Shevchenko K.L., Doctor of Technical Sciences, Professor, National Technical University of Ukraine «Ihor Sikorsky Kyiv Polytechnic Institute»
Smirnov D.O., Candidate of Medical Sciences, State Institution «Institute of Traumatology and Orthopedics of the National Academy of Medical Sciences of Ukraine»

METHODS AND MEANS FOR ASSESSING THE ELECTROMAGNETIC COMPATIBILITY OF MATERIALS IN CONTACT WITH HUMAN TISSUES

1. Modern concepts of compatibility of materials in contact with human tissue

Throughout his or her life, a person is in constant contact with the environment, materials, and substances of natural and artificial origin, as well as products made from them. The physical and mechanical characteristics of substances and materials have a significant impact on the human condition and sensations. For example, everyone has experienced the impact of uncomfortable or seasonally inappropriate clothing on the physical, moral, and psychological state of a person. In this case, we are talking about only one of the many parameters that can cause discomfort, namely the temperature in the underwear space. In fact, there are many such parameters, and assessing their compliance with certain indicators is an important task. In most cases, the parameters that affect the interaction of materials with human skin or tissue can be estimated numerically, i.e. they have certain numerical values. Taking into account the values of the parameters allows us to conclude that each material is compliant or not compliant under certain conditions of human use. To assess the conformity of substances and materials, it is advisable to use the term «compatibility».

Evaluating the compatibility of substances and materials with human tissues is an important step in the development, production, and use of various medical devices, clothing, household products, and other goods that have direct contact with skin or tissues.

To conduct a compatibility assessment, it is advisable to perform some preliminary procedures, including material composition analysis, toxicity assessment, study of the reaction of body tissues, determination of the impact on physiological processes, compliance with standards, etc.

When analyzing the composition of materials, it is advisable to analyze the documentation from manufacturers or analyze the chemical composition, including chemical compounds, impurities, and other components.

The procedure for analyzing the composition of materials allows you to assess its toxicity due to the presence of substances that can cause irritation, allergic reactions, or other negative effects on human skin or tissue.

The data obtained on the composition and toxicity allow us to assess the compliance of the material or substance with the established standards and regulations regarding safety and compatibility with human tissues.

In case of a positive result of the above procedures, it is advisable to study the reaction of body tissues to the interaction with the material. This stage is experimental and involves conducting experiments or testing on volunteers to assess the skin's reaction to contact with the material or substance. Even if the composition is appropriate and there are no toxic substances, contact with certain materials can cause irritation, redness, itching, skin rashes, and other symptoms.

Determining the impact on physiological processes is a rather complicated and lengthy procedure. First of all, it is advisable to determine the effect of the material on such processes as skin respiration, heat transfer, moisture removal, etc.

Taking into account the results of the above studies, it is possible to preliminarily assess the compatibility of substances and materials with human tissue and minimize risks to the health of users. However, the final conclusion about compatibility can only be made when numerical indicators of the parameters that determine the compatibility of materials with human tissue are obtained.

For example, for clothing materials, such parameters are usually divided into four groups: hygienic, technological, aesthetic, and economic [1].

Hygienic parameters include the ability to absorb and permeate moisture and air, and thermophysical, optical, and acoustic properties. In particular, they determine the ability of clothing to protect the human body from environmental influences, remove moisture and carbon dioxide from the undergarment space, and maintain the microclimate necessary for the body's vital activity in the undergarment space, i.e., they determine the hygiene of clothing.

Technological parameters can only partially be attributed to the determinants of compatibility with the human body. These include material strength, resistance to friction and bending, elongation due to stretching, stiffness, and others.

Aesthetic and economic parameters can also only conditionally be attributed to the determinants of compatibility, mostly characterizing the appearance and consumer's ability to use certain materials.

These are currently the generally accepted ideas about the compatibility of materials in contact with the human body.

Unfortunately, they do not take into account an essential component of the interaction of materials with human tissue. This component is the electromagnetic interaction of materials used both in everyday life and for medical purposes. The peculiarities of this interaction and the mechanisms of electromagnetic radiation generation are discussed below.

2. General information on intrinsic electromagnetic fields and their interaction

The electromagnetic radiation (EMR) surrounding a person throughout life can be divided into two components by origin: natural and man-made.

The Sun and outer space irradiate the Earth with broad-spectrum electromagnetic waves. It includes signals in the optical (ultraviolet (UV) to visible spectrum), microwave, radio, and low-frequency ranges. Most of the ultraviolet radiation is absorbed by the Earth's atmosphere. Radiation with longer wavelengths passes freely through the Earth's atmosphere. The peculiarity of the UV component of radiation (wavelength 180...400 nm) is a significant quantum energy (3.1...6.2 eV) and ionizing ability. UV radiation can have both a positive effect (bactericidal effect, increased immunity, stimulation of photochemical synthesis of vitamin D, and other effects) and a negative effect (burns, stimulation of gene mutation processes, and skin cancer) [2]. The visible part of the spectrum covers optical electromagnetic radiation in the range of 400...750 nm, and infrared (thermal) radiation with a wavelength of more than 750 nm. The energy of the quanta of these radiation components is lower (1.24...2.95 eV), but the depth of penetration into human tissue is greater. If the protective reaction of the human body against UV radiation is manifested in the form of a tan on the skin surface, then the radiation of the visible and infrared ranges is better absorbed and has a greater effect on the inner layers of human tissues. This is also true for the microwave range of EMR.

This effect is widely used in various spheres of human activity, in particular for diagnostics and treatment of humans [3].

Of particular interest is the EMR of cosmic origin in the millimeter wavelength range (frequency 30...300 GHz). It includes microwave relict radiation with a maximum intensity at a frequency of 160 GHz [4]. The energy of the millimeter-wave signals is much lower than that of the 1.24 optical band (10^{-5}...10^{-4} eV), so their effect on the human body at equivalent power will be more «mild».

The Earth's atmosphere absorