THE ACTION OF MICROWAVES ON LIVING ORGANISMS AND BIOLOGICAL STRUCTURES

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THE biological action of radiofrequency electromagnetic fields has been studied for about forty years. During this time, as radio technology has developed, the field of investigation has extended to higher and higher frequencies. Studies of the biological action of microwaves have covered an especially large scope.* In the course of about twenty years since this range was technically made accessible, more than 1000 papers have been published on the problems of the electrical properties of living tissues in the microwave range, the absorption and transformation of microwave energy in tissues, the action of these waves on living organisms and biological structures and the determination of the mechanism of this action, the application of microwaves in physiotherapy, the study of the harmful action of microwaves, and finally, the use of microwaves in biological research.

It has been established that microwaves affect living organisms of the most varied degrees of organization—from the simplest to the most highly developed, and that this influence occurs even at very low irradiation intensities and is characterized by varied effects—from reactions of the whole organism to changes at the molecular level. There are grounds for supposing that microwaves even take part in some biological processes.

Biologists and doctors have been drawing physicists and engineers more and more into studies on the biological action of microwaves. These trends have been especially noticeable in recent years, when the experimental material already accumulated has made it possible to proceed to studying the biophysicochemical mechanisms of this action. In addition, physicists and radio engineers have also found topics of independent interest in these studies: the possibility of studying certain specific biological phenomena, and also some initial data for constructing physical models of certain biological systems and processes.

This gives us grounds for thinking that the necessity has come to a head of acquainting physicists with the experimental and theoretical studies on the biological action of microwaves, since the pertinent reviews have been published heretofore mainly in the biological and medical journals.[1-11] On the other hand, far from all of the articles that have appeared in the electronics journals[12-16] are distinguished by enough thoroughness of presentation.

*In biological and medical literature, microwaves are understood to cover the broad range from 100 megacycles to 100 gigacycles.

In this article we shall discuss those experimental and theoretical studies that we deem to be of greatest interest to physicists, and we shall try to do this in a form accessible to non-specialists in biology and medicine.

Since the studies of the biological action of microwaves are related to a considerable extent to corresponding studies in other regions of the radiofrequency spectrum (and recently even in the low and infralow frequency regions), we shall sometimes find occasion to go beyond the limits implied by the title of this article.

1. ELECTRICAL PROPERTIES OF TISSUES IN THE MICROWAVE RANGE

A considerable number of studies have been concerned with the electrical properties of tissues and cell suspensions in the microwave region, including several special review articles.[17-19]

The early studies[6,18] had already established that the dielectric constant and resistivity of tissues at frequencies lower than tens of megacycles are determined mainly by the cell membranes, which act as thin films of high capacitance and resistance. The frequency-dependence of the impedance of cell membranes gives rise to the observed decline in the impedance of tissues with increasing frequency.

In the microwave range (above 100 megacycles), cell membranes become practically short-circuited. Hence, the electrical properties of cell suspensions and tissues of high water content are determined by the water, salt, and protein content of the intra- and intercellular medium. The electrical properties of fatty tissues are determined by the parameters of the fat cells and the electrolytic medium surrounding them.

People have generally measured the complex dielectric constant of animal and human tissues in freshly excised specimens at a temperature of 37°C (at 27°C in some measurements). Here they used the waveguide and resonance methods that are well known in radio technology, modified to take account of the high values of the dielectric constant and the tangent of the loss angle in living tissues.[20-23] For measurements in the range 100—1000 megacycles, a two-wire transmission line has been used,[24-26] a coaxial line[27,28] in the range 1—3 gigacycles, and a waveguide[29-31] at higher frequencies. The measurements on liquid substances were performed with the same methods, and also with the use of coaxial and waveguide bridges.[32]

Table I. Complex dielectric constant of human tissues in the microwave range at 37°C

Type of tissue	Frequency, Mc							
	100	400	1000	3000	4600	8500	9400	24 000
ε' — dielectric coefficient								
Muscles	73.5	53.0	50.5	46.5	47.3	41.0	—	—
Skin	—	—	—	43.5	—	35.5	—	23.0
Liver	77.5	46.0	46.5	42.5	—	36.0	—	—
Fat	—	5.5	6.4	6.5	5.85	4.0	4.5	3.4
Bone marrow	—	—	5.8	5.0	—	4.9	—	—
Bones	—	—	—	8.35	7.83	—	7.6	6.3
Whole blood	—	61.5	62.5	53.0	—	—	45.0	32.0
Water	74.4	74.5	—	74.4	71.5	—	65.3	41.6
ε'' — loss coefficient								
Muscles	—	51.5	23.4	18.0	18.6	17,6	—	—
Skin	—	—	—	16.5	14.0	—	16.0	13.0
Liver	107.0	39.0	17.6	12.2	—	13,3	—	—
Fat	—	3.7	2.08	1.6	1.17	0,66	0.95	1.1
Bone marrow	—	—	1.27	1.05	—	0,68	—	—
Bones	—	—	—	1.32	1.3	—	1.45	1.1
Whole blood	—	58.5	28.0	15.0	—	—	23.0	20.0
Water	0.3	0.95	—	8.2	12.8	—	22.3	34.5

Notes: 1. The values of ϵ'' at 100–3000 megacycles were obtained by recalculation from the corresponding conductivity data.
2. The values of ϵ' and ϵ'' for blood were obtained by recalculation from the corresponding data at 27°C (using the temperature coefficients).
3. The values of ϵ' and ϵ'' for water were obtained by recalculation from the corresponding data for 20° and 25°C.

Resonance methods, in which the sample is placed in a coaxial or volume resonator, have been applied only for small samples of biological materials.[33,34]

We can classify[5,6,18] the tissues of living organisms into three groups in terms of the values of the complex dielectric constant $\epsilon^* = \epsilon' + j\epsilon''$ and its type of dispersion in the microwave range, in line with their water content: fluid tissues (blood, lymph), tissues of high water content (muscle, skin, liver, etc.), and tissues of low water content (fat, bone).

Table I, which is compiled from the data of various authors,[5,6,18,28-31,35] gives the values of ϵ' and ϵ'' for typical human tissues at various frequencies. Also given are the corresponding data for water.[5,25,36] The corresponding animal tissues likewise show similar values of the discussed quantities[27] (see Table I).

The data given in the table show that tissues of high water content show high values of the dielectric constant, while tissues of low water content show low values. The values of the dielectric constant of blood prove to be about 30% lower than the corresponding values for water (or a physiological solution). This difference has been ascribed[25,26] to the presence in the blood of protein molecules (mainly hemoglobin), which act like "dielectric cavities" of low dielectric constant (20–25 or less) in an electrolytic medium of high dielectric constant.

The data in the table illustrate the frequency-dependence, or dispersion of the complex dielectric constant in the microwave range. A theoretical analysis of the form of the dispersion for tissues of high water content has been made[37,38] by examining the data for blood. The structure of the latter is well known, and one can easily compare the results for it with the corresponding data for water. Figure 1 shows the dispersion curves of the dielectric constant and the resistivity of blood.[6]

A number of studies[25,36,38,39] have shown that the Debye-Danzer equations[40] satisfactorily approximate the trend of the dispersion for blood at frequencies below 100 megacycles. These equations were derived on the basis of the Maxwell-Wagner theory for spherical particles suspended in a medium having

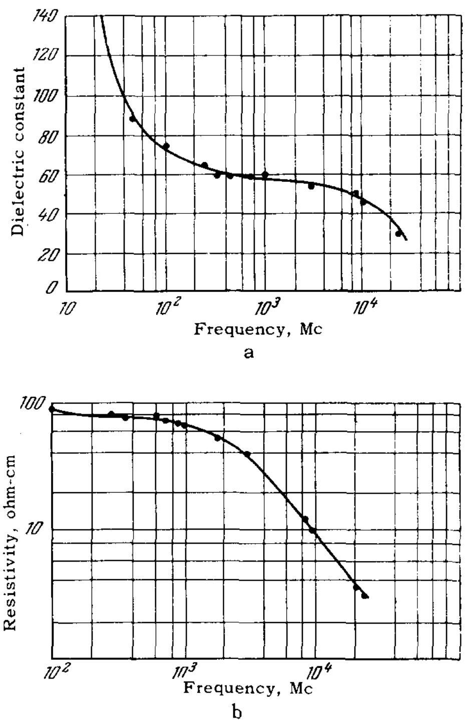


FIG. 1. Dispersion of the dielectric constant (a) and the resistivity (b) of blood in the radiofrequency range.

differing values for the complex dielectric constant:

$$\varepsilon' = \varepsilon'_\infty + \frac{\varepsilon'_0 - \varepsilon'_\infty}{1 + (\omega T)^2}, \quad \varkappa = \varkappa_0 + \frac{\varkappa_\infty - \varkappa_0}{1 + (\omega T)^2}(\omega T)^2, \qquad (1)$$

where

$$\left.\begin{aligned} T &= RC_m \frac{\varkappa_i + 2\varkappa_a}{2\varkappa_i\varkappa_a + RG_m(\varkappa_i + 2\varkappa_a)}, \\ \varepsilon'_0 &= \frac{9}{4\varepsilon_r} \frac{pRC_m}{\left[1 + RG_m\left(\frac{1}{\varkappa_i} + \frac{1}{2\varkappa_a}\right)\right]^2}, \\ \varkappa_\infty &= \varkappa_a\left(1 + 3p\frac{\varkappa_i - \varkappa_a}{\varkappa_i + 2\varkappa_a}\right), \\ \varkappa_0 &= \varkappa_a\left[1 - \frac{3}{2}p\frac{1 + RG_m\left(\frac{1}{\varkappa_i} - \frac{1}{\varkappa_a}\right)}{1 + RG_m\left(\frac{1}{\varkappa_i} + \frac{1}{2\varkappa_a}\right)}\right], \end{aligned}\right\} \qquad (2)$$

ϵ is the dielectric constant, κ is the conductivity (ohm^{-1}/cm), T is the relaxation time constant, R is the radius of the blood particles (cm). p is the fraction of the volume occupied by the particles, C_m and G_m are the capacity and conductivity of the membrane per cm^2, and $\epsilon_r = 8.85 \times 10^{-14}$ farad/cm.

The subscripts 0 and ∞ refer respectively to zero and infinite frequencies, and the subscripts i and a refer to the particles and the surrounding medium.

It was hard to explain the slow variation of ϵ^* in the range 100–1000 megacycles. At these frequencies the cell membranes no longer exert an effect, while the polar properties of the water molecules are not yet manifested. We also cannot expect at these frequencies a relaxation polarization of the protein molecules, whose relaxation frequencies are about 10 megacycles. However, it has been suggested[25] that individual parts of protein molecules possess degrees of rotational freedom, and the relaxation frequencies of these parts are of course higher than for the molecule as a whole. To test this hypothesis experimentally, measurements were made on molecular compounds comparable in dimensions and properties with the polar groups in the hemoglobin molecule. For certain amino acids and peptides, they found a spectrum of relaxation frequencies from 400 to 3000 megacycles. Another interesting suggestion[25] consists in the idea that the water molecules hydrating the hemoglobin molecule are in a state intermediate between ice and free water from the dielectric point of view, and have relaxation frequencies in the range 300–500 megacycles. Under these conditions, the ϵ' of the "bound" water should show a dispersion between the limits 78 to 5 over the range 100–900 megacycles. This might explain the dispersion of ϵ' of blood in this range.

The form of the dispersion at frequencies above 1 gigacycle is explained satisfactorily by the polar properties of the water molecules. The dispersion curves for ϵ' and ϵ'' are well enough approximated by the cited equations (1) of Debye for a single relaxation time, provided that we introduce an additional term into the expression for ϵ'' to take account of the ionic conductivity:[28,33]

$$\varepsilon'' = \frac{\varepsilon_0 - \varepsilon_\infty}{1 + (\omega T)^2}\omega T + 1.3 \cdot 10^{13}\frac{\sigma}{\omega}, \qquad (3)$$

where σ is the ionic conductivity, which is assumed independent of the frequency.

The form of the dispersion of ϵ^* of fatty tissues is due to the structure of the latter. It has been shown[28] that the dielectric parameters of purely fatty tissues are practically independent of the frequency in the microwave range, whereas tissues consisting of fat cells surrounded by an electrolytic medium exhibit dispersion. The nature of the dispersion of the parameters of bone tissues has been found[28] to fit Debye's equations with a relaxation time of 0.7×10^{-11} sec and a correction for ionic conductivity.

2. ABSORPTION OF MICROWAVES IN TISSUES OF LIVING ORGANISMS

On the basis of the electrical properties of tissues, the absorption of microwave energy in them has been ascribed[1,5,6,29,30] to two fundamental processes: energy losses due to ionic conductivity and dielectric losses due to relaxation polarization of water molecules. As the frequency increases, an increasingly substantial fraction of the absorbed energy is due to the dielectric losses: 50% in the 10-cm range, 90% at 3 cm, and 98% at 1 cm.[29,30]

As we know, this absorption of microwave energy involves transforming it into heat. On this basis, many researchers have considered heating of tissues

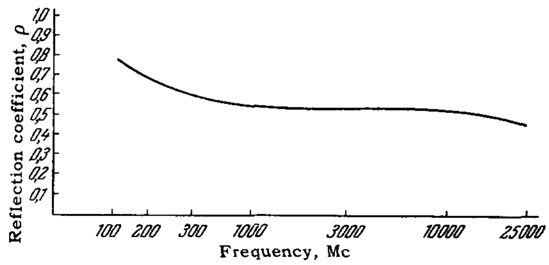


FIG. 2. Frequency-dependence of the coefficient of reflection of radio waves from the surface of the human body.

to be the only cause of the biological action of microwaves. They have stated[19] that the action of microwaves shorter than 10 cm practically does not differ from the action of infrared rays. Still, such an identification seems unsubstantiated[3] even by virtue of the difference between the processes by which these two forms of radiant energy are transformed into heat. In fact, in infrared irradiation, the heating of the tissues results from the increase in the kinetic energy of a disordered motion of the molecules. However, for microwaves it results from an ordered motion, namely, the coherent vibration of ions and water molecules at the microwave frequency (or more exactly, a frequency close to it). If we consider that membranes having superficial oriented layers of hydrated protein molecules play a large role in biological structures, the essential difference between the biological effects in these two processes becomes obvious. As we shall show below, this idea has been confirmed in experiments (to be described in Chapter 6). They showed that, when living tissues were heated to the same extent by infrared rays and by microwaves in the 1-cm range, biological effects were noted only in the latter case.

The possibility has been discussed of the absorption of microwaves involving intramolecular processes in protein molecules. Thus, e.g., it has been suggested[41] that absorption of microwave energy can involve rotation of intramolecular structures about C—C bonds, or translational shifts of hydroxyl groups from one hydrogen-bonded position to another, or rotational energy levels in metastable states, etc. The possibility has also been discussed of ionization effects of microwaves to form O_2 and OH radicals at high pulsed powers.[42] However, these hypotheses have not yet been confirmed experimentally.

The theoretical and experimental data on resonance absorption of microwaves by biostructures are more convincing. This absorption was first found[43-45] in measuring the complex dielectric constant of methyl palmitate ($C_{15}H_{31}COOCH_3$) in the frequency range from 50 cycles to 30 gigacycles. They observed a maximum in tan δ and a plateau in the ϵ' curve at a frequency of 4 gigacycles. The temperature independence of this frequency favored the idea that this effect was of a resonance type. However, the maxima of tan δ decreased with decreasing temperature, in contradiction of a purely resonance effect. The authors concluded that one should consider the observed absorption to be a combination of a resonance and a relaxation-polarization absorption.

Recently an interesting hypothesis has been advanced on the possibility of resonance absorption of microwaves and ultrashort waves by protein molecules.[46,47] The possibility of microwave absorption by enzyme molecules has been related to dipole-dipole interactions arising from fluctuations in the proton distribution in the molecule. When the mean distance between side groups of the molecule is about 9.5 Å, a dipole-dipole transition corresponds to the quantum energy of 3-cm waves. The wavelength corresponding to the interaction energy increases with increasing distance between the groups. An author[46] has suggested that the effect of microwaves on the proton distribution in an enzyme molecule can lead to a change in the reactivity of the enzyme-substrate complex. To test this assumption, experiments were performed on the irradiation of a solution containing such a complex with microwaves of frequency sweeping over the range 8.2—12.4 gigacycles. Irradiation for one minute led to a change in the absorbance of the solution.

The nature of the absorption and distribution of microwave energy in animal and human body tissues is determined by the degree of reflection from the surface of the body, by the anatomic distribution of the layers of tissues, and by the dimensions of the body with respect to the wavelength.

The reflection coefficient ρ has been calculated[6,48-50] according to the well-known formula for a plane wave incident from air onto a plane surface having the value of ϵ^* for skin and $\mu = 1$ (as is true of animal tissues):

$$\rho = \left(\frac{\sqrt{\epsilon^*} - 1}{\sqrt{\epsilon^*} + 1} \right)^2. \tag{4}$$

Figure 2 shows the variation in the value of the reflection coefficient as a function of the frequency caused by the corresponding variation of ϵ^* of the skin. However, the fact was not taken into account in this calculation that there is a layer of subcutaneous fatty tissue having a considerably lower value of ϵ' between the skin layer and the muscle tissues, which have about the same value of ϵ'. A theoretical analysis has shown[51-53] that the subcutaneous fat layer can play the role of a peculiar impedance transformer between the air space and the muscular tissue. Hence, the fraction of the incident energy absorbed by the body tissue can vary over the broad range from 20% to 100%, depending on the wavelength and the thicknesses of the skin and fat layers. Figure 3 shows such variations.

The depth of penetration of microwaves into a tissue (corresponding to decline by a factor of e) has

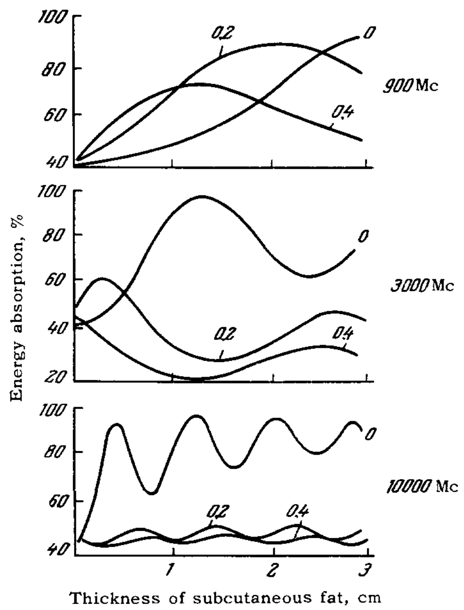


FIG. 3. Relation of the absorption of microwave energy at various frequencies by animal body tissues to the thickness of the subcutaneous fat layer for various skin thicknesses (numbers above the curves).

been calculated from the equation of propagation of electromagnetic waves in a lossy dielectric medium.[6,50] Table II gives the values calculated for various tissues at different frequencies.

A theoretical study of the absorption of the energy of a plane wave in a semiconducting sphere has been made in order to elucidate the relation of the absorption of microwaves in animal body tissues to the linear dimensions of the latter.[54] The adopted measure of absorption was the "relative absorbing cross-section" S, which amounts to the ratio of the power absorbed in the sphere (ϵ_1, δ_1) of radius a to the power incident on the transverse cross-section of the sphere when the plane wave is propagated in air (ϵ_2, μ_2):

$$S = \frac{W_a}{P_d \pi a^2}, \qquad (5)$$

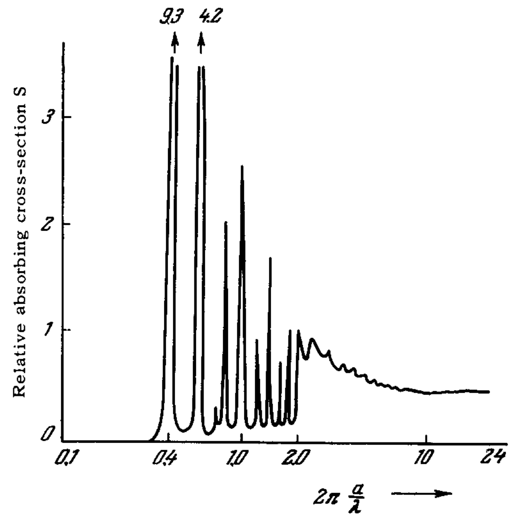


FIG. 4. Absorption of the energy of a plane wave (λ = 10.4 cm) in a semiconducting sphere (ϵ_1 = 60, σ_1 = 1 megohm) as a function of the ratio of the radius a of the sphere to the wavelength λ.

where $W_a = W_t - W_s$ is the power absorbed in the sphere, W_t is the power received by the sphere from the plane wave (partly absorbed, partly scattered), W_s is the power scattered by the sphere, and

$$P_d = \frac{E_0^2}{2\sqrt{\varepsilon_2/\mu_2}} = \frac{E_0^2}{754} \text{ watts/cm}^2$$

is the flux density of the power.

Calculations (made on a Univac-type computer) of the quantity S as a function of $\alpha = 2\pi a/\lambda$ showed:

a) When $a < \lambda$ ($\alpha < 2.4$), S oscillates with an amplitude considerably greater than unity (Fig. 4). That is, when the dimensions of the object are small in comparison with λ, it can absorb more power than is incident on its cross-section.

b) as α increases, S decreases smoothly, and at $\alpha = 6$ it reaches the constant value S = 0.5 ± 0.1 (see Fig. 4), irrespective of the values of σ_1 and a. Thus, when the dimensions of the object are large enough in comparison with the wavelength, it will absorb about

Table II. Depth of penetration of microwave energy into various animal tissues, cm

Type of tissue \ Frequency, Mc	100	200	400	1000	3000	10 000	24 500	35 000
Bone marrow	22.9	20.66	18.73	11.9	9.924	0.34	0.145	0.0730
Brain	4.132	3.56	2.072	1.933	0.476	0.168	0.075	0.0378
Lens of the eye	9.42	4.39	4.23	2.915	0.500	0.174	0.0706	0.0378
Vitreous body	2.17	1.69	1.41	1.23	0.535	0.195	0.045	0.03145
Fat	20.45	12.53	8.52	6.42	2.45	1.1	0.342	—
Muscles	3.454	2.32	1.84	1.456	—	0.134	—	—
Whole blood	2.86	2.15	1.787	1.40	0.78	0.148	0.0598	0.0272
Skin	3.765	2.78	2.18	1.638	0.646	0.189	0.0722	—

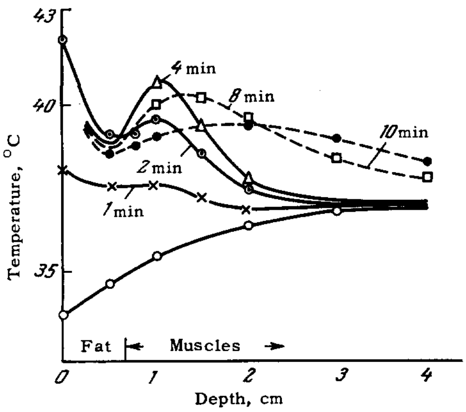


FIG. 5. Heating of tissues at various depths from a microwave-irradiated (λ = 10 cm) surface of a region of a dog's femur for various periods of irradiation.

50% of the energy, regardless of the shape of the object, its electrical conductivity σ_1, and the wavelength. These rules have been confirmed in studies on models.[55]

A considerable number of studies have been concerned with elucidating the relation of the heat production in tissues to the intensity and time of irradiation, and with determining the nature of the temperature distribution in the tissues of the irradiated region.[1,2] However, the results of most of these studies have been contradictory: in some cases they noted a more pronounced heating in the deep tissues than in the superficial ones, others showed the opposite temperature distribution, and in still others, they found either a positive or a negative temperature gradient, depending on the irradiation conditions. The major reasons for these discrepancies have been considered to be[2,56] imperfections in determining the absorbed power and lack of comparability in a number of the experimental conditions.

More definite results have been obtained by "contact irradiation."[56-58] The irradiated region of the body was placed in contact with the aperture of the applicator of a waveguide system, thus permitting adjustment of this load to the wave resistance of the wave guide. The skin temperature at the center of the irradiated region was measured during the irradiation with a thermocouple, the lead for which was laid perpendicular to the electric lines of force. The temperature in the deep tissues was measured by a thermocouple at the end of a hypodermic needle within 30—60 sec after turning off the radiation. Figure 5 shows graphs of the heating of tissues in the irradiated region of a dog's thigh. The author explained the lesser heating of the subcutaneous fat layer by its low energy absorption, and the equalization of the temperature among the layers as the irradiation was prolonged was explained by the heat conductivity of the tissues and heat dissipation due to increased blood supply.

The distribution of heating between the layers of the skin, subcutaneous fat, and muscle tissues also depends on the relation between the thicknesses of these layers at a given frequency of microwave irradiation, which is due to the matching effect. Figure 6 shows graphs of the heat generation in the layers as a function of the thickness of the subcutaneous fat layer and the frequency.[53]

Attempts have been undertaken to calculate the amount of heat generated at a given depth from the irradiated surface, and to estimate the possible temperature rise as a function of the intensity of irradiation.[58-60] However, since these calculations were based on rather crude assumptions, the results obtained approximated the experimental results only for short irradiation.

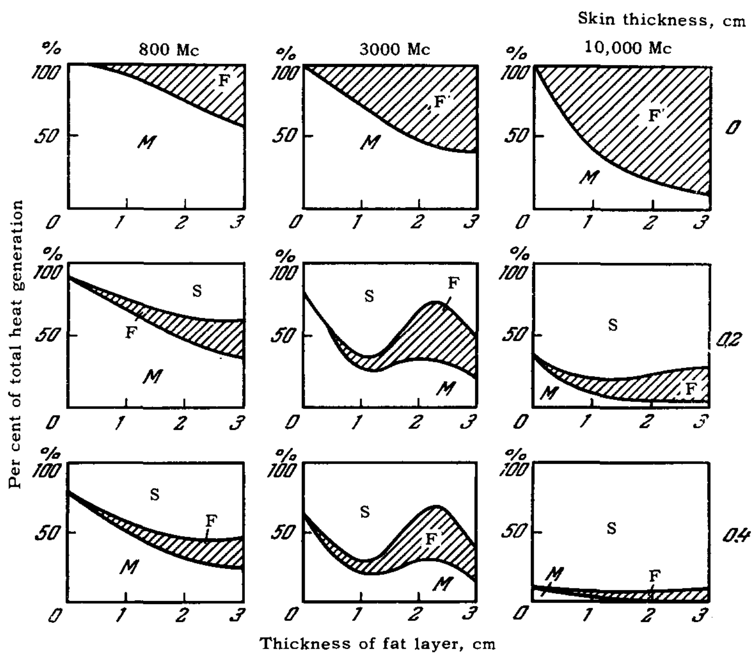


FIG. 6. Generation of heat in skin (S), in the subcutaneous fat layer (F), and in the muscles (M) when regions of the human body are irradiated with microwaves of various frequencies, as a function of the thickness of the subcutaneous fat layer and the thickness of the skin in the irradiated region.

3. DOSIMETRY OF MICROWAVES IN ESTIMATING THEIR ACTION ON HUMANS AND IN ANIMAL EXPERIMENTS

It has been suggested to use various quantities in estimating the intensity of microwave action on persons tending the testing and use of generators, and in determining the irradiation of animals in experiments: irradiation intensity (flux density of power),[48,61-63] total absorbed power,[63] dose (absorbed energy),[63] and density of electromagnetic energy.[64] However, it seems obvious that one must start from the concrete problem of study in choosing any of these quantities.[65]

In estimating the conditions of irradiation of humans located in a microwave radiation zone, and also in experimental irradiation of animals, the body dimensions of which are at least comparable with the wavelength, it is expedient to measure the irradiation intensity (conveniently expressed in milliwatts/cm^2). However, in determining the fraction of the energy absorbed in the superficial layers of the body, one can calculate the "effective intensity," or difference between the intensities of the incident and reflected waves. In order to measure the irradiation intensity under industrial conditions, near radar stations and in experiments, a number of instruments have been developed[16,61,62,66,67] to serve as power meters (most often thermistor instruments), with a corresponding antenna.

In experimental irradiation of small animals, it may prove necessary to estimate the total power absorbed in their bodies. Such an estimate has been made at a frequency of 350 megacycles by putting a rabbit inside a waveguide and measuring the input and output powers.[68] Methods have also been proposed of irradiating animals in volume resonators.[69,70] However, these methods have not been put into practical application because of considerable technical difficulties.

It is considerably easier to attain complete absorption in the irradiated region of the animal or human body by using the "contact method"[55-57] mentioned above, in which the effective intensity is directly measured. This method has been applied with lesser accuracy also for the irradiation of small animals placed below the applicator (irradiation from the back) or above the applicator (irradiation from the abdomen); the appropriate adjustment with the transfer line was carried out.[49,71] Measurement of the absorbed power has been used[72-74] in the irradiation of small biological objects (tissue preparations, protein solutions, unicellular organisms in an aqueous medium, etc.).

In physiotherapy one uses most often a relative measurement in terms of the output power of the generator and the distance from the radiator (with hemispherical and corner reflectors) to the irradiated surface. By measuring the temperature at different points in the region being irradiated, diagrams have been obtained of the intensity distribution.[75] This method of measurement has been used widely in experimental studies as well.

Attempts have been made to obtain complete absorption of the energy supplied to the irradiator within the irradiated portion of the patient's body by putting adjusting plates, or "quarter-wave transformers," between the irradiator and the body surface.[76] Recently a contact method has been suggested using a ceramic dielectric radiator.[77]

We point out for comparison that the conditions of action of relatively low-frequency electromagnetic fields, when the object is placed in an induction zone, are estimated by separate measurement of the field intensities of the electric and magnetic components.[70,78]

4. REACTION OF THE ANIMAL ORGANISM TO IRRADIATION WITH MICROWAVES OF MEDIUM AND HIGH INTENSITIES

One of the marked reactions of an animal organism to overall microwave irradiation at medium and high intensities (tens and hundreds of milliwatts/cm^2) is a temperature rise of the body (usually one measures the rectal temperature). This thermal effect of microwaves, which is related to the thermoregulation processes and active adaptation of the organism, can result in either reversible or irreversible changes, depending on the irradiation conditions and on the physiological state of the irradiated animal.

Studies have been made[79] of the role of the thermoregulation processes in the thermal effect of microwaves. They were based on the well-known law that the resultant heat transfer at a given body temperature is equal to the algebraic sum of the heat generation due to metabolic processes and heat loss from radiation and from breathing (for humans, one adds the losses due to perspiration). This is shown in Fig. 7a. In the thermoregulation interval (between the intersections of the resultant curve with the horizontal axis), heat losses predominate. This leads to the restoration of the normal temperature. However, if the heating proceeds further, the heat exchange can become positive and the body temperature rises to the lethal temperature for the animal. Microwave experiments have been performed in the thermoregulation interval, with automatic maintenance of a given temperature in the irradiated animal. Figure 7b shows the resultant curve, which is similar to that given in Fig. 7a. The maximum possible absorption of microwaves (corresponding to the maximum heat loss) was established when the temperature was raised by 4.5° in rats, 3.5° in rabbits, and 2.5° in dogs.

A series of studies on prolonged irradiations of animals by high-intensity pulsed microwaves (200 megacycles and 2.8 gigacycles, 100 and 165 milliwatts/cm^2) elicited reactions indicating the onset of

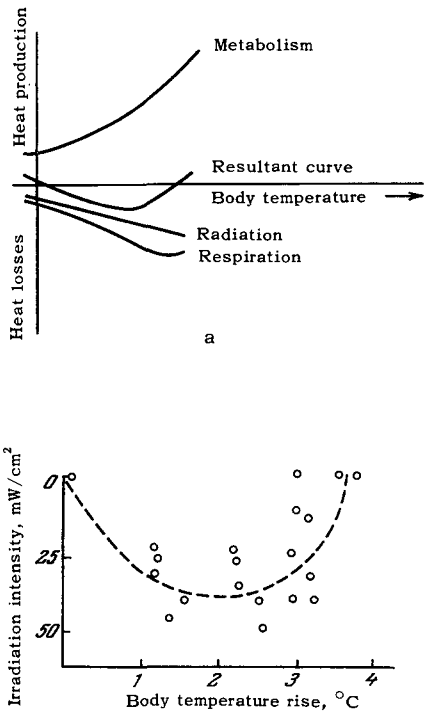


FIG. 7. a) The nature of the heat exchange in warm-blooded animals as a function of the body temperature; b) the relation between the irradiation intensities and the temperature rise of a dog's body under general microwave irradiation (λ = 10 cm).

active adaptation processes.[80–82] They showed that three consecutive phases of temperature change are observed as the irradiation proceeds: an initial rise, an equilibrium state, and a rapid rise to the critical temperatures (41—42°C) leading to the death of the animal if the irradiation is not stopped. Irradiation at 2.8 gigacycles gave a greater heat effect than at 200 megacycles for the same intensity. Anesthetization of dogs led to a shortening or disappearance of the equilibrium phase. In rabbits and rats, anesthesia reduced the heat effect at 2.8 gigacycles, but increased it in rats at 200 megacycles. An increase in the resistance of the organism was observed in the course of repeated irradiations: the temperature-equilibrium phase was prolonged, and the animals endured longer and longer irradiation.

Besides the temperature reactions, irradiation caused considerable changes in the state of the formed elements of the blood: a fall in the erythrocyte concentration, followed by a rise upon prolonged irradiation, an increase in the number of neutrophils, and a decrease in the lymphocytes and eosinophils. Similar changes have also been observed[83,84] in overall irradiation of rats by 24-gigacycle microwaves at an intensity of 24 milliwatts/cm^2, as is shown in Fig. 8.

In the same series of investigations[81,85,86] they studied the combined action of microwaves and ionizing radiation. They showed that animals that had been subjected to ionizing radiation reacted more strongly to microwaves. With a simultaneous irradiation with microwaves (2.8 gigacycles, 100 milliwatts/cm^2) and γ-rays (250 kV), the neutrophil level in the blood was reestablished more quickly than without the microwave irradiation. On the other hand, the number of neutrophils rose eight times higher than with microwave irradiation alone. Preliminary irradiation with microwaves (2.8 megacycles) at an intensity 100 milliwatts/cm^2 for 3—6 hours reduced the mortality from a subsequent ionizing irradiation (340 roentgens) by a factor of almost four. A briefer irradiation (0.5—1.5 hours) gave no effect. On the other hand, a prolonged but more intense irradiation (165 milliwatts/cm^2) also gave no effect. Finally, a repeated microwave irradiation to which the animals had adapted reduced the mortality from ionizing radiation by a factor of about 1½

The authors considered these adaptational effects to be a manifestation of the heat-stressor action of the microwaves.* However, a number of experimental data disagreeing with this hypothesis have been obtained. Thus, e.g., it has been observed[83] that 24-gigacycle microwaves (which are completely absorbed in the skin) produce a four times greater temperature rise than infrared rays with the same duration and intensity of irradiation. Also, eight times shorter irradiation by microwaves was required to kill the animals than by infrared rays of the same intensity.

As was pointed out, repeated irradiation of dogs by high-intensity microwaves diminished the sensitivity of the animals to irradiation. It has been found further[87] that repeated irradiation of rats by low-intensity microwaves (3 gigacycles, 1 milliwatt/cm^2) conversely sensitizes the organism to the lethal

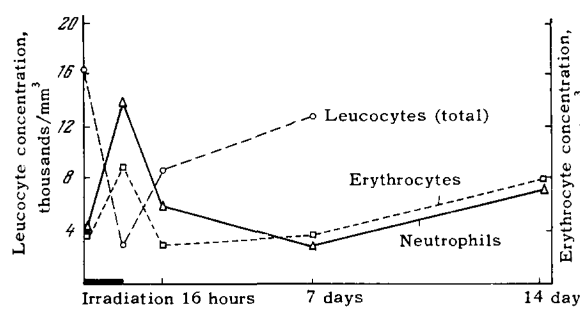


FIG. 8. Change in the concentration of leucocytes and erythrocytes in rat blood due to microwave irradiation (24 gigacycles, 24 milliwatts/cm²).

*Stress, or the general adaptational syndrome, is the set of adaptive reactions of an organism to any dangerous influence (heat, chemicals, psychic trauma, etc.). These reactions follow the pattern: the acting agent (stressor) stimulates the activity of the hypothalamus and the secretion of the hormone ACTH by the hypophysis. In turn, the latter activates the hormonal activity of the adrenal cortex. The described changes in the blood are characteristic of the early manifestations of heat stress.

action of irradiation at higher intensity (65 milliwatts/cm^2), and that the lethal period of irradiation by continuous microwaves is 4—5 times greater than with pulsed irradiation at the same mean intensity. Further, earlier studies[88] had established that animal tissues are heated to the same extent by pulsed and continuous microwaves at the same intensity, while continuous microwaves proved even more effective than pulsed microwaves in raising the overall body temperature.[81]

A combined action of microwaves and ionizing radiation has recently been observed[89] at intensities and durations of microwave irradiation so small that a heat-stressor effect was improbable. Rats were irradiated for 30 minutes daily for 25 days with continuous microwaves (2.5 gigacycles, 10 milliwatts/cm^2). A threefold decline in mortality from subsequent γ-irradiation (600 roentgens) as compared with the controls was noted. Irradiation with pulsed microwaves (1 μsec, 700 pulses/sec) gave no effect with other conditions held constant.

A comparison of the discussed data leads to the hypothesis[3] that stressor reactions to the action of microwaves of medium and high intensity arise from direct action on all the skin receptors (rather than the heat receptors alone) and on brain structures, while the effects of irradiation at low intensity involve only action on the brain structures.

Studies of the reactions of animals to microwave irradiation of the head are of interest. In experiments with rats,[90,91] irradiation of the back of the head by 2.4-gigacycle microwaves of intensity 300—400 milliwatts/cm^2 for three minutes brought on convulsions with an increase in the temperature of the brain to 40°C.

Experiments[92] were recently performed in which the head of a monkey was irradiated in a cylindrical resonator supplied from a 225—399 megacycle generator of power 100 watts, while the body was not subjected to irradiation. When the head was fixed with chin elevated, irradiation for one minute elicited successively: agitation, drowsiness, loss of mobility, and disturbance of sensitivity, while a three-minute irradiation produced convulsions ending in death. With the chin lowered, irradiation produced only agitation and drowsiness. When the head was free to move, no disturbance was noted, but the animals raised their heads, looking at the antenna supplying the resonator.* Irradiation of the entire body of an animal elicited no reactions. While the head was being irradiated, the body temperature changed insignificantly, and the rhythm of the brain waves slowed down (with a 5-cycle rhythm predominating) and increased in amplitude. They noted the breaking of interneuronal connections in the brain. If the irradiation was not fatal, then all these objective changes and the described behavioral disturbance disappeared within 24 hours after the experiment. The authors consider the described effects of microwaves to be non-thermal, and arising from the disruption of the functions of the diencephalon and mesencephalon, apparently due to molecular changes in the cells.

