and without exposure to millimetre waves. Mössbauer spectroscopy allows observation of the dynamic behaviour of the protein's side groups, located near the haem, with characteristic times of $\sim 10^{-7}$ s, providing information through measurement of the parameters of the so-called 'quasi-elastic' line in the Mössbauer spectrum. The experimental results demonstrated that electromagnetic radiation does not affect the average values of the parameters of the 'quasi-elastic' line; however, it significantly alters the amplitude distribution of this line. Interpretation of the results within the framework of a damped Brownian oscillator model suggests an increase in the amplitudes of low-frequency oscillations in the haemoglobin molecule under the influence of electromagnetic radiation.

Structural changes in protein molecules are closely related to their functional activity. This aspect was first addressed in the 'protein machine' hypothesis [4], proposed to examine the interaction of protein molecules with the electromagnetic field. The structure of protein molecules is determined by both the system of bonds between peptide residues in the protein chain and the bonds between peptides and water molecules in the hydration shell. An example of such a structure is the principal component of the skin: collagen. This protein is highly hydrated [5]. Peak collagen hydration is found in skin regions close to joints, where the concentration of mechanoreceptors (Ruffini corpuscles) is elevated. Hydrated collagen exhibits electrical and piezoelectric properties. Its structure, and therefore dimensional changes induced by electromagnetic radiation, may trigger spontaneous activity in Ruffini corpuscles, generating a signal to the central nervous system.

Thus, the examples considered here of the interaction between protein molecules and electromagnetic radiation allow us to regard these macromolecules as primary candidates for the role of electromagnetic wave receptors. This aspect is considered in § 1.2. Paragraph 1.3 is dedicated to changes in the permeability of biological membranes under the influence of electromagnetic waves. The influence of electromagnetic radiation on nerve impulse propagation is considered in § 1.4. The effects of electromagnetic waves on the biological properties of microorganisms are the subject of § 1.5. The following paragraph provides a review of some research findings on the influence of electromagnetic radiation on metabolic processes in cells. These processes are linked to the activity of the cell as a whole, and particularly to mitotic division, which is considered in § 1.7. The state of the membranes determines the interaction with the surface (adhesiveness) and between cells (cooperativity). The influence of electromagnetic radiation on these properties is considered in §§ 1.8 and 1.9, respectively. The effect of electromagnetic radiation on cells can be so potent that it can lead to cell death. This situation is the subject of § 1.10. Finally, § 1.11 is dedicated to the effects of electromagnetic radiation on malignant tumours.

1.2. Effects of electromagnetic radiation on conformational states in proteins

Models of the interaction of electromagnetic radiation with protein molecules, as considered in § 1.1, demonstrate the possibility of synchronising internal oscillations of certain chains, and consequently, concentrating sufficient energy to induce conformational changes in macromolecules. Experimental confirmations of the existence of conformational transitions under the influence of electromagnetic radiation have been obtained in several studies. Principally, these include Mössbauer measurements performed on haemoglobin molecules. The results of these measurements are presented in the work of N.P. Didenko [6]. Mössbauer spectroscopy provides highly precise information about the electric field distribution and, consequently, the molecular structure in the vicinity of the Mössbauer isotope. In haemoglobin, the isotope ^{57}Fe is present. It is located at the centre of the haem complex, surrounded by the protein component of the globule. The transition of the haemoglobin molecule to a new conformational state is accompanied by a change in the electric field at the nucleus of the isotope ^{57}Fe, which manifests as a change in the parameters of the Mössbauer spectrum of the protein. The measurement results are shown in Fig. 1.3.

In the range 44.50–50.36 GHz, 10 frequency values were found where interaction of electromagnetic radiation with haemoglobin molecules was observed. This interaction manifested in Mössbauer spectra as the appearance of an additional doublet of lines corresponding to a novel conformational state. The parameters of these doublets, appearing upon interaction at resonant frequencies, are shown in Fig. 1.3. It should be noted that the response of haemoglobin molecules to electromagnetic radiation varies across different frequencies. Presumably, each resonant frequency corresponds to a transition to a specific conformational state associated with that frequency, suggesting a large conformational space. However, this fact seems surprising, as the iron atom in haemoglobin simultaneously forms bonds with only a few parts of the globule.

This conclusion is supported by the results of Mössbauer studies on the interaction of the haemoglobin molecule with electromagnetic radiation at helium temperatures [7]. In this case, the Mössbauer spectrum of haemoglobin comprises two sub-spectra. One of these is a well-resolved doublet of lines, corresponding to low-spin component of haemoglobin. Another sub-spectrum takes the form of an asymmetric doublet of broadened lines. It corresponds to the high-spin component of methaemoglobin, characterised by an intermediate relaxation time that is insufficient to fully resolve the hyperfine magnetic structure.

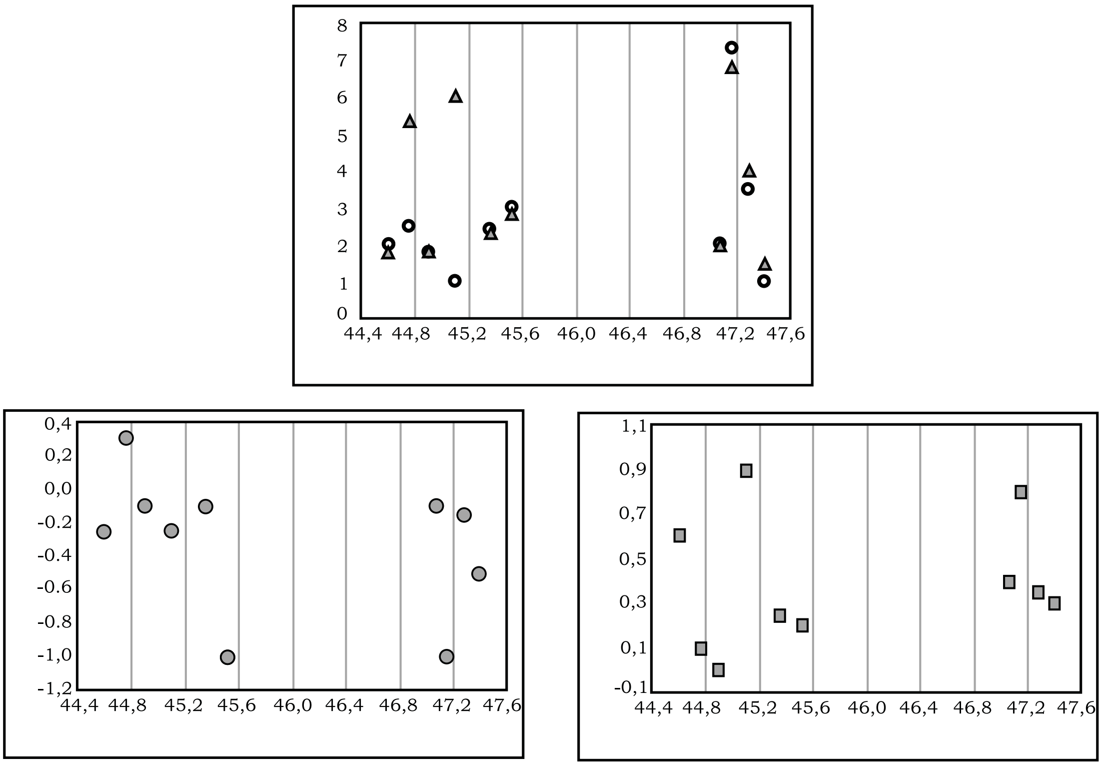

Fig. 1.3. Parameters of additional doublets in the Mössbauer spectra of haemoglobin: white circles – ratio of line widths; grey triangles – ratio of line areas; grey circles – quadrupole splitting; grey squares – chemical shift.

During resonant interaction of the haemoglobin molecule with electromagnetic radiation, the parameters of the first doublet remain practically unchanged, while the parameters of the high-spin sub-spectrum at the resonant frequencies of interaction with millimetre waves change significantly, indicating conformational transitions specifically in this component of methaemoglobin. Moreover, the ratios of the areas of the lines corresponding to both components remain constant in magnitude, indicating that the induced transitions are not spin-related. Thus, the measurement results indicate that the transition of a globular biomacromolecule from one conformational state to another under the influence of electromagnetic radiation is accompanied by a rearrangement of the system of internal bonds within the protein's tertiary structure.

Conformational transitions in protein molecules are closely linked to the structure of internal motions within biomacromolecules. Mössbauer measurements of the effect of electromagnetic waves on the dynamics of haemoglobin [8, 9] have shown that interaction at resonant frequencies increases the intensity of transitions within a specific conformational subspace. Mössbauer spectra indicate an overall stabilisation of the molecular structure under the influence of electromagnetic radiation. This indicates a synchronisation of internal motions within the protein molecule by the electromagnetic field. Consequently, electromagnetic radiation acts most effectively on those conformational states that possess natural frequencies close to the frequency of the external generator. An increase in the amplitude of these oscillations leads to a conformational transition.

Changes in the structure of bonds in protein molecules were also recorded using infrared spectroscopy. In the work of L.V. Kalyuzhnaya [11], this method was used to investigate the effect of electromagnetic radiation on blood plasma. It was found that irradiation with electromagnetic waves leads to changes in infrared spectra, associated with the disruption of hydrogen bonds. In the work of T.V. Chenskaya and I.Ya. Petrova [12], the infrared spectra of lecithin and human serum albumin were measured following irradiation with electromagnetic radiation with a wavelength of 8.6 mm and a power flux density of 50 mW/cm^2. These spectra indicated that millimetre waves do not induce irreversible changes in the secondary structure of protein molecules, including phase transitions in lipids and transitions from α-helices to β-turns. However, electromagnetic radiation modified protein dynamics, which manifested as an increased hydrogen exchange in human serum albumin. This effect was fully reversible.

The potential for conformational changes in protein molecules under the influence of electromagnetic waves was investigated using an immunological method [13], based on the antibody binding reaction with specific antigens. This reaction requires a high degree of chemical and spatial correspondence between determinant groups. Therefore, measurements of the degree of binding allow estimation of the spatial correspondence of the binding sectors and, consequently, the conformational state of the molecule.

1.3. Probability of alterations in cell membrane state

The previous paragraph demonstrated the possibility of induced conformational transitions in protein molecules upon exposure to electromagnetic waves. In this paragraph, we shall consider how conformational changes in protein molecules manifest in the functioning of cell membranes.

Alterations in the state of gating and other protein molecules under the influence of electromagnetic radiation can be determined by modifications to their functional properties. In this regard, the study of cellular membrane responses to the action of electromagnetic waves is of considerable interest.

Several studies have been conducted to investigate the effects of electromagnetic radiation on the condition of erythrocyte membranes. The influence of millimetre waves on erythrocyte membrane resistance was investigated by A.S. Koryagin [14] using a noise signal in the frequency range 53–78 GHz with a spectral intensity of $\sim 6.10^{-17}$ W/Hz, corresponding to an integrated power of ~1.5 μW. An increase in membrane resistance was observed. In the control experiment, complete haemolysis of erythrocytes occurred at a NaCl concentration of 0.35 %, whereas under the influence of electromagnetic radiation, it occurred at a concentration of 0.23 %. In both cases, the onset of haemolysis was observed at 0.55 %.

It was established that irradiation with millimetre waves leads to a reduction in the concentration of one of the products of lipid peroxidation in the blood. This indicates a decrease in the rate of processes associated with free radical formation. It is known [15] that the weakening of hydrophobic bonds is accompanied by intensified lipid peroxidation in membranes, and vice versa. The data presented above demonstrate an enhancement of hydrophobic interactions in cell membranes under the influence of electromagnetic radiation.

The increase in membrane resistance may also be explained by another mechanism: modulation of the activity of the membrane enzyme system. To verify the possibility of such a mechanism, a study was conducted on the following enzymes: a) alanine aminotransferase, which catalyses the reversible transfer from alanine to α-ketoglutaric acid and has a molecular weight of 114 Daltons; b) amylase, which belongs to the hydrogenase class and catalyses the hydrolytic cleavage of glycosidic bonds in starch and glycogen, its molecular weight being 48 Daltons [16]. Electromagnetic radiation did not affect the first enzyme but increased the efficiency of the second by a factor of 1.7. Enzymes differ from one another firstly in the magnitude of their molecular mass and, consequently, the frequency of their natural oscillations, and secondly in that amylase requires water for the reaction, whereas alanine aminotransferase does not. This difference is due to the resonant interaction of electromagnetic radiation with amylase, which alters its spatial structure and converts it into a more active form, as this enzyme exists in several different configurations in solution [16]. It should be noted that a number of enzymes can be classified as hydrogenases. These include enzymes of energy metabolism and enzymes associated with maintaining membrane potential and nerve impulse transmission, for example, Na^{+}, K^{+} ATPase, Ca^{2+} ATPase.

Indirect information regarding the condition of the erythrocyte membrane can be obtained from measurements of parameters such as the electrophoretic mobility of these cells. It depends on the charge distribution on the membrane surface. In the work by S. Ivanov, M. Kuzhmanova [17] investigated the effect of electromagnetic radiation with a wavelength of 5.6 mm on the electrophoretic mobility of rat erythrocytes. In the experiment, three groups of animals were used: a control group, a group exposed to electromagnetic radiation, and a group exposed to a combined exposure of electromagnetic radiation and ionising radiation. The experimental results showed that millimetre waves increased the electrophoretic mobility of erythrocytes in the initial days, but it subsequently returned to control levels. Irradiation with rays leads to a decrease in this parameter throughout the observation period; however, exposure to electromagnetic radiation prior to irradiation largely compensates for this reduction. Irradiation with rays induces conformational changes in erythrocyte membranes, resulting in a redistribution of charges. Millimetre waves also alter the membrane structure, but these alterations exhibit a different and, to some extent, opposing trend – they stabilise the state of the membrane before subsequent irradiation.

Similar results were obtained in studies investigating the effect of electromagnetic radiation in the 53–78 GHz frequency band, under noisy conditions, on isolated rat erythrocytes [18]. The spectral power density was 4.10^{-17} W/Hz; the inhomogeneity of the field was within ±3 dB, and the integrated power was 1 μW. Exposure to electromagnetic radiation with these parameters also resulted in increased electrophoretic mobility.

In experiments with phototrophic microorganisms Spirulina platensis [19], irradiation of these cells with millimetre waves was found to induce changes in growth rate at different stages, and in the concentrations of sodium and nitrate ions in the culture medium.
It should be noted that the transport of sodium ions into the cell is a rapid process, since the direction of movement aligns with the electrochemical potential gradient. Conversely, the removal of nitrate ions from the cell is a slow process dependent on both illumination and metabolic activity. Therefore, alterations in membrane permeability occur primarily with respect to sodium ions, which determines the corresponding dynamics of this ion's concentration.

Attention should also be given to experiments using high-power nanosecond microwave pulses, as the electric field strength in such radiation is comparable to that within the membrane (50...300 kV/cm). It was found that exposing frog skin membranes to such high-power pulses (with a wavelength of 3 cm, a pulse duration of 10 ns, and a peak power of 30 MW) resulted in accelerated active sodium ion transport and increased membrane permeability to water molecules [20].

The effect of electromagnetic radiation at a frequency of 75 GHz and an integral power of 8 mW on the fast potassium current in a mollusc neuron was investigated by S.I. Alekseev [21]. The results indicated that the exposure led to a reduction in the time constants of activation and inactivation by 7.5% and 16%, respectively. The rate of inactivation increases to a greater extent than that of activation. This suggests that electromagnetic radiation effectively influences the function of fast potassium channels, potentially explained by conformational changes in the gating molecules.

1.4. Alterations in nerve impulse transmission

Changes in the functioning of gating molecules, considered in t-he previous paragraph, are closely related to nerve impulse transmis-sion. The latter is significant in terms of the organism's overall respo-nse to electromagnetic exposure. Therefore, studies of the influence of electromagnetic waves on nerve impulse transmission are crucial for understanding the organism's reaction to this exposure.

In experiments with isolated frog bladder preparations [22], chang-es in the spontaneous impulse activity of brush-like receptors were me-asured at the nerve leading from the bladder. Irradiation of this prepar-ation with electromagnetic radiation at a frequency of 42.194 GHz incre-ased the mean overall frequency of impulse activity. The dynamics of c-hanges in the relative magnitude of this parameter under the influence of electromagnetic radiation are shown in Fig. 1.4, in comparison with t-he corresponding values for the control and infrared irradiation.

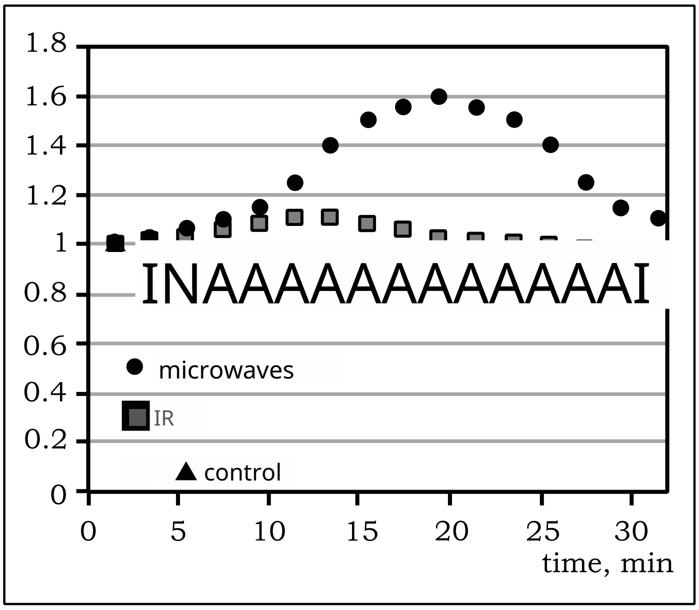

Fig. 1.4. Dependence of the frequency of spontaneous impulse activity of frog nerve on time.

Fig. 1.4 shows that electromagnetic waves affect the bush-like re-ceptors differently from the thermal effects caused by infrared radiat-ion. Electromagnetic radiation increases the frequency of background activity in these receptors, although partial adaptation is observed d-uring exposure. The mechanism of this action may be related to the reception of electromagnetic radiation within the innervation zone of action potentials.

Receptor responses to electromagnetic radiation at frequencies ranging from 40.00 to 42.25 GHz and at 42.31 GHz were investigated in the work of N.G. Zheltov [23]. Mechanoreceptors of frog skin in a semi-intact state, as well as isolated skin-nerve preparations, were irradiated with electromagnetic waves. The afferent flow of nerve impulses during mechanical stimulation of the receptors was recorded using an external recording from a branch of the dorsal nerve innervating the area of irradiation. At the maximum incident power flux density (~35 mW/cm ^{2}), the temperature increase was 1–2 °C.

The first series of experiments was performed within a temperature range of 18–22 °C, that is, within the thermoneutral zone for frog mechanoreceptors, which is 13–26 °C, thus indicating a non-thermal effect of electromagnetic radiation on mechanoreceptors. However, exposure to electromagnetic waves resulted in neither the activation of spontaneous activity nor any modification of the response.
In the second series of measurements, performed within a thermosensitive temperature range of 27...30 °C for the mechanoreceptor system, irradiation with electromagnetic radiation at a frequency of 48 GHz was found to decrease induced mechanoreceptor activity.

Electromagnetic radiation may also be received directly within nerve fibres. In this case, the electromagnetic field modifies the transmission of the nerve impulse. A.Yu. Sazonov [24] investigated the effect of electromagnetic radiation at a frequency of 42.19 GHz on the function of the grass frog's nerve. The recovery time of the action potential amplitude following excitation by electrical impulses was measured during irradiation under three conditions:
a) prior to stimulation; b) during recovery; c) prior to excitations during recovery. A reduction in recovery time of 20...40% compared to control values was recorded in all three conditions.

The effect of electromagnetic waves on nerve fibres can be not only stimulatory but also inhibitory. In the work of G. Burachas [25] also investigated the influence of electromagnetic radiation on the sciatic nerve of frogs. Exposure to millimetre waves of an unspecified frequency caused the action potential amplitude to decrease exponentially to zero. Following the irradiation session, the amplitude gradually recovered.

The data presented above highlight two features of the influence of electromagnetic radiation on nerve impulse transmission when acting on receptors and nerve fibres. Firstly, the effect is frequency-dependent, which is consistent with the hypothesis of resonant interaction of radiation with functionally competent protein molecules. Secondly, the response to pre-irradiation of preparations with electromagnetic waves, and the significant time course of the effect, suggest a slow relaxation of conformational changes in protein molecules.

In addition to the action on receptors and nerve fibres, the passage of a nerve impulse may be modified reflexively. An example of this situation is provided in the work of Yu. Gaponyuk [26]. Eighteen of twenty patients with hypertension exhibited an increased action potential repetition rate in the afferent fibres of the median nerve in the left arm , following 1 minute of irradiation to a skin area near acupuncture point 9.9 of the pericardium meridian. The frequency of the electromagnetic radiation varied from 53.596 to 53.603 GHz, with an amplitude modulation frequency of 0.05 Hz. The incident power flux density was less than 5 mW/cm ^{2} . Frequency analysis of the electroencephalogram revealed an increase in the power of the theta rhythm spectral interval compared to the background level in these patients. Blocking the median nerve between the irradiation zone and the zone for measuring action potentials led to a decrease in the frequency of background impulse activity and EEG spectral power in all patients. Irradiation with electromagnetic radiation did not cause changes in these parameters.

1.5. Influence of electromagnetic radiation on the biological properties of microorganisms.

The role of conformational changes in protein molecules for cell membrane function was noted above. However, such changes are important not only for membrane proteins, but also for other molecules that determine the biological properties of cells, particularly their growth. In experiments with E. coli and S. aureus cultures [27], radiation frequencies were identified that affected these cultures.

altered their growth. Irradiation at some of these frequencies stimulated growth, whereas at others it suppressed it. It should be noted that no correlation was found between the power level of the electromagnetic radiation and the extent of its biological effect on these bacteria.

In addition to biochemical reactions important for cell growth, exposure to electromagnetic radiation can lead to alterations in cell structure, as has been demonstrated, for example, in experiments with pertussis microbes [28]. Research suggests that exposure to electromagnetic radiation at specific frequencies leads to alterations in the immunological properties of these cells. These properties were assessed by the presence of surface antigens – agglutinogens 1, 2, and 3. It was found that cells increase the synthesis of agglutinogen 1 under the influence of electromagnetic radiation with wavelengths of 6.39, 7.00, and 7 .80 mm, and decrease the synthesis of this antigen when irradiated at a wavelength of 6.90 mm. Exposure to electromagnetic waves with wavelengths of 6.59 mm and 6.00 mm caused a significant reduction in the level of agglutinogen 2 and 3 synthesis by these microbes.

The work of L.S. Kholodnaya [29] demonstrated that millimetre waves modify the immunological properties of staphylococcus antigens. Moreover, the principal pathogenic factor of staphylococcus, protein A, was found to alter its capacity to interact with immunoglobulins following electromagnetic wave irradiation.

Research into the effects of electromagnetic radiation on the photosynthetic microorganisms S.Platensis and P.Vividis [30] has shown that this exposure stimulates microorganism growth, increases cellular chlorophyll content, and intensifies oxygen production. This work confirms that the primary action of electromagnetic radiation, by altering membrane permeability and consequently the transport of sodium and nitrate ions, leads to a shift in the equilibrium between respiration and photosynthesis towards the latter.

Similar studies on B.Subtilis bacteria [31] have demonstrated the existence of frequencies at which exposure to electromagnetic radiation stimulated biomass growth and protein production. Frequencies were also identified at which exposure suppressed the functional activity of these microorganisms. Stimulation manifested as a 30% increase in biomass, whereas suppression manifested as a 50% decrease relative to control values. Concurrently, the protein concentration increased by 70 % upon irradiation with electromagnetic waves at the stimulating frequency, and decreased by only 5% at the inhibiting frequency.

frequency. Thus, millimetre waves alter the metabolism of B.Subtilis bacteria, but do not modify the entire process as a whole; rather, they affect various metabolic reactions depending on the acting frequency.

The effect of electromagnetic radiation on the growth of microorganisms differs at different stages of cell culture development. Two experimental variants were performed with the Spirostomum.sp culture [32]:
a) irradiation of the culture with electromagnetic radiation during population formation; b) irradiation of the culture with electromagnetic radiation of an unformed population due to the limited volume of the Petri dish. The cultures were 6 days old and were irradiated with electromagnetic radiation with a wavelength of 7.1 mm for 30 min.

In the first series of experiments, population relationships were established in the control group, but irradiation on days 2, 4, and 7 led to a significantly earlier population emergence. The growth curve matched that of the control group only when irradiation occurred at a stage when the population was almost fully established (days 9–11). In this case, regulatory mechanisms predominated over the electromagnetic influence.

In the second series of experiments, a population did not form in the control group. Exposure to electromagnetic radiation at various stages of culture growth led to stabilisation, which manifested as the formation of population relationships. Irradiation during stages of rapid growth (days 4, 7, and 9) resulted in a more stable population than irradiation at the inoculation stage (day 2).

Experimental data indicate that electromagnetic radiation can affect microorganisms at a genetic level. Changes in the genome of E. coli under the action of millimetre waves were investigated in the work of A. V. Gusev [33]. It was found that radiation activates the lysogenic prophage □ □ chromosome and the □ galactosidase (lactose) gene of the plasmid in E. coli cells. The expression of these operons is normally blocked by the C1C1epressor □ □ of the phage

Irradiation of lysogenic K□ 12 cells under growth conditions showed the presence of several frequencies at which the amplification of phage expression was 5 to 6 orders of magnitude above the background level. The dependence of galactosidase gene induction in CSH 36 culture on the frequency of electromagnetic radiation was investigated near one of these frequencies. Maximum gene induction was recorded in the frequency range 70.5...70.7 GHz, giving a relative resonance width of $\sim 3.10^{-3}$.

1.6. Influence of electromagnetic radiation on metabolic processes at the cellular level

The modification of microorganism properties described above is largely attributable to changes in the metabolic process, particularly with regard to cell growth. Therefore, this paragraph focuses on the effect of electromagnetic radiation on cellular metabolism.

Experiments with E. coli culture [27] have demonstrated a correlation between the effect of electromagnetic radiation on the growth rate of this culture, and the effect of this factor on the parameters of phospholipid and energy metabolism proteins within the cell, and the activity of its dehydrogenases. Photosynthesising bacteria Ph.Leognathi were the subject of research into the effect of electromagnetic radiation on the membrane structure regulating metabolic processes in cells [34]. The advantage of studying such microorganisms resides in the ability to obtain information regarding the effects of electromagnetic radiation on vital cellular functions via an intact approach, using the light response of the biochemical system. The measurement results indicated that exposure to electromagnetic waves at a frequency of 3.2 GHz induced luminescence quenching, and this effect was independent of the incident power density within the range of 1.3 to 13 μW/cm ^{2} . The source of luminescence in these bacteria is the reduction reaction of flavin mononucleotide and lipoaldehyde by molecular oxygen. This reaction results in the formation of a long-lived enzyme-substrate complex in an excited state, and its relaxation is accompanied by light emission. It can be hypothesised that the quenching of luminescence under the action of electromagnetic radiation is primarily associated with alterations in cell membranes. Restructuring in lipid fractions can lead to a change in the aldehyde factor and a reduction in luminescence intensity. Activation of oxygen consumption within the cell can be considered as an alternative pathway of influence. This also leads to a decrease in luminescence levels during electromagnetic irradiation and a restoration of luminescence intensity upon cessation of irradiation. The important role of molecular oxygen in alterations to metabolic processes under the influence of electromagnetic radiation was noted by A.K. Tambiev and N.N. Kirikova [35], who studied the effects of electromagnetic waves on cyanobacteria S. Platensis and other microorganisms.

The mechanism of action of electromagnetic radiation on cells, based on its interaction with the membrane, is indirectly corroborated by data obtained from the treatment of cardiac patients using millimetre waves [36]. In the pathogenesis of these diseases, the activation of lipid peroxidation of phospholipids within cellular and intracellular membranes, particularly in cardiomyocytes and platelets, plays a significant role. This process disrupts the function of membrane-dependent enzymes, and alters the structure and permeability of membranes.

1.7. Modification of the mitotic cycle

The alterations in metabolic processes, considered in the preceding paragraph, may be linked to the mitotic cycle, as cell division requires a specific level of metabolic activity.
Therefore, electromagnetic radiation can be expected to affect the mitotic cycle. According to experimental data, electromagnetic waves do indeed influence cell division. These effects exhibit a resonant nature; that is, electromagnetic waves alter the rate of mitotic division only at particular frequencies.
Changes can be directed towards both the stimulation and the suppression of mitosis, depending on the frequency of the incident radiation. Such results were obtained in experiments with cultures of E. coli and S. aureus [27], as well as with photosynthetic microorganisms S. Pla tensis and P. Vividis [30]. Irradiation of a leucocyte culture with electromagnetic waves of 7.1 mm wavelength led to a 50–70% increase in growth rate in the first and second passages, whereas electromagnetic radiation of 5.6 mm wavelength caused a 52% increase in cell growth activity only in the first passage [37].

The stimulation of cell proliferation can be explained by biochemical alterations resulting from exposure to electromagnetic radiation. A study of the effects of millimetre waves on lymphocytes from healthy individuals in vitro [38] found that these cells produced a cytoplasmic factor – a cytokine associated with dehydrogenase activation, which functions as a growth factor.

Electromagnetic radiation can act directly on chromosomes, potentially modifying cell division processes. V.A. Starshina [39] investigated the effect of electromagnetic radiation in the frequency range 40.75...48.25 GHz on the polytene chromosomes of C. plumosus larvae. The study found that initial chromosomal changes occurred immediately following irradiation for 15 or 30 minutes. In both cases, the genetic activity of continuously transcribed chromosome segments changed in a similar manner. The greatest changes occurred 1...2 hours post-irradiation, indicating a trigger mechanism of electromagnetic radiation action that initiates a slow process within the cells. Furthermore, exposure at a specific frequency elicits effects with opposite signs in different chromosome segments: stimulating genetic activity in some while suppressing it in others. Presumably, this result is more closely related to the structure-function differentiation of the macromolecular complex (DNA histones, nucleic proteins) in various chromosomal segments.

Besides cell division, stimulating and inhibitory frequency-dependent effects of electromagnetic radiation have also been observed with regard to the functional activity of microorganisms. For example, millimetre waves modified the fibrinolytic activity of B.Firmus and the synthesis of penicillin by S.Aureus [40, 41]. Millimetre waves also alter the reading of the genetic code in *E. coli* cells [33]. When lysogenic cells were irradiated under growth conditions, several resonant frequencies were found in the 69.72 GHz range. When irradiated at these frequencies, the phage yield increased by 5 to 6 orders of magnitude compared with the control group. In studies of the effect of electromagnetic radiation on the induction of the galactosidase gene in CSH 36 culture, the relative width of the resonance curve was found to be $\sim 3.10^{-3}$.

1.8. Modification of cell adhesive properties

The adhesive properties of cells are primarily determined by the state of their membranes and their ability to interact with other bodies through molecular and Coulomb forces. One indicator of this ability is the interaction with similar cells, that is, cell aggregation. The degree to which this property is manifested, particularly in blood cells, is highly important for the functioning of the organism in both normal and pathological states.

The rheological properties of blood in patients with acute stroke were studied in the work of I.A. Podolyako [42]. The results of these studies show that *in vitro* irradiation of erythrocytes from patients with electromagnetic radiation at a carrier frequency of 53.53 GHz and frequency modulation within ±25 MHz led to a 10% decrease in the aggregation index and a 20% increase in the erythrocyte deformation index. This can be interpreted as a reduction in the degree of interaction between molecules on the surface of these cell membranes.

Similar measurements on platelets showed a more significant effect of electromagnetic radiation on cell aggregation. Table 1.1 shows the indices of spontaneous (K_{sp}) and induced aggregation on days 2, 4 and 8 (K_2 , K_4 and K_8) for these cells. This table shows that the ratio of the induced aggregation index in the control group to the corresponding index under irradiation decreases over time; however, the modification of cell membranes due to electromagnetic radiation remains noticeable in all cases.

Table 1.1

Effect of electromagnetic radiation on cell aggregation

Indicator	Experiment	Control	P
K_{sp}	11,96 ± 0,29	6,09 ± 0,62	< 0,001
K_2	12,42 ± 1,32	21,44 ± 1,82	< 0,001
K_4	25,55 ± 2,73	42,62 ± 3,47	< 0,001
K_8	37,82 ± 3,70	61,54 ± 4,58	< 0,001

Studies conducted by T.V. Golovacheva [43] showed that the ability of erythrocytes to aggregate changes under the influence of electromagnetic radiation, including following in vivo irradiation. Erythrocyte aggregation index decreased from (1.23 ± 0.03) to (1.08 ± 0.02) units upon irradiation cardiac patients with electromagnetic radiation at wavelengths of 5.6 and 7.1 mm. Concurrently, the erythrocyte deformation index increased from (1.06 ± 0.02) to (1.20 ± 0.02) relative units. These data corroborate a significant modification of the surface properties of erythrocyte membranes under the influence of electromagnetic radiation. An increase in the coagulation potential of blood was detected during the treatment of prostatitis with 5.5 mm wavelength electromagnetic radiation [44].

Studies on the effect of electromagnetic waves with a wavelength in the range 5.6–7.1 mm on patients with thrombovascular disorders, conducted by G.E. Markov and V.F. Kirichuk [45], also showed a change in platelet aggregation ability. Irradiation at frequencies selected individually for each patient resulted in the normalisation of platelet function.

1.9. Features of intercellular cooperation

The previous paragraph considered the ability of cells to interact with each other. However, the state of the membrane also determines interactions with cells of other types. This is evident from the results of experiments with *Bordetella pertussis* [28]. Such cells exhibit high variability, whereby exposure to electromagnetic radiation can induce a reduction in the number or complete loss of certain surface antigens and, consequently, a change in antibody synthesis.

Further evidence of the modification of the degree of cell interaction under the influence of electromagnetic radiation is provided by erythrocyte research [46]. Freshly drawn blood with a preservative (sodium citrate) to prevent coagulation at low circulation rates was exposed to electromagnetic waves, and its viscosity was then measured. The measurement results, as a function of exposure time, are shown in Fig. 1.5. At low circulation rates, blood viscosity is determined by the reversible binding of erythrocytes and is therefore dependent on the state of their cell membranes. According to Fig. 1.5, exposure to electromagnetic waves alters the state of the membrane, but this effect is dependent on the duration of exposure.

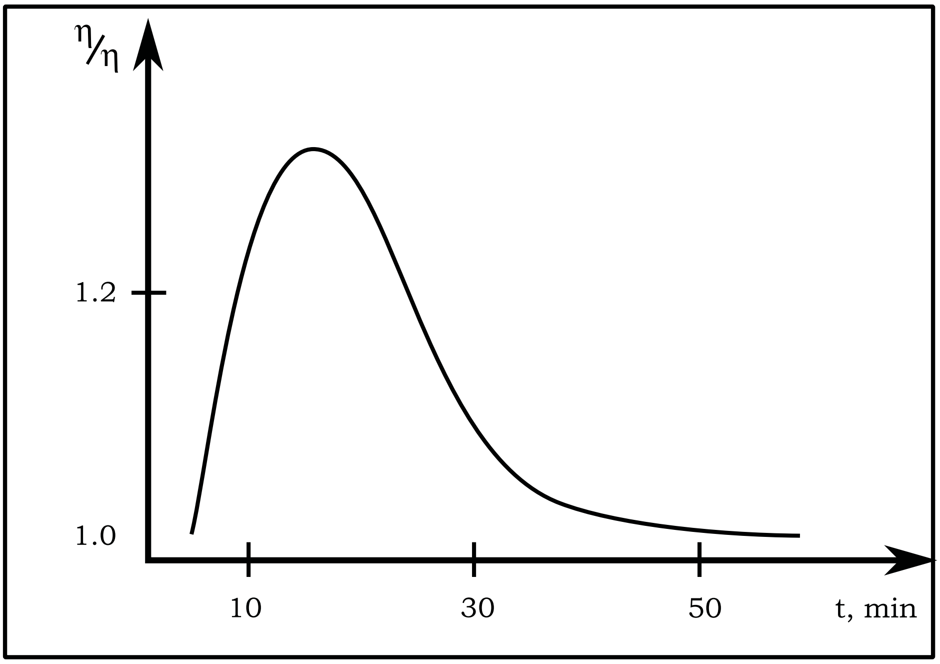

Fig. 1.5. Dependence of blood viscosity on exposure time.

The ability of erythrocytes to aggregate changes significantly under the influence of powerful electromagnetic pulses of nanosecond duration. N.D. Devyatkov [47] investigated the effect of such pulses ($\lambda = 3$ cm, $\tau = 10$ ns, Ppeak = 30 MW) on erythrocytes, the membranes of which had been previously disrupted by electrical breakdown. Following exposure to microwave pulses, the membranes and their capacity for aggregation were restored.

The work of V.F. Kirichuk [48] investigated the effect of millimetre waves at a frequency of 42.2 GHz on platelets in vitro. It was found that the degree of aggregation, and its initial and maximum rates, were significantly reduced by this exposure. It is proposed that the mechanism by which the functional activity of platelets is altered involves conformational modification of proteins on the membrane surface under the influence of electromagnetic waves.

This correction of platelet functional activity is important in the treatment of various diseases. For example, the irradiation of cardiac patients with electromagnetic radiation at a frequency of 42.2 GHz, in combination with drug treatment, led to a pronounced normalisation of platelet aggregation [49]. A similar pattern of changes in platelet functional activity under the action of electromagnetic radiation was also observed during in vitro irradiation of platelet-rich plasma at higher frequencies, ranging from 149 to 154 GHz [50].

1.10. Electromagnetic radiation as an inducer of apoptosis

The effects discussed above indicate a change in the functional activity of cells under the influence of electromagnetic radiation. However, such an impact can be so acute that it triggers apoptosis (programmed cell death) in cells irradiated by electromagnetic waves. In study [51], the effect of electromagnetic radiation with a frequency of 42.2 GHz and an incident power flux density in the range of 0.1...50 mW /cm ^{2} on skin structure was investigated. Irradiation was found to induce dynamic ultrastructural changes in the cells of the epidermis and dermis.
Two hours post-irradiation, cavities with a diameter of 0.2...3 µm were observed in the cytoplasm and nuclei of these cells. Six hours post-irradiation, these cavities remained. Subsequently, some cells recovered, while others began to degrade. Twelve hours post-irradiation, the cells exhibited clear signs of apoptosis, including chromatin condensation, the appearance of large perinuclear spaces and large vacuoles in the plasma, and cell fragmentation. Detailed investigations have shown that at least some of these cavities formed during mitochondrial degradation.

The problem of apoptosis has also been investigated at low frequencies of applied electromagnetic fields. In the work of V.N. Voronkov [52], *in vitro* experiments were conducted using two transformed cell lines and one non-transformed cell line. An increase in the number of cell deaths, morphologically consistent with apoptosis, was observed exclusively in the transformed cell lines. The induction of cell death was observed in a magnetic field with a magnetic flux density exceeding 1 mT. This effect was independent of the magnetic field frequency and increased when a combination of a static magnetic field and an alternating field at 50 Hz was used.

Contradictory results were obtained in the study by R. Gomes [53]. The effect of the electromagnetic field was studied in vitro using two cell lines, which differed from those used in the study by R. Gomes [52].
Cells were exposed to an electromagnetic field with a frequency of 25 Hz and a magnetic flux density of 1.5 mT for 2 h. No significant changes in cell cycle phases, nor any induction of apoptosis, were detected. It is likely that each cell type requires a specific frequency to trigger apoptosis. This conclusion is supported by the results of M. Simko [54], which examined the effects of a low -frequency Simko [54], which examined the effects of low-frequency

field. Two cell lines were investigated: one transformed and the other non-transformed. A statistically significant increase in micronucleus formation and the induction of apoptosis in transformed cells was r-ecorded under the influence of a 50 Hz electromagnetic field after 48 –72 h of exposure. However, this effect was not observed in non-tra-nsformed cells.

1.11. Effects of electromagnetic radiation on malignant tumour cells

The induction of apoptosis, discussed in the previous paragraph , is an important factor in the treatment of malignant tumours. In th-is regard, powerful electromagnetic pulses of nanosecond duration are of considerable interest. The use of generators producing such pulses in modes with a high duty cycle will provide a non-thermal le-vel of electromagnetic radiation, whilst also enabling the creation in biological tissues of fields with an intensity comparable to the natur-al quasi-static fields in biological membranes $\sim 10^{2} \ldots 10^{5}$ V/cm.

In the work by M. Simko [54] conducted experiments exposing V-istar rats to high-power electromagnetic pulses. Generators providi-ng peak powers of 100, 10, and 4 MW at frequencies of 10, 20, and 40 GHz, respectively, were used. The pulse duration was 10 ns. Irradiati-ng rats with Walker carcinoma with 120 pulses resulted in a 1.5-fold decrease in the rate of tumour growth and a 30% increase in life exp-ectancy compared to the control group. Exposure to electromagnetic waves in combination with drug treatment slowed the rate of tumo-ur growth by a factor of two. An in vitro study of the effect of this ele-ctromagnetic radiation on tumour cells demonstrated cell destruction .

N.D. Devyatkov [55–57] also conducted in vitro studies on the ef-fect of powerful electromagnetic pulses on tumour cells (Walker car-cinoma). It was found that, with this exposure, dystrophic changes o-ccur in cells at the lysis stage.

It is noted that the electric field intensity within cell membranes increases sharply in tumour cells during division.
Proliferation in tumour cells differs from that in normal cells; therefore, electromagnetic radiation can alter tumour cell metabolism.

1.12. Conclusion

Thus, electromagnetic radiation affects biological objects even at very low intensities, and the effective frequency range is extensive . The most significant biological and medical effects of electromagnetic radiation at the molecular and cellular levels are presented in Table 1.2.

Table 1.2

Effects of electromagnetic radiation at the molecular and cellular levels

Target of Exposure	Frequency Range	Consequences of exposure to electromagnetic radiation
Biomacro molecules	1...150 GHz	1. Conformational transitions in protein molecules. 2. Alteration of functional activity: a) Enzymes; b) Transport proteins; c) Ion channels. 3. DNA strand breaks. 4. Alteration of the tertiary structure of chromosomes. 5. Modification of the transcription of genetic information.
Membranes	1...150 GHz	1. Alteration of charge distribution on the surface of membranes. 2. Modulation of resistance to external factors. 3. Alteration of affinity for biomolecules. 4. Alteration of permeability to ions and biomolecules cules.
Cells	$0.1...2\cdot10^{11}$Hz	1. Alteration of metabolism. 2. Modulation of growth and division. 3. Modification of functional activity. 4. Initiation of apoptosis.

References for this chapter

1. Karnaukhov A.V., Ponomarev V.O. Dissipative resonance – a novel class of physical phenomena. Some approaches to analytical description // Biomedical Engineering and Electronics. – 2001. – No. 8. – P. 23–31.
2. Features of the effect of electromagnetic radiation on biomolecules / A.R. Karimov [et al.] // Raman scattering – 70 years of research. – M., 1998. – Pp. 243–249.
3. Influence of millimetre-wave electromagnetic radiation on the rapid dynamics of the haemoglobin molecule / V.V. Gorbunov [et al.] // Abstracts of the VII All-Union Seminar "The use of low-intensity electromagnetic radiation in biology and medicine". – M., 1989. – P. 74 .
4. On cooperative (coherent) phenomena in biological events (the concept of 'coherent excitation' and 'protein machine')/ D.S. Chernavskii [et al.]. – Preprint FIAN. – 1986. – No. 185.
5. Betsky O.V., Yaremenko Yu.G. Skin and electromagnetic waves // Millimetre waves in biology and medicine. – 1998. – No. 1(11). – pp . 3–15.
6. Investigation of multi-resonant interaction of electromagnetic oscillations with a haemoglobin molecule using Mössbauer spectroscopy / N.P. Didenko [et al.] // Proceedings of the Research Institute of Nuclear Physics. – Tomsk, 1983. – No. 10. – pp. 77–81.
7. The role of induced conformational transitions in the mechanism of resonant interaction of millimetre waves with biomacromolecules / N.P. Didenko [et al.] // Letters to JTF. – 1987. – Vol. 14. – P. 842–846.
8. Changes in protein dynamics under the influence of non-thermal electromagnetic oscillations / N.P. Didenko [et al.] // Letters to JTF. – 1985. – Vol. 11. – P. 1515–1520.
9. Conformational slow-relaxing fluctuations in protein molecules / N.D. Devyatkov [et al.] // Reports of the USSR Academy of Sciences. – 1987. – Vol. 293. – No. 2. – P. 469–472.
10. Anomalous temperature dependence of quadrupole splitting of methaemoglobin / N.P. Didenko [et al.] // Letters to JTF. – 1983. – Т. 9. – № 6. – С. 332–335.
11. Effect of physical factors on blood plasma / L.V. Kalyuzhnaya [et al.] // Abstracts of the VII All-Union Seminar «The Use of Low-Intensity Electromagnetic Radiation in Biology and Medicine». Moscow, 1989 . – M., 1989. – P. 54.

12. Chenskaya T.B., Petrov I.Ya. Investigation of the effect of millimetre -wave electromagnetic radiation on membrane components using IR spectroscopy // Abstracts of the VII All-Union Seminar «The Use of Low-Intensity Electromagnetic Radiation in Biology and Medicine». Moscow, 1989 – M., 1989. – P. 77.
13. The effect of electromagnetic radiation on the affinity of haemagglutinating i-mmunoglobulins / N.P. Didenko [et al.] // Research Institute of Nuclear Physics , TPU. – Tomsk, 1984. – 10 p. – Dep. at VINITI 17.05.84, No. 3178-84.
14. The effect of electromagnetic radiation on erythrocyte membrane resistance, lipid peroxidation and the activity of blood plasma enz-ymes / A.S. Koryagin [et al.]. // Millimetre Waves in Biology and M-edicine. – 2000 – No. 2 (18). – Pp. 8–10.
15. Lipid peroxidation and the cooling factor / V.Yu. Kulikov [et al.] – Novosibirsk: Nauka, 1988.
16. Fersht A. Enzyme Structure and Mechanism. – M.: Mir, 1980.
17. Kuzhmanova M., Ivanov S. Effect of millimetre waves and g□ iz□ radi-ation on the surface electric charge of erythrocyte membranes // P-roceedings of the X All-Russian Symposium «Millimetre Waves in M-edicine and Biology». Moscow, 24–26 April 1995 – M., 1995. – C. 105–107.
18. The influence of millimetre-wave electromagnetic radiation on the electrophoretic mobility of erythrocytes / V.N. Krylov [et al.] // Milli-metre Waves in Biology and Medicine. – 2000. – № 2 (18). – Pp. 5–7 .
19. The influence of electromagnetic radiation on the growth of the immune status of the culture medium S. Platensis / A.Kh. Tambiev [et al.] // Millim-etre Waves in Biology and Medicine. – 1996. – № 8. – Pp. 23–28.
20. The effect of low-energy microwave pulses of nanosecond duration , with high peak power and varying wavelengths, on ion transport, cell membrane permeability, cell regeneration processes, and the development of malignant tumours / N.D. Devyatkov [et al.] // Re-ports of the XII All-Russian Symposium "Millimetre Waves in Medic-ine and Biology". Moscow, 30 October – 1 November 2000. – M., 200 0. – Pp. 84–86.
21. The effect of millimetre-wave electromagnetic radiation on the rap-id potassium current in mollusc neurons / S.I. Alekseev [et al.] // A-bstracts of the VII All-Union Seminar "The Use of Low-Intensity Ele-ctromagnetic Radiation in Biology and Medicine". Moscow, 1989 – M., 1989. – P. 78.

22. A study of the effect of millimetre waves on tufted receptors / A.Yu. Sazonov [et al.] // Proceedings of the X All-Russian Symposium «Millimetre Waves in Medicine and Biology». Moscow, 24–26 April 1 995 – M., 1995, pp. 105–107.
23. Zheltov, N.G. A study of the influence of millimetre-wave electrom-agnetic radiation on the electrophysiological activity of frog skin m-echanoreceptors // Abstracts of the VII All-Union Seminar «The Use of Low-Intensity Electromagnetic Radiation in Biology and Medicine». Moscow, 1989 – M., 1989, p. 80.
24. Sazonov A.Yu., Ryzhkova L.V. The influence of millimetre waves on bi-ological objects of varying degrees of complexity // Proceedings of t-he X All-Russian Symposium "Millimetre Waves in Medicine and Biol-ogy". Moscow, 24–26 April 1995 – M., 1995. – Pp. 112–114.
25. Burachas G. Suppression of action potential in nerve by millimetre waves // Abstracts of the VII All-Union Seminar "The Use of Low-In-tensity Electromagnetic Radiation in Biology and Medicine". Mosc-ow, 1989. – M., 1989. – P. 80.
26. Gaponyuk Yu. The role of reflex mechanisms in the effect of millim-etre-wave electromagnetic radiation on the human organism // A-bstracts of the VII All-Union Seminar "The use of low-intensity elec-tromagnetic radiation in biology and medicine". Moscow, 1989. – M., 1989. – p. 23.
27. The effect of millimetre waves on bacteria in experiments in vitro and in vivo / G.M. Shab [et al.] // Proceedings of the X All-Russian Symposium "Millimetre Waves in Biology and Medicine". Moscow, 2 4–26 April 1995 – M., 1995. – pp. 95–97.
28. Studies of the effect of millimetre-wave electromagnetic radiation on the immunogenetic characteristics of the whooping cough pat-hogen / I.A. Alekseeva [et al.] // Proceedings of the X All-Russian S-ymposium "Millimetre Waves in Medicine and Biology". Moscow, 24 –26 April 1995 – M., 1995. – pp. 97–98.
29. Kholodnaya L.S. The effect of millimetre waves on the immunobiolog-ical characteristics of conditionally pathogenic bacteria // Proceedin-gs of the X All-Russian Symposium "Millimetre Waves in Medicine and Biology". Moscow, 24–26 April 1995 – M., 1995. – p. 100.
30. Tambiev A.K., Kurikova N.N. Fundamental regularities of millimetre -wave electromagnetic radiation effects on photo-integrating obje-cts // Proceedings of the X All-Russian Symposium «Millimetre Waves in Medicine and Biology». Moscow, 24–26 April 1 995. – M., 1995. – pp. 100–102.

31. The effect of coherent millimetre-wave electromagnetic radiation of non-thermal intensity on the growth rate of Bacillus subtilis / A. Yu. Krinitskaya [et al.] // Biomedical Electronics. – 2001. – No. 2. – pp. 49–53.
32. The influence of low-intensity millimetre waves on the growth and development of a protozoan culture / M.Z. Levina [et al.] // Abstracts of the VII All-Union Seminar «The Use of Low-Intensity Electromagnetic Radiation in Biology and Medicine». Moscow, 1989 – M., 1 989. – P. 82.
33. Selective induction of a repressed operon in the Escherichia coli genome / V.A. Gusev [et al.] // Abstracts of the VII All-Union Seminar «The Use of Low-Intensity Electromagnetic Radiation in Biology and Medicine». Moscow, 1989 – M., 1989. – P. 81.
34. The effect of millimetre-wave electromagnetic radiation on bacterial bioluminescence / L.Yu. Berzhanskaya [et al.] // Millimetre Waves in Biology and Medicine. – 1993. – No. 2. – pp. 63–67.
35. Tambiev A.K., Kirikova N.N. Effect of millimeter radiation on metabolism of cyanobacteria Spirulina platensis and other photosynthesizing organisms // Crit. Rev Biomed. Eng. – 2000. – V. 28 (3-4). – P. 589–602.
36. Dynamics of lipid peroxidation processes in patients with unstable cardioneuralgia during millimetre-wave therapy / A.Yu. Lebedeva [et al.] // Millimetre Waves in Biology and Medicine. – 1995. – pp. 18–20.
37. The effect of millimetre waves on the functional activity of human leukocytes (in vitro) / V.A. Starshina [et al.] // Abstracts of the VII All-Union Seminar "The Use of Low-Intensity Electromagnetic Radiation in Biology and Medicine". Moscow, 1989 – M., 1989. – 34 pp.
38. Production of a cell proliferation growth factor by lymphocytes and fibroblasts upon irradiation with electromagnetic waves / V.I. Govallo [et al.] // Reports at the International Symposium “Millimetre Waves of Non-Thermal Intensity in Medicine”. – M., IRE AS USSR, 1991. – Part 2. – P. 340–344.
39. Effect of millimetre-wave electromagnetic radiation on polytene chromosomes of Chironomus plumosus / G.G. Brill [et al.] // Millimetre Waves in Biology and Medicine. – 2000. – No. 1(17). – P. 3–7.
40. Rebrova T.V. The effect of millimetre-wave electromagnetic radiation on the vital functions of microorganisms // Millimetre Waves in Biology and Medicine. – 1992. – No. 1. – P. 37–47.

41. Garaj Vrhovac V. Micronucleus assay and lymphocyte mitotic activity in risk assessment of occupational exposure to microwave radiation // Chemosphere. – 1999. – V. 39 (13). – P. 2301–2312.
42. In vitro changes in the rheological properties of blood under the action of millimetre waves in patients during the acute phase of stroke / I.A. Podolyako [et al.] // Millimetre Waves in Biology and Medicine. – 2000. – № 4 (20). – C. 53–55.
43. Millimetre-wave electromagnetic radiation as a pathogenetic therapy for cardiovascular diseases / T.V. Golovacheva [et al.] // Millimetre Waves in Biology and Medicine. – 2000. – № 1 (17). – C. 18–25.
44. Suvorov S.A., Kirichuk V.F. Correction of haemostatic system disorders in patients with prostatitis using electromagnetic radiation in the millimetre range // Millimetre Waves in Biology and Medicine. – 2000. – No. 1(17). – P. 39–46.
45. Kirichuk V.F. Markova G.E. Condition of the vascular-platelet component of the haemostatic system and its correction using millimetre waves // Millimetre Waves in Biology and Medicine. – 2000. – No. 1 (17). – P. 8–17.
46. The separation factor under the influence of millimetre-wave radiation on living cells / A.P. Kuznetsov [et al.] // Proceedings of the X All-Russian Symposium "Millimetre Waves in Medicine and Biology" . Moscow, 24–26 April 1995 – M., 1995. – Pp. 102–105.
47. The effect of low-energy pulsed microwave radiation of nanosecond duration, with high peak power and low-intensity millimetre-wave radiation, on ion transport, cell membrane permeability, cell regeneration processes, and the development of malignant tumours / N.D. Devyatkov [et al.] // Proceedings of the XII All-Union Symposium "Millimetre Waves in Medicine and Biology". Moscow, 30 October – 1 November 2000. – M., 2000. – Pp. 84–86.
48. Characteristics of changes in platelet functional activity within the millimetre wave range in patients with unstable cardioneuralgia under the influence of electromagnetic radiation in vitro / V.F. Kirichuk [et al.] // Millimetre Waves in Biology and Medicine. – 2001. – № 1–2 (21–22). – Pp. 11–21.
49. Kirichuk V.F., Volin M.V. Changes in platelet functional activity when using millimetre-wave therapy in the integrated treatment of patients with unstable cardioneuralgia // Millimetre Waves in Biology and Medicine. – 2001. – № 1–2 (21–22). – C. 11–21.

50. The influence of millimetre-wave electromagnetic oscillations, at the frequencies of the molecular absorption and emission spectrum of nitric oxide, on platelets as effector cells of the haemostatic system / V.F. Kirichuk [et al.] // Millimetre Waves in Biology and Medicine. – 2001. – № 1–2 (21–22). – P. 3–10.
51. Ultrastructural changes in the skin of mice caused by millimetre-wave electromagnetic radiation / V.N. Voronkov [et al.] // Proceedings of the XI All-Russian Symposium «Millimetre Waves in Medicine and Biology». Moscow, 2–12 April 1997 – M., 1997. – P. 117–118.
52. Static and ELF magnetic fields induce tumor growth inhibition and apoptosis / S. Tofani [et al.] // Bioelectromagnetics. – 2001. – V. 22(6). – P. 419–428.
53. 25 Hz electromagnetic field exposure has no effect on cell cycle distribution and apoptosis in U-937 and HCA-2/1cch cells / Ruiz Gomez M.J. [et al.] // Bioelectrochemistry. – 2001. – V. 53(1). – P. 37–40.
54. Effects of 50 Hz EMF exposure on micronucleus formation and apoptosis in transformed and nontransformed human cell lines / M. Simko [et al.] // Bioelectromagnetics. – 1998. – V. 19(2). – P. 85–91.
55. The effect of low-energy microwave pulses of nanosecond duration with high peak power and millimetre-wave radiation on biological structures (malignant tumours) / N.D. Devyatkov [et al.] // Proceedings of the X All-Russian Symposium «Millimetre Waves in Medicine and Biology». Moscow, 24–26 April 1995 – M., 1995. – P. 115.
56. Influence of low-energetic pulse microwave and millimeter radiation of nanosecond duration with large peak power on biological structures (malignant tumors) / N.D. Devjatkov [et al.] // Biomedical electronics. – 1998. – № 1. – P. 56–62.
57. The effect of low-energy microwave radiation of nanosecond duration with high peak power and low-intensity millimetre-wave radiation on malignant tumours in an experiment / N.D. Devyatkov [et al.] // Proceedings of the XII All-Union Symposium «Millimetre Waves in Medicine and Biology». Moscow, 30 October – 1 November 2000 – M., 2000. – Pp. 87–90.

2. THE INFLUENCE OF ELECTROMAGNETIC RADIATION ON THE ORGANISM AS A WHOLE

The previous chapter considered the effects of electromagnetic radiation on bio-objects at the microscopic level, specifically on biomolecules and cells. Evidently, the modification of the properties and activity of microscopic biological structures under the influence of electromagnetic waves leads to changes in the properties of biological tissues and functional systems of the organism. In this chapter, we will consider the manifestation of such local and systemic changes. Section 2.1 presents data on local changes concerning the functional and morphological features of biological tissues.
Systemic changes in the organism under the influence of electromagnetic radiation are discussed in the following paragraphs. The topic of Section 2.2 is the characteristics of the responses of the nervous and endocrine systems of the organism.
The stressor and adaptogenic effects of electromagnetic waves are considered in Section 2.3. Paragraph 2.4 is devoted to considering the influence of electromagnetic radiation on animal behaviour. Changes in operator behaviour under conditions of exposure to electromagnetic radiation are considered in § 2.5. The possibilities of targeted correction of the status of physiological systems of the organism are shown in § 2.6. Finally, § 2.7 is devoted to presenting data regarding the dependence of local and general effects on irradiation parameters , in particular, the power and frequency of electromagnetic radiation , the duration of exposure, and the irradiation mode.

2.1. Functional and morphological modification of biological tissues under the action of electromagnetic radiation

Changes occurring in biological tissues under the action of non-thermal electromagnetic radiation are of considerable interest from the perspective of determining the pathogenic influence of electromagnetic waves and their application in therapeutics. These changes are, naturally, a consequence of the modification of biological processes under the influence of electromagnetic radiation. However, published data are typically phenomenological in nature and lack an analysis of the mechanisms underlying these changes. The work of V.M. Perel'muter[1] investigated the effect of non-thermal millimetre waves on murine skin. Upon irradiation of the left thigh, the overall effect manifested as an increase in blood perfusion in the vessels of the skin of both the left and right thighs, and a decrease in the number of mast cells (belonging to the class of immunocompetent cells), but only in the non-irradiated skin. The local effect of electromagnetic radiation was an increase in the number of mast cells and lymphocytes in the irradiated zone. Upon irradiation of the right thigh, the local effect was a decrease in the blood content of the vessels in that limb.

Several studies have investigated the effect of electromagnetic radiation on tissue regeneration processes, examining the treatment of wounds in experimental animals. Areas of full-thickness circular skin wounds in mice were irradiated with electromagnetic waves at frequencies of 53.53 GHz and 42.96 GHz for five days post-surgery. Information on the extent of granulation tissue formation was obtained by measuring glycoprotein concentration. The measurement results are presented in Table 2.1.

Table 2.1

Effect of electromagnetic radiation on the extent of granulation tissue formation

	Control	Electromagnetic radiation frequency		
		53.53 GHz	42.96 GHz	42.96 GHz
		No modulation	No modulation	Modulation ±200 MHz
Hydroxyproline (HP)	100 ± 0.52	81,15 ± 2,72 P < 0.01	82,12 ± 2,72 P < 0.01	129 ± 2,67 P < 0.01
Hydroxylisine (HL)	100 ± 0,04	91,95 ± 7,00 P > 0.05	103,78 ± 2,23 P > 0.05	155,17 ± 2,37 P < 0.05
HL/HP	0,46 ± 0,03	0,51 ± 0,03 P > 0.05	0,61 ± 0.02 P < 0.05	0,55 ± 0,21 P < 0.05

According to Table 2.1, electromagnetic wave irradiation without carrier frequency modulation significantly reduces glycoprotein synthesis. It should be noted that these proteins are the main components of inflammatory lymph, which is considered essential to the wound-healing process. Therefore, a reduction in their content under the influence of electromagnetic radiation can be interpreted as a suppression of the inflammatory response. An increase in collagen content, as assessed by the concentration of hydroxyproline, indicates optimised scar formation.

Since granulation tissue forms mainly via an extracellular pathway, it can be assumed that electromagnetic radiation at fixed frequencies of 53.53 and 42.96 GHz suppresses the synthesis of extracellular proteins, but does not affect collagen structures; this is supported by the maintenance of the GL/GP concentration ratio. Exposure to electromagnetic radiation with carrier frequency modulation results in the activation of protein synthesis. The concentration of collagen proteins, assessed by tyrosine content, remained virtually unchanged in all experiments.

Millimetre waves exert a stimulating effect on nerve fibre regeneration. Thus, the skin on a rat's thigh near the suture was irradiated with electromagnetic waves at a frequency of 53.57 GHz and an incident power flux density of 4 mW/cm ^{2} . Action potential measurements after 5 months. Post-operative measurements demonstrated a stimulating effect of electromagnetic radiation on nerve rehabilitation, manifesting as a 30% increase in action potential propagation velocity compared to the control group.

To understand the mechanism of biological tissue response to electromagnetic radiation exposure, investigations on isolated tissue preparations are important. In the work of V.N. Krylov and I.V. Oshevensky [2], muscle tissue was irradiated with electromagnetic waves in the frequency range 53–78 GHz with a spectral density of 4.10^{-4} W/Hz at an integral power of 1.5 mW. The intrinsic tonic activity of the tissue (tone, frequency, and amplitude) remained unchanged following this exposure. The response to the parasympathetic mediator (acetylcholine) was also unchanged, but the intensity of the response to the sympathetic mediator (noradrenaline) was twice as great. It can be hypothesised that electromagnetic radiation increases the mediator sensitivity of adrenergic receptors on the cell membranes of intestinal smooth muscle tissue, which may occur in relation to

-, as well as adrenoreceptorsThe reaction of the former (-) may be associated with an increase in transmembrane potassium current and, accordingly, suppression of intrinsic myogenic activity, while that of the latter (-) may be associated with a decrease in calcium current and, therefore, suppression of the conjugation between stimulation and muscle cell contraction.

Irradiation of keratinocytes, which are the main component of human skin, with electromagnetic radiation at a frequency of 61.22 GHz showed that such exposure causes a small but statistically significant increase in the intercellular level of interleukin-1. Concurrently, this exposure did not alter cell proliferation or chemotaxis, nor did it affect the adhesive properties of keratinocytes.
These data indicate that irradiation of human skin can activate basal keratinocytes, stimulating interleukin-1 synthesis.

Irradiation of nerve tissue with electromagnetic waves may lead to morphological changes. Destruction of the cytoplasm in myelinated and unmyelinated nerve fibres was detected immediately following 15-minute irradiation with electromagnetic waves at a frequency of 42.25 GHz.

2.2. Peculiarities of changes in the nervous and endocrine systems of the organism under the influence of electromagnetic waves.

The responses of the nervous system to electromagnetic radiation are highly diverse, depending on the conditions of irradiation and the state of the object exposed. Therefore, accounting for all details of irradiation is crucial for establishing general patterns in the nervous system's response to electromagnetic radiation. One method of assessing the functional state of the autonomic nervous system involves spectral analysis of cardiac rhythms. Vegetative effects give rise to three components of cardiac rhythm: a low-frequency component (less than 0.05 Hz), a mid-frequency component (0.08–0.12 Hz), and a high-frequency component (0.15–0.5 Hz). The first of these is associated with the metabolic regulatory system, the second with the baroreflex, and the third with respiration. The influence of electromagnetic radiat-ion was studied in practically healthy individuals aged 20 to 30 years. T-he dorsal surface of the hand was irradiated with electromagnetic rad-iation at a power flux density of 5 mW/cm ^{2} . The research results dem-onstrated a strong response in the mid-frequency component of the heart rate. The amplitude of this component increased by a factor of 1 .5, whereas sham exposure (placebo) slightly reduced it (to 94%). The-refore, it can be postulated that the principal changes in the autonom-ic nervous system are associated with the vascular system.

Studies of the central nervous system's response to electromag-netic radiation are typically conducted using electroencephalography (EEG). Based on research results, the following key features of EEG r-esponses to electromagnetic irradiation can be identified:

1) An increase in the number of spindle-shaped oscillations and slow waves (synchronisation);
2) Changes in the EEG appear as a response to the initiation or cessa-tion of electromagnetic exposure with a time step of 10–20 s (n-on-specific response);
3) EEG changes are accompanied by alterations in the biopotentials of subcortical structures, particularly the hippocampus, hypoth-alamus, specific and non-specific thalamic nuclei, and reticular nuclei of the midbrain. This indicates that, during short-term ex-posure to electromagnetic waves, changes in the summed and pulsed biopotentials of the cerebral cortex are a direct effect of penetrating factors on the brain.

It should be noted that EEG responses to electromagnetic radia-tion are dependent on the individual's emotional state. In treating p-atients with gastroduodenal ulcers using electromagnetic waves [3], a desynchronisation reaction of the EEG rhythm was observed. This reaction occurred particularly frequently with exposure to frequenci-es of 58.0–59.5 and 61.5 GHz. A.P. Alistov [3] suggests that the stimul-ation of background activity in millimetre-wave therapy is a non-spe-cific reaction and may reflect increased sensitivity in the patient und-er observation. The inactivation response of background activity refl-ects the patient's transition into an emotional state of comfort and d-rowsiness. This coincides with the relaxation of clinical indicators of peptic ulcer.

In treating hypertensive patients, an increase in the action potential repetition rate of afferent fibres in the median nerve of the left arm was recorded following irradiation of the skin near acupuncture point 9.9 on the pericardium meridian for 1 minute. The frequency of the electromagnetic radiation varied from 53.596 to 53.603 GHz, with a modulation frequency of 0.05 Hz and an incident power flux density of less than 5 mW/cm ^{2} . EEG analysis revealed an increase in the intensity of the spectral component within the --rhythm range compared to the baseline value in 18 of 20 patients. During novocaine blockade of the median nerve, exposure to electromagnetic radiation resulted in changes to the parameters of background impulse activity and the spectral characteristics of the EEG.

A generalisation of the research findings regarding sensory responses to electromagnetic exposure allows the following conclusions to be drawn [4]:

- a human is capable of distinguishing electromagnetic exposure from sham exposure (placebo);
- a human's sensitivity to electromagnetic waves depends on both the individual characteristics of the person and the parameters of the radiation;
- the type of sensations experienced (pressure, touch, tingling, burning) suggests the involvement of cutaneous receptors in the response to electromagnetic wave exposure;
- the latency period of sensory responses to electromagnetic waves can reach 15 minutes;
- sensory asymmetry in the perception of electromagnetic waves (the reaction depends on which hand was exposed to the radiation) occurs.

Based on these observations, it can be postulated that the influence of electromagnetic waves can trigger signal generation by mechanoreceptors (tactile sensitivity) or pain receptors (nociceptors), given that the reaction develops rather slowly (up to 15 minutes). The slowest mechanoreceptors can be identified as possible 'receptors' of electromagnetic waves. These are tactile discs, Merkel discs, and Ruffini endings. Sensory 'receptors' of electromagnetic radiation may also include nociceptors, which are free nerve endings with thin myelinated and unmyelinated nerve fibres. Besides the type of sensation (tingling or burning), this assumption is supported by the disappearance of electromagnetic sensitivity.

when treating a skin area exposed to radiation with ethyl chloride, which disables nociceptors.

In addition, electromagnetic radiation can induce epileptiform activity, manifested by the appearance of low-frequency (2–4 Hz) high -amplitude (over 300 μV) peaks in the EEG [5].

The possibility of such activity appearing as a result of electromagnetic radiation under certain conditions (following the administration of chlorpromazine) was noted in the work of A.V. Sidorenko and V.V. Tsaryuk [6], which investigated the effect of continuous and pulsed electromagnetic radiation with a carrier frequency of 42.2 GHz on the brains of animals under various functional states of the central nervous system. The variation in functional state was reflected in the EEG response. Active animals demonstrated a synchronisation reaction upon exposure to electromagnetic radiation, whereas narcotised animals exhibited an EEG with an increase in - and - rhythms and indications of increased dynamic characteristics in the central nervous system.

The reaction of the nervous system to electromagnetic radiation is accompanied by endocrine changes. The effect of electromagnetic waves on the concentrations of serotonin and catecholamines in rat lymph nodes was investigated. As early as 15 minutes after electromagnetic exposure, the concentration of these substances increased sharply in the lymph nodes. Furthermore, an increase in the number of intrafollicular luminescent cells was also observed.

The effect of electromagnetic radiation on the human sympathoadrenal system was studied. The electromagnetic waves had wavelengths of 5.6 and 7.1 mm and an incident power flux density of approximately 10 mW/cm^2. The region of the external occipital protuberance was exposed in both practically healthy individuals and patients with disorders of the sympathoadrenal system. The data obtained in this work allow us to assert that

- electromagnetic waves act on the sympathoadrenal system, altering the metabolism of catecholamines and other mediators;
- this action is adaptive, as the sympathoadrenal system reacts appropriately:

  a) with initially low levels of catecholamine release, exposure to electromagnetic waves resulted in a 65% increase in dopamine release, a 140% increase in noradrenaline, and an 80% increase in adrenaline;

b) with initially normal and high levels of catecholamine release, the system's response to electromagnetic waves differed, s-howing a 70% decrease in dopamine levels, a 90% increase in noradrenaline, and a 4% increase in adrenaline.

Thus, exposure to electromagnetic radiation with wavelengths of 5.6 and 7.1 mm may lead to the correction of catecholamine meta-bolism, a key integrating link within the sympathoadrenal system; al-terations in the state of this system are adaptive in nature.

2.3. Characteristics of the stressor and adaptogenic effe-cts of electromagnetic waves

Yu.A. Kholodov [7] hypothesised that the nervous system's react-ion to exposure to electromagnetic radiation stems from the brain's initial response. This reaction precedes stress and, with short-term e-xposure, elicits an anti-stress effect, increasing the organism's resist-ance. Biochemical investigations into the anti-stress effects of millim-etre-wave radiation were conducted on non-linear white rats. The re-sults indicated that the correction of the sequelae of stress is depen-dent on the organism's initial state. For
'Vigorous' animals exhibit a stress-induced reduction in serotonin lev-els within the microphages of the thymus's subcapsular zone; followi-ng electromagnetic exposure, these levels are restored to normal. Se-rotonin levels in brain lymphocytes increased following stress and de-creased after subsequent exposure to electromagnetic waves.
In cortical lymphocytes, stress decreased catecholamine levels, while exposure to millimetre waves restored them.

Different results were recorded for
'Drowsy' animals. Stress led to a change in monoamine levels in the opposite direction to that observed for
'Lively' animals. In this instance, the serotonin level increased in subca-psular microphages and decreased in brain lymphocytes, while the cat-echolamine level in cortical lymphocytes increased. Exposure to

electromagnetic radiation did not lead to a correction of monoamide alterations. Moreover, it increased the serotonin level in microphages. Thus, electromagnetic radiation acts in a unidirectional manner with respect to biochemical changes. And its use is justified if the stress response requires correction in this specific direction.

The work of N.A. Temuryanov [8] investigated the anti-stressor effect of millimetre-wave radiation with a wavelength of 5.6 mm and a power flux density of 10 mW/cm^2 under conditions simulating hypokinesia in white rats. To assess the anti-stressor effect of electromagnetic waves, the cytochemical status of peripheral blood neutrophils (peroxidase and lipid content) and lymphocytes (succinate and glycerophosphate dehydrogenase content) was measured. Such measurements provide information on changes in non-specific resistivity.

The measurement results indicated that the anti-stressor effect was dependent on the animals' typological status and the zone of irradiation. In animals with low and medium mobility, an anti-stressor effect was observed following irradiation of the occiput and the external aspect of the right femur, but no response was observed with irradiation of the left femur. The anti-stressor effect manifested as an increase in cytochemical lipid indicators and dehydrogenase activity in lymphocytes. Evaluations of adaptation efficacy, based on the morphological composition of blood, indicated that the animals' response to electromagnetic exposure constituted a training reaction.
In animals with high mobility, an anti-stressor effect was achieved by irradiating the occiput and left hip, whereas exposure of the right hip did not limit the stress response.

A description of the asymmetry of anti-stressor effects induced by electromagnetic radiation was also reported by V.M. Perel'muter [9]. Hypokinetic stress was induced by placing mice in irradiation chambers. Two types of chamber were used: one was designed to irradiate the right thigh and had a corresponding aperture on the right side, and the other had an aperture on the left side.
The 'right-sided' chamber induced short-term lymphopenia and a reduction in the number of thymocytes in the left thymus. Irradiation of the right thigh resulted in marked lymphopenia being recorded one hour after irradiation, which then resolved within the subsequent 24 hours. In addition, an increase in the number of thymocytes was recorded in the right

thymus. Irradiation of the left thigh led only to transient lymphopenia in the initial minutes after irradiation.

Continuing this work, the dependence of the anti-stress effect of electromagnetic exposure on both the wavelength of the radiation and the duration of exposure was investigated [10]. It was found that exposure at a wavelength of 5.6 mm is more effective than at a wavelength of 7.1 mm. In the latter case, exposure to electromagnetic waves limited the development of stress but did not increase the level of functional activity in blood cells. The anti-stress effects of electromagnetic radiation with a wavelength of 5.6 mm were dependent on the duration of exposure. Positive results were observed even with a 15-minute exposure.

The effect was more pronounced with a 30-minute irradiation period, but a 60-minute exposure was less effective than exposures of 15 and 30 minutes.

It should be noted that the anti-stressor effect induced by radiation with a wavelength of 5.6 mm was not observed under all stressor conditions. The work of A.Yu. Arzumanov [11] investigated the dependence of the anti-stressor effect on the severity of stress. The results indicated that under conditions of severe stress in animals (immobilisation, including head fixation), no significant anti-stressor effect was observed. In this case, all behavioural responses (feeding, sex, ‘open field’ test, ‘forced swimming’ test) were suppressed by stress.

Under conditions of less severe stress, specifically kinetic constraints, the anti-stressor effect of electromagnetic radiation was more pronounced when animals were in life-threatening situations. One such situation is employed in the Vogel test, where animal behaviour is assessed by the number of attempts to obtain a drink, during which they receive an electric shock. Concurrently, the stressor effect was more strongly manifested in animals' behavioural responses to a positive biological stimulant.

The work of N.N. Lebedeva and O.P. Sulimova [12] investigated the effect of electromagnetic radiation, with a wavelength of 7.1 mm, on heart rate and EEG under conditions of psychological stress induced by an experimental procedure. Data obtained from 5 volunteers indicated the potential for developing a stress reaction. This is corroborated by the results of electromagnetic treatment on 52 patients, who were divided into groups based on the severity of their burns, as assessed using the Frank index. The intensity of the stress response was determined by the lymphocyte count in the blood. Irradiation of patients resulted in an increased lymphocyte count compared to the corresponding control group. The anti-stressor effect was independent of burn area and depth within a range of several to 50 units of the Frank index, and also independent of the degree of initial stress caused by the burn.

Beyond phenomenological studies, investigations into the mechanisms of the anti-stressor effect are of considerable interest. One such study examined the role of lipid peroxidation and thiosulphide exchange in limiting the stress response [13]. The selection of these biochemical processes was based on their important role in regulating the suppression and activation processes of the central nervous system. Lipid peroxidation is dependent on many factors, in particular the lipid composition of membranes, and the activity of proteins and non-proteins within pro- and antioxidant systems. The activity of these systems is controlled by neurohumoral mechanisms. One of the most important elements of the physiological antioxidant system is thiol-disulphide exchange.

The results of a study on lipid peroxidation in mice under hypokinetic stress during irradiation with 7.1 mm wavelength electromagnetic waves showed that this electromagnetic exposure modifies the process, and the direction of change is opposite to the effect of stress. Where hypokinetic stress led to a marked increase in lipid peroxidation products in the thalamus and hypothalamus, electromagnetic exposure induced a change in the levels of these products towards normalisation.

2.4. Effect of electromagnetic radiation on animal behaviour

Experimental studies into the effects of electromagnetic waves on animal behaviour are most frequently conducted on rats and primates. The effect on rats of an electromagnetic field generated by ultra-wideband (UWB) pulses was investigated. The aim of the investigations was to determine teratological and behavioural changes following exposure under the following regimes:

1) daily exposure to UHP pulses during pregnancy, for 3–18 days;

2) exposure for 10 days postnatally.

Irradiation was performed with pulses of the following parameters: electric field strength – 55 kV/m; leading edge duration – 0.3 ns; pulse duration – 1.8 ns. The experimental results showed no changes in animal behaviour following exposure to UWB pulses, with the single exception that rats emitted more noise during the irradiation session than in the control.

UWB pulses with the following parameters were used: pulse duration was 5...10 ns, frequency bandwidth was 0.25...2.5 GHz, and pulse repetition rate was 60 Hz. Brief (2 min) exposure of rats to these pulses did not induce changes in animal behaviour in the 'open field' and 'forced swim' tests.

The effect of electromagnetic waves on rat behaviour was also investigated. Three groups of animals were used: a control group; a group exposed to microwave electromagnetic waves; and a group exposed to radio frequency waves. The electric field strength of the electromagnetic field was 5 mV/m, and irradiation was performed daily for 10 minutes over a period of 10 days. The rats' ability to learn and remember was assessed after each irradiation session and again 10 days after the final session. The rats in the second and third groups demonstrated a greater capacity for learning and memory compared to the animals in the first group. The effect is attributed to the influence of electromagnetic waves on the central nervous system, enhancing microcirculation and potentially exerting a direct effect on certain structures within the cerebral cortex.

Studies have been conducted on the effect of electromagnetic waves of various wavelengths on the behaviour of rats. The animals were irradiated with electromagnetic radiation in the metre, decimetre, and centimetre wavelength ranges, with an incident power flux density of 10 mW/cm^2. The research results demonstrated that electromagnetic radiation in these ranges can slow the development of normal behavioural responses. This was manifested upon irradiation with electromagnetic waves in the metre range. In the centimetre wave range, the effect manifested with a certain time delay. Changes were observed at non-thermal intensities, and the animals readily adapted to the experimental conditions. The effects investigated were the effects of electromagnetic radiation with sinusoidal modulation at a frequency of 2–50 Hz. The carrier frequency was 30 MHz, and the electric field strength was 30–120 V/m. It was found that this exposure inhibited the formation of conditioned reflexes in animals.

Experimental studies on the biological effects of microwave pulses from marine radar systems have demonstrated that these effects are dependent on radiation intensity and exposure duration. The influence of this radiation on the behaviour of animals (white rats) was assessed using the 'open field' paradigm. It was observed that the response to electromagnetic exposure is dependent on the animal's behavioural type.

Studies on primates are of considerable interest, as their behaviour closely resembles that of humans. The effect of UWB pulses on primate behaviour was investigated. The exposure duration was 2 minutes, and the effective frequency bandwidth ranged from 0.1 to 1.5 GHz. The pulse repetition frequency was 60 Hz, and the electric field strength of the electromagnetic field was 250 kV/m. Animal behaviour was assessed using the 'equilibrating platform' test, where the monkey had to compensate for platform tilts generated pseudo-randomly by a computer program using a joystick.

In addition to these experiments, studies were conducted on baboons. An electromagnetic field with an electric field strength of 30 and 60 kV/m was used. Exposure to this field resulted in the monkeys ceasing their activities on the first day, but the situation returned to its initial state by the second day. Cessation of activity accompanied the termination of exposure sessions after 6 weeks, as observed on the first day of exposure. In measurements of the electric field sensitivity threshold in baboons, the value is 12 kV/m. This value corresponds with that observed in rats and humans.

2.5. Changes in Human Behaviour under the Influence of Electromagnetic Radiation

Information regarding the effects of electromagnetic radiation on human behaviour is limited: studies have investigated the influence of millimetre-wave electromagnetic radiation on the functional state of operators during irradiation of the biologically active point T[20] on the head. Research results have demonstrated that this exposure significantly improves the overall well-being and functional status of operators, thereby enhancing their work performance. Furthermore, the principal neural processes within the cerebral cortex are intensified.

Indirect information regarding the responses of the nervous system in operators can be derived from phenomenological observations, such as physiological assessments of the nervous system status of personnel working under pulsed exposure to low-intensity electromagnetic waves. The radiation had the following parameters: carrier frequency – 1 GHz, pulse repetition frequency – 32 Hz, pulse repetition rate within the burst – 250 Hz, and incident power flux density at workstations – from 0.34 to 312 μW/cm^2.

Statistically significant changes were registered in the functional activity of the operators' nervous system, including autonomic dysfunctions. The following syndromes were noted: vasovegetative dystonia (85 %), asthenia (49 %), vestibulopathy (31 %), and polyneuropathy (87 %). The development of these changes in nervous system function depended on length of service and, consequently, on the cumulative duration of operator exposure.

Clinical studies of US Air Force personnel exposed to electromagnetic radiation revealed that a significant proportion of those examined presented with mental abnormalities. These included complaints of severe headaches lasting several weeks without any neurological symptoms. It should be noted that no ophthalmological or neurological disorders, typically associated in the USA with excessive electromagnetic radiation exposure, were observed.

Socio-hygienic studies were conducted, employing an analysis of the relationship between working conditions and the health status of specialists regularly exposed to electromagnetic waves at airports. The results demonstrated a statistically significant increase in the incidence of cardiovascular and nervous system diseases, and premature ageing of the organism (by 3.5 years). Impairments of the organism 's defence systems, leading to immunodeficiency, were identified to a greater extent in personnel working with radar than in individuals in contact with radionavigation and radio communication systems.

Treatment of patients with gastroduodenal ulcers [3], including irradiation at frequencies of 58.0–59.5 GHz and 63.5 GHz using dielectric waveguides in contact with acupuncture points. EEG recording showed the development of a rhythm desynchronisation reaction. At several frequencies within the specified range, patients exhibited an inactivation reaction of background activity, accompanied by a comfortable emotional state and drowsiness.

2.6. Targeted correction of the state of physiological systems of the organism

Modulation of immune status

Biological effects of electromagnetic radiation can be used for the targeted correction of the state of the organism's immune system . A number of studies have explored the modification of immune status through exposure to electromagnetic waves. For example, the effect of millimetre-wave radiation on the survival rate of white mice with lethal influenza infection has been investigated. Irradiation regimes and test results are presented in Table 2.2.

According to Table 2.2, the modification of the immune status in mice exhibits a time lag, and the magnitude of modulation is dependent on the duration and mode of exposure.

Generators based on IMPATT diodes can be used for the targeted correction of the immune system response. Medical studies have confirmed the effectiveness of these devices in treating nervous system dysfunctions, immune system disorders, and metabolic disorders.

Table 2.2

The effect of millimetre-wave radiation on the lifespan of mice infected with influenza virus.

Group number	Irradiation regime	Wavel-ength, mm	Animal mortality, %	Average lifespan, days
1	14 days post-infection	7,1	42 + 12	8,3
2	14 days pre-infection	7,1	0	14,0
3	7 days pre-infection	7,1	36 + 14	8,6
4	7 days pre- and 14 days post-infection	7,1	16 + 10	11,1
5	7 days pre- and 14 days post-infection	5,6	25 + 13	10,1
Control	–	–	70 + 14	7,6

The work of V.N. Zaporozhan [41] demonstrated that correcting the immune status using low-intensity millimetre waves can limit alterations to the immune system associated with suppression of the T- and B-cell immune systems in the postoperative period.

However, modification of the immune status can have both positive and negative effects. The effect of electromagnetic radiation on murine immune system cells was studied. The results demonstrated that electromagnetic waves with a frequency of 41.95 GHz suppress the activity of these cells by 20%. Suppression was also observed when the same radiation was used, but modulated at frequencies of 16 and 50 Hz.

With modulation at 1 Hz in the carrier frequency range 41.95–42.05 GHz , activation of immune system cells was registered, but in the range 41.8–41.9 GHz, suppression of their activity was detected.

Thus, an appropriate exposure regimen can purposefully alter the status of the organism's immune system.

Regulatory influence on the haemopoietic system

Several series of experiments investigated the possibility of regulating haemopoiesis in the bone marrow. N.P. Didenko [15] investigated haemopoiesis in the bone marrow of the femurs of mice in both the irradiated and contralateral limbs. The animals were irradiated for one hour with electromagnetic waves with a wavelength of 7.00–7.30 mm and an incident power flux density of 10 mW/cm ^{2} . On the third day post-irradiation, a weak reaction of the erythroid lineage was apparent, with a slight increase in the absolute number of basophilic normoblasts.

basophilic normoblasts. A retrospective study of the animals' initial s-tate enabled the identification of two groups. Group A – mice progn-ostically 'sensitive' to electromagnetic radiation and characterised by an initially low leukocyte count in the peripheral blood. Group B – 'in-sensitive' animals with an initially high leukocyte count (greater than $12 \cdot 10^{9}$ l^{-1}). Changes were observed only in the irradiated limb. In Gr-oup A, a 25% increase in the total number of erythroid elements was recorded, including basophilic normoblasts.

Another series of experiments [16] investigated the prognostic s-ignificance of the initial erythrocyte count in peripheral blood followi-ng exposure to electromagnetic radiation with the same parameters as those used by N.P. Didenko [15], for cerebral haematopoiesis in C-BA mice. Mice were divided into two groups based on erythropoietic measurements: 'low-erythrocyte' – with a level less than $8 \cdot 10^{6}$ l^{-1} – a-nd 'high-erythrocyte' – with a level exceeding this value. It was found that changes in bone marrow haematopoiesis were initiated in ani-mals of the first group upon exposure of the left hind limb, and in m-ice of the second group – the right hind limb.

Thus, the leukocyte and erythrocyte counts in peripheral blood are a prognostic indicator of the regulatory effects of electromagnet-ic radiation.

Initiation of a protective effect against harmful environmental factors

Among the adverse environmental factors, chemical pollution a-nd naturally occurring biological allergens, which lead to allergic dis-eases, have recently caused the greatest concern among ecologists and physicians. In such diseases, it is important to correct the status of the immune system with regard to cellular and humoral immunity . The work of V.P. Adaskevich [17] was devoted to the study of millim-etre-wave electromagnetic radiation as a factor initiating processes t-hat correct immunological and neuroendocrine indicators in patients with atopic dermatitis. The research results demonstrated that the a-pplication of electromagnetic waves led to a stable improvement and positive changes in immunological (immunoglobulins E, M and G) a-nd neuroendocrine (T_3, T_4, cortisol, oestradiol) parameters.

The antioxidant and antitoxic systems of the blood play a crucial role in protecting the organism from adverse effects.
The influence of low-intensity radiation with a wavelength of 7.1 mm on blood systems in vitro was investigated. It was found that this exposure increased the activity of glutathione reductase, catalase, and superoxide dismutase. Glutathione peroxidase and glutathione S-transferase did not react to this exposure, and the reaction of glucose-6-phosphate dehydrogenase was dependent on the level of initial activity. At low initial activity, electromagnetic radiation activated this enzyme, whereas at high initial activity, it reduced its activity. Thus, in this instance, the effect was corrective.

Modification of the effects of ionising radiation

Of the research results in this area, those pertaining to experiments with lethal doses of radiation are particularly noteworthy. An experiment describing the protective effect of millimetre-wave electromagnetic waves, performed on white mice, is presented. The experimental results showed that preliminary exposure of the animals to electromagnetic waves at a frequency of 42.19 GHz for 10 days, or preliminary exposure for a period of
Exposure for 5 days, with a further 30 days' exposure post-irradiation, leads to a 1.6 to 2.0-fold decrease in mortality at a radiation dose of 6.5 Gy.
Mouse mortality increased 3.3-fold if the mice were exposed to electromagnetic radiation only after the initial exposure.

Microwave pulses were used in experiments investigating the protective effect of electromagnetic radiation on CBA-line mice.
Preliminary exposure to these electromagnetic waves for 24 hours increased survival rates and mean lifespan tenfold at a radiation dose of 7.0 Gy, and threefold at a dose of 7.5 Gy. Treatment of animals with these electromagnetic waves, administered concurrently with exposure to radiation (7.0 Gy), resulted in a five-fold increase in survival rate and average lifespan compared to the control group.
However, at a radiation dose of 8.0 Gy, the electromagnetic waves conferred no protective effect.

Mice underwent pre-exposure to millimetre waves for 1 hour, commencing 2 hours before irradiation. The protective effect of millimetre waves was observed at radiation doses ranging from 3 to 8 Gy. The most pronounced protective effect was observed at a dose of 4.0 Gy. It should be noted that the reduction in stress-related effects in animals, induced by the experimental conditions, also led to increased survival. Certain experimental conditions in themselves, in particular housing animals in irradiation chambers, positively modified the effect of ionising radiation, since hypodynamic stress leads to stable hypoxia, which elicits a radioprotective effect.

However, as a protective effect of electromagnetic waves was observed when reducing the degree of hypokinetic stress through exposure to millimetre waves, the mechanisms of these effects are inherently different, and their direction is opposite.

2.7. Dependence of local and general effects on electromagnetic wave frequency, specific absorbed power on exposure duration, and radiation type (continuous or pulsed mode)

The dependence of the biological effects of millimetre-wave electromagnetic radiation on its parameters is discussed in detail in review [19]. First and foremost, a threshold dependence of the effects on the incident power flux density is observed. Under experimental conditions, particularly during in vivo irradiation, determining the power absorbed by the biological object is difficult, but controlling the incident power level is relatively straightforward. If the experiment is correctly designed and measurements of reflected and transmitted power are successful, a power balance will allow determination of the absorbed power. In any case, the incident power level provides an upper estimate of the power absorbed by the biological object. Therefore, the incident power flux density is a suitable measure of the energetic interaction between biological entities and electromagnetic waves. Figure 2.1 illustrates the experimental relationship between the induction coefficient KI of colicin synthesis and the incident power flux density, exemplifying the threshold behaviour of biological effects induced by electromagnetic waves. This figure indicates that the effect becomes apparent at a specific threshold value of the incident power flux density, and that the magnitude of the effect remains constant at higher flux densities.

unchanged. The threshold value is determined by the characteristics of the biological object and the exposure conditions.

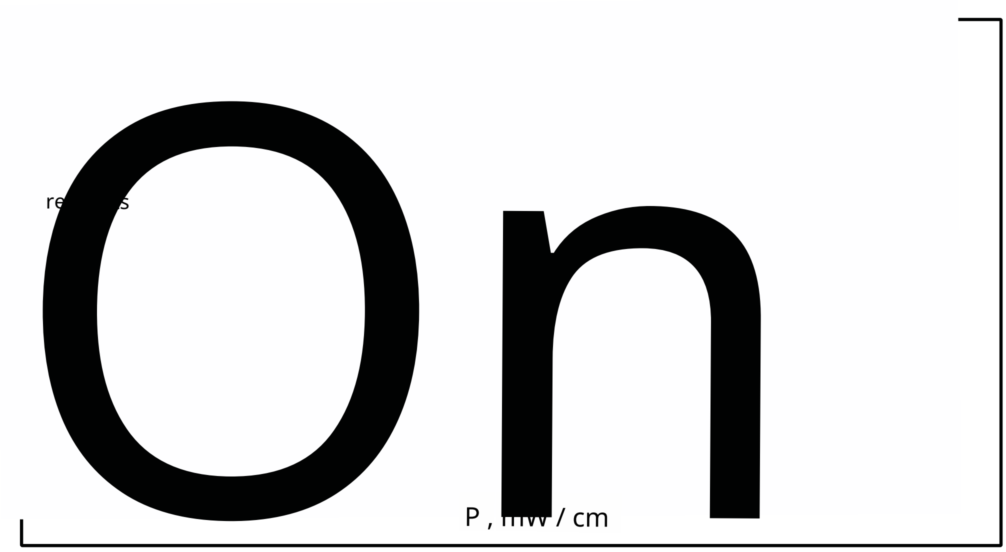

Fig. 2.1. Dependence of colicin synthesis on incident power density.

A second characteristic of the interaction of electromagnetic waves with biological objects is the resonant response of biosystems to electromagnetic exposure, meaning that a change in the state or function of a biological object is observed only when subjected to electromagnetic radiation within a narrow frequency range. The relative width of this interval is of the order of 10^{-3}. This does not imply that such changes in biological objects occur solely under the action of electromagnetic radiation within this specific frequency range. Several frequencies elicit a qualitatively similar response from biosystems upon exposure.

An example of this is the dependence of the induction coefficient of colicin K_I on the wavelength of the incident radiation, as shown in Fig . 2.2.

Measurements were performed to determine the dependence of the intensity of a person's endogenous electromagnetic radiation on the frequency of the applied electromagnetic waves. The exposure was conducted in the frequency range of 40–70 GHz, with an incident power flux density of approximately $1\ \mu W/cm^2$. Endogenous radiation from the individual was recorded within the frequency interval (1.000 ± 0.025) GHz. The measurement results indicated that this relationship exhibits a resonant behaviour. The central frequency of this resonance is located around 57.8 GHz, and its relative width was 10^{-2}. It was noted that the response to

Electromagnetic exposure was observed at incident radiation intensities from 1 to 10 μW/cm ^{2} .

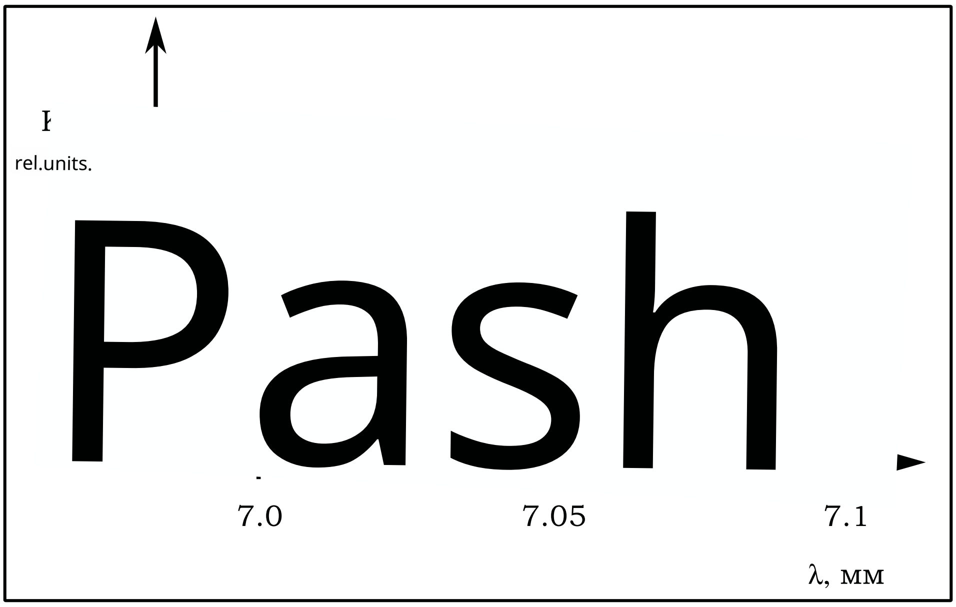

Fig. 2.2. Dependence of colicin induction on wavelength

General effects manifesting at the organism level depend on the location and duration of electromagnetic wave irradiation. These dependencies have been investigated in a number of studies. Exposure to electromagnetic radiation was performed on mice at wavelengths of 5.6 mm and 7.1 mm. Irradiation was performed for 15, 30, and 60 minutes at the following locations: a) left thigh; b) right thigh; c) occiput. The effect was assessed by non-specific resistivity, for which measurements were taken of peroxidase, acid phosphatase, alkaline phosphatase, and lipid content in neutrophils, as well as the concentrations of succinate dehydrogenase and glycerophosphate dehydrogenase in lymphocytes.

The data obtained in this study indicate that exposure to electromagnetic radiation at a wavelength of 5.6 mm for 60 minutes results in a less pronounced effect than exposure for
15–30 minutes. In the latter case, a significant decrease in the levels of redox and hydrolytic enzymes was observed in neutrophils and lymphocytes compared to the control groups on the 3rd and 5th days; these levels returned to baseline values by the 9th day post-irradiation. Adaptation to electromagnetic radiation with a wavelength of 7.1 mm developed later and less effectively than with irradiation at that wavelength.

5.6 mm. The localisation of exposure also modified the effect of the electromagnetic waves. Exposure during irradiation of the occipital region was more effective than exposure of the external surfaces of the thighs.

In most studies, irradiation was performed at the projection of acupuncture points. In this case, the mechanism of action was non-specific in nature but was not related to local heating.

The effect of electromagnetic radiation at a frequency of 53.37 GHz on the arterial blood pressure of Vistar rats was investigated. Irradiation was applied to the area of the renzhong acupuncture point (upper third of the philtrum); the second area was the midline of the nasal bone. The incident power flux density was 10 μW/cm ^{2} . The experimental results showed that electromagnetic radiation only affected the arterial blood pressure of SHR rats with hypertension, but had no effect on Wistar rats. After 4–6 minutes of irradiation, the arterial blood pressure changed from 147/101 to 114/62 mm. Following the cessation of irradiation, arterial blood pressure returned to baseline levels. An increase in incident power flux density up to 100 μW/cm ^{2} resulted in heating of the irradiated area by 3...4°C; however, this did not produce any additional effects.

The data obtained indicate that low-intensity millimetre-wave radiation applied to acupuncture points does not alter the functions of a healthy organism, but normalises them in pathological states.

2.8. Conclusion

Therefore, the effect of electromagnetic radiation with the aforementioned characteristics is evident across all bodily systems.

The most significant biological and medical effects of electromagnetic radiation on the whole organism are presented in Table 2.3.

Table 2.3

Effect of Microwave-Radiation on the Organism

System	Site of action	Radiation parameters	Results
Skin, tissues	Wound area	42.96 GHz + 200 MHz modulation	Accelerated wound healing (stimulation of granulation)
	Thigh skin		Asymmetry of local effects: changes in blood filling, mast cell count, lymphocytes
	Skin in the area of the suture	53.57 GHz, 4 mW/cm^2	Acceleration of nerve regeneration
	Skin	42.25 GHz	Destruction of the cytoplasm of myelinated and unmyelinated nerve fibres
CNS	Head region		Changes in electroencephalogram parameters: 1) Synchronisation (increase in the number of spindle-shaped oscillations and slow waves); 2) alteration of biopotentials in subcortical structures (hippocampus, hypothalamus, thalamic nuclei, reticular nuclei of the midbrain)
CNS		58.0–59.6 GHz, 61.5 GHz	Desynchronisation of rhythm, activation of background activity. Sensory sensations, positive emotional colouring, drowsiness
CNS		42.2 GHz	Awake animals – synchronisation. Anaesthetised animals – increase in high-frequency rhythms, increased dynamism of the central nervous system. Epileptiform activity, manifesting as rare (2–4 GHz) high-amplitude (> 300 µV) peaks.
CNS	Point 9.9 peri- channel carda	53.596–53.613 GHz, modulation 0.05 Hz, <5 mW/cm^2	Increase in the power of the spectral component in the and rhythm ranges , and an increase in the frequency of action potential trains in the afferent fibres of the median nerve. Sensory sensations
CNS		7.1 mm, 10 mW/cm^2	Anti-stress effect: Normalisation of inhibition and activation processes (thalamus and hypothalamus)

Continuation of Table 2.3

Autonomic nervous system	Dorsal aspect of the hand	mm, 5 mW/cm^2	Change in heart rate (0.05 Hz, 0.08–0.12 Hz, 0.15–0.5 Hz)
	Whole-body irradiation	Chronic irradiation, Carrier 1GHz, Packet 32Hz, In packet 250Hz	Vegetative dysfunctions
	Jian jian point + midline of the nose	53.52 GHz	Reduction of elevated blood pressure
Neuroendocrine system		mm	Sharp increase in serotonin and catecholamine levels in the lymphatic nodes
Sympathoadrenal system	Region of the external occipital protuberance	5.6 mm, 7.1 mm, 10 mW/cm^2	Correction of adaptive changes (alterations in catecholamine and other mediator metabolism, cytochemical lymphocyte indicators, morphological blood state, adequate response). Behavioural reactions – anti-stress effect under mild stress
Behaviour (laboratory animals)		UWB pulse. 5 kV/m, peak time 300 ps, duration 1.8 ns	Decrease in the sensitivity threshold to ultrasound exposure
		m, dm, cm, 10 mW/cm^2	Slowing the formation of conditioned reflexes
		30 MHz sine wave. mod. 2...5 Hz, 30...120 V/m	Blocking the development of conditioned reflexes
		0.25...2.5 GHz, 5–10 ns, frequency repetition rate 60 GHz	Improvement in learning ability and memory
Operators	Area of the occipital protuberance on the posterior surface of the head	53.57 GHz, 42.25 GHz, 10 mW/cm^2	Behavioural reactions: anti-stress effects under mild stress
	Point T [20] parietal canal	mm	Increased work capacity, improvement of functional state, increased mobility of the main neural processes in the cerebral cortex

End of Table 2.3

Correcti-on of p-hysiolog-ical sta-te	Whole-body irra-diation	53.57 GHz, 42.25 GHz	Increased survival upon infection with lethal influenza
	In vitro	42.25 GHz	Correction of antioxidant and anti-toxic blood systems
	limbs	mm	Sustained improvement, positive dynamics of immune (IgE, IgM, IgG) and neuroendocrine (T3, T4, corti-sol, oestradiol) indices
		38.96–42.31 GHz, 10 mW/cm^2	Change in the erythroid lineage: Increased erythrocyte and leukocy-te count in peripheral blood
Modifica-tion of the effect of ionising radiation	Whole-body irra-diation	42.19 GHz, 42.19 ± 0.19 GHz	Reduced mortality following irradi-ation. Correction of immune system stat-us.

References for this chapter

1. Skin changes under the influence of millimetre-wave EMF / V.M. P-erel'muter [et al.] // Abstracts of the VII All-Union Seminar 'Application of low-intensity microwave radiation in biology and m-edicine'. Moscow, 1989 – M., 1989. – p. 53.
2. Krylov V.N., Oshevensky I.V. Influence of EHF exposure on isolated smooth muscle tissue of rat intestine // Millimetre Waves in Biology and Medicine. – 2000. – No. 2. – pp. 11–14.
3. Preliminary results of using electroencephalographic criteria for s-electing the therapeutic frequency of millimetre-wave electromag-netic radiation in the treatment of gastroduodenal ulcers / Alisov A.P. [et al.] // Abstracts of the VII All-Union Seminar "The Use of Low-Intensity Millimetre-Wave Electromagnetic Radiat-ion in Biology and Medicine", Moscow, 1989. – M., 1989. – p. 8.
4. Lebedeva N.N., Kotrovskaya T.I. Experimental-clinical studies in the field of biological effects of millimetre waves (review, part 1) // Mil-limetre Waves in Biology and Medicine. – 1999. – No. 4. – pp. 3–13.
5. Kholodov Yu.A. Epileptiform electrical activity of the brain under the influence of electromagnetic fields // Electromagnetic fi

and human health: proceedings of the II international conference on « Problems of human electromagnetic safety: fundamental and applied r-esearch». Standardisation of EMF: philosophy, criteria, and harmonisat-ion. Moscow, 20–24 September 1999 – M., 1999, pp. 73–74.

6. Sidorenko A.V., Tsaryuk V.V. Bioelectrical activity of the brain during microwave irradiation in experiment // Millimetre Waves in Biology and Medicine. – 2000. – No. 4. – pp. 12–20.
7. Kholodov Yu.A. Millimetre radiation in neurobiology // Reports of t-he X All-Russian Symposium 'Millimetre Waves in Biology and Med-icine'. Moscow, 24–26 April 1995. – pp. 155–156.
8. Millimetre-wave EMF from localisation of exposure in rats with vari-ous typological features / N. A. Temur'yants [et al.] // Millimetre W-aves in Biology and Medicine. – 1993 – No. 2. – pp. 51–59.

9. Asymmetry of the adaptation syndrome developing under the infl-uence of millimetre-wave EMF / V. M. Perel'muter [et al.] // Abstra-cts of the VII All-Union Seminar «Application of low-intensity micro-wave radiation in biology and medicine». Moscow, 1989. – M., 1989. – p. 63.
10. Dependence of the anti-stressor effect of EHF EMR on exposure pa-rameters / N.A. Temuryants [et al.] // Millimetre Waves in Biology and Medicine. – 1994. – No. 3. – P. 11–15.
11. Investigation of the stress-protective action of EHF electromagnetic waves in animals / A.Yu. Arzumanov [et al.] // Millimetre Waves in Biology and Medicine. – 1994. – No. 3. – P. 5–10.
12. Lebedeva N.N., Sulimova O.P. Modifying effect of millimetre waves on the functional state of the central nervous system during stress modelling // Millimetre Waves in Biology and Medicine. – 1994. – No. 3. – P. 16–21.
13. Martynyuk, V.S., & Temuryants, N.A. (1995). The role of lipid peroxi-dation and thiol-disulphide exchange in the mechanisms of the an-ti-stress action of extremely high frequency electromagnetic radia-tion. *Millimetre Waves in Biology and Medicine*, *5*, 6–9.

14. Zaporozhan, V.N., [et al.]. The influence of extremely high frequen-cy electromagnetic radiation on the state of the endocrine, immune and proteolytic systems in patients after surgical removal of beni-gn ovarian tumours. *Proceedings of the XI All-Russian Symposium «Millimetre Waves in Biology and Medicine»*. Moscow, 21–24 April 1997 – M., 1997 – pp. 36–38.

15. Predicting and controlling the stimulating effect of electromagnetic radiation on erythropoiesis in outbred white mice / N.P. Didenko [et al.]. – 7 p. – Dep. VINITI 26.11.85, No. 81548185.

16. Dependence of erythroid and lymphoid system reaction on their i-nitial state under millimetre-wave electromagnetic oscillation exp-osure / N.P. Didenko [et al.] // "Application of Low-Intensity Millim-etre-Wave Radiation in Biology and Medicine". – M.: IRE AS USSR, 1 985. – Pp. 108–116.
17. Adaskevich, V.P. Clinical efficacy, immunoregulatory and neurohu-moral action of millimetre-wave and microwave therapy in atopic dermatitis // Millimetre Waves in Biology and Medicine. – 1995. – No. 6. – Pp. 30–38.
18. Rezunkov, A.G., Rezunkova, O.N. Study of the modifying effect of preliminary microwave exposure on survival in radiation sickness / / Millimetre Waves in Biology and Medicine. – 1993. – No. 2. – Pp. 5 9–62.
19. Lebedeva N.N., Kotrovskaya E.I. Experimental and clinical research in the field of biological effects of millimetre waves (review, part 1) // Millimetre Waves in Biology and Medicine. – 1999. – No. 3(15) – pp. 3–13.

3. PATHOGENIC EFFECTS OF EMF IN THE SHF BAND

The previous chapter considered the regulatory effects of electromagnetic radiation on the systems of the organism. However, particular attention should be given to the pathogenic effects of electromagnetic waves on systems of vital importance. These primarily include the hereditary, reproductive, and neuroendocrine systems. It is also important to understand the extent to which such effects are irreversible, and the conditions under which their manifestations are most significant. This chapter provides a review of such research. Section 3.1 considers the pathogenic effects of electromagnetic waves on the genome. Possible mechanisms of non-thermal electromagnetic radiation's effect on the reproductive system are analysed in § 3.2. Disorders in the neuroendocrine system caused by electromagnetic fields are the topic of § 3.3. Paragraph 3.4 is devoted to considering the reversibility of pathogenic effects of electromagnetic radiation.

3.1. Genomic changes: mutagenic effect, developmental malformations (teratogenic effects)

A direct influence of electromagnetic radiation on the genome was observed in the work of G. Lai and N. Sinha [1] investigated the effect of microwave pulses with a carrier frequency of 2.45 GHz and a power density of 2 mW/cm ^{2} on adult Sprague-Dawley rats. Rat brain cells were examined by agarose gel electrophoresis four hours after two hours of irradiation. The results showed the presence of single- and double-strand DNA breaks. These breaks were not observed if melatonin was administered subcutaneously to rats before or immediately after irradiation, or if N-tert-butyl-α-phenylnitrone was administered intraperitoneally as a free radical scavenger.

These results suggest that the effect of electromagnetic radiation on the genome is indirect. A schematic of the mechanism of action is shown in Fig. 3.1. Electromagnetic radiation initiates the formation of free radicals, the action of which on DNA molecules leads to single- and double-strand breaks. At this stage, the effect of electromagnetic waves is similar to that of ionising radiation, although the mechanisms of free radical formation differ.

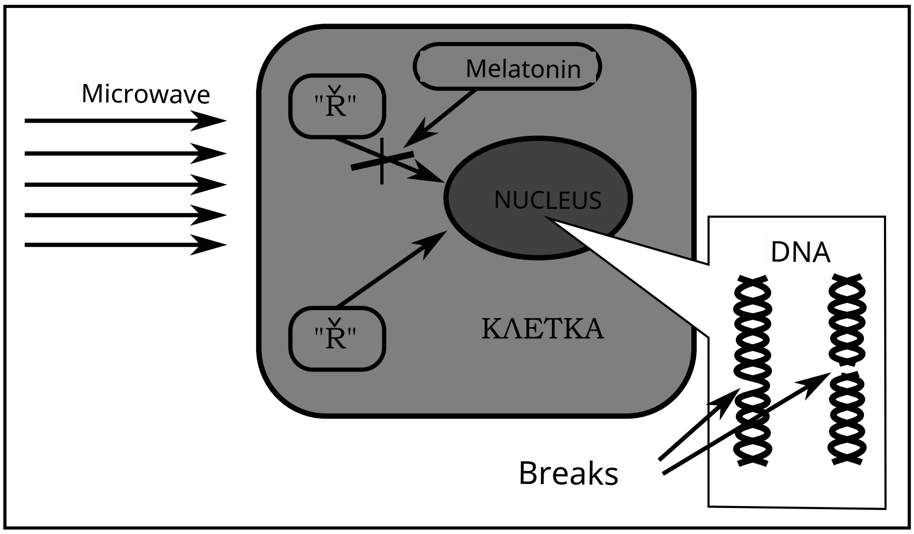

Fig. 3.1. Damage to DNA strands in rat neurones by free radicals (R) formed under the influence of pulsed microwave radiation.

Conflicting results were obtained using two types of frequency modulation: frequency-modulated continuous wave radiation, with a central frequency of 835.62 MHz, and code modulation with a mean frequency of 847.74 MHz at a specific absorption rate of 0.6 W/kg [2]. The effect of heating was excluded by maintaining a constant temperature of 37.0°C. Exposure of mammalian cell cultures (murine fibroblast cells C3H 10T1/2 and human glioblastoma cells – U87MG) does not cause DNA damage, as confirmed by the results of the alkaline comet assay.

An indirect study of the effects of electromagnetic radiation on the genome was carried out using drosophila [3]. Drosophila embryos, aged 1.5 and 15 hours, were irradiated with a continuous power flow at a frequency of 460 MHz. The effect of exposure was assessed by the degree of interrupted development, defined as the percentage of imagoes failing to emerge relative to the number of embryos, and serving as a measure of the extreme manifestation of teratogenesis.

of teratogenesis. No effect of the radio frequency signal was found on the percentage of interrupted development in embryos aged 1 and 5 hours. For 15-hour embryos, the effect was dose-dependent on the a-bsorbed power. The percentage of interrupted development increas-ed 1.4-fold only at a specific absorption rate of 6 W/kg.