A series of studies has been conducted[93-96] on treatment of the head or isolated brain of a rabbit with pulsed and continuous microwaves (2.4 gigacycles and 575 megacycles, 0.002—1000 milliwatts/cm^2), UHF fields (43 megacycles, 1000 V/m) and a constant magnetic field (800 Oersteds). It turned out that all these factors produce similar reactions: the appearance of slow or fast rhythms in the electroencephalogram in 40—90% of the experimental animals, depending on the intensity of the treatment. Characteristically, a paradoxical relation was noted upon irradiation with continuous microwaves: in going from relatively high (2—10 milliwatts/cm^2) to lower intensities (0.08—0.4 milliwatts/cm^2), the percentage of cases showing changes in the electroencephalogram dropped correspondingly from 79—84% to 40—65%. However, at an even lower intensity (0.02 milliwatts/cm^2), the percent of cases showing changes rose again unexpectedly to 67—90%.

Transection at the level of the mesencephalon produced an increase in the percentage of cases in which the animals reacted to turning on the field, but did not change it in reactions to turning off. The reaction persisted when the olfactory and optic nerves were also cut. The authors explain the described reactions by the direct action of the applied fields on the structures of the diencephalon and forebrain.

The extreme manifestation of the irreversible action of microwaves, or termination in death, has been studied for a long time, but the criteria for lethal conditions of irradiation have not been established yet with sufficient definitiveness.

In experiments on rats, the periods of irradiation by pulsed microwaves of various frequencies and intensities sufficient to kill the animal (immediately after irradiation or some time thereafter) have been estimated approximately.[82,83,98,99] The data of these estimates are given in Table III.

As we see from Table III, we cannot discern a frequency-dependence of the "lethal period." In addition, it has been established[87,100,101] that these periods depend on a number of conditions of irradiation and on the state of the animal. For a given intensity, a shorter irradiation is required to kill the animal when the temperatures of the body and the environment are higher, when the dimensions of the animal are smaller, and when the body temperature rises more slowly during the irradiation (it is faster when the animal is placed in the plane of polarization

*The authors point out that in other studies, the rats oriented their bodies, while dogs turned their heads in the direction from which the radiation of wave lengths 1.25 and 10.7 cm was coming.

Table III. Minimum periods of irradiation by microwaves of various intensities lethal to rats, min

Irradiation intensity, mW/cm² \ Frequency, Mc	3000	24 000
150—165	20	35
100—120	60	45
35—40	120	120

than when perpendicularly).

The *hazardous intensity in local irradiation* has been estimated in humans in terms of the point of barely perceptible pain sensation.[60] This happened when the skin was heated to a temperature of 46—47°C, which required a microwave intensity (at 3 gigacycles) four times higher than for infrared rays (for the same duration of irradiation). This difference was explained by the deeper penetration of microwaves of this frequency range into the tissue, as compared with infrared. However, experiments with shorter microwaves (24 gigacycles)[83] showed that the same degree of heating of rat skin requires (for the same duration) an intensity of microwaves three times lower than for infrared rays.

The pain effect upon direct irradiation of a peripheral nerve in a cat by pulsed microwaves (2.5 and 10 gigacycles) has been studied in comparison with the effect of heating the nerve by infrared and convected heat.[102,103] Regardless of the type of agent, physiological reactions were noted when the temperature of the nerve was raised to 46°C, indicating pain sensation (accelerated respiration and heartbeat, expansion of the pupils, rise in blood pressure, etc.)

The discussed experimental data permit us to note two fundamental features of the action of microwaves of medium and high intensities: first, we cannot explain this action by the heat effect alone, and second, the manner in which this action is manifested is practically independent of the frequency, although the extent to which some manifestation is expressed may vary with the frequency.

5. REACTIONS OF THE HUMAN OR ANIMAL ORGANISM TO IRRADIATION WITH LOW-INTENSITY MICROWAVES

The lower limit of the heat effect of microwaves has been estimated for overall and local irradiation. Using the data on heat exchange in man, it has been suggested[58] that upon general irradiation it is improbable to expect an appreciable rise in the body temperature when the irradiation intensity is less than 10 milliwatts/cm^2. The same order of threshold intensity has been established by measuring the heating of a person's skin in a region of the body (shoulder, back) being irradiated by microwaves (3 gigacycles).[104] It has been established experimentally that upon irradiating a region of the human body with 3-gigacycle microwaves a minimal heat sensation appears at an irradiation intensity about 10 milliwatts/cm^2, whereas it appears at about 1 milliwatt/cm^2 in infrared irradiation.[105] However, in irradiation with shorter waves (24 gigacycles), the threshold intensity for heat sensation amounts to 61—78% of the corresponding intensity for infrared.[106]

In animal experiments,[79,83,107,108] overall irradiation caused a body-temperature rise only at intensities above 10 milliwatts/cm^2. Here, this value proved to be about the same for pulsed and continuous microwaves in the centimeter and decimeter ranges. Also, a certain temperature rise of 0.4—0.5° has been noted upon irradiating animals with millimeter waves of intensity 10 milliwatts/cm^2.[109]

Thus, irradiation intensities below 10 milliwatts/cm^2 can be considered "non-thermal" for pulsed and continuous microwaves of various frequencies, either with general or local irradiation of humans and animals. The reason for this "universality" evidently consists in the fact that at an intensity of 10 milliwatts/cm^2, the energy transformed into heat (about 5 milliwatts/cm^2) is approximately equal to the heat losses per square centimeter of body surface of humans and warm-blooded animals under normal environmental conditions.

Convincing proofs of non-thermal action of microwaves have been obtained in numerous experimental and clinical studies conducted in the USSR.[110-114] These studies have established that microwaves of non-thermal intensities (especially with chronic irradiation) exert a reversible influence on the functions of the nervous system. It is manifested in two basic forms: in the form of "vagotonic" reactions indicating functional changes favoring prevalence of the parasympathetic division of the vegetative nervous system (slowing of the pulse, fall in arterial blood pressure, decrease in cholinesterase activity, etc.), and in the form of disturbance of the functional state of the brain structures (hindrance of conditioned-reflex activity, decrease in sensitivity to auditory stimulation, change in the electroencephalogram, breaking of interneuronal connections in the cortex, etc.).

We should note that all these manifestations of non-thermal action of microwaves on the nervous system have been noted over a broad range of wavelengths (from millimeters to decimeters), beginning at very low irradiation intensities of the order of tenths of milliwatts/cm^2. Here the general character of any given manifestation was practically independent of the wavelength throughout the studied range. However, the extent to which the observed changes were expressed depended regularly on the wavelength: the brain-function disturbances were increased with increasing wavelength, while conversely the vagotonic reactions declined. This relation is in accord with the increase in penetration of microwaves into tissues with increasing wavelength. The latter has been confirmed experimentally: it has been found[115-117] that when animals are irradiated with millimeter waves, the most marked morphologic changes were noted in the cutaneous receptors, while when irradiated with 10-cm waves, they showed breakage of interneuronal connections in the cerebral cortex.

In connection with these data, the hypotheses have been advanced[3,118] that the vagotonic reactions appear as a reflex owing to the direct action of the microwaves on the cutaneous receptors, while the disturbances of brain functions result from the action of the microwaves on brain structures. These hypotheses have been partially confirmed by the results of studies of changes in the rhythm of the heartbeat in animals during irradiation by microwaves (at 2.4—3 gigacycles)[119-120]:

In rabbit experiments, irradiation of the ventral parts of the body (from the abdominal side) by low-intensity microwaves (7—12 milliwatts/cm^2) elicited a vagotonic effect (slowing of the heartbeat). The same effect appeared upon irradiation of any part of the body with microwaves of medium and high intensities (70—200 milliwatts/cm^2). However, if the sensitivity of the cutaneous receptors in the irradiated portion was suppressed by anesthesia, then the effect did not appear under the stated irradiation conditions.

These results rather convincingly indicate that the pulse retardation results from a reflex from the cutaneous receptors subjected to the direct action of the microwaves. However, frog experiments[121] give us grounds to suppose that the reflex arc is completed in the subcortical structures of the brain (apparently in the vagus nerve center, which is situated in the medulla oblongata). This is because the pulse-retardation effect in frogs under the action of microwaves disappeared when any of the links of this reflex arc was broken, from the cutaneous receptors to the centrifugal nerves of the heart.

A more complex pattern was observed upon irradiation of the dorsal regions of the body of a rabbit (from the back), and especially the head. Irradiation of the head by low-intensity microwaves elicited the opposite effect, an acceleration of the heartbeat, while this effect was enhanced when the receptors in the cutaneous covering of the head were anesthetized. However, irradiation of the head at medium and high intensities slowed the pulse, while no changes took place when the cutaneous receptors were anesthetized. Further, it turned out that one can choose a certain intermediate intensity at which irradiation of the heat without anesthesia of the cutaneous receptors slows the pulse, but accelerates it with anesthesia.

Of course, these data are insufficient even for definite conclusions on the mechanism of the discussed phenomena, but we can set forth some notions. It seems probable that the type of change in the heart rhythm when the head is irradiated without anesthetizing the cutaneous receptors depends on which of the excitable structures react more at a given irradiation intensity, the receptors or the brain structures. On the other hand, we must take into account the characteristic well-known to physiologists of how the nuclei of the vagus nerve react to direct action:[123] a mild stimulation of this brain structure accelerates the heartbeat, while a strong one retards it.

6. CHANGES IN TISSUES AND ORGANS OF ANIMALS UNDER THE ACTION OF MICROWAVES

When animals have been subjected to prolonged irradiation by high-intensity microwaves, marked changes have been observed in tissues and organs (hemorrhage, burns, necrosis of tissues, etc.). Most authors[124-126] have considered them to result from the marked overheating of the tissues.

A considerable number of experimental studies have been conducted on irradiation of the eyes and testicles, which can be heated most effectively with microwaves, owing to their poor supply of blood vessels. The results of these experiments showed, however, that the changes produced by microwaves in these organs cannot be ascribed solely to the heat effect.

Irradiation of rat testicles with 2.5-gigacycle microwaves for 10 minutes, which heated the tissues to 30—35°C, led to degenerative changes. However, infrared irradiation produced such changes only when the temperature was raised to 40°C.[127] In other studies,[128] for the same degree of heating, microwaves (2.3 gigacycles) caused earlier and more significant changes in rat testicles than infrared. The comparative diagrams are shown in Fig. 9. It has been found[124] in addition that the irradiation of rat testicles by microwaves (2.4 gigacycles) that heated the tissues to 41°C led to endocrine disturbances in the genital system without visible changes in the testicles. However, infrared irradiation producing the same temperature rise caused no disturbances. A single irradiation of mice[130] by microwaves (10 gigacycles, 370—400 milliwatts/cm^2) for five minutes led to a decline in the number of progeny and an increase in the number of stillborn. Here the alterations in the sexual functions of the animals were more substantial than one observed in ordinary body heating.

Numerous studies[131] have shown an irreversible action of microwaves of medium and high intensities on the eyes, manifested in the appearance of cataracts in the lens of the eye. These developed either immediately after irradiation, or after several days or even weeks. The threshold intensities for appearance of cataract after a single irradiation of varying length were established:[132] from 120 to 600 milliwatts/cm^2 at durations of 270 min and 5 min, respectively. In

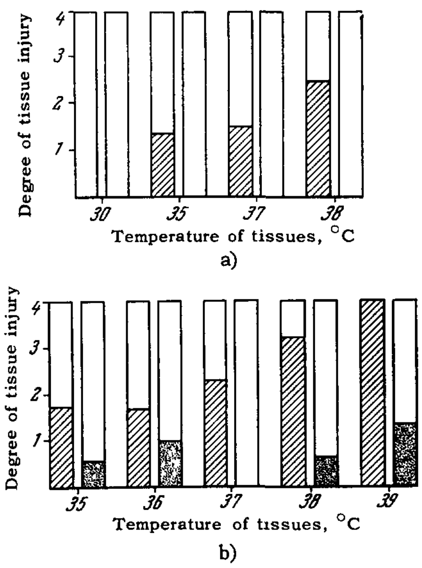


FIG. 9. Injury to rat testicle tissues (estimated on a 2 four-point scale) due to heating to various temperatures by microwave irradiation (left-hand bars) and infrared (right-hand bars). a) 1 hours, b) 2 days after irradiation.

addition, cataracts have been observed[133-135] to arise from repeated irradiation at intensities considerably below the threshold value for single irradiation. This cumulative effect and prolonged period of development of cataract has induced scientists to seek the reasons for it in the action of microwaves on biochemical processes occurring in the lens, rather than in their heat effect. It was found[136] that microwave irradiation of the eyes decreases the activity of certain enzymes in the lens, and also decreases the ascorbic acid and glutathione content there.[133-138] The authors note that other biochemical changes are observed when cataract formation arises from other causes (alloxan diabetes).