The appearance of radiofrequency electromagnetic radiation-in-duced changes in the genome of peripheral blood lymphocytes in in-dividuals exposed through their occupational activity was noted in t-he work of N.D. Devyatkov et al. [4]. The presence of genomic chang-es was determined by the increased frequency of micronuclei and al-teration of cell distribution across the first, second, and third mitotic classes. Irradiation of lymphocytes with an electromagnetic field at a frequency of 50 Hz also introduces changes to the genome of these cells. Following irradiation of lymphocytes latently infected with the Epstein-Barr virus, an increase in the number of cells expressing the viral antigen was recorded [5]. This indicates alterations in DNA, mo-difying the reading of genetic information under the influence of ext-ernal electromagnetic radiation. Changes in leukocyte chromosomes are also noted in studies by N.P. Didenko et al. [6].

The consequences of the mutagenic effect of electromagnetic r-adiation include the occurrence of tumours, associated with changes in genetic information. However, studies into the possibility of a carc-inogenic effect of microwave radiation generally yield negative resul-ts. The possibility of increased cancer proliferation upon exposure to radio-frequency radiation is indicated in the article by J. Goldsmith [6] . In the review by L. Vershaeva [7] analysed reports in which most re-searchers found an increased frequency of leukaemia and central n-ervous system (CNS) tumours among children exposed to electroma-gnetic radiation.

To explain the mechanism of low-power microwave radiation and radio-frequency fields on biological systems under conditions where t-he temperature of the object under study does not change significantly during the experiment, a hypothesis has been proposed that,
that non-thermal doses of microwave and radiofrequency radiation can trigger a cascade of reactions, particularly lipid peroxidation with the formation of free oxygen radicals, leading to mutagenesis and c-arcinogenesis [8].

3.2. Effects on the reproductive system

Changes to the genome under the influence of electromagnetic radiation, as considered in the previous paragraph, can undoubtedly have reproductive consequences. A possible manifestation of such an influence on the genome is a change in the sex ratio, as discovered in the work of V. James [9]. Exposure of mothers to high-frequency electromagnetic fields resulted in a higher birth rate of female offspring. Significantly, this effect differs from that of ionising radiation, which causes sex-linked lethal mutations.

However, changes in the sex ratio may also be associated with modification of the reproductive system's function. In the work by M. Akdag et al. [10] it is demonstrated that microwave radiation significantly affects the reproductive system. In a study, male Sprague Dawley rats were exposed to 9.45 GHz electromagnetic waves at a power density of 2.65 mW/cm ^{2} and a specific absorption rate of 1.8 W/kg, for 1 hour daily over 13, 26, 39, and 52 days.
A noticeable reduction in seminal fluid within the epididymides was detected, but only after 52 days of exposure. The percentage of abnormal seminal fluid changed markedly after 26, 39 and 52 days of irradiation, with significant changes in the weight of the testes and epididymides also observed.

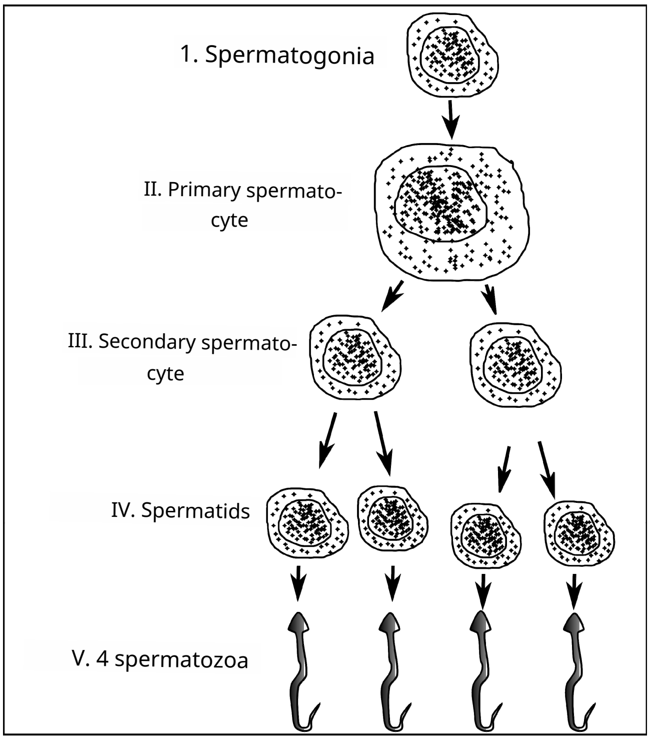

Fig. 3.2. Schematic of spermatogenesis

In the testes of exposed rats, necrotic changes in the tubules, interstitial oedema, a reduction in spermatogenesis, and, in some tubules, an absence of germinal epithelium were noted. The process of spermatogenesis is shown in Figure 3.2. Microwave radiation disrupts spermatogenesis in the seminiferous tubules. At stage I, it causes inhibition of spermatogonia differentiation, and at stages II–IV, necrosis of spermatid precursor cells. Atrophy, interstitial oedema, cellular infiltration, and increased fibroblast activity were observed in the adnexa.

Therefore, chronic exposure to low-intensity microwave radiation results in changes to the functional and morphological state of the reproductive system. Evidently, morphofunctional changes in the reproductive system, akin to those described above, contribute to an increased frequency of adverse reproductive outcomes, particularly spontaneous abortions.

3.3. Disorders of neuroendocrine regulation

In addition to the systems considered above, the neuroendocrine system also demonstrates a rapid response to electromagnetic radiation. The work of N.I. Karpikova and S.N. Lukyanova [11] examines the effect of modulated microwave radiation on the neuroendocrine system. The incident radiation had the following characteristics:
carrier frequency – 1 GHz, pulse frequency – 250 Hz, burst frequency – 32 Hz, incident power flux density at the workplaces – from 0.34 to 314 μW/cm ^{2}. Clinical and neurophysiological assessment of the health status of personnel working under these conditions indicates the development of statistically significant alterations in nervous system function. The phenomenology of these changes is characterised by a symptom complex of autonomic dysfunction: vegetative-vascular dystonia syndrome (VVD – 85 %), asthenic syndrome (49 %), vestibulopathy syndrome (21 %), and polyneuropathy syndrome (87 %). The development of a symptom complex of autonomic dysfunction depends on work experience: 1–5 years – autonomic-vascular dystonia of the hypertonic type, 6–25 years – autonomic-vascular dystonia of the mixed type, 26–35 years – arterial hypertension.

A general reaction of the neuroendocrine system to acute local exposure to microwave radiation is possible. See article P. Marchiori [12] described a case of multiple acute neuropathy following accidental exposure from a microwave oven with a faulty radiation interlock upon opening the door. The injured party placed her right hand into the oven chamber, rested her left hand on the door, and peered into the open chamber. After 10 minutes , she experienced numbness and tingling in the fingertips of her right hand . The following day, a burning pain developed in her right hand. Subsequently, paraesthesia and a decreased sensitivity developed in her left hand. After 10 days, the pain intensified, and dystrophic changes appeared in the nails of her right hand. Sensory disturbances presented in the right side of the face, with a decrease in visual acuity in the right eye.

Alterations in the functional state of the central nervous system also arise under conditions of microwave radiation exposure for therapeutic purposes. In the work of A.A. Kovalev [13], the spatial organisation of cortical processes and the functional significance of its dynamics were studied under the influence of non-thermal intensity millimetre-wave electromagnetic radiation (MM-EMR). Electroencephalographic examination during local EHF exposure was performed on 85 patients aged 18 to 56 years, who were receiving inpatient treatment for chronic visceral pathology without evidence of central nervous system (CNS) involvement. Reorganisation of the coherent composition of the EEG was observed in specific narrowband regions of the alpha range, against a background of psychosomatic status indicators characteristic of the normal organism, or normalisation under the influence of EHF radiation. In the presence of uncorrectable pathological deviations in the functional state of the somatovisceral innervation sphere, the prevailing shifts in spatial synchronisation manifested as activation of a coherent structure at 15 Hz . Possibly, these manifestations reflect the functioning of the homeostatic regulation mechanism.

Similar sensory indications have been observed in humans upon local exposure to various electromagnetic fields [14]. The subtle sensations that arise suggest the involvement of the nociceptive system in responses to electromagnetic radiation, i.e. a painful reaction. During EEG studies, a synchronisation reaction was observed in humans. Reactions to electromagnetic waves showed heightened activity in the anterior regions of the right cerebral hemisphere. The predominance of slow-wave activity on the EEG is consistent with the inhibitory effect of electromagnetic radiation on conditioned reflex activity. The processes of formation and preservation of conditioned reflexes are more vulnerable.

tion and preservation of conditioned reflexes. The author concludes that the totality of brain reactions indicates an initial adaptive response of the brain to EMF, playing an important role in both the therapeutic and pathogenic effects of EMF on the organism.

3.4. Reversibility of Changes in Systems Sensitive to Microwave EMF Exposure

In a limited number of studies describing pathogenic effects, the reversibility of changes and the long-term consequences of microwave radiation exposure are assessed. Disruption of spermatogenesis in rats proved reversible after prolonged exposure (3 months) to an electromagnetic field with a wavelength of 8 mm and a power density of 35 μW/cm^2 [15]. Three months after continuous irradiation ceased, the sperm count not only recovered but also exceeded baseline levels.

In a therapeutic study involving 528 patients with diverse pathologies, using non-thermal level millimetre-wave microwave therapy devices [16], 3 patients exhibited cutaneous changes. Patient M. (36 years old), who was undergoing treatment for rheumatoid polyarthritis, developed a complication on the 5th day of microwave therapy, concurrent with a reduction in the primary disease symptoms – a pruritic rash on the chest and abdomen, which had spread to the entire body by the 7th day. The rash disappeared 10 days after microwave therapy was discontinued. Upon repeating the microwave therapy after 3 months, the complication recurred. Patient Ya. (46 years old) received two courses of therapy (18 and 15 procedures) for the treatment of psoriasis. During each course, an itchy urticarial rash appeared all over the body from days 5–7, resolving after the treatment ended.
Patient G. (54 years old) received three courses of therapy for the treatment of duodenal ulcer. On the 5th–7th day of each course, an itchy, urticaria-like rash appeared across the body. Following cessation of treatment, the rash disappeared. In all cases, treatment of the underlying condition proved effective.

Analysis of the results of microwave radiation exposure suggests that the pathogenic effect may be based on the activation of lipid peroxidation, with the formation of free oxygen radicals. These radicals damage the genome, causing mutations which underlie both teratogenesis (increased percentage of unhatched Drosophila imagoes) and carcinogenesis. The effects are largely dependent on the level of absorbed power and the duration of exposure to microwave radiation. As with the effects of other physical, toxic, and stressor agents, spermatogenesis is one of the most sensitive systems when exposed to a microwave field. Exposure to pulsed microwave radiation can cause significant disturbances in the functioning of the central nervous system in humans. This is unsurprising, as even exposure to microwave radiation at therapeutic parameters leads to changes in EEG characteristics. It is important to emphasise that the observed disturbances in conditioned reflex activity are somewhat stereotypical and do not depend on the parameters of electromagnetic radiation (from low-frequency fields to those in the millimetre-wave range).

One should agree with M. Liang and V. Zang [17] that the primary challenge in studying the effects of microwave radiation on the human population is the lack of clarity surrounding biological mechanisms and the weak experimental evidence of such effects. One should agree with M. Liang and V. Zang [17] that the primary challenge in studying the effects of microwave radiation on the human population is the lack of clarity regarding biological mechanisms and the weak experimental evidence for these effects.

References for this chapter

1. Henry L., Narendra S.P. Melatonin and a sping-trap compound block radiofrequency electromagnetic radiation-induced DNA strand breaks in rat brain cells // Bioelectromagnetics. – 1997. – № 6. – P. 446–454.
2. Measurement of DNA damage after exposure to 2450 MHz electromagnetic radiation / R.S. Malyapa [et al.] // Radiat. Res. – 1997. – № 6. – P. 608–617.
3. Bolshakov, M.A. The effect of 460 MHz electromagnetic radiation on Drosophila embryos of different ages / M.A. Bolshakov, I.R. Knyazeva, E.V. Evdokimov // I International Symposium «Foundation. science and alternative. medicine». Pushchino, 22–25 Sept., 1997 – Pushchino, 1997. – P. 52–53.
   nauki i alternativ. med.». Pushchino, 22–25 Sept., 1997 – Pushchino, 1997. – P. 52–53.
4. Garaj-Vrhovac V. Micronucleus assay and lymphocyte mitotic activity in risk assessment of occupational exposure to microwave radiation // Chemosphere. – 1999. – V. 39 (13). – P. 2301–2312.
5. Magnetic fields and childhood cancer – a pooled analysis of two Scandinavian studies / M. Feychting [et al.] // Energ. Sante. – 1996. – V. 2. – P. 303–304.

6. Goldsmith J. R. Epidemiological studies of radio-frequency radiation: Current status and areas of concern // Int. Conf. «Eff. RF-Electromagn. Radiat. Org.». Skrunda, June 17–21 1994. – Sci. Total Environ., 1996. – № 1. – C. 3–8.
7. Verschaeve L. Can non ionizing radiation induce cancer? // J. Cancer. – 1995. – V. 5. – P. 237–249.
8. Sarkar S. Biological consequences of microwave stress: Implications for mutagenesis and carcinogenesis / S. Sarkar, W. Selvamurthy, M.M. Gupta // IETE Techn. Rev. – 1997. – V. 3. – P. 153–163.
9. James W.H. The sex ratios of offspring of people exposed to non-ionizing radiation // Occup. and Environ. Med. – 1997. – № 8. – P. 622–623.
10. Effect of chronic low-intensity microwave radiation on sperm count, sperm moorphology, and testicular and epididymal tissues of rats / M.Z. Akdag [et al.] // Electro- and Magnetobiol. – 1999. – № 2. – P. 133–145.
11. Karpikova, N.I., Lukyanova, S.N. A clinical and neurophysiological study of the state of the nervous system operating under conditions of pulsed microwave irradiation of low intensity. III Congress on Radiation Research. «Radiobiology, Radioecology, Radiation Safety». Moscow, 14–17 October 1997 – Pushchino, 1997. – Vol. 3. – pp. 188–189.
12. Acute multiple mononeuropathy after accidental exposure to oven microwaves / P.E. Marchiori [et al.] // Occup. Med. – 1995. – V. 5. – P. 276–277.
13. Kovalev A.A. Unconscious effects of non-thermal millimetre-wave electromagnetic radiation on the integrative links of self-regulation in human organism homeostasis // Millimetre Waves in Biol. and Med. – 1997. – No. 9–10. – pp. 18–24.
14. Kholodov, Yu.A. Initial adaptive reaction of the brain to electromagnetic fields // Millimetre waves in medicine and biology. – 1997. – pp . 156–157.
15. Some indicators of rat spermatogenesis after exposure to microwaves / A.V. Lyulko [et al.] // V All-Union Seminar "Application of low-intensity EHF radiation in biology and medicine". Moscow, 1989 – M., 1989. – pp. 66–67.
16. Gun'ko, V.T., Kozhina, N.M.. On some complications of EHF therapy // Millimetre waves in biology and medicine. – 1993. – № 2. – Pp. 102–103.
17. Mingshan L., Wenyan Zh.. Influence of microwave radiation on superoxidedysmutase and fat peroxide products of mices // Dongwuxue zazhi. – 1995. – № 6. – P. 24–27.

4. THERAPEUTIC EFFECTS OF MMW RADIATION

As demonstrated in Chapter 1, the influence of electromagnetic radiation can have both positive and negative biological effects. Pathological manifestations of this influence were discussed in detail in the preceding chapter. However, numerous studies demonstrating the diverse effects of microwave radiation on biological objects at varying levels of organisation allow these effects to be considered as a basis for the broad testing of the potential use of microwave radiation for the therapy of various diseases. This chapter is dedicated to the therapeutic applications of electromagnetic waves. Section 4.1 provides a concise overview of the therapeutic effects of electromagnetic radiation at thermal power levels. Paragraph 4.2 is dedicated to a consideration of the therapeutic effects of non-thermal intensity electromagnetic waves. Separate paragraphs are devoted to microwave therapy for the most important systems of the human organism. Section 4.3 considers the therapeutic effect of electromagnetic radiation on the haematopoietic system. The therapeutic effects of electromagnetic waves on the immune system are the subject of Section 4.4. Paragraph 4.5 is devoted to the effects of electromagnetic radiation on the healing of ulcers in the gastrointestinal tract. Section 4.6 considers the electromagnetic stimulation of bone tissue regeneration. Paragraph 4.7 is dedicated to determining the dependence of the therapeutic effects of electromagnetic radiation on its parameters.

4.1. Therapeutic effects of microwave electromagnetic radiation within the thermal power range

The therapeutic effects of electromagnetic radiation are associated with the heating of biological tissues. The literature contains data on thermoregulatory reactions in humans during whole-body microwave irradiation, causing an increase in deep tissue temperature.
In determining the threshold of thermal perception in the median region of the spine in adult men, it was found that sensitivity increases monotonically with increasing microwave radiation frequency across the range 2.5–94 GHz. The threshold determined at 94 GHz was more than an order of magnitude lower than that at 2.5 GHz, and comparable to the perception threshold of IR radiation [1]. At lower frequencies, effects related to thermal exposure may not be accompanied by strong sensory perception.

4.2. Therapeutic effects of non-thermal microwave EMF

In a review published in 1998, A WHO review analysed the biological effects of low-intensity radiofrequency electromagnetic fields (from 10 MHz to 300 GHz) [2]. It noted numerous gaps in knowledge in this area, requiring further research. It also highlighted the existence of publications concerning the therapeutic application of low-intensity electromagnetic radiation.

The feasibility of treating thyroid pathology using low-intensity millimetre-wave radiation has been investigated [3]. Therapy in 284 patients with diffuse toxic goitre, diffuse non-toxic goitre, and nodular goitre resulted in a reduction in gland volume in the majority of patients. Following therapy, patients with diffuse thyrotoxic goitre exhibited normalised serum T_3 and T_4 lymphocyte levels, and their thyrotoxicosis syndrome was alleviated. In any of the observation groups, the authors found no negative side effects from millimetre-wave therapy.

Exposure of acupuncture points to low-intensity millimetre-wave radiation in patients (16 days, 5 minutes at each of 5-7 points) with ischaemic stroke resulted in marked therapeutic effects [4]. An earlier recovery of speech was observed, and the disease course was almost 3.5 times less frequently complicated by the development of pneumonia.

For the treatment of benign prostatic hyperplasia (BPH) and chronic prostatitis (CP), 10 sessions of millimetre-wave microwave radiation, with wavelengths of 5.6 and 7.1 mm in frequency modulation mode and a power flux density of 10 mW/cm ^{2} [5], were used in conjunction with hyperbaric oxygenation. Although the treatment did not result in a reduction in prostate volume, in patients with both BPH and CP, it was possible not only to achieve improved urination parameters, but also to reduce the intensity of the inflammatory response. The latter was evidenced by a reduction of more than twofold in the number of leukocytes in prostatic secretions. With isolated BPH, no therapeutic effect was observed.

4.3. Stimulation of haematopoiesis

Electromagnetic radiation can have a stimulatory effect on the human haematopoietic system. Thus, in the treatment of burn patients exposed to electromagnetic waves with a wavelength of 7.1 mm, the number of reticulocytes increased in groups with facial burns covering less than 10%, and in those with torso burns affecting up to 20 % of the body surface area [6]. In the group with torso burns ranging from 10 to 30%, no effect was observed. This clinical effect of erythropoiesis stimulation is consistent with results demonstrating increased repopulation by bone marrow stem cells of CBA and C57Bl6 (F1) hybrid mice following irradiation with 7.1 mm electromagnetic radiation [7].

The conditions for stimulating erythrocyte formation in the bone marrow of animals were studied in the article by N. P. Didenko et al. [8]. It has been established that the response of the blood vascular system depends on its initial state and the location of electromagnetic radiation (EMR) exposure. Considering these conditions, it became possible to predict and control the stimulating effect of EMR on erythropoiesis, both in healthy animals [9] and in the correction of anaemia following blood loss [10].

4.4. Stimulation of the immune system

The ability of microwave radiation to affect cellular metabolism and alter the state of the neuroendocrine system suggests the possibility of modulating the immune system. Alterations in immune status during microwave therapy have been recorded in 16 patients with acute myocardial infarction, who underwent 60 minutes of irradiation to the skin of the lower leg with 5.6 mm wavelength microwave radiation [11]. A total of 14 procedures was performed. A tendency towards an increase in T and B lymphocytes was observed, while the number of T helper cells remained unchanged and T suppressor cells decreased. The levels of IgG and IgM immunoglobulins increased, whereas IgA levels decreased. These changes in immune parameters were accompanied by an improvement in the clinical picture: a decrease in the intensity and frequency of episodes of retrosternal pain, and a more rapid positive trend on the ECG.

The immunomodulatory effect of microwave radiation is predicated on the formation of free radicals. This is evidenced by data from studies investigating the effects of weak electromagnetic fields (8...18 GHz, 1 μW/cm ^{2}), which showed an increase in tumour necrosis factor induction in murine macrophages. The application of ubiquinones , which act as antioxidants, reduces the effects of electromagnetic fields in the microwave range [12].

4.5. Effect on the healing of gastrointestinal ulcers

Peptic ulcer disease remains a significant medical challenge, and research continues into more effective treatments. Unsurprisingly, gastric and duodenal ulcer disease was one of the first conditions where microwave therapy was trialled. E.S. Timofeeva [13] summarised the results of electromagnetic radiation therapy at wavelengths of 7.1 and 5.6 mm in 534 patients with peptic ulcer disease. Biologically active points were irradiated (from 1 to 4 areas per session) for 40 minutes. Two-thirds of the patients presented with moderate or severe disease. Depending on the variant of the com-

Four patient groups were identified, based on the combination of electromagnetic therapy and traditional treatment regimens. Treatment efficacy was monitored by fibrogastroduodenoscopy and histological examination of biopsy specimens from the ulcer margins. The results led the author to conclude that millimetre-wave (MMW) therapy is highly effective for peptic ulcer disease. Furthermore, monotherapy with electromagnetic waves did not differ in effectiveness from combination therapy using drug regimens. However, poor tolerance of electromagnetic therapy was noted in 6 patients, which led to treatment discontinuation. In 17 patients, MMW therapy either had no positive effect or was followed by early disease relapse. It transpired that all of these patients presented with complicated variants of peptic ulcer disease.

The application of electromagnetic waves at a frequency of 62 GHz and a power flux density of up to 3 mW/cm ^{2} in continuous or pulsed generation modes yielded a positive effect in the treatment of gastric and duodenal ulcers, including complicated forms of these diseases [14].

Comprehensive treatment of duodenal ulcers, incorporating electromagnetic therapy, reduced the extent of inflammatory infiltration and connective tissue formation in the ulcer area, as evidenced by histological examination. Concurrently, complete eradication of Helicobacter pylori and stimulation of regenerative processes, including normalisation of the endocrine elements of the intestinal mucosa, was achieved in the majority of patients [15].

To elucidate the nature of the therapeutic effect of electromagnetic radiation, and to exclude the leading role of psychophysiological processes associated with patient expectation of a positive outcome (the placebo effect), a comparative evaluation of sham and 'true' exposure to low-intensity millimetre waves was performed [16]. The therapeutic effect of simulated EHF therapy was found to manifest as 75% complete or incomplete healing of gastroduodenal ulcers. The actual impact of EHF radiation on acupuncture points or Head's zones resulted in a 20...30% increase in the rate of complete ulcer healing.

4.6. Stimulation of bone tissue regeneration

Electromagnetic therapy was found to have a beneficial effect on wound healing in patients with limb injuries complicated by purulent infection, particularly in those exhibiting an unfavourable response in the absence of pharmaceutical or other essential treatments [17]. Electromagnetic therapy has proven beneficial in the comprehensive treatment of deforming osteoarthritis [18].

The therapeutic effects of electric and magnetic fields have been studied primarily with the aim of using them to restore connective tissues. The most extensively studied methods concern bone restoration, facilitating reduced treatment durations for recent fractures, non-unions, complications arising from bone tissue transplantation, osteoporosis, and osteonecrosis. The application of electromagnetic field effects has been reported for the restoration of cartilage and soft fibrous tissues. In all these experimental studies and clinical applications, accelerated synthesis of the extracellular matrix and reduced tissue treatment times were observed [19].

There is considerable evidence that direct current and alternating electric fields are generated in living bone due to metabolic processes and mechanical deformations, respectively. External direct current is applied to treat non-unions as a means of stimulating mitosis and restoring osteogenic cells, possibly via electrochemical reactions at the electrode-tissue interface. Alternating electromagnetic fields are also used to treat non-unions, osteonecrosis, and osteoarthritis, and to stabilise implants [20].

Pulsed electromagnetic fields affect the in vitro growth of bone and cartilage, making them potentially useful in the treatment of arthritis. Stimulation with these fields is an established method in the treatment of non-union fractures and shows promise for use in the treatment of osteoarthritis, osteonecrosis, osteoporosis, and wounds. Permanent magnets may, under certain circumstances, provide temporary pain relief [21].

4.7. The dependence of therapeutic effects on the specific absorption rate, frequency, exposure duration, continuous and pulsed modes, considering the pulse duration, repetition rate, and shape parameters of microwave electromagnetic field (EMF) pulses.

Despite the importance of studying the dependence of the therapeutic effect of microwave therapy on the parameters of electromagnetic radiation, this aspect remains the least well understood. The effectiveness of different electromagnetic therapies was compared in 23 patients with progressive angina pectoris [22]. In the first group, a radiation source with a wavelength of 7.1 mm was employed. The procedure lasted 60 minutes a day for 10 days. In the second group of patients, a radiation source with a wavelength of 5.6 mm was used for 5 days, followed by a source with a wavelength of 7.1 mm for 5 days. The radiation power is 10 mW/cm ^{2}. Exposure to electromagnetic waves results in a reduced heart rate. The result was independent of the wavelength and application regimen of EHF therapy.

A study of the effect of low-intensity electromagnetic radiation (1...2 µW/cm ^{2}) within the 26 to 140 GHz frequency range on the human body, using electroacupuncture diagnostics (EAD) according to R. Voll, revealed four biologically active ranges. These ranges are separated by relatively quiescent frequency intervals and exhibit distinct types of radiation interaction with the body [23]. Voll's method revealed four biologically active ranges, separated by relatively quiescent frequency intervals and differing in the type of radiation interaction with the body [23]. Specifically, the 8 mm range is characterised by a general constitutional tonic effect, the 5 mm range by a local normalising effect, the 4 mm range by a general constitutional sedative effect, and the 2.5 mm range by a local normalising effect.

4.8. Conclusion

The results of microwave therapy suggest a definite effectiveness in correcting the state of the haematopoietic and immune systems, stimulating the regeneration of ulcerative defects of the stomach and duodenum, and promoting bone and connective tissue repair (Table 4.1). However, the inadequate definition of indications and contraindications for microwave therapy is notable. As a rule, the physical parameters of radiation in the treatment of a specific disease are selected without adequate justification, and without attempting to determine the optimal exposure regimen. The initial state of physiological systems is not adequately considered; under pathological conditions, these systems respond to microwave radiation in a way that largely determines its outcome. Addressing these issues may prove promising for enhancing the efficacy of microwave therapy.

Table 4.1

Therapeutic effects of microwave radiation

System	Site of action	Radiation parameters	Results
Endocrine system		mm	Reduction in thyroid gland volume in patients with diffuse toxic goitre, normalisation of T3 and T4 lymphocyte levels.
Immune system	Tibia	5.6 mm	Change in the immune status of patients with acute infarction (increase in the number of T and B lymphocytes, IgG and IgM, decrease in IgA level) – improvement in clinical presentation.
Gastrointestinal tract	Biologically active points	7.1 mm, 5.6 mm	High efficacy in the treatment of uncomplicated gastric and duodenal ulcers.
		62 GHz, 3 mW/cm^2	Treatment of gastric and duodenal ulcers, including complicated cases, resulting in a reduction of inflammatory infiltrate, accelerated regeneration, and normalisation of the endocrine elements of the intestinal mucosa.
Cardiovascular system		mm<10 mW/cm^2	Reduced recovery times and a decreased probability of stroke complications (pneumonia).
Urogenital system		5.6 mm; 7.1 mm, 10 mW/cm^2	Improvement of therapeutic efficacy, reduction of inflammation during the simultaneous treatment of prostatic hyperplasia and chronic prostatitis
Haematopoietic system	Tibia	7.1 mm	Stimulation of erythropoiesis in burn disease (increased reticulocyte count)
Musculoskeletal system		53.53 GHz, 42.96 GHz, modulation	Acceleration of wound healing, activation of the inflammatory response, stimulation of scar formation, activation of extracellular protein synthesis. Improvements in the complex therapy of deforming osteoporosis, fractures, and osteonecrosis.

References for this chapter

1. Human sensory and thermoregulatory responses to microwave irradiation / D.W. Blick [et al.] // Abstr. 67th Annu. Sci. Meet. Aerospace Med. Assoc., Atlanta, Ga, May 5–9 1996. – 1996. – V. 7. – P. 690.
2. Repacholi M.H. Low-level exposure to radiofrequency electromagnetic fi-elds: health effects and research needs. // Bioelectromagnetics. – 1998. – № 19(1). – P. 1–19.
3. The use of millimetre wave therapy in the treatment of thyroid gland di-seases / A.I. Gulyaev [et al.] // Millimetre Waves in Biology and Medicine . – 2001. – No. 3 (24). – pp. 35–43.
4. The application of novel reflexotherapeutic methods based on the ther-apeutic and diagnostic complex "Charm" in the treatment of patients w-ith cerebral circulatory disorders / N.D. Devyatkov [et al.] // Millimetre Waves in Biology and Medicine. – 1996. – No. 8. – pp. 5–13.
5. The use of therapeutic millimetre-wave electromagnetic radiation in conjun-ction with hyperbaric oxygenation in patients with benign prostatic hyperpl-asia, and its combination with chronic prostatitis / O.B. Loran [et al.] // Milli-metre Waves in Biology and Medicine. – 1996. – No. 8. – P. 13–16.
6. The effect of millimetre-wave EMF on the progression of burn anaemia / N.P. Didenko [et al.] // VII All-Union Seminar «Application of low-intensi-ty EHF radiation in biology and medicine». Moscow, 1989 – M., 1989. – P. 19.
7. The effect of low-intensity millimetre-wave radiation on the repopulati-on potential of haematopoietic stem cells / L.P. Ignasheva [et al.] // VII All-Union Seminar on «Application of EHF radiation of low intensity in bi-ology and medicine». Moscow, 1989 – M., 1989. – P. 59.
8. The effect of electromagnetic oscillations in the millimetre range on the blood system of animals, depending on their initial state and irradiation zone / N.P. Didenko [et al.] // Biophysics. – 1986. – Vol. 31 (3). – P. 882–8 50.
9. The Possibility of Predicting and Controlling the Stimulating Effect of Elect-romagnetic Radiation on Erythropoiesis in Outbred White Mice / N.P. Dide-nko [et al.] – SRI of Nuclear Physics at TPU. – Tomsk, 1985. – 7 pp. – Dep. in VINITI 26.11.85 No. 815481815.
10. Stimulation of Erythropoiesis in Post-Haemorrhagic Anaemia in Mice Under the Influence of Microwave Radiation / N.P. Didenko [et al.]. – SRI of Nuclear Physics at TPU. – Tomsk, 1985. – 9 pp. – Dep. in VINITI 26.11.85, № 8155-B-85.
11. Golovacheva. Changes in the immune system during EHF therapy in patie-nts with acute myocardial infarction / Golovacheva, V.Yu., Ushakov, V.M., Pavlyuk // VII All-Union Seminar «Application of Low-Intensity EHF Radiati-on in Biology and Medicine». Moscow, 1989 – M., 1989. – P. 15.

12. Natural antioxidants and cellular immunity under conditions of ionising and non-ionising radiation / V.R. Makar [et al.] // II Open. mountain. Scientific Conference of Young Scientists, Pushchino, 1997 – Pushchino, 1997. – Pp. 107–108.
13. Timofeeva, E.S. Effectiveness of millimetre-wave therapy combined with medication in patients with peptic ulcer disease // Millimetre Waves in Biology and Medicine. – 1994. – No. 3. – Pp. 91–93.
14. Briskin, B.S. On the application of EHF therapy for complicated gastroduodenal ulcers / B.S. Briskin, V.N. Bukatko, A.N. Nikitin // Millimetre Waves in Biology and Medicine. – 1996. – No. 7. – Pp. 26–30.
15. Chizh A.G., Osadchuk M.A. Pathogenetic aspects of millimetre-wave electromagnetic radiation application in the comprehensive therapy of patients with duodenal ulcer // Millimetre Waves in Biology and Medicine. – 2000. – No. 1 (17). – P. 34–38.
16. Rodstat I.V. Therapeutic effects of placebo and objective criteria for healing // Millimetre Waves in Biology and Medicine. – 2001. – No. 3 (24). – P. 16–23.
17. Kamenev Yu.F. The application of electromagnetic radiation in traumatology and orthopaedics // Millimetre Waves in Biology and Medicine. – 1999. – No. 2 (14). – Pp. 20–24.
18. Rationale for the use of EHF radiation for stabilising degenerative-dystrophic changes in articular cartilage in deforming osteoarthrosis / Yu.F. Kamenev [et al.] // Millimetre Waves in Biology and Medicine. – 1996. – No. 7. – Pp. 30–35.
19. Aaron R.K., Ciombor D.M. Therapeutic effects of electromagnetic fields in the stimulation of connective tissue repair // J Cell Biochem. – 1993. – V. 52(1). – P. 42–46.
20. Otter M.W. Effects of electromagnetic fields in experimental fracture repair / M.W. Otter, K.J. McLeod, C.T. Rubin // Clin. Orthop. – 1998. – (355 Suppl). – S90-10. – P. 14.
21. Trock D.H. Electromagnetic fields and magnets. Investigational treatment for musculoskeletal disorders // Rheum Dis. Clin. North Am. – 2000. – V. 26(1). – P. 51–62.
22. Changes in haemodynamic parameters and myocardial contractility in patients with coronary artery disease under the influence of EHF radiation / N.D. Devyatkov [et al.] // VII All-Union Seminar "Application of Low-Intensity EHF Radiation in Biology and Medicine". Moscow, 1989. – M., 1989. – P. 14.
23. Resonances of human organs in the EHF band from the perspective of the R. Voll method / I.L. Brandt [et al.] // XI Russian Symposium with International Participation "Millimetre Waves in Medicine and Biology". Moscow, 21–24 April 1997 – M., 1997. – Vol. 1. – Pp. 100–101.

5. DEPENDENCE OF THE INFLUENCE OF MICROWAVE ELECTROMAGNETIC RADIATION ON THE ORGANISM ON THE FUNCTIONAL STATE OF ITS PHYSIOLOGICAL SYSTEMS

The characteristics of electromagnetic radiation's effect on biological objects at various levels of organisation, discussed in the preceding chapters, demonstrate the multifactorial nature and diverse orientations of electromagnetic field effects. Conversely, numerous observations suggest that microwave radiation, particularly at low intensities, does not 'impose' a specific qualitative or quantitative response on the corresponding functional systems. Rather, it elicits a 'response' dependent on both the initial state of those systems and the organism as a whole. This chapter therefore considers the role of the initial state and asymmetry of the organism in shaping the response to electromagnetic exposure. Paragraph 5.1 is dedicated to a review of studies investigating the dependence of the organism's response to electromagnetic radiation on the initial state of its physiological systems. Section 5.2 considers the influence of asymmetry in the organism's systems, as represented by paired organs, on the formation of a response to electromagnetic wave irradiation. Finally, Section 5.3 discusses the possibility of predicting the biological effects of electromagnetic radiation.

5.1. The role of the baseline activity level of physiological systems

The premise that the effect of electromagnetic radiation at the level of the whole organism is largely dependent on the physiological state of the 'responding' systems is supported by the results of several studies. If the reaction of a functional system were not dependent on its initial state, then irradiation would have to induce the same changes in the skin's receptor apparatus across all animals, generate afferent signals of the same type, and the 'responding' systems would receive identical regulatory efferent signals. As a result, a uniform reaction to the exposure would be expected. However, research data indicates that only a proportion of animals respond to electromagnetic wave irradiation.

Thus, it was found [1] that exposing non-pedigree mice for one hour to electromagnetic radiation with a wavelength of 7.09...7.20 mm and a power flux density not exceeding 10 mW/cm^{2} resulted in dissimilar changes in the erythroid component of bone marrow haematopoiesis in the experimental animals. Local stimulation of the erythroid lineage was registered only in animals with initially low leukocyte counts (less than $12 \cdot 10^{9}$ l^{-1}) or in mice with a high percentage of lymphocytes in the peripheral blood, three days after exposure. In mice with initially high leukocytosis, changes in the erythroid lineage were not observed. The authors posited that the role of the initial state of the adaptive (neuroendocrine) system in the erythroid lineage's response to electromagnetic radiation could be discussed, as the number of lymphocytes in the peripheral blood reflects the degree of glucocorticoid activity.

The baseline activation level of the erythroid lineage was investigated in a separate experiment [2]. Depending on their initial state, CBA mice were divided into two groups based on erythrocyte counts: those with counts less than and those with counts greater than $8 \cdot 10^{12}$ л$^{-1}$ ('low-erythrocyte' and 'high-erythrocyte' animals). Irradiation was performed using electromagnetic waves with a frequency in the range of 42.10–42.35 GHz at a power flux density of approximately 10 mW/cm^{2}. The authors' principal finding is that erythropoiesis can be stimulated in specific regions of the bone marrow in both animal groups, provided that 'low-erythrocyte' animals are irradiated on the left hind limb, and 'high-erythrocyte' animals on the right.

To clarify the findings of the aforementioned studies, a comparative study of haematopoiesis was conducted using CBA and C57BL/10 mice, which exhibit an almost two-fold difference in peripheral blood leukocyte counts [3]. Simultaneous consideration of baseline levels of both leukocytes and erythrocytes in the peripheral blood allowed the authors to demonstrate that, in mice with an initial leukocyte count of less than $12 \cdot 10^{9}\ L^{-1}$ and an erythrocyte count of $8 \cdot 10^{12}\ L^{-1}$, there was a change in erythropoiesis in the bone marrow of the left femur and sternum. In the remaining animals, stimulation of erythropoiesis was observed in the bone marrow of the right femur.

Despite the extremely limited research into the significance of the initial state of the organism as a whole, and its individual functional systems, in the development of a response to electromagnetic radiation, it is important to acknowledge the necessity of considering this factor when studying the pathogenic and therapeutic effects of radiation.

5.2. Significance of functional asymmetry in systems represented by paired organs

A weak influence, such as low-intensity electromagnetic radiation , differs little in magnitude from the influence of the experimental conditions themselves. In this regard, to distinguish between the inherent effects of electromagnetic radiation and the organism's responses to concomitant exposure conditions, it is important to consider the subtle patterns of functioning within the 'responding' physiological systems. One characteristic of systems featuring paired organs is their functional asymmetry.

The importance of initial functional asymmetry (as with the initial state) has been demonstrated in several studies [4–6]. The authors investigated the reaction of the thymico-adrenal system in mice to electromagnetic radiation with a wavelength of 7.1 mm and a radiation power density of less than 10 mW/cm^{2} . To exclude the influence of experimental conditions, the state of the studied systems in the animals of the experimental group was compared with that of a background group of intact mice and with animals in a control group, which were kept in the irradiation chamber for one hour. Changes were detected immediately after one hour's exposure. Isolation of animals in the irradiation chamber (control group) constituted a stressor. This is evidenced by hypertrophy of the cells in the adrenal zona fasciculata. Furthermore, the initially less activated left adrenal gland exhibited a greater degree of hypertrophy. Consequently, the sign of asymmetry was altered. Despite hypertrophy of the zona fasciculata cells, involutional changes in the thymus were minimal.

At one hour, adrenocorticocyte hypertrophy persisted, accompanied by a reduction in the total number of thymocytes in the left thymus. After 24 hours, the volume of adrenocorticocytes in the zona fasciculata had normalised. Furthermore, in comparison to a considerably activated background, adrenocorticocyte activity in the right adrenal gland was reduced. Consequently, as in previous timeframes, the sign of the asymmetry coefficient remains consistent. An increased specific cellularity was observed in both thymuses.

Irradiation of the skin on the left thigh of the mouse, immediately following one hour of exposure, resulted in similar changes in adrenocorticocytes as seen in the control group. However, the involutive changes were more marked in the left thymus. After one hour and at 24 hours, the changes in adrenocorticocytes and the thymus were almost indistinguishable from those in the control group.

Irradiation of the right thigh area proved to be a less pronounced stressor, since, despite adrenocorticocyte hyperfunction in the zona fasciculata, thymic involution did not occur at any time point during the observation period. If, during irradiation from the left, the involutional changes in the left thymus observed in the control group animals were slightly increased and occurred earlier, irradiation from the right abolished them. The results of measurements made while studying the influence of thymico-adrenal system asymmetry on the organism's response to electromagnetic radiation are shown schematically in Fig. 5.1.

Thus, under conditions of animal isolation in a chamber and exposure to electromagnetic radiation, activation of adrenocorticocytes in the zona fasciculata occurred, more prominently in the left adrenal gland. Involutional changes occurred only in the left thymus. The regular involution of the left thymus, leading to the dominance of the right thymus, was associated with right-sided asymmetry of activity in the zona fasciculata, irrespective of the absolute activity values of the right and left adrenal glands. Irradiation of the left thigh exacerbates the stressor effect of the chamber (involution of the left thymus). Irradiation of the right thigh, conversely, mitigates the stressor effect of the chamber.

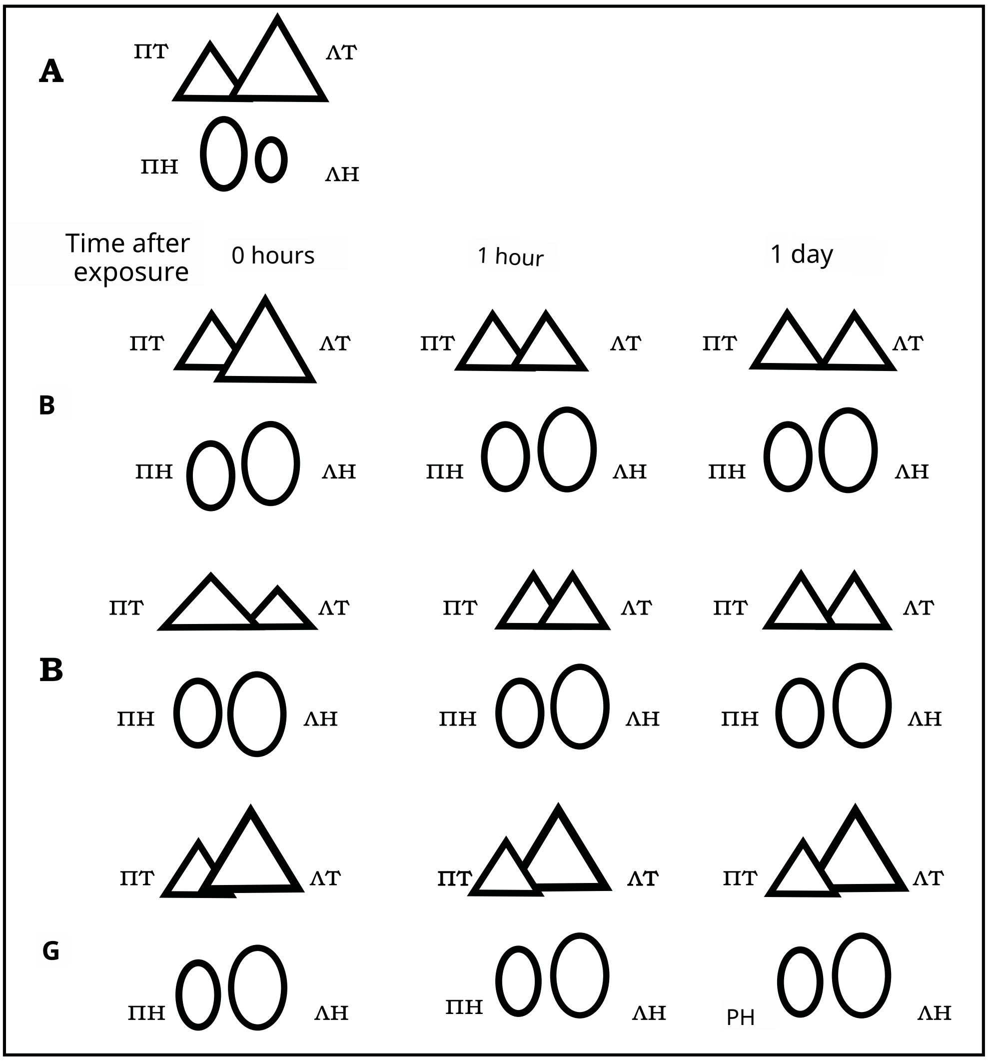

Fig. 5.1. Dependence of thymus and adrenal gland reaction on the initial functional asymmetry of the thymic-adrenal system and side of exposure: A – "background"; B – "control"; B – irradiation of the left thigh; C – irradiation of the right thigh; "rt" and "lt" – right and left thymus; "ra" and "la" – right and left adrenal gland

Accounting for the functional asymmetry of the thymic-adrenal system under study allowed the authors to correctly interpret the results obtained, avoiding incorrect conclusions regarding both the absence of effect from electromagnetic radiation (had only the right thymus or irradiation from the right side been studied by chance), and the erroneous attribution of the effects of experimental conditions to the action of electromagnetic waves.

5.3. Prediction of biological effects of microwave EMF

Analysis of the literature indicates that studies on the biological effects of microwave radiation generally do not emphasise the variability in individual responses to exposure. Without such research, it is impossible to predict the consequences of exposure to electromagnetic radiation or to determine the indications and contraindications for its application. Consequently, the extreme paucity of attempts at targeted individual correction of the state of specific functional systems is understandable.

In one such study [7], following the induction of post-haemorrhagic anaemia (to 30–40% of the baseline level), animals underwent two one-hour irradiations of the left hind limb, irrespective of their initial condition. The radiation frequency was (42.25 + 0.1) GHz, with an incident power flux density not exceeding 10 mW/cm^2. The exposure proved ineffective, with only a slight increase in the number of reticulocytes in the peripheral blood being observed. In the next series of observations, animals with post-haemorrhagic anaemia were exposed to EMF with the same parameters, taking into account the initial (pre-anaemisation) state of the erythroid lineage. In mice with a baseline erythrocyte count of less than $8 \cdot 10^{12}$ l^{-1}, the left hind limb was irradiated; in those with an erythrocyte count exceeding this level, the right hind limb was irradiated. A similar approach proved to be effective. This manifested as a statistically significant increase in haemoglobin concentration and a more pronounced increase in the number of reticulocytes in animals of both groups compared with the first series. Furthermore, the methaemoglobin content decreased almost 3.5-fold, indicating a more optimal course of redox processes in erythrocytes under the influence of microwave radiation.

As another example, based on the ability to predict effects, consider an attempt to use microwave radiation to mitigate the manifestations of radiation sickness following neutron irradiation of animals [8]. Animals were irradiated with a flux of fast neutrons at doses of 4.0, 5.25, 6.5, and 7.75; and 9.0 Gy on a U-120 cyclotron at the Research Institute of Nuclear Physics (Tomsk), where the average neutron energy in air was 6 MeV. Mice in the experimental group were treated with non-thermal intensity electromagnetic radiation of an unspecified frequency 50 minutes before neutron irradiation. Me-

The electromagnetic wave exposure conditions were chosen to amplify the stress response within the first 24 hours post-exposure.
The observation period lasted 30 days. The results indicated that selecting an individualised protective regime using electromagnetic radiation increased the resistance of animals to neutron irradiation by 70% (dose modification factor – 1.7). Furthermore, the spectrum of radiation-induced complications in the deceased animals altered.

The results presented suggest promising avenues for research aimed at developing individualised exposure regimens using centimetre and millimetre-wave electromagnetic radiation, capable of eliciting the required positive effects.
Specifically, taking into account the operator's individual characteristics (the baseline state of their key functional systems, including any functional asymmetry in paired organs), and by varying the exposure site, it may be possible, using low-intensity electromagnetic radiation of a specific frequency, to 'tune' the organism's functional parameters in such a way as to minimise the negative consequences of external factors. These factors could include electromagnetic radiation with unfavourable parameters that lead to pathogenic effects.

References for this chapter

1. The possibility of predicting and controlling the stimulating effect of electromagnetic radiation on erythropoiesis in outbred white mice / N.P. Didenko [et al.]. – NIIYaF TPU. – Tomsk, 1985. – 7 p. – Dep. in VINITI 26.11.85, No. 815481815.
2. Dependence of the reaction of erythroid and lymphoid systems on their initial state when exposed to electromagnetic oscillations in the millimetre range / N.P. Didenko [et al.] // Application of Low-Intensity Millimetre-Wave Radiation in Biology and Medicine. – M., 1985. – P. 108–116.
3. The influence of millimetre-wave electromagnetic oscillations on the blood system of animals, depending on their initial state and the zone of irradiation / N.P. Didenko [et al.] // Biophysics. – 1986. – Vol. 31 (5). – P. 882–885.
4. Perelmuter V.M. Reflection of the functional asymmetry of the thymico-adrenal system in the state of the zona reticularis of the adrenal glands during

homotransplantation of the right or left half of the thymus // Bull. eksp. biol. i med. – 1997. – No. 11. – P. 577–579.

5. Asymmetry of adaptive system responses to EHF radiation / V.M. Perel'muter [et al.]. – Tomsk, 1993. – 7 p. – Dep. in VINITI 01.07.93, No. 182518 93.

6. Dynamics of early morphofunctional changes in the adrenal glands under the influence of EHF radiation / Yu.V. Paderov [et al.]. – Tomsk , 1993. – 7 p. – Dep. in VINITI 01.07.93, No. 181718 93.

7. Stimulation of Erythropoiesis in Post-Haemorrhagic Anaemia in Mice Under the Influence of Microwave Radiation / N.P. Didenko [et al.]. – SRI of Nuclear Physics at TPU. – Tomsk, 1985. – 9 pp. – Dep. in VINITI 26.11.85, № 8155-В-85.

8. Influence of millimetre-wave electromagnetic radiation on animal survival during neutron irradiation / N.P. Didenko [et al.] // Medicobiological aspects of millimetre radiation. – M., 1987. – pp. 74–78.

6. MECHANISMS UNDERLYING THE EFFECTS OF M-ICROWAVE ELECTROMAGNETIC RADIATION

The biological effects of electromagnetic radiation discussed in previous chapters have shown that even low-intensity fields can lead to significant changes in biological processes, and consequently, to alterations in the state of the organism. Furthermore, as noted in § 0 .1, a fundamental point is that the effect is achieved by radiation with a quantum energy much less than kT.

Therefore, it is important to distinguish between thermal and non-thermal eff-ects of exposure; these issues are addressed in Sections 6.1 and 6.2. The rece-ption of electromagnetic radiation at the cellular level is reflected in changes in the functioning of the human nervous system. The mechanisms of the direct reaction of the whole organism to the effects of microwave radiation are cons-idered in Section 6.3. Directly related to the reaction of the nervous system is t-he question of the sensory perception of the impacting electromagnetic waves . Section 6.4 considers the possible sensory systems of mammals.

6.1. Physical mechanisms of radiation exposure at the thermal level

The effect of electromagnetic radiation on biological objects is b-ased on its absorption by these objects. In other words, the impact is energetic in nature. This statement does not contradict the hypothe-sis of an 'informational' effect of low-intensity millimetre waves [1], s-ince even an informational signal must carry a certain amount of en-ergy to elicit a response in the receiver. From a thermodynamic pers-pective, the absorption of energy in a biological system corresponds to two distinct areas of effect manifestation [2], as shown in Fig. 6.1.

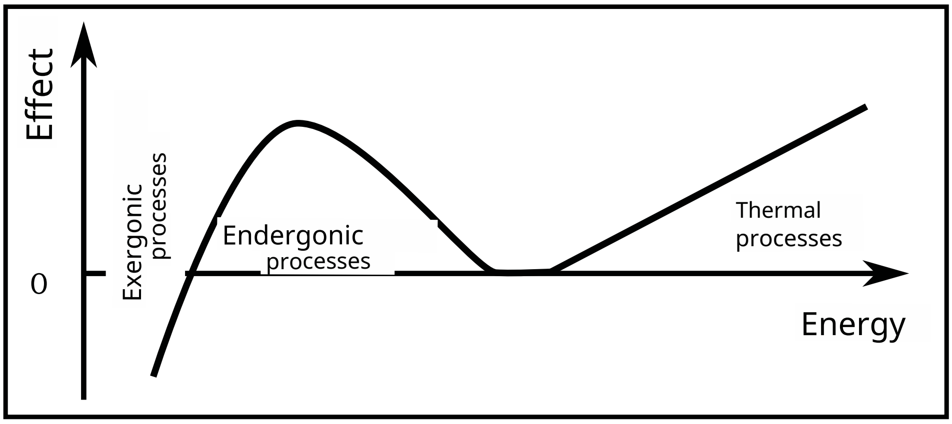

Fig. 6.1. Relationship between isothermal and thermal biological effects of electromagnetic radiation

The left-hand side of the figure illustrates the area of bioeffects where the absorbed energy of external electromagnetic radiation leads to the synchronisation of internal oscillations, inducing non-thermal (isothermal) endoergic processes in biological systems. An analogy with microwave travelling-wave tubes is appropriate here, where a relatively weak input signal, acting within the resonant frequency band, leads to the self-organisation of the device's internal environment, which is incomparably stronger energetically, resulting in a powerful output signal. In a sense, this effect can be considered 'informational', since a weak applied signal induces a transition of the system to a new state, a transition for which the external signal does not provide sufficient energy, but which is available within the system itself. A review of the mechanisms of this interaction is provided in the following paragraph; here, we will consider only the thermal effects of electromagnetic radiation, the area of which is shown in Fig. 6.1 on the right.

The absorption of electromagnetic wave energy in biological tissues occurs due to the electrical component of the electromagnetic field. At low frequencies, energy loss from the electromagnetic field is primarily due to ionic currents, whereas in the microwave range, the predominant mechanism is loss resulting from polarisation of the substance. Electronic and ionic polarisations have relaxation times of $10^{-16}...10^{-14}$ s and $10^{-14}...10^{-12}$ s, respectively. Therefore, within our frequency range of interest, it is only sensible to consider dipole polarisation, the relaxation times of which are comparable to the oscillation period of the influencing electromagnetic waves.

In biological tissues, the primary interaction partner with electromagnetic radiation is in the centimetre and milli-

metre waves is water. Firstly, water molecules in their free state possess a significant dipole moment. Secondly, the relaxation time of this molecule at body temperature is ~ $6 \cdot 10^{-12}$ s.
Thirdly, water is the main component of biological tissues. Living organisms contain between 65 and 98 % water. Human tissues and organs have a high water content. For example, the brain contains approximately 70% water, blood 83%, lungs and heart approximately 79%, liver 69%, muscles 75%, skin 72%, and so on.

Water is a complex physical object containing hexagonal clusters in addition to free water molecules.
Energy losses from microwave electromagnetic waves are mainly associated with the dipole polarisation of free water molecules, as the dipole moments of water molecules within hexagonal clusters are balanced. As temperature rises, the number of free molecules increases due to cluster breakdown. Consequently, the specific losses increase.

The frequency dependence of the dielectric permittivity is described, as is known, by the Debye equation:

$$\varepsilon(\omega) = \varepsilon_{\infty} + \frac{\varepsilon_0 - \varepsilon_{\infty}}{1 + i\omega\tau}, \qquad (1)$$

where ω – frequency of the external electromagnetic field; i – imaginary unit; τ – relaxation time; $\varepsilon_{\infty} = 4...5$ – dielectric permittivity at the high-frequency limit. Water in biological tissues exists as solutions, wherein its molecules form hydrogen bonds with other molecules. Since the relaxation time will change slightly, instead of a single relaxation time in expression (1), a relaxation time distribution function $G(\tau)$ must be substituted. The energy losses of electromagnetic waves in biological tissues are then determined by the imaginary part of expression (1):

$$\varepsilon''(\omega) = (\varepsilon_0 - \varepsilon_{\infty}) \int_0^{\infty} \frac{G(\tau)\,\omega\tau\, d\tau}{1 + \omega^2\tau^2}.$$

The dependence of losses attributable to the polarisation of water molecules takes the form shown in Fig. 6.2. According to the figure, in the frequency range of interest, and especially in the high-frequency region, the absorption of electromagnetic wave energy in the water component of biological tissues approaches a maximum. At a sufficiently high power level, electromagnetic radiation will cause rapid heating of biological tissue.