The experimental data on the effect of microwaves on embryonic development are of interest.[138-139] After a 48-hour incubation at 39°C, a hen's egg was irradiated for five minutes with microwaves (2.4 gigacycles) while maintained at the same temperature. This led to a disruption of the development of the embryo. Further tissue growth ceased in the undifferentiated structures, while subsequent differentiation ceased in the partially differentiated structures. Other studies[140] have shown a retardation of the heartbeat in the chick embryo when irradiated with 1875-megacycle microwaves, whereas the heating of the embryo due to the microwaves should accelerate the heartbeat. Changes have also been noted[141,142] in the electrocardiogram of the chick embryo heart when irradiated by microwaves, indicating a disturbance of the metabolic processes. Finally, irradiation of chick-embryo tissue cultures by 1.4- and 10-gigacycle microwaves produced no heating, but led to a stimulation of tissue growth.[143]

Studies have been undertaken on the action of microwaves on malignant tissues. A series of experiments[144-146] has shown a retardation of tumor growth in mice under repeated irradiations (5—10 minutes each) with 1875- and 3000-megacycle microwaves. However, the tumor growth resumed some time after cessation of the irradiations. Retardation of tumors also took place after injection of sick animals with extracts of non-malignant skin and fat that had been irradiated for five minutes in a test tube. Conversely, injection of irradiated glycogen accelerated tumor growth. The author correlated these opposite effects with the distinction that he had observed in the action of microwaves on these substrates (which will be discussed below). A retardation of malignant-tumor growth has been observed[5] in mice when irradiated with 3- and 10-gigacycle microwaves of high intensity. This was ascribed to thermal coagulation of tissues. On the other hand, there is a report[147] on sarcoma resorption in mice upon irradiation with 6-gigacycle microwaves at very low intensity.

7. STUDY OF THE EFFECTS OF MICROWAVES AND ELECTROMAGNETIC FIELDS OF OTHER FREQUENCIES ON THE CELLULAR AND MOLECULAR LEVEL

The action of radiofrequency electromagnetic fields on unicellular organisms and biological structures has been studied over a broad range from low to ultrahigh frequencies.

A number of studies have been concerned with the action of high-intensity fields on bacteria, which they explained in terms of the heat effect. Thus, e.g., when a medium containing bacteria was heated to 55—60°C by pulsed fields in the range from 65 cycles to 600 megacycles, the viability of the bacteria was lowered.[148,149] Irradiation of fowl sarcoma viruses by high-intensity microwaves (3 gigacycles)[150] caused complete loss of activity, which was explained by the heating of the medium. No non-thermal action was observed in recent experiments on irradiation of luminous bacteria by 2.6—3 gigacycle microwaves, although the author[151] does not deny the possibility of such an effect under other irradiation conditions.

A non-thermal bactericidal action was first noted in experiments with 20-megacycle pulsed fields.[152] Intestinal bacteria were destroyed in 5—10 seconds when treated with these fields at an intensity of 205 V/cm, the medium being heated to 40°C. However, with simple heating this effect was obtained at 60°C in ten minutes. Hoof-and-mouth viruses were completely inactivated by a field of intensity 260 V/cm in 10 minutes, and in 2.4 seconds at 480 V/cm. Here the medium was heated no higher than 37°C. Such an effect due to simple heating to the same temperature took 60 hours. In other experiments from the same period,[153] field of frequencies 12—300 megacycles manifested a bactericidal action in five minutes, al-

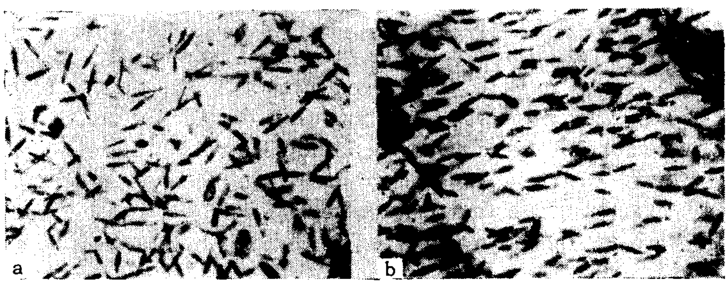


FIG. 10. Oriented motion of flagellate unicellular organisms (euglena) when treated with an electromagnetic field (5–7 megacycles). A) Disordered motion before application of the field; b) motion parallel to the electric lines of force of the field.

though the temperature of the medium did not exceed 37°C.

A non-thermal action of microwaves of 21-cm wavelength on a number of bacteria, as manifested in retardation or cessation of multiplication, has been observed[143] at a temperature rise that was biologically insignificant. The same effects of microwaves on bacteria have been noted[154] at temperatures of 37—42°, which are not fatal for bacteria.

In recent years, the attention of many researchers has been attracted to studying the effect of orientation of particles and unicellular organisms by UHF fields of various frequencies.[155-159] These studies obtained the following basic results:

a) When treated with pulsed or continuous UHF fields (1—100 megacycles), suspended particles of carbon, starch, milk, erythrocytes, and leucocytes arrange themselves in chains parallel to the electric lines of force of the field. Each type of particle has an optimum frequency range within which the field intensity required to produce the effect is a minimum.

b) Unicellular organisms (flagellates and ciliates) move parallel or perpendicular to the lines of force of the field, depending on the frequency. Here each type of unicellular organism has its specific frequency ranges. Thus, e.g., euglena orients itself parallel to the field (Fig. 10) at frequencies 27—30 megacycles. Amoebas orient themselves along the lines of force at about 5 megacycles, and perpendicularly at 27 megacycles.

c) When unicellular organisms are oriented along the lines of the field, their intracellular unsymmetrical particles can be oriented perpendicularly.

d) Along with the orientational motions, one observes various rotational motions of the unicellular organisms at certain frequencies (which are specific for each species). The frequency and the type of motion could not be definitely correlated.

A theoretical treatment of the orientational effects[160-162] has been carried out by analyzing the attractive forces between particles in which dipole charges are induced by the action of a field. They showed that the time constant for formation of oriented chains is proportional to the cube of the radius of the particles and inversely proportional to the field intensity with strong fields. The effects are assumed possible even at microwave frequencies, but at high and medium intensities (hundreds of milliwatts/cm^2).

This is especially so in electrolytic media, which shunt the field to a considerable extent. They determined the frequency ranges at which "parallel" and "perpendicular" orientations can occur, depending on the values of the dielectric parameters of the particles and the suspending medium.[163]

However, recent studies[164-166] give grounds for supposing that the behavior of unicellular organisms when subjected to electromagnetic fields involves an excitable structure that they are assumed to possess. This is, so to speak, a prototype of the neuro-muscular system.[167] They established that infusoria (paramecia) respond to pulses of direct and alternating current at definite threshold potentials by an "electroshock reaction" (ESR). This is manifested in the form of marked stoppages of motion, with rotation of the body axis parallel to the lines of force. Also, the threshold potentials proved to depend on the duration of the pulses and the alternating-current frequency in the same way as for the corresponding cases of stimulation of nerve and muscle tissues of animals and man (Fig. 11). Paramecia react to prolonged action of an

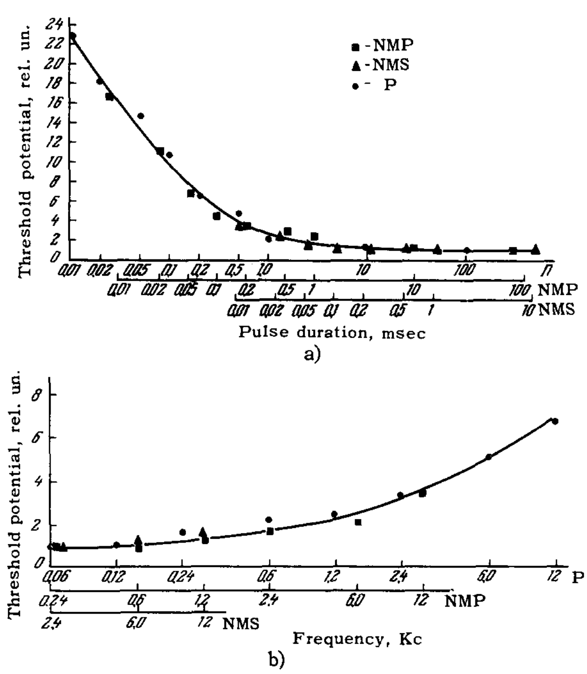


FIG. 11. Comparison of the relation of the excitability threshold of paramecia (P), frog nerve-muscle preparation (NMP), and human nerve-muscle system (NMS) to the duration of stimulating direct-current (a), and to the frequency of alternating current (b).

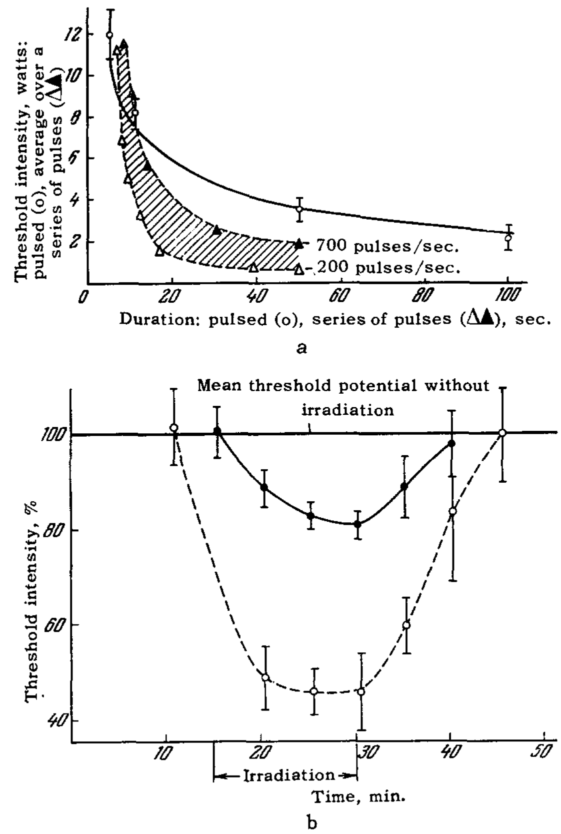


FIG. 12. The effect of microwaves (λ = 10 cm) on the excitable system of paramecia. a) Threshold power of pulses (or series of pulses) of microwaves producing stimulation (ESR) in paramecia, for various durations of pulses (or series): solid curve – relation existing for stimulation with single pulses; cross-hatched area – relation for stimulation with series of short (1 μsec) pulses of varying frequencies of repetition. b) Variation in the threshold potential of alternating-current pulses (1200 cps, 100-120 msec) producing stimulation (ESR) in paramecia, while the latter were being stimultaneously irradiated with microwave pulses of subthreshold power: solid curve: variation when irradiated with microwave pulses of the same duration as the alternating-current pulses; dashed curve – variation when irradiated with series of short pulses for which the duration of the series was the same as that of the alternating-current pulse.

alternating current by movements of various types (depending on the values of the frequency and potential) that are characteristic of these infusoria under the natural conditions of their existence.

The results of these studies, which were performed over a wide range of frequencies from 20 cycles to 10 megacycles, confirmed the existence in paramecia of an excitable structure sensitive to alternating electromagnetic fields, and raised the expectation that this structure would be sensitive also to microwave-frequency fields. Indeed, a series of special investigations[168,166a] showed such a sensitivity to microwaves.

It turned out that paramecia show the ESR reaction when subjected to microwave pulses (2.4—3 gigacycles) of varying durations, or to a series of short (1 μsec) pulses. The threshold values of the power per pulse (or the mean power of the series of pulses) at which this reaction ensued were inversely proportional to the duration of the pulses (or series of pulses). This is shown in Fig. 12a. It was further shown that, although microwaves do not elicit the ESR at subthreshold power values, one notes a rise in the sensitivity of the paramecia to other stimuli. Such a sensitization of paramecia to stimulation by alternating-current pulses when acted on by microwaves is illustrated by Fig. 12b.

We should note some characteristic features of the discussed phenomena: first, the nature of the ESR affecting the motion of paramecia was identical when the agents were alternating currents of varying frequencies (from 20 cycles to 10 megacycles) and microwaves; second, the threshold values of the potentials and powers at which the ESR appeared were inversely proportional to the square roots of the pulse duration and the frequency (rather than the first powers of these quantities); third, the heating of the medium in which the paramecia were put was insignificant for all the types of agents eliciting the ESR.

We can conclude from these features that the ESR is to be considered as resulting from a non-thermal action of the electromagnetic fields, and that the nature of this reaction is independent of the frequency of the acting fields. Thus, we encounter in the reaction of the excitable structure of paramecia to electromagnetic fields the same characteristic features as have been noted above for the reactions of the nervous system of animals and man.

We must mention here some recent studies[169] on the effect of microwaves on the physiological function in paramecia of phagocytosis. It turned out that under the action of 2375-megacycle microwaves, the phagocytic activity of the infusoria (ingestion of india-ink particles into vacuoles) varies in two phases depending on the intensity: in the range from 1.5 to 275 milliwatts/cm^2, one first notes an almost twofold increase in activity, and then a decrease to the normal level, and finally, a fall below the normal level.