This primarily affects the water component. This can lead to changes in water structure, modification of the bonds between water molecules and protein molecules, and consequently, altered functional activity of enzymes, resulting in changes to metabolic processes within cells. In extreme cases, heating can lead to protein denaturation, resulting in the complete loss of their functional properties. Even a partial loss of the functional properties of proteins leads to cell death. This circumstance is exploited in diathermy for cancer treatment, where microwave heating induces the death of tumour cells. The thermal effects of electromagnetic radiation are hazardous to all systems of the organism, but the reproductive system, eyes, and blood coagulation system are the most sensitive.

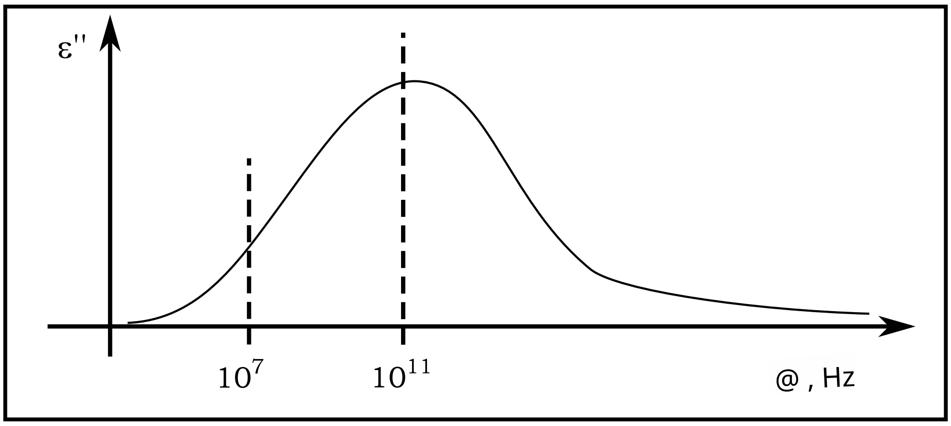

Fig. 6.2. Dependence of losses in biological tissues on frequency

6.2. Probable physical mechanisms of action of non-thermal radiation

As mentioned previously, the primary physical challenge concerning the interaction of electromagnetic radiation with biological objects at non-thermal power levels is the mechanism by which energy accumulates, leading to potential structural transitions within biological structures and subsequent alterations in their functional activity. It has been demonstrated that such accumulation can occur via the mechanical vibrations of biomacromolecules. To understand the mechanism of physical reception of electromagnetic radiation, it is important to identify the primary physical entities within biological tissues that interact with electromagnetic waves.

The direct targets of electromagnetic radiation are electrical charges (electrons and ions) and dipoles, which are represented either by molecules or by discrete groups of macromolecules, possessing mechanical degrees of freedom. A primary candidate for the physical receptor that directly interacts with electromagnetic radiation is the water molecule, owing to its significant dipole moment (~1.8D).

The frequency spectrum of rotational and librational motions of water molecules lies within the centimetre and millimetre wave ranges. Concurrently, the dynamic state of aqueous organic and inorganic systems is influenced by the effects of various electrolytes and non-electrolytes, which is reflected in alterations to their microwave and millimetre-wave spectra [3]. Consequently, the frequency values at which electromagnetic waves can interact with water molecules in biological tissues depend on the specific composition of the liquid phase of those tissues. Water itself, as a chemical reagent, can have its activity altered by electromagnetic waves [3]. The activity of water, when altered by electromagnetic radiation, can lead to changes in the hydration of protein molecules; the degree of hydration of protein molecules strongly influences their physiological activity [5] (Fig. 6.3).

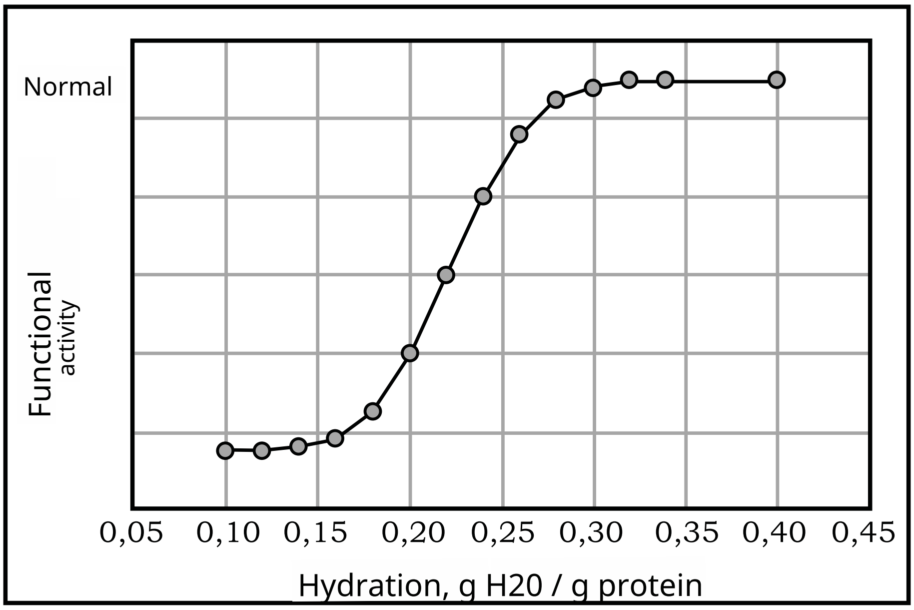

Fig. 6.3. Dependence of the functional activity of protein molecules on their degree of hydration

Hydration of protein molecules can change, not only through modification of the chemical activity of water in the medium surrounding the hydration shell of the protein molecule, but also through direct interaction of radiation with water molecules within this hydration shell. The energy of electromagnetic waves is converted into the kinetic energy of translational or rotational motion of molecules. The energy of movement of free water molecules dissipates as heat within a period of $10^{-10}...10^{-9}$ s; however, even at these dissipation values, such movements can alter the degree of hydration of protein molecules [6].

Therefore, the primary mechanism of electromagnetic radiation reception by biological objects, via interaction with water molecules, is as follows [6]. Electromagnetic waves activate specific degrees of freedom in water molecules within the liquid phase of biological tissues. In this instance, the increased activity of water enhances the exchange between the environment and the hydration shells of biomacromolecules. Consequently, the chemical activity of macromolecular (predominantly membrane) structures is stimulated, leading to modulation of the functional properties of enzymatic, transport, and receptor proteins, which in turn influences cellular metabolic processes. Under the influence of electromagnetic waves, bound water molecules undergo rocking oscillations and can act as transducers, converting electromagnetic oscillations into mechanical oscillations, the energy of which is then transferred to biological structures.

The interaction of electromagnetic waves with water can occur not only at the level of individual molecules, but also with water clusters. In the article by V.I. Petrosyan et al. [7], the physical resonances of the interaction between a microwave electromagnetic field (4–120 GHz) and biological objects and water were investigated. The presence of resonance was recorded as an increase in the noise energy of the irradiated object's own radiation, resulting from the dissipation of the pump wave energy. The results demonstrated the presence of such resonances and the identical resonant frequencies for water and the tissues of human and animal organisms.
According to the authors, this indicates a unified physical basis for the interaction of electromagnetic radiation with bio-objects, linked to the molecular structure of water. Electromagnetic waves in the range of 30–100 GHz can interact resonantly with water molecules within clusters exhibiting a hexagonal structure, which undergo vibrational (angular) oscillations in the radial and axial directions [8]. When the frequency of the electromagnetic

wave coincides with the frequency of the intrinsic oscillations of water clusters, the wave may not propagate deeply into tissues. When acting on molecular clusters of water with frequencies close to resonance, an external electromagnetic field can lead to a shift in the frequencies of intrinsic oscillations towards the applied frequency, synchronising them and thereby affecting the state of biological structures , which may elicit a biological effect.

A mechanism has also been proposed whereby electromagnetic radiation indirectly alters the structure and properties of water, due to its interaction with a biomolecule. A molecule of cyclic adenosine monophosphate may act as one such receptor. A.P. Zhukovsky et al. [9] consider this possible because: 1) it is present in almost all cells; 2) the spectra of rotational movements of this molecule lie in the EHF band; 3) the volumetric relaxation time during the rotational transition of this molecule in water, under the influence of electromagnetic waves, is comparable to the change in the magnitude of the rotation period and much shorter than the rotation period itself. This ensures efficient transfer of excitation to water molecules located around the cyclic adenosine monophosphate molecule, both in the free state and in clusters. Perturbations of the water structure manifest in its interaction with biological objects inside the cell, modifying metabolic processes [10].

Biomolecules interacting with electromagnetic radiation can serve not only as receivers of electromagnetic waves and transmitters of physical effects to other biological structures, but can also themselves respond to this interaction through structural rearrangements and modifications to their biological function. This applies primarily to protein molecules. The possibility of energy accumulation during interaction with electromagnetic radiation and, consequently, conformational transitions are discussed in detail in §§ 1.1–1.3. As an example of such rearrangements of protein molecule structure and changes in their functional activity, one can cite the results of a study on the dependence of adenosine triphosphate content and the electrophoretic mobility of rat erythrocytes on the duration of the animals' exposure to a millimetre-wave electromagnetic field [11]. It has been recorded that the adenosine triphosphate content increases by 37% on the 5th day of irradiation, and erythrocyte electrophoretic mobility increases by 23%. Changes in adenosine triphosphate content may be explained by modification of the pro-

-cesses of glycolysis by millimetre waves, i.e. by a change in the activity of a range of enzymes. Changes in erythrocyte electrophoretic mobility may occur due to altered charge distribution on erythrocyte membrane surfaces, suggesting an interaction between millimetre waves and receptor molecules within the cell membrane.

Another possible mechanism for the reception of electromagnetic radiation is the excitation of acoustic waves in supramolecular structures, particularly within membranes [5]. When electromagnetic waves pass from air into a condensed medium with a dielectric permittivity, ε the frequency remains constant, but the wavelength decreases by a factor of ε ½. Thus, at a frequency of $3 \cdot 10^{10}$ Hz, the dielectric permittivity ε of biological tissues is 25, and the wavelength is 2 mm.
The acoustic wavelength is approximately 10^5 times smaller. Therefore, the biological micro-objects (macromolecules, membranes) involved in acoustic oscillations will effectively be situated within a homogeneous electric field that changes periodically with time, at a frequency close to the natural frequency of the biological oscillators. Let us consider a possible mechanism for the generation of acousto-electric waves on a membrane [12]. Consider a cell with radius R and a hydrophobic membrane region of thickness Δ_m (Fig. 6.4).

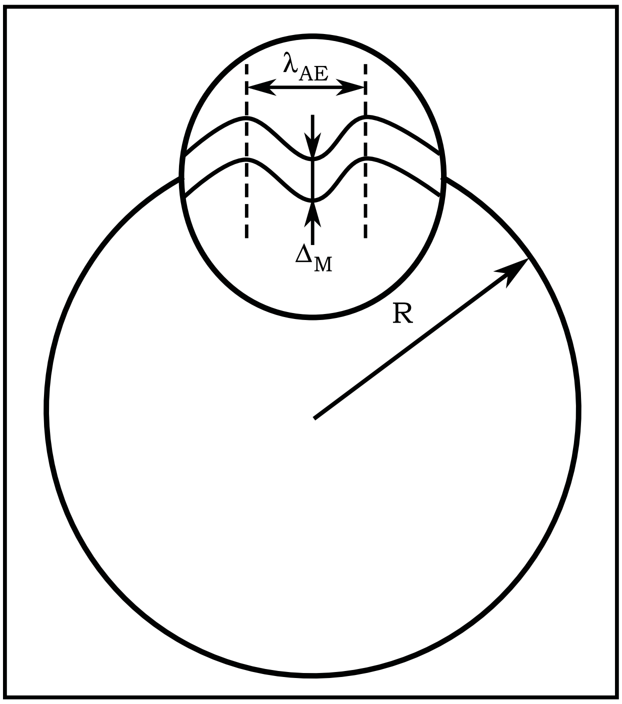

Fig. 6.4. Diagram of acousto-electric wave excitation in the membrane.

In a homogeneous field of an electromagnetic wave incident upon a cell, an acousto-electric wave arises on the membrane. This is due to an excess pressure of the cytoplasm within the cell and oppositely directed interaction forces between charges on the membrane and the electrical component of the electromagnetic wave. In this case, the frequencies of the electromagnetic (EM) and acousto-electric (AE) waves are equal. Then , the wavelength of the acousto-electric (AE) wave is equal to:

$$\lambda_{AE} = \lambda_{EM}\, n \frac{a}{c},$$

where $n = 1.3$ is the refractive index for biological tissues, $a = \sqrt{\frac{k}{\delta_m}}$. Here, $k = 0.45$ N/m is the elastic modulus; $\rho = 800$ kg/m 3 is the density, and the density and $\delta_m = 3.10^{-9}$m is the thickness of the hydrophobic part of the membrane; $c = 3.10^{8}$ m/s is the speed of light of the electromagnetic wave in a vacuum . Hence - here - AE = 1.7...17 nm at a wavelength of - EM = 1.10 cm. If the c-ell diameter is 0.5...10 µm, then at least 30 wavelengths of the acousto-elec-tric wave can be accommodated on the membrane. The resonant frequen-cy, at which excitation results in an integer number of acousto-electric wa-ve oscillations fitting on the membrane, will depend on the size of the me-mbrane and its elastic properties, including the density of protein molecul-es on the membrane surface, and the number of ion channels.

Ideologically, this approach stems from the well-known work of G. Fr öhlich [13], which, based on general biophysical considerations, substan-tiated the possibility of acousto-electric oscillations existing in membran-es, with a frequency range of $10^{11}...10^{12}$ Hz. Based on this idea, an 'infor-mational' approach to the biological action of low-intensity millimetre-w-ave EMFs [1] was developed, postulating that healthy cells possess inher-ent acousto-electric oscillations within their membranes. The role of the-se oscillations may be to 'massage' the membrane, providing the necess-ary degree of permeability for transport channels. Any disturbances in t-he cell's life processes will alter the amplitude or frequency of these oscil-lations, which in turn affects membrane permeability. External electrom-agnetic influence at the membrane's natural frequency can synchronise oscillations in its individual sections or amplify damped oscillations, lead-ing to the desired correction of cell metabolism.

Beyond reception at the molecular and supramolecular levels, the biological response to electromagnetic radiation may also arise from macroscopic effects. When an organism is irradiated with electromagnetic waves, interference can occur at inhomogeneities in the biophysical parameters of tissues. As a result, temperature gradients may arise due to differences in the absorbed dose between adjacent tissue areas. At an incident power level of up to 10^{-5} W/cm^{2}, gradients of up to 5 degrees/mm may occur [6]. Such gradients may lead to changes in biochemical processes, modify the transmission of nerve impulses, and thereby result in the emergence of afferent neural and humoral signals.

The location of local maxima is highly sensitive to the frequency of the incident electromagnetic wave. A frequency change of 200 MHz within the millimetre wave range can lead to a qualitative change in the heating profile. The response to electromagnetic exposure can exhibit sharp resonance, and the 'equivalent Q-factor' can reach a value of 500 or more [14]. The heating rate at field maxima exceeds the average by an order of magnitude or more; consequently, a non-specific sensory reaction of the organism is possible, although this falls under the domain of physiology. The physiological aspects of electromagnetic radiation reception are considered in the following paragraph.

6.3. Physiological mechanisms of electromagnetic radiation reception at the level of the whole organism

The physical mechanisms of electromagnetic radiation reception considered in the previous paragraph provide an understanding of how the functional activity of biomacromolecules and supramolecular structures changes under the influence of electromagnetic waves. The question arises as to how these changes manifest themselves in the physiology of the organism, and what reactions are elicited by the direct effect of low-intensity radiation. This paragraph provides an overview of research findings on this topic.

N.N. Lebedeva [15] considers the differences between the neurophysiological mechanisms underlying the biological effects of electromagnetic fields at extremely low frequencies (ELF, $f = 1...50$ Hz) and extremely high frequencies (EHF, $30...100$ GHz). The detected differences in EEG responses to ELF and EHF fields are summarised as follows. Under the influence of ELF fields, changes in the brain's electrical activity occur in the frontocentral regions, as well as in the parietal region of the contralateral hemisphere (increase in [illegible] [illegible] rhythms). The reaction to EHF radiation manifests as an increase in alpha-rhythm power in the occipital regions. These results suggest differing neurophysiological mechanisms underlie these reactions: a predominant involvement of the specific lemniscal sensory system in the case of ELF fields, and the non-specific, extra-lemniscal system in the action of EHF radiation. Perhaps these differences are determined by the physical properties of electromagnetic waves. ELF fields penetrate deeply into organism tissues, involving the vascular system and muscle fibres by acting directly on nerve fibres. In contrast, EHF radiation is almost completely absorbed by the skin, acting only on superficial receptors; therefore, the mechanism of action in this instance is reflex-mediated.

The nature of neocortical bioelectrical activity arising after prolonged exposure to EHF and ELF fields indicates the development of a non-specific activation reaction, that is, an increase in cerebral cortex tone. One of the physiological mechanisms mediating the effect of millimetre waves on internal organs – given their very shallow penetration depth into biological tissues – may be lymphocyte mediation. I.V. Rodshtat [16] provides data on the modulation of brain tissues by EHF radiation.

It is known that approximately 50% of lymphocytes can circulate from the blood to lymphoid tissue and back. The majority of recirculating lymphocytes are found in the regional lymph nodes. These immunocompetent cells can influence the brain via the inhibitory action of soluble mediators they release.

The effect of millimetre waves on the human and animal brain is characterised by asymmetry. Irradiation of the left half of the body is directed predominantly towards the right hemisphere in humans, and in experimental animals is accompanied by an increase in the population of long-lived lymphocytes in the lymph nodes on the irradiated side [17]. The effect observed when irradiating the right side of the body consists of an increase in the population of short-lived lymphocytes in lymphoid organs, which is explained by a more uniform targeting of the effect on both hemispheres. It can be assumed that, upon irradiation of the left half of the body with EHF,

EHF-induced modulation of brain activity is realised via nervous and humoral mechanisms, whereby the nervous signal is directed primarily to the right hemisphere, and the humoral signal to the hypothalamus. The response to irradiation of the right half of the body is primarily due to nervous mechanisms, with signals being directed more evenly to both hemispheres.

When considering the physiological mechanisms of electromagnetic radiation reception, it is necessary first to identify the primary physiological targets within the zone of action of electromagnetic waves. Apparently, structures close to the cutaneous layer can receive the entire frequency band. N.N. Lebedeva [18] identifies five primary physiological targets within the zone of direct action of electromagnetic radiation: 1) receptors of the central nervous system (mechanoreceptors, free nerve endings); 2) cells of the diffuse neuroendocrine system, specifically mast cells and Merkel cells; 3) cells of the immune system – cutaneous T-lymphocyte depots; 4) the microcapillary bed of the circulatory system; 5) biologically active points (BAPs).

These five primary targets determine the involvement of the corresponding systems in realising the biological effects of electromagnetic radiation. After the 'triggering' of these systems, a complex process of mediated action begins, affecting other systems (circulatory, humoral, and autonomic nervous systems) and internal organs. The characteristics of the reaction at this stage are determined by the properties of the electromagnetic radiation and the irradiation regime, as well as the initial state of the organism. The overall effect manifests as a reaction of increased non-specific resistance of the organism, which is, in turn, associated with high-level, anti-stressor reactivity [18].

The following data were obtained from a study investigating the effect of low-intensity millimetre-wave electromagnetic radiation (5.6 mm wavelength) on the functional state of the cerebral cortex [19].

1. The functional state of the cerebral cortex changes as early as 20 ms after the commencement of electromagnetic irradiation of the skin in the region of the distal third of the sternal projection.
2. Processes developing under the influence of millimetre-wave electromagnetic radiation in the neocortex, including the primary projection zone of the visual analyser, not only precede but can also invert the polarity of the initial cortical component of visual evoked potentials elicited by a flash of light synchronised with the onset of electromagnetic irradiation.

3. A necessary condition for the manifestation of the millimetre-wave r-adiation effect is the preferential synchronisation of cortical pote-ntials within a specific sub-band of the - rhythm (peak effectivene-ss at 11 Hz), coupled with the absence of conscious afferentation.

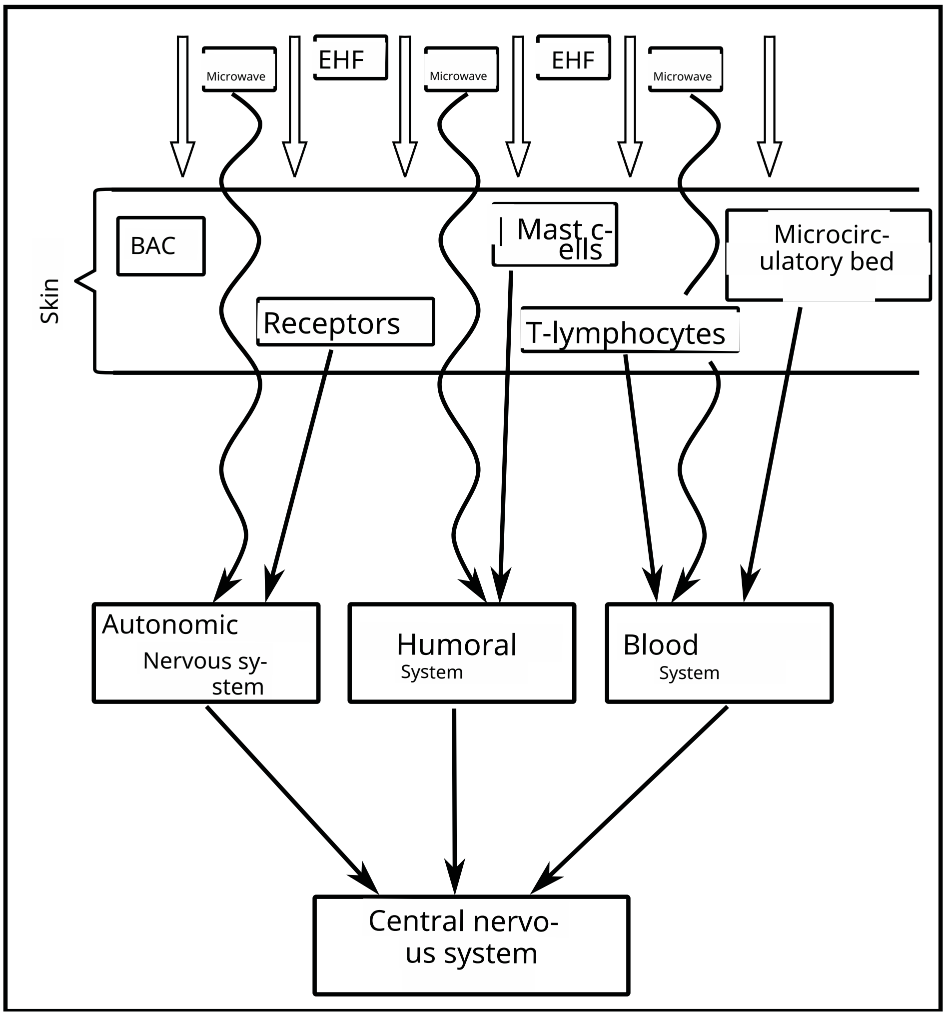

Fig. 6.5. Probable physiological mechanisms of electromagnetic field i-

nfluence on the central nervous system. Kovalev and Presnyakov [19] propose that the most likely mechanism for this cerebral cortex re-action to electromagnetic exposure is the modulation of background i-mpulse activity of neurons in the spinal ganglia, caused by the absorp-tion of electromagnetic waves in receptors. In this case, the backgrou-nd activity of neurons causes the constant propagation of potentials t-owards the brain (afferentation) along the fastest conducting excitation (group A) fibres of the posterior columns of the spinal cord and the m-edial lemniscal system. Electromagnetic radiation

Hence, influencing cutaneous receptors alters the nature of these s-pontaneous, constantly transmitted afferent signals, shifting the ne-ocortex to a different state, thereby modifying the response to simu-ltaneously acting light impulses.

In a study of sensory responses to low-intensity millimetre-wave electromagnetic waves [20], it was found that the perception of this exposure depends on the individual characteristics of the subject. In-dividuals displaying the highest power in EEG rhythms, as observed in the parieto-occipital leads, were more sensitive to these stimuli. T-hey exhibited a lower pain threshold to electric current and the high-est critical flicker fusion frequency. It was noted that recognition of t-he electromagnetic signal required a considerable time (over 400 ms). Apparently, awareness of the stimulus's significance and its classifi-cation requires interaction between sensory and non-sensory syste-ms, employing conceptual frameworks. Sensory systems enabling t-he recognition of electromagnetic influence are discussed in the foll-owing paragraph.

6.4. Sensory systems of mammals.

Role of the structural organisation of the skin in EMR reception

Experimental studies using broad-spectrum electromagnetic ra-diation have shown that humans and animals perceive this influence, even at low electromagnetic field intensities. Are there specific recep-tors for this? If these sensations are non-specific, caused only by ele-ctromagnetic fields, what are the systems that 'translate' electroma-gnetic effects into the 'language' of non-specific sensations? Let us c-onsider this question.

Research into the mechanisms of electromagnetic radiation recep-tion has been actively conducted since the 1970s. of the last century, p-rimarily with respect to specific receptors. As the electromagnetic field possesses both magnetic and electrical components, both magneto- a-nd electroreception are implicated. Among the most developed approaches applicable to terrestrial mammals, two can be distinguished: direct magnetoreception, based on the presence of magnetite particles within tissues, and indirect magnetoreception, based on Faraday's law, which is effectively electroreception.

Work conducted initially by J.L. Kirschvink [21, 22] confirms that all human tissues and organs contain magnetite particles. Particularly high concentrations have been found in brain tissue [23], the adrenal glands, and the bone tissue of the sphenoethmoidal sinus [24]. The hypothesis, based on the use of magnetite for magnetoreception in animals, proposes that sensitivity to the direction of a magnetic field can be explained by the presence of a small number of magnetosome-like structures associated with hair cells (as found in iron-containing bacteria). However, structures that might be responsible for implementing the reception mechanism involving magnetite particles have not been identified. The detailed operational mechanism of the sensory system based on magnetite remains unknown.

Another potential avenue for magnetoreception is indirect magnetoreception, as seen, in particular, in elasmobranch fish. In terrestrial animals, it is feasible if several requirements are met by a potential organ for electromagnetic radiation reception [25]: the organ should resemble a coil, comprising one or more turns of a conductor, and its dimensions must be at least several millimetres. A structure fulfilling these requirements has been identified in mammals and constitutes the Voigt line system [26]. The Voigt line system comprises orderly arranged hair follicles, forming a network of lines perpendicular to the animal's longitudinal body axis [27] (Fig. 6.6).

The resulting image closely resembles a solenoid, with its turns formed by the animal's skin structure. Here, the 'conductors' are, firstly, the Voigt lines. These consist of sequentially arranged groups of hair follicles encompassed by a network of capillaries, which exhibit greater conductivity than the connective tissue separating the Voigt lines. This connective tissue acts as insulation between the solenoid's turns.

Voigt lines, forming the turns of a 'solenoid', are hypothesised to represent a physical system [28] capable of generating a signal perceived by the animal organism. This system can operate over a very wide frequency range – from direct current to extremely high frequencies (EHF) – analogous to a system of coupled oscillatory circuits. At low frequencies, including within a constant magnetic field, when an animal moves within the Voigt lines, as the turns of a so-

In the solenoid, electrical currents will be induced. In the case of EHF fields, the line system acts as a diffraction grating, modulating wave transmission into the subcutaneous layers. At intermediate frequencies, resonances (modes of oscillations) may occur, in accordance with the multimode nature of the frequency response of the oscillatory system under consideration (the 'solenoid' – Voigt lines). The induced signal at low and ultra-low frequencies can lead to the generation of an afferent nerve impulse, while at high frequencies, up to EHF, mediation may occur due to the effects of electromagnetic radiation at the molecular level.

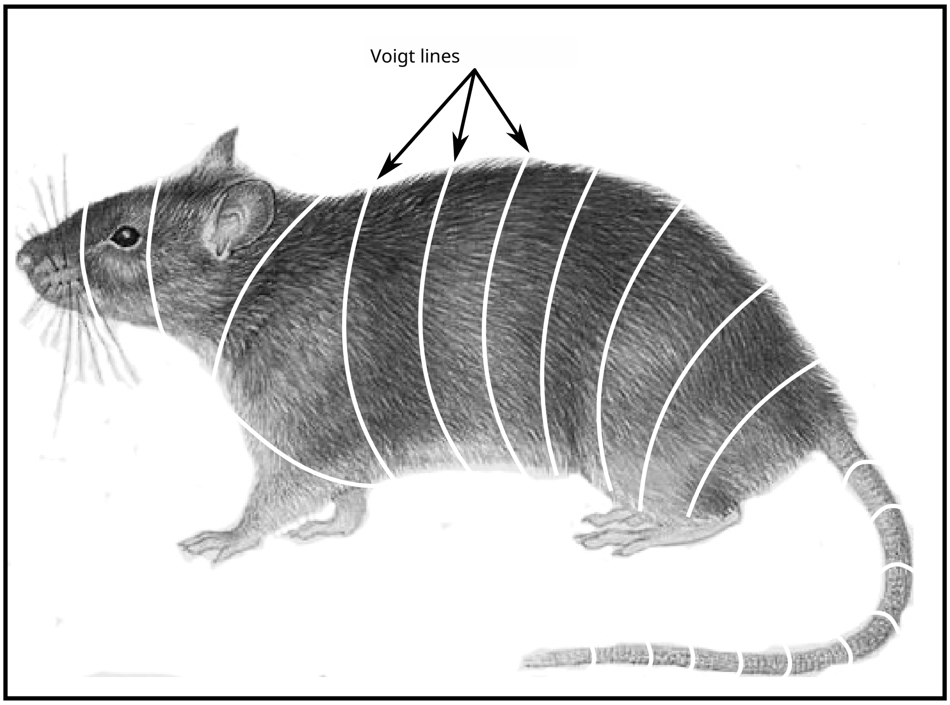

Fig. 6.6. Location of Voigt lines on the animal's body. Experimental confir-

mation of the validity of these arguments comes from the results obtained when irradiating mice with millimetre-wave EMF in the thigh region [29]. Measurements of the absorption characteristics of EHF oscillations in the frequency range from 41.0 to 43.0 GHz, both in the skin of intact mice and in animals with surgically created skin flaps, showed a linear dependence of EHF radiation absorption on the distance between adjacent Voigt lines. These results are consistent with the hypothesis that Voigt lines within this electromagnetic radiation (EMR) frequency range act as a diffraction grating. Finally, the observed frequency dependence of VSWR, associated with radiation absorption by the skin and sensitive to EMR, confirms that Voigt lines act as a primary transducer, where the physical parameters of the skin are determined by the presence of so-called 'conductors' and 'insulators' formed by Voigt lines [30].

The observed frequency dependence of VSWR, associated with radiation absorption by the skin, sensitive to EMR, confirms that Voigt lines act as a primary transducer, where the physical parameters of the skin are determined by the presence of so-called 'conductors' and 'insulators' formed by Voigt lines [30].

The results obtained from experiments on mice [31] suggest that the animals respond to the direction of the geomagnetic field vector (GMF). According to current understanding, the larger the surface area of an animal's body that is perpendicular to the magnetic field vector, the greater the induced signal and corresponding animal reaction expected. The results of experiments in a static magnetic field (SMF) [32] also demonstrated that, compared with baseline levels, the behavioural reactions of mice following exposure are dependent on the animal's position within the experimental field. The greatest effect was observed when the direction of the animal's main body axis coincided with the field strength vector, i.e. when the vector is perpendicular to the 'solenoid turns' formed by the Voigt lines.

The authors of the sensory system hypothesis for EMF perception [28] suggest that, regardless of the mechanism and material substrate mediating this, the most significant factor in EMF reception is the emergence of an afferent signal, leading to a change in the activation level of the hypothalamic-pituitary-adrenal system. Essentially, animals, through such a system, possess the capacity to modify their adaptive state, thereby maintaining it at a specific level, optimal for responding to any stimuli the animal may encounter.

A key aspect in the discussion of the proposed hypothesis is the presence of asymmetry within the Voigt line system. All the mice studied displayed asymmetry in the Voigt lines between the right and left sides, which, according to the authors, enhances sensitivity to the in-phase signal. By analogy with various technical differential systems (starting with a differential amplifier), asymmetry results in increased sensitivity to signal difference.

When moving, the mouse crosses the magnetic field lines of the Earth's geomagnetic field. This can lead to the induction of currents in 'conductors', the magnitude of which depends on the rate of change of magnetic flux through the conducting loop and the resistance of the 'conductors' ($F = HS \sin \square$, where F – magnetic flux; S – area of the loop; $\square$ – angle between the plane of the loop and the direction of the field lines).

Thus, the linear displacement of the mouse, the animal's respiratory movements, and rotations and elevations, can induce induction currents. Therefore, when the animal is positioned east to west or west to east, respiratory movements do not induce currents. When the mouse moves perpendicularly to the horizontal component of the geomagnetic field vector, an electromotive force is induced on the dorsal (dors), ventral (ventr) and lateral (side) surfaces, inducing the generation of corresponding currents:

$$U_h^{side} \square \frac{dl}{dt} k\, H_h;$$

$$U_v^{dors} \square U_v^{ventr} \square \frac{dl}{dt} k\, H_v,$$

где H_h – horizontal component of the geomagnetic field; H_v – vertical component of the geomagnetic field; V – speed of the mouse's movement; $I_h{}^r$ – currents induced when crossing the horizontal component of the GMF during the animal's respiration; $I_v{}^m$ – currents induced when crossing the vertical component of the GMF during the animal's movement; $\square S$ – change in the cross-sectional area of the mouse's chest during exhalation.

When a mouse moves along the horizontal component of the GMF vector, an electromotive force is induced on the dorsal and ventral surfaces, inducing the generation of corresponding currents:

$$\square U^m \square U_v^{dors} \square U_v^{ventr}.$$

With a similar mouse placement, its respiratory movements, which cause changes in the cross-sectional area of the thorax, induce an EMF across the entire body surface. The direction of the induced currents depends on the direction of change in the cross-sectional area, that is, inhalation and exhalation result in the generation of oppositely directed currents:

$$\square U^r \square \quad \square(U_h^{dors} \square U_h^{ventr} \square 2U_h^{side}).$$

Summing the effects of movement and respiration, we obtain (inhalation):

$$\square U \square 2U_h^{side} \square (U_h^{dors} \quad U_v^{dors}) \square (U_h^{ventr} \square U_v^{ventr});$$

$$\square U \square 2\frac{dS^{side}}{dt} k\, H_h \square \frac{dS^{ventr}}{dt} k\, H_h \square \frac{dl^{ventr}}{dt} k\, H_v \square$$

$$\square \frac{dS^{dors}}{dt} k\, H_h \quad \frac{dl^{dors}}{dt} k\, H_v.$$

Therefore, the currents induced on the lateral surfaces are dependent on respiratory movements. Currents induced on the dorsal surface are maximal during exhalation and minimal during inhalation . Currents induced on the ventral surface are maximal during inhalation and minimal during exhalation.

An investigation into human perception of electromagnetic radiation [33] leads T.I. Kotrovskaya to the conclusion that there is an absence of any specific formations. In their work, they rely on the potential participation of known receptors. Studies of human sensory responses to weak electromagnetic influences have shown that, according to subjective reports from subjects, the modalities of the resulting sensations are distributed as follows: tingling – 38.2%, pressure – 29% , heat/cold – 12%, touch – 9.2%, vibration, pulsation – 5.2%, aching, distension – 3%, itching, pain, burning – 3% [34]. Based on the modality of the resulting sensations, either mechanoreceptors or free nerve endings – unmyelinated efferent fibres lacking corpuscular structures at their terminals – are involved in the reception of the electromagnetic stimulus [35, 36].

Since the reception of such weak stimuli as low-intensity electromagnetic fields requires either slowly adapting receptors, receptors with background activity, or preferably both, only Ruffini endings, tactile discs, and Merkel discs, of the mechanoreceptors, can fulfil these criteria.

Cutaneous pain receptors (nociceptors) also meet these requirements. They are free nerve endings comprising thin myelinated or unmyelinated nerve fibres and are characterised by the following properties: polyspecificity with respect to stimuli; sensation modality – such as tingling and burning – which specialists interpret as 'pre-pain'; disappearance of electromagnetic sensitivity following treatment of the skin with chloroethyl, which 'switches off' pain receptors; sensory response in the affected organ upon irradiation of the corresponding dermatomes (convergence of nociceptive afferents from dermatomes of internal organs onto the same neurons of pain pathways, with skin hypersensitivity manifesting due to visceral impulses increasing the excitability of interneurons, resulting in facilitation, i.e., 'easing').

Studies on the perception of electromagnetic signals have demonstrated a prolonged latency period prior to their recognition, which, the authors suggest, is associated with the content of the perceptual process [34].

The latter can be conventionally divided into three stages: 1) analysis of the physical characteristics of the stimulus; 2) synthesis of sensory and non-sensory information regarding the stimulus; 3) identification of the stimulus, that is, its classification within a specific object group. It has been established that sensation arises solely during the second stage of the sensory-perceptual process. Consequently, the external object is represented in the mind as an aggregation of its physical characteristics. Awareness of the stimulus occurs at the third stage.

Each stage corresponds to a specific type of response: the first is an automated conditioned reflex with a latency of approximately 100...200 ms from the stimulus onset; the second, a reaction to sensation (200...400 ms); and the third, organismal responses formed on the basis of a complete awareness of the stimulus significance. Reactions of this type exhibit unlimited latency, because the response may occur after a considerable duration [37]. It is probable that the recognition reaction to an electromagnetic signal follows the 3rd type, with the latent period being three orders of magnitude longer than the reaction time in the visual and auditory sensory systems, amounting to 40...50 s.

Considering the possible causes of signal delays in sensory reactions, four main components of the reflex arc are identified: the receptive field → conducting pathways → subcortical component of stimulus analysis → cortical component of analysis, sensation formation and verbalisation [38]. In the first component, there should be no delays; in the second component, delays are possible with a large number of synaptic switches, conduction of afferent signals along unmyelinated nerve fibres, and the inclusion of humoral components; In the third and fourth blocks, significant delays may occur due to difficulties in identifying a signal, such as an electromagnetic field.

A detailed study of the changes in brain activity arising under the influence of electromagnetic interference (EMI) revealed that microwave (MW) fields induce a non-specific (parameter-independent) diffuse (throughout all brain regions) EEG synchronisation reaction, characterised by an increase in the number of slow waves and spindles in the EEG [39]. According to other data, the most intense reaction was observed in the cerebral hemispheres, hypothalamus, and non-specific nuclei of the thalamus [40]. Reports exist regarding the gradation of EEG reaction intensity to microwave fields, with the highest intensity in the hypothalamus, decreasing in the following order: cortex, thalamus, hippocampus, reticular formation [41]. Experimental data [33] concerning the sensory indication of EHF radiation have demonstrated the influence of the latter on the spatiotemporal organisation of human brain biopotentials. These data do not permit the assignment of pathways for signal transduction from electromagnetic exposure to specific pathways.

In turn, a non-specific system is characterised by afferent inputs that are less clearly defined; the system can be excited by converging signals from all sensory surfaces (polymodal or polysensory convergence). The characteristics of electromagnetic signal perception and transduction have led to the suggestion [38] that this is mediated primarily by the non-specific (extralemniscal) somatosensory system. The primary functions of the non-specific system are the emotional colouring of perception, the control of the state of consciousness, and orienting reactions.

6.5. Conclusion

The main characteristics of electromagnetic radiation on organisms, as considered in §§ 6.1–6.3, can be briefly summarised in tabular form. Tables 6.1–6.3 below present those manifestations of physical and physiological mechanisms impacting the systems of the organism that are of direct significance for human health. An analysis of these data is included in the review's overall conclusion. With regard to sensory systems that could provide sensory perception of electromagnetic radiation, there is very little specific research on this topic; most relates to the low-frequency range. Therefore, the conclusions drawn from a review of the available literature are tentative. The central tenet is that the sensory system contains non-specific sensors (mechanoreceptors, nociceptors, nerve endings), the signals from which are generated by changes in the state of biological structures at the micro level. Voigt lines can be considered as a macrosystem that contributes to the formation of such signals by amplifying the effect of the electromagnetic field on sensors.

Table 6.1

Thermal effects

1	Mechanism of action of thermal-level radiation	1. Heating of biological tissues due to polarisation losses within the aqueous component
2	Consequences at the cellular level	1. Alteration in the chemical activity of water and electrolytes. 2. Alteration in the functional activity of proteins, including enzymes. 3. Alteration in metabolic processes, reduction in cell viability. 4. Cell death
3	Consequences at the organism level	1. Suppression and discoordination of organismal system function. 2. Reduced immunity. 3. Chronic diseases

Table 6.2

Effects of non-thermal electromagnetic radiation

Pos.	Target of impact action	Possible physical mechanism	Biologically significant consequences
1	Water molecules	Excitation of oscillations in water clusters a) during direct interaction with electromagnetic radiation; b) due to interaction with biomolecules such as ATP	• Alteration of the chemical activity of water and electrolytes. • Alteration of the degree of hydration of proteins, and consequently, alteration of their functional activity.
2	Biomacro molecules	Synchronisation and accumulation of energy in vibrational modes within the chain structures of proteins and DNA.	• Conformational transitions in protein molecules, and consequently, alteration of functional activity: a) Enzymes; b) gate proteins; c) transport proteins. • DNA strand breaks. • Alteration of the tertiary structure of chromosomes and modification of transcription
3	Membranes	Excitation of acousto-electric waves	• Alteration of charge distribution on the membrane. • Conformational transitions in protein molecules embedded in the membrane, and alteration of their functional properties.
4	Biological tissues	Local heating in antinodes of standing waves during electromagnetic wave interference	Alteration of metabolic process activity

Table 6.3

Physiological mechanisms of reception

		Type of manifestation
1	Radiation r-eception	1. Mechanoreceptors: a) Ruffini corpuscles; b) Merkel discs. 2. Pain receptors. 3. Immunocompetent cells: a) Mast cells; b) Lymphocytes.
2	Afferent me-diation	1. Nerve signal: a) Action potential modulation; b) Action potential generation. 2. Humoral signal. 3. Vascular-autonomic response
3	CNS reaction	1. Cerebral cortex – integral assessment of afferent somatosensory information. 2. Hypothalamus – reactions of the centres regulating autonomic functions, including the reaction of the system regulating corticosteroid levels in the blood.
4	Efferent response	1. Neurohumoral. 2. Nervous. 3. Vasomotor: a) Change in tone; b) Change in tissue blood supply.

References for this chapter

1. Devyatkov, N.D., Golant, M.B., & Betsky, O.V. Millimetre waves and their role in life processes. – M.: Radio and Communication, 1991. – 169 p.
2. Chukova, Yu.P. Isothermal processes of interaction of the electromagnetic field with biological objects. Millimetre waves in biology and medicine, 1996, No. 8, P. 48–61.
3. Millimetre absorption spectroscopy of aqueous systems / Yu.Y. Khurgin [et al.] // Advances in Chemical Physics. – 1994. – V. 87. – P. 483.
4. Khurgin Yu.I. On the role of water activation in medicinal and EHF therapy / Yu.I. Khurgin, O.V. Lebedev, E.Yu. Maksareva // Millimetre Waves in Biology and Medicine. – 1994. – № 4. – C. 28–32.
5. Betsky O.V., Lebedeva N.N. Modern understanding of the mechanisms of action of low-intensity millimetre waves on bio-

gical objects // Millimetre Waves in Biology and Medicine. – 2001. – № 3. – C. 5–19.

6. Betsky O.V. Mechanisms of primary reception of low-intensity millimetre waves in humans // Reports of the X Russian Symposium 'Millimetre Waves in Medicine and Biology'. Moscow, 24–26 April 1995 – M., 1995. – pp. 135–138.
7. Physics of millimetre-wave interaction with biological objects / V.I. Petrosyan [et al.] // Proceedings of the 10th Russian Symposium ' Millimetre Waves in Medicine and Biology'. Moscow, 24–26 April 1995 – M., 1995. – Pp. 140–143.
8. The role of resonant molecular-wave processes in nature and their use for monitoring and correcting the state of ecological systems / V.I. Petrosyan [et al.] // Biomedical Radioelectronics. – 2001. – No. 5–6. – Pp. 62–127.
9. On the biophysical mechanism of the effect of millimetre-wave radiation on biological processes / A.P. Zhukovsky [et al.] // Proceedings of the X Russian Symposium "Millimetre Waves in Medicine and Biology". Moscow, 24–26 April 1995 – M., 1995. – pp. 152–153.
10. On the biochemical mechanism of the effect of millimetre-wave radiation on biological processes / A.P. Zhukovsky [et al.] // Millimetre Waves in Biology and Medicine. – 1993. – No. 2. – pp. 36–42.
11. On biophysical mechanisms of the effects of extremely high frequency electromagnetic fields on cell membranes / M. Kuzmanova [et al.] // Reports of the X Russian Symposium «Millimetre Waves in Medicine and Biology». Moscow, 24–26 April 1995 – M., 1995. – p. 157.
12. Biophysical mechanism of acousto-electric wave generation on the cell membrane / A.N. Volobuev [et al.] // Millimetre Waves in Biology and Medicine. – 1995. – No. 5. – pp. 14–17.
13. Frohlich H. Bose condensation of strongly exited longitudinal electric modes // Phys. Lett. – 1968. – V. 26A. – P. 402.
14. Khizhnyak, E.P., and Ziskin, M.S. Mechanisms of Interaction of Millimetre-Wave Electromagnetic Radiation with Biological Objects. In: Collection of Reports of the XI Russian Symposium, "Millimetre Waves in Medicine and Biology". Moscow, 2–12 April 1997. – M., 1997. – C. 128-131.
15. Lebedeva, N.N. Neurophysiological Mechanisms of Biological Effects Following Peripheral Exposure of Humans to Non-Ionising, Low-Intensity Fields. In: Reports of the X Russian Symposium, "Millimetre Waves in Medicine and Biology". Moscow, 24–26 April 1995 – M., 1995. – Pp. 138–140.

16. Rodshtat, I.V. Physiological mechanisms of EHF modulation of immunoreactive and nervous tissues based on experimental and clinical studies // Reports of the X Russian Symposium "Millimetre Waves in Medicine and Biology". Moscow, 24–26 April 1995 – M., 1995. – Pp. 145–147.
17. Gurevich, M.E. Reaction of mouse lymph nodes to millimetre-wave microwave radiation, depending on the site of exposure and the initial state of the animals: author's abstract of dissertation ... Candidate of Medical Sciences / M.E. Gurevich; Tomsk Medical Institute. – Tomsk, 1987.
18. Lebedeva, N.N. Physiological mechanisms of biological effects of low-intensity millimetre-wave electromagnetic waves // Reports of the XI Russian Symposium «Millimetre Waves in Medicine and Biology», Moscow, 2–12 April 1997. – M., 1997. – P. 126–128.
19. Kovalev, A.A., & Presnyakov, O.V. Mechanism of the primary influence on the human cerebral cortex of transformation manifestations in its organism due to external low-energy EHF radiation // Millimetre Waves in Biology and Medicine. – 1999. – № 2(14). – P. 25–36.
20. Lebedeva, N.N., & Kotrovskaya, T.N. (1996). Electromagnetic reception and individual characteristics of humans. *Millimetre Waves in Biology and Medicine*, *7*, 14–19.
21. Magnetit in human tissues: the mechanism for biological effects of weak ELF magnetic fields / J.L. Kirschvink [et al.] // Bioelectromagnetics. – 1992. – V. 1. – P. 101–103.
22. Kirschvink J.L., Gould J.L. Biogenic magnetit as a basis for magnetic field detection in animals // BioSystems. – 1981. – V. 13. – P. 181.
23. Kirschvink J.L. Magnetit biomineralization in a human brain / J.L. Kirschvink, A. Kobayashi-Kirschvink, B.J. Woodford // Proc. Natl. Acad. Sci. USA. – 1992. – V. 89 (16). – P. 7683–7687.
24. Becker, R. Robin. Magnetoreception in humans and other primates . (1989). In *Biogenic Magnetite and Magnetoreception* (Vol. 2, pp. 342–374). Mir.
25. Rosenblum, B. Rosenblum, B., Jungerman, R.L., & L. Limitations in considering the induction hypothesis of magnetoreception. Longfellow Low // Biogenic magnetite and magnetoreception. – M.: Mir, 1989. – Vol. 1. – P. 293–305.
26. Kalantaevskaya, K.A. Morphology and physiology of human skin. – Kiev, 1972. – P. 267.
27. Chuprikova, E.M., Perelmuter, V.M. Features of hair follicle location on mouse skin // Actual problems of medical biology. – Tomsk: SGMU, 2002. – P. 54–55.

28. Hypothesis: 'Voigt lines (ordered arrangement of hair follicles) constitute a sensory system for electromagnetic radiation'/ V.I. Zelentsov [et al.] – Intellectual Product No. 72200200008, registered with VNTIC on 06.03.2002.
29. Shalovay, V.V. Morphofunctional characteristics of murine skin under the influence of low-intensity EHF radiation in the millimetre wave range: abstract of dissertation ... Candidate of Medical Sciences / V.V. Shalovay. – Tomsk, 1995. – 29 p.
30. Shalovay, V.V. The connection of Voigt line parameters with an adaptive system / V.V. Shalovay, V.M. Perel'muter, Z.I. Rzhevskaya. – Tomsk, 1993. – 9 p. – Dep. In VINITI 01.07.93, No. 18161893.
31. A method for registering the biological effects of weak electromagnetic fields / V.I. Zelentsov [et al.]. – M., 1999. – Patent for invention of 10.09.99 No. 98102648/14(992080).
32. Chuprikova, E.M. The role of hierarchical status of experimental animals in responding to weak influences // Collection of articles by young scientists and students «Modern problems of fundamental and clinical medicine». – Tomsk, 1999. – Pp. 39–40.
33. Kotrovskaya, T.I. 'Sensory reactions of humans under the influence of a weak electromagnetic stimulus'. *Millimetre Waves in Biology and Medicine*, 1994, no. 3, pp. 32–38.
34. Lebedeva, N.N. 'Reaction of the central nervous system of humans to electromagnetic fields with various biotropic parameters': Dissertation abstract for the degree of Doctor of Biological Sciences / N.N. Lebedeva. – M., 1992. – 48 p.
35. Korinevskaya, I.V., Kholodov, Yu.A., and Korinevsky, A.V. 'EEG correlates of humans under diverse peripheral influence by a variable magnetic field'. *Human Physiology*, 1993, vol. 19(3), pp. 71–79.
36. Ivanitsky, A.M. Information processes of the brain and mental activity / A.M. Ivanitsky, V.B. Strelets, I.A. Korsakov. – M.: Nauka, 1984. – 201 p.
37. Kholodov, Yu.A., Lebedev, N.N. Reactions of the human nervous system to electromagnetic fields. – M.: Nauka, 1992. – P. 96.
38. Rodshtat, I.V. A psychophysical approach to the evaluation of organismal reactions under the therapeutic effect of millimetre waves. – Preprint № 11(52). – M.: IRE AS USSR, 1989. – P. 21.

CONCLUSION

The biological effects of electromagnetic radiation discussed in this r-eview provide a general understanding of the significance of this physical factor to human health. Electromagnetic waves, even at non-thermal pow-er levels with an intensity comparable to background noise or spurious ra-diation from household and industrial devices, exert an influence on biolo-gical structures, from biomolecules to the organism as a whole.

The principal observed effects of non-thermal intensity electrom-agnetic radiation on biological objects at varying levels of organisation , which are most relevant to human health, can be summarised in the generalised table below.

Table

Biological effects of electromagnetic radiation

Target of Exposure	Frequency Range	Effect
Water molecules in biological objects		
Water molecul-es in biological o-bjects	1...150 GHz	a) Alteration of water cluster structure; b) alteration of the chemical activity of water; c) alteration of the hydration of protein m-
olecules (Biomolecules);		
DNA	1...80 GHz	chain breakage, blocking of readout
Enzymes		change in conformational state, resulting in alt-ered functional activity
Membrane proteins		change in the efficiency of ion and molecule transp-ort across membranes
Transport proteins		modulation of affinity for transported molecules (Me-mb-
ranes)		
Membranes	50...80 GHz	a) increase in membrane stability
	50...80 GHz	b) alteration of charge distribution on the surfa-ce, alteration of membrane potential
	50...80 GHz, ultrashort p-ulses with c-arrier f = 10 G-Hz	c) alteration of permeability for Na^+ and K^+ ons and water molecules
	40...60 GHz	d) alteration of nerve impulse conduction

Table continued

Cells		
Cells	1... 70 GHz	1. Alteration of membrane resistance. 2. Changes in the dynamics and structure of the protein system on the surface of membranes, alteration of the functional properties of immunocompetent cells. 3. Modification of metabolic processes. 4. Inhibition or stimulation of cell division. 5. Programmed cell death
Tissues		
Tissues	40...60 GHz	Stimulation of tissue regeneration
Functional systems of the organism		
Nervous system	1... 60 GHz	1. Activation of spontaneous receptor activity. 2. Synchronisation reaction of the central nervous system during wakefulness. 3. Increased dynamism of the central nervous system in an inhibited state, up to epileptiform activity.
Endocrine system		Adaptive reaction, leading to the correction of hormone concentrations within the endocrine system.
Reproductive system		Change in the functional state of the reproductive system, with an increase in the number of adverse reproductive outcomes and spontaneous abortions.
Holistic organism		
Holistic organism	1–70 GHz	a) The occurrence of sensations such as burning , tingling, and pressure; b) behavioural disturbances; c) memory alteration; d) the development of diseases;

A review of studies investigating the effects of electromagnetic radiation on biological objects allows the following conclusions to be drawn.

1. Biological effects of electromagnetic radiation in the centimetre and millimetre range are observed even at non-thermal intensity levels.
2. These effects are predicated on resonant interactions between the electromagnetic wave and water molecules within biological structures, as well as with biomacromolecules and membranes.
3. Although the energy of a quantum of the electromagnetic field in the 1...150 GHz frequency range is low compared with the thermal energy of the biological medium kT, the structural properties of biological molecules and membranes facilitate energy accumulation in acousto-

electrical oscillations to effect structural (conformational) transitions.

4. Such transitions modify the functional capabilities of biomacromolecules, which, in turn, alters the course of biological processes (metabolism, transport, impulse conduction, etc.).

5. Changes in the dynamics of biological processes can be either stimulatory or inhibitory, depending on the parameters of the incident electromagnetic radiation, primarily its frequency.

6. The effectiveness of the impact is determined not only by the radiation parameters, but also by the correspondence of that frequency to the resonant frequencies of biological structures, the spectra of which may vary between subjects. This largely accounts for the poor reproducibility of experimental results.
7. The outcome of exposure at the level of the whole organism depends on the initial state of functional systems and the site of exposure, owing to functional asymmetry.
8. The pathological and therapeutic effects of electromagnetic radiation described typically occurred with repeated or chronic exposure. However, the available data are insufficient to determine the most effective or dangerous frequencies and radiation modes.
9. This is particularly true for short microwave pulses (shorter than those used in radar) and ultra-wideband signals.
   Only a few experimental studies on animals have examined the biological effects of such pulses.
10. Given that the radiation spectrum of these signals, as calculated in the chapter, and the frequency range in which biological effects are observed overlap, it is reasonable to expect that such pulses will affect human health, potentially causing pathological effects. However, direct extrapolation of results obtained with other radiation parameters to predict the hazard of ultra-wideband signals is not currently justified due to a lack of sufficient data. Further research is necessary, ideally using generators of ultrashort microwave pulses.

Educational publication

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Study Guide

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