In addition to these experiments showing an effect of electromagnetic fields on the infusorial cell, there are experimental grounds for assuming that the fields can also influence intracellular processes. An example of such an effect is given by the results of a study of the action of pulsed UHF fields on cell-division processes in growing garlic root.[156,159] In root cells subjected to five-minute treatment (5—40 megacycles, 15—30 μsec, 500—1000 pulses/sec, 250—6000 V/m peak field), they noted chromosomal aberrations: at the stage of development at which the chromosomes should divide into two daughter groups, they were linked by bridges which disintegrated into fragments to form micronuclei, as is shown in Fig. 13. Such changes should lead to changes in hereditary traits. Indeed, the same authors observed such changes in experiments with drosophila flies under analogous treatment (from 5 minutes to 1 hour): the number of

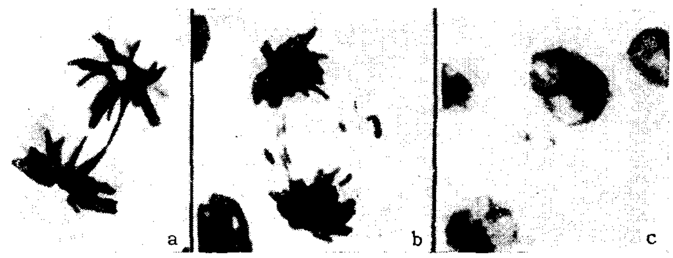


FIG. 13. Changes in the chromosomal apparatus of dividing garlic-root cells when treated with pulsed UHF fields. Formation of: a) bridges between daughter groups of chromosomes; b) bridges and fragments; c) micronuclei from the fragments.

lethal and externally-manifested mutations increased approximately 13-fold as compared with the mean number of such mutations in flies not subjected to the treatment.

An effect of microwaves on the structures of biological molecules was first found in 1940—1946.[144,145,170,171] Irradiation of a glycogen solution with microwaves of frequencies 1875 and 3000 megacycles led to a decrease in the rotation angle of the plane of polarization in this optically active solution. The size of this effect and its course of development during the irradiation depended on the frequency of the acting waves, the concentration, and the viscosity of the solution. The frequency 3000 megacycles proved to be considerably more effective, and hence it was used in most of the experiments.

The dependence of the effect on the concentration and viscosity proved to be very marked, as is illustrated by Fig. 14b.* When an aqueous solution of glycogen was irradiated, the percentage decline in the rotation angle of the plane of polarization increased with decreasing concentration to the "optimum" value of 0.1%, at which total loss of optical activity of the solution was observed (100% change). In a solution of glycogen in glycerol, the same maximum effect occurred at a concentration of 0.05%, which was not the "optimum" for the aqueous solution. It was also found that the effect of microwaves on an aqueous solution of glycogen changes markedly when one adds several drops of KOH or $(NH_4)_2SO_4$ to the solution, as is shown in Fig. 14a.

The optical activity of an aqueous solution of glycogen varied as a function of the irradiation time in a stepwise fashion (Fig. 14c). Here both the slope of the stepwise transitions and the number of them depended on the concentration of the solution.

Microwaves exerted the opposite effect on optically inactive extracts of skin and fat tissues of rats (in carbon disulfide): irradiation converted these extracts into optically active substances rotating the plane of polarization to the right.[145,146,171]

*The graphs shown in Fig. 14 have been altered somewhat in comparison with the originals by taking into account the remarks and data given in[170].

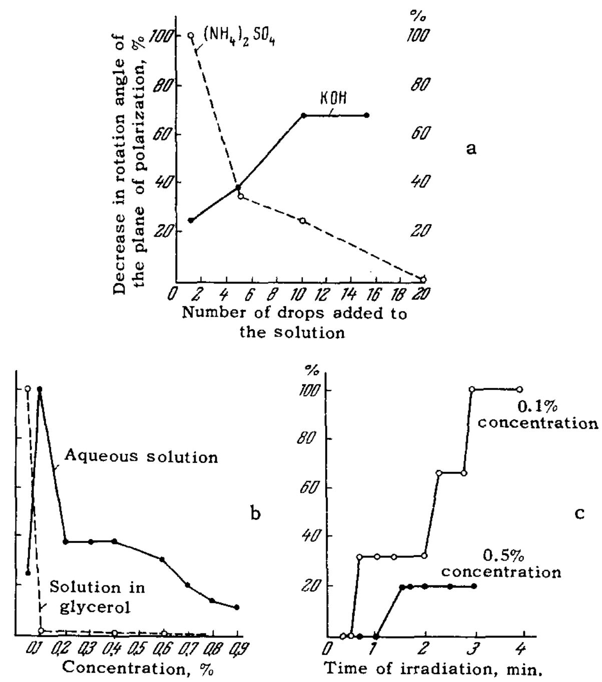


FIG. 14. Variation in the rotation angle of the plane of polarization in a glycogen solution treated with microwaves (3 Gc) as a function of: a) addition of KOH to the solution (3 min irradiation); b) concentration and viscosity of the solution; c) time of irradiation.

In addition to these effects, an action of microwaves on the structure of colloidal solutions of starch has also been observed.[162] Irradiation for one minute increased the rate of coagulation of the solution, and here this effect also depended on the concentration of the solution (Fig. 15).

The described results stimulated studies of the action of electromagnetic fields on human gamma-globulins.[172,173] Since the previously established effect of X-rays on a solution of gamma-globulins had been expressed in a change in the electrophoretic pattern from a single to a double peak and also in a change in the antigenic activity of the solution, these methods of indication were also adopted in the studies using electromagnetic fields.

Gamma-globulins in physiological solution were treated with fields in the range 10—200 megacycles with pulsed (10—60 μsec, 500—200 pulses/sec) and continuous irradiation for 20 minutes. Investigation at intervals of 10 megacycles revealed "effective frequencies" of 30, 60, 140, 180, and 200 megacycles, at which double peaks appeared in the electrophoretic pattern. With 1-megacycle intervals and thermostatting at 22°C, the effective frequencies proved to be 10, 15, 20, and 25 megacycles. This indicates the presence of harmonics of 5 megacycles.

Using Debye's equations (for the given viscosity of the solution) the authors recalculated these effective frequencies for temperatures of 30—40°C. The experi-

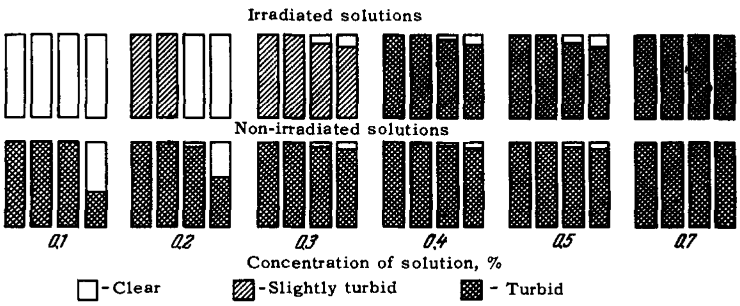


FIG. 15. Coagulation in starch solution irradiated with microwaves (3 gigacycles, 1 min irradiation). First bar – immediately after irradiation; second bar – 30 min after irradiation; third bar – 60 min after irradiation; fourth bar – 90 min after irradiation.

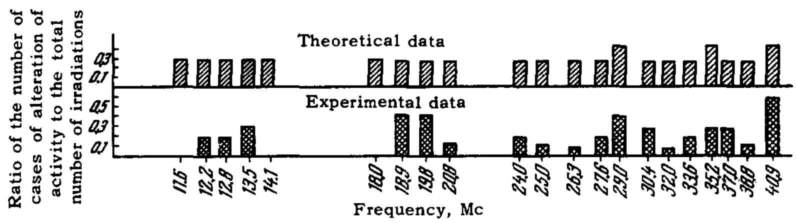
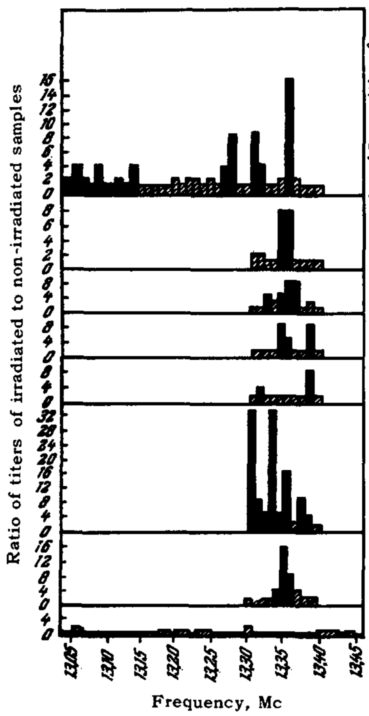


Fig. 16. Alteration in gamma-globulin activity of human blood (estimated from the change in the electrophoretic pattern) when treated with UHF electromagnetic fields of certain frequencies.



Repetition frequency, pulses/sec.	Pulse duration, μsec	Field intensity, V/cm	Mean intensity, milliwatts/cm²	Duration of irradiation, min.	Total absorbed energy, J	Volume of solution, cm³	Total irradiation time, sec.
525	60	130	2.11	20	5680	0.9	38
250	10	40.0	0.013	30	63	0.8	4.5
100	10	40.0	0.005	30	24	0.8	1.8
200	10	20.0	0.0025	30	11	0.8	3.6
300	10	13.3	0.0016	30	7.8	0.8	5.4
Continuous irradiation	Continuous irradiation	13.3	0.54	10	875	0.8	600
		6.7	0.135	30	655	0.8	1800
		4.7	0.07	30	330	0.8	1800

FIG. 17. Alteration in gamma-globulin activity of human blood (estimated by titrating with rabbit serum immunized to human gamma-globulins) when treated with UHF fields with variation of the treatment schedule.

mental data obtained at an interval of 20 kilocycles at 37.5°C agreed well with the calculated data, as is illustrated by Fig. 16.

The study of the effect of microwaves on the antigenic activity of gamma-globulins was performed by titrating irradiated and non-irradiated solutions against rabbit serum (immunized to human gamma-globulins). They found "effective frequencies" at which the irradiated solutions showed considerably higher titers than the unirradiated solutions or those irradiated at other frequencies. The effective frequencies either coincided with the corresponding frequencies manifested in the electrophoretic studies, or they were somewhat shifted with respect to the latter, either to lower or higher frequencies (by tens of kilocycles).

Figure 17 shows the data of these studies under various conditions of irradiation. They show that the effect is manifested upon irradiation at low intensities, and here the field intensity plays the major role, rather than the energy absorbed in the solution.

The authors concluded that the heating of the solution plays no role in the effect discovered. Temperature change of the solution only shifts the effective frequencies, in accordance with Debye's theory. They assume that the increase in the activity of the gamma-globulins is due to the "unwinding" of the helices of the gamma-globulins under the action of the fields.

The same authors[174] have reported a total inactivation of the enzyme amylase (from swine pancreas) resulting from treatment with electromagnetic fields at frequencies of 12, 14, 15, and 16 megacycles. The temperature of the material was kept constant at 37.5°C.

In addition, a change in the activity of certain enzymes has also been observed in the action of microwaves on animals. Thus, irradiation of guinea pigs with microwaves for 5—10 minutes reduced the activity of amylase and lipase,[175] and lowered the glutathione content in the blood (one of the activators of a series of enzymes).[176] The action of 2.4-gigacycle microwaves increased the splitting activity of the enzyme phosphorylase in rat muscles.[177]

In concluding this section, we shall refer to some studies on protein molecules performed with microwaves. The degree of hydration of certain protein molecules has been determined from measurements of the dielectric constant of blood sera over a wide range of microwave frequencies. The degree of hydration for human hemoglobin molecules proved to be 0.23 ± 0.1 g/100 g water,[36,37] for bovine serum albumins it was 0.15 g,[178,179] and for human serum albumins it was 0.42 ± 0.1 g (or within the range 0.04—0.65 when all possible errors had been taken into account).[180]

A group of authors has studied the complex dielectric constant of the keratins.[33,181,182] The studies were based on the fact that the dielectric constant of the keratins at 13 megacycles proved to be considerably greater than the square of the refractive index. This allowed them to suggest the presence of atomic and ionic polarization in the keratin molecules, which should lead to a variation in the dielectric constant in the microwave range, depending on the orientation of the wool fibers with respect to the electric lines of force. However, no such variation was found. On the other hand, the data obtained upon varying the amount of water adsorbed by the wool fibers gave grounds for assuming the existence of three forms of water: "localized water," whose molecules are bound without freedom to rotate by the polar groups of the keratin molecule; "mobile water," which has the properties of a liquid; and "intermediate water," whose potential energy of adsorption lies between the corresponding values for localized and mobile water.

Studies of the dielectric properties of certain crystalline proteins, peptides, and amino acids in the frequency range 1 kilocycle—4 gigacycles and the temperature range 0—100°C[34] have allowed the conclusions that these molecules become polarized by relaxation of their polar groups in accordance with the Debye model with a broad spectrum of relaxation times, and that this relaxation is partially limited, both by intrachain and by external hydrogen bonds. Some ideas were expressed on the possibility of resonance absorption of microwaves by protein molecules, especially in solution.

8. RECEPTION AND GENERATION OF ELECTROMAGNETIC FIELDS IN LIVING ORGANISMS

The effect of microwaves on the sense organs of man has been established experimentally:[183] the sensitivity of the olfactory and visual analyzers was lowered in persons subjected to chronic irradiation at non-thermal intensity (starting at hundredths of milliwatts/cm^2). Rabbit experiments[184] showed that injury to the olfactory analyzer sharply diminishes the reaction to irradiation of the head by UHF fields, namely, the change in the electroencephalogram. The author concluded that this indicates two possible ways of action of fields on the brain cortex: via the olfactory analyzer, and by direct action on the structures of the mid- and forebrain.

Direct reception of microwaves by man was recently discovered[185] in the form of auditory sensations appearing in persons during irradiation by pulse-modulated microwaves. Detailed studies of this interesting phenomenon[186-188] have made it possible to establish some of its regularities.

a) When the pulse-modulated microwave transmitter is turned on, persons situated in the radiation zone hear sounds in the form of buzzing, whistling, or clicking (depending on the modulation pattern). The sound source is sensed to be somewhere in the region of the back of the head. Shielding experiments showed that the perception of "radiosound" takes place only in the temporal region of the head.

b) The "radiosound" is in good agreement with the sound that can be generated in a loudspeaker by the amplified random oscillations of the envelope of the modulation pulses, with cutoff of frequencies below 5 kilocycles and with maximum spread toward higher frequencies. Persons able to perceive sounds only by bone conduction but at frequencies above 5 kilocycles hear "radiosound" just as well as normal persons.

c) "Radiosound" was perceived upon irradiation with microwaves at frequencies 425, 1310, and 2982 megacycles, and off-duty ratio of pulses from 0.0004 to 0.028. The threshold pulse intensities at which "radiosound" was heard were 230—270 milliwatts/cm^2 at frequencies 425 and 1310 megacycles (mean intensities 0.4—7 milliwatts/cm^2), and 5250 milliwatts/cm^2 at 2982 megacycles. However, the effect was not observed upon irradiation with microwaves of frequency 8900 megacycles, even at an intensity of 25,000 milliwatts/cm^2.

d) Surrounding noise up to 90 decibels did not eliminate the "radiosound" effect, although it reduced sensitivity to it. Experiments with earplugs and corresponding calculations showed that when the subject is placed in a soundproof chamber, one may expect perception of "radiosound" at very low microwave pulse intensities of the order of 0.3 microwatts/cm^2.

e) It is assumed that the perception of microwaves occurs directly in the auditory nerves and the cells of the auditory zone of the brain cortex by various "detectors," and that other sensations besides "radiosound" can occur upon irradiation (depending on the form of the latter).

The author suggests that studies of such effects can provide essential information on the functioning of the nervous system, and in particular, on the nature of the coding of signals arriving in the central nervous system. On the other hand, he thinks that microwaves can be successfully used to stimulate the nervous system, since here no unavoidable injuries involved in the introduction of electrodes will be inflicted.

We should point out here some recent short communications indicating the reception of microwaves by living organisms.[13] The irradiation of persons by microwaves in the range 380—500 megacycles caused hallucinations, which appeared at definite frequencies for each subject. When ants were irradiated with microwaves in the 3-cm range, the insects oriented their antennae along the electric lines of force of the field, and lost the ability to "communicate" to other individuals on the finding of food sources. The dimensions of the antennae for the large ants were close to one-quarter of the wavelength.

According to modern conceptions,[189] the activity of the sense organs is not limited solely to reception involving sensation, but is manifested also in functions of the receptors having no equivalent in the form of sensations. Studies in recent years have established[190,191] that throughout the course of existence of the animal world (and even in some cases of the plant world), the very same fundamental mechanisms have been the basis of the functions of reception and biological movement. These are based on the elementary sensitivity of protein molecules, which respond to external influences by structural change.

In the light of these assumptions, we could consider the ESR described above as the manifestation of the reception of microwaves by unicellular organisms, and the changes in activity of gamma-globulins treated by UHF fields as reception on the molecular level.

In addition to the discussed examples of reception of microwaves and other electromagnetic fields by various excitable structures of living organisms, there are also data on the existence of receptors specialized for the perception of electric fields. High sensitivity of certain species of fishes to electric fields has recently been discovered (the minimum variations in the field gradient perceived by the fishes amount to 0.003 μV/mm).[192] The author considers this capability to be a new "sense," whose organs are specialized "electroreceptors."

In recent years, some animals have been found capable of generating electric and magnetic fields. Fishes of certain species emit electric pulses (of duration 0.2—10 msec and frequency 60—1000 pulses/sec).[192] When electric pulses are propagated in an excited frog nerve, corresponding electric and magnetic field pulses appear around the nerve.[193,194]

The problem of the possibility of emission of electromagnetic fields by animal organisms arose as early as the thirties in connection with a report[195] that it had been possible by heterodyne methods to detect emission of radio waves by persons in a state of strong emotional excitement. Such reports have been treated skeptically for a number of years, in view of the imperfection of the radio apparatus used in these experiments. However, a report[13] has recently appeared on a successful repetition of these investigations, using refined modern apparatus.

Recently performed (and very properly designed) experiments have discovered emission of electromagnetic fields by human muscles.[196] During contraction, muscles emit fields of frequencies from tens of kilocycles to 150 kilocycles (and even higher, as the authors suggest). The greatest effect was observed from the small muscles, and a moderate effect from the gastrocnemius. No radiation was noted from the muscles of the head. With different methods of measurement (wide-band, narrow-band, and isolation of specific frequencies), they found variations in the nature of the emission, depending on the age and health of the subjects.

A hypothesis has been advanced[3,97] on the possible role of electromagnetic fields in processes of vital activity. It was based on analyzing the experimental data on the biological action of electromagnetic fields, and on the reception and generation of these fields in living organisms. It is assumed that, in addition to the nervous and humoral systems for information transfer and control, these functions are also fulfilled in living organisms by means of electromagnetic fields. Such a system of communication and control seems probable on all levels of functioning of the living organism, on the molecular, cellular, organ, and systemic levels (and possibly even between individuals of a biological species). On the basis of considerations of reliability, electromagnetic communication on the cellular level is assumed to be wide-band, in a range of about 100 to 1000 megacycles. In this range, the frequency-dependence of the impedance of the cell membranes is already insignificant, while the polar properties of the water molecules are not yet manifested. On the molecular level, the interaction is assumed to be sharply selective, and probably occurring both in the microwave and infrared regions, and in the low-frequency region. We should note here the previously-advanced hypothesis[198] of the existence of direct electrodynamic coupling between closely situated molecules.

9. PROBLEMS OF THE MECHANISM OF THE BIOLOGICAL ACTION OF MICROWAVES AND ELECTROMAGNETIC FIELDS OF OTHER FREQUENCIES

The accumulated experimental material is not yet sufficient for a genuine physicochemical analysis of the biological action of electromagnetic fields in the microwave range and at longer wavelengths. On the other hand, in recent years several hypotheses have been proposed (mostly phenomenological) on the mechanism of this action. We can conveniently consider them as starting points for further study.

Since most of the data on the biological action of microwaves have been obtained by studying physiological changes in an irradiated organism, it was expedient to investigate the mechanism of this action via the course leading from reactions of the organism to the primary physicochemical reactions. These are the standpoints from which the possible mechanisms of the action of microwaves on the physiological functions of human and animal organisms have been treated.[3,199,200]

As was shown above, the nature of the different physiological reactions of animals to microwave irradiation indicates that microwaves act mainly on the nervous system, and most probably on the peripheral receptors and the structures of the brain. On the basis of the data on the penetration of microwave energy into the body tissues of animals and man, we can rather definitely answer the question of which of these excitable structures is acted on to produce any particular reaction of the animal organism to irradiation by microwaves of a given frequency.

Under the assumption that the occipital region of the head of man, rabbit, or rat is being irradiated, an approximate estimate was made of the microwave absorption in the skin, muscle, and brain tissues (without taking account of the small absorption in the subcutaneous fatty tissue and the bones of the skull). Figure 18 shows the frequency characteristics of the microwave absorption with account taken of the fact that 50% of the incident energy on the average is reflected from the surface of the body. Analysis of these curves shows that when a person is irradiated with microwaves of relatively low frequencies, action on the subcortical structures predominates over action on the cutaneous receptors; at frequencies of 600—1000 megacycles, both types of action become comparable; and at higher frequencies we can consider only action

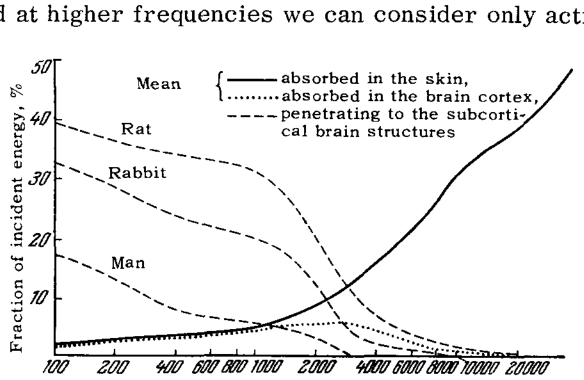


FIG. 18. Frequency dependence of the microwave absorption in the brain structures of man, rabbit, and rat when the head is irradiated.

on the cutaneous receptors. When rabbits and rats are being irradiated, the "comparable-action" frequencies amount to 2000 and 3000 megacycles, respectively. Absorption in the brain cortex is small at all frequencies, and is comparable with the absorption in the skin up to frequencies of 1000—2000 megacycles.

These conclusions are in rather good accord with the experimental observations on the effect of microwaves of various ranges on the central nervous system of man and animals. The comparative data given in Table IV show that whenever the physiological reactions can be unambiguously ascribed to direct action of the microwaves on brain structures, the effectiveness of these reactions increases regularly with the wavelength. Whenever the reaction of the organism can be explained by reflex effects due to direct action of the microwaves on superficial receptors, the effectiveness of the reactions declines with increasing wavelength. Finally, when the physiological reactions can be considered to result from a combination of reflex and direct action of microwaves, one cannot discern any definite regular dependence of the effectiveness of the reactions on the wavelength.

The changes in the functions of the nervous system produced by microwaves are not specific. As is known, such changes are produced by any means of stimulation or variation of the excitability of the peripheral and central parts of the nervous system. Hence, we can naturally assume that also the action of microwaves on the nervous system is due to stimulation or variation of the excitability of the nervous tissues. Also, it has been possible in experiments on frog nerve-muscle preparations[3,207] to observe such an action of microwaves directly. Irradiation with continuous waves (2.4 gigacycles, 11 milliwatts/cm^2) prolonged the absolute and relative refractory phases of the nerve, while irradiation with pulsed waves (3 gigacycles, 1 μsec, 700 pulses/sec, 12 milliwatts/cm^2) enhanced the excitability of the nerve and the rate at which excitation was transmitted along it. We can suggest the action of microwaves on the so-called spontaneous electrical activity of the peripheral nervous system as another primary physiological mechanism of their action on the nervous system. As is known, this activity plays an important role in maintaining the general excitability of the nervous centers. Finally, the above-described experiments on paramecia[168] show that microwaves can stimulate the excitable structure or increase its sensitivity to other stimuli. In conjunction with the data on the action of microwaves on bacteria and tissue cultures (described above), these results provide grounds for considering the possibility of an effect of microwaves on the excitable structures of any living cells whatever.

The elucidation of the physicochemical mechanisms of action of microwaves on excitable structures involves considerable difficulties. First of all, this is because the physicochemical mechanism of excitability

Table IV. A comparison of the effectiveness of the influence of microwaves of various ranges on the central nervous system of animals and man for direct and reflex action

<table>
<tr><th rowspan="3">Assumed type of action</th><th rowspan="3">Observed physiological changes and method of estimating them</th><th colspan="5">Wavelength range</th></tr>
<tr><th rowspan="2">milli-meter</th><th colspan="2">centimeter</th><th rowspan="2">deci-meter</th><th rowspan="2">meter</th></tr>
<tr><th>3 cm</th><th>10 cm</th></tr>
<tr><td rowspan="2">Direct action on brain structures</td><td>Change in the electroencephalogram in rabbits:[201] % of animals in which changes are noted</td><td>–</td><td></td><td>64</td><td>77</td><td>81</td></tr>
<tr><td>Perception of "radiosound" by man:[186] sensitivity = 1/(minimum perceptible intensity), relative units</td><td>–</td><td>0</td><td>1.9</td><td>37–43</td><td>–</td></tr>
<tr><td rowspan="2">Reflex action via superficial receptors</td><td>Fall of blood pressure in rats:[202] Student's criteria</td><td>5.25</td><td>4.60</td><td>4.09</td><td>2.88</td><td>–</td></tr>
<tr><td>Slowing of the pulse in humans:[203] % of persons in whom changes are noted</td><td>–</td><td colspan="2">73</td><td>–</td><td>24</td></tr>
<tr><td rowspan="3">Combination of reflex and direct action</td><td>Change in the reaction of rats to auditory stimulation:[204] % of animals in which changes are noted</td><td>50</td><td>58</td><td>100</td><td>50</td><td>–</td></tr>
<tr><td>Decrease in cholinesterase activity in the brain stem (numerator) and in the blood (denominator) in rats:[205] % decrease</td><td>$\frac{37}{15}$</td><td colspan="2">$\frac{30}{27}$</td><td>$\frac{48}{36}$</td><td>–</td></tr>
<tr><td>Change in conditioned-reflex activity in rats:[206] qualitative estimate</td><td>Medium</td><td colspan="2">Weak</td><td>Strong</td><td>–</td></tr>
</table>

of living tissue in general is still far from clear. Nevertheless, it is reasonable to take up here certain ideas that have been expressed on the mechanism of action of microwaves on the functional state of excitable structures.[3,199,200]

One of the probable mechanisms is suggested to be the detection of microwaves in the nerve-cell membrane, with the possible result of raising the excitability or of exciting the latter. This hypothesis is based on data on the rectifying properties of the nerve-cell membrane.[208] There are experimental grounds for assuming rectifying properties in the cell membrane of paramecium,[3] since the amplitudes of the threshold excitability potentials of paramecium proved to be the same upon comparative stimulation by pulses of alternating current, rectified (half-wave) alternating current, and series of direct-current pulses of the same frequency and off-duty ratio.

One can arrive at another possible mechanism from the standpoint of modern ideas on the hydration of sodium and potassium ions in aqueous solutions.[209] These ideas imply that the thermal, and especially the translational, motion of the water molecules surrounding a sodium ion is hindered in comparison with the motion in pure water (positive hydration), whereas the water molecules near a potassium ion are more mobile than in pure water (negative hydration). Also, the translational motion of the ions themselves involves exchange of nearest neighboring water molecules. We can assume that the effect of microwaves on the water molecules surrounding the sodium and potassium ions will differ. Hence, the corresponding changes in the mobility of these ions will differ. In turn, this should alter the potassium-sodium gradient between the cell and the extracellular medium, and hence, excite the cell or change its excitability.*

A third possible mechanism of the excitation effect of microwaves can be alteration of the permeability of the cell membrane. We can assume that the vibrations produced by the microwaves in the water molecules hydrating the protein molecules of the superficial layer of the membrane must to some extent affect the

*This concept may prove fruitful in elucidating the mechanism of the differing permeability of the nerve-fiber membrane to potassium and sodium.

permeability of the membrane, and thus lead to excitation or to change in excitability.

Another approach to elucidating the mechanism of the biological action of microwaves (and electromagnetic fields of other frequencies) can be based on the above-cited hypothesis on the role of electromagnetic fields in vital-activity processes.[3,197] In the light of this hypothesis, the disturbance of physiological functions of the organism when acted on by microwaves could be considered to result from "radio interference" introduced by the microwaves into the "radio communication" effectuating certain informational interactions in the internal media of the organism. Further, we can assume that under certain conditions, microwave irradiation (of a certain frequency, intensity, and type of modulation) can "impose" non-characteristic rhythms of functioning on the biological systems of the organism. Finally, the possibility is not ruled out that under certain special conditions, microwave irradiation will prove "equivalent" to the biological systems of the organism, and will enhance their natural functions. However, the concept of the effect of electromagnetic fields on informational interaction in the living organism requires especial study.

The mechanism of the cumulative action of microwaves arising from repetitive irradiation of animals and man is of great interest. However, we can set forth only the most general notions on this topic.

The experimental data indicate the possibility of "beneficial" accumulation of the effect of microwaves of medium intensities, for which one notes a gradual adaptation of the organism to subsequent irradiations,[80-82] and "harmful" accumulation from low-intensity microwave irradiations, which gradually sensitize the organism to subsequent, more intense irradiations.[87] As has been stated, systematic irradiations result in morphological changes, both in peripheral receptors and in brain structures.[115-117] Apparently, the reason why the cumulative effect of microwave irradiation occurs in a particular place under given conditions (in the peripheral or central nervous system) depends on its nature, i.e., whether it is "beneficial" or "harmful."

Certain hypotheses have been advanced in recent years on the molecular mechanism of the biological action of microwaves and electromagnetic fields in other ranges.

The possibility of denaturation of molecules by microwave action has been tested in experimental studies.[87] Microwave irradiation (10 gigacycles, 245 milliwatts/cm^2) was applied to a solution of human serum albumins. The heating of the solution caused by the irradiation (Fig. 19) led to denaturation of the macromolecules. Here this process depended on the irradiation time in a manner not differing from the corresponding case when the solution was heated in the ordinary way to the same temperature (Fig. 20). These data indicated a thermal mechanism of the denaturation of molecules by microwaves under the described conditions. However, the author does not rule out the possibility of non-thermal denaturation at high intensities of pulsed irradiation.

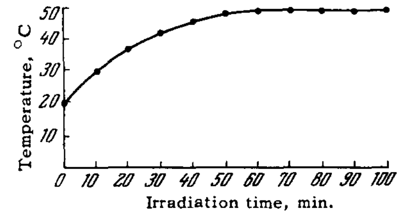


FIG. 19. Temperature rise of a solution of human serum albumins irradiated with microwaves (10 gigacycles, 245 milliwatts/cm^2).

The probability of non-thermal denaturation of protein molecules when acted on by pulsed microwaves has been discussed[32] from the standpoint of the onset of "dielectric saturation". It is assumed that all the polarized side chains of the protein molecules can be oriented by strong pulsed-microwave fields. This should create the possibility of breaking hydrogen bonds and altering the hydration zone on which the solubility of the molecules depends. Such processes can cause the denaturation or coagulation of protein molecules.

It has been concluded[210] on the basis of a theoretical study that when electromagnetic fields are propagated in electrolytes, Lorentz forces will act on the ions, under the condition that the energy losses in the medium are small. In the author's opinion, this condition is satisfied when pulsed waves are propagated in a liquid medium. Such phenomena are also assumed to be probable in biological media.

Another theoretical study[47] has been concerned with the fact that a number of biological phenomena show intermolecular forces distinguished by a stronger interaction between identical or similar molecules. This interaction arises from the fluctuations of proton and electron charges in each molecule. This creates a favorable distribution of charges in an adjacent molecule, leading to an interaction of the molecules. However, the surrounding water molecules hinder this attraction. Thus, the latter must be expelled, and this process depends on whether the interacting molecules are similar or different. The above-cited hypothesis[46] on the dipole-dipole interaction of enzyme and substrate molecules and the effect of microwaves on

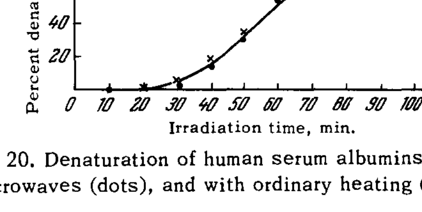


FIG. 20. Denaturation of human serum albumins when treated with microwaves (dots), and with ordinary heating (crosses).

this interaction was advanced on the basis of these assumptions.

A theoretical study of the possible influence of an electric field on the relative stability of two possible states or configurations of macromolecular systems is of interest.[211] The author concluded that an electric field of intensity of the order of 10,000 V/cm can separate the molecular chains in DNA (transition between the unpaired and the paired state). It can also exert an influence on the elasticity of protein chains (transition between a long and a short chain), i.e., result in muscular contraction. Experimental data have recently been obtained indicating the existence in living organisms of a previously unknown control system.[212] A study of surface electric potentials did not reveal the previously proposed dipole symmetry of the equipotential lines. Instead, a distribution was found corresponding to the anatomical arrangement of the major portions of the central nervous system, as is shown in Fig. 21 for a lizard (a similar distribution has been found also in man). Studies using the Hall effect showed that the found potential distribution is due to a flow of electrons along the nerve in the direction dendrite—neuron body—axon (whereas the biocurrents of the nerve arise from the radial motion of ions in the nerve fiber). Thus, the peripheral end of a sensory nerve is at a positive potential, while that at the end of a motor nerve is negative (Fig. 22). The authors suggested that the discovered system of electrical activity controls the biocurrents of the nerve by influencing the rate of transfer of information and control in the living organism. In addition, they consider this system to be related to the slow transfer of information on pain and injuries, and to the psychic state, as has been confirmed experimentally. Broader conclusions were also drawn from the obtained results:

a) The slowly-varying potentials of the brain are a mechanism controlling the behavior of man and animal.

b) External electric and magnetic fields must affect this control system, and hence, the behavior of man. The authors correlate these hypotheses with

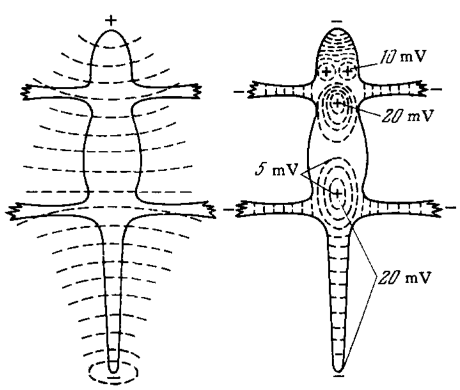


FIG. 21. Distribution of surface electric potential over the body of a lizard. Left – assumed, right – experimentally found.

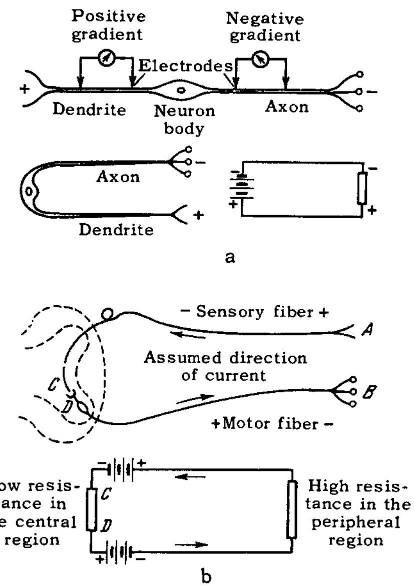


FIG. 22. Distribution of potential along spinal-cord neurons, and the corresponding equivalent circuit diagrams for a neuron (a) and for a nerve center in the spinal cord (b).

statistical data on the relation between changes in the intensity of the Earth's magnetic field and mental diseases. It turned out that marked increases in mental diseases are firmly correlated with magnetic storms.

CONCLUSION

The impression may have developed out of the discussed experimental and theoretical material that the microwave range is the most active from the biological standpoint, from among the entire broad range of electromagnetic fields. In fact, in the course of decades no one was able to find any biological effects of electromagnetic fields of high and ultrahigh frequencies other than purely thermal, whereas in microwave experiments, biological action was exhibited very promptly, and in most varied manifestations.

However, the point here is not the especial biological activity of microwaves, but the fact that the studies in this range proved more fruitful from the methodological standpoint: it was relatively easy to measure the intensity of irradiation acting on local regions of the bodies of animals, and to regulate the depth of penetration of the energy by varying the frequency. We must also take into account the important fact that about the time of the technological development of the microwave range, new, more refined methods of biological study had already been developed: electrophysiological, microscopic, biochemical methods, etc.

In addition, the successful results achieved in biological studies with microwaves have stimulated a broad study of the biological action of electromagnetic fields of other frequency ranges. In line with these advances, interest arose again in the old problem of the possible role of electromagnetic fields in the evolutionary development of life, and in the vital activity of organisms. It suffices to say that tens of papers have been published in recent years on the effect of low-frequency and infra-low-frequency fields on living organisms, on the appearance in humans, animals, and plants of physiological reactions to periodic changes in the magnetic and electric fields of the Earth, on the generation of electromagnetic fields of various frequencies by living organisms, and on the participation of these fields in vital processes. The number of studies along these lines is growing intensely, and even several review articles have already appeared.[213-218]

The study of the interaction of living nature with electromagnetic energy in the optical and ionizing regions of the spectrum led to the creation of the new branches of biology, "photobiology" and "radiobiology." Following this path, all the above material gives us grounds for thinking that the remaining part of the electromagnetic spectrum is being "mastered" at present, from submillimeter radio waves to slowly-varying electric and magnetic fields. A new branch of biology is being created, which might be called "electromagnetic biology."

Of course, it would be premature to make any generalizations on this new general biological problem, which hasn't yet gained its "legal rights" in science. However, an analysis of the experimental data on the biological action of microwaves and electric fields of other frequencies leads to the notion of one general feature of this action.[219]

The biological action of electromagnetic fields most often amounts to some effect on the processes of control and intercommunication in the living organism: between systems, between cells, or between molecules. In other words, an electromagnetic field exerts an influence on the informational interactions in the organism, and apparently, the energy of the field serves only as a means of exerting this influence. In fact, it has been established experimentally that the nature of a given physiological reaction to an electromagnetic field remains practically invariant when the amount of energy in the acting field is varied over rather wide ranges. Furthermore, the effectiveness of the reaction can even increase with decreasing intensity of the treatment.

All this leads us to propose that the biological activity of electromagnetic fields is not due to energetic interaction, but to informational interaction with living organisms. That is, the major interaction here is not the transformation of electromagnetic energy into other forms, but the effect of electromagnetic fields on processes of transformation, transfer, coding, and storage of information in living systems. Further research will show how valid this conception is.

In conclusion, we would like to emphasize that the accumulated experimental material and some theoretical considerations on the interaction of life with electromagnetic fields already give us sufficient grounds to think that this problem is worthy of serious discussion and many-sided research.

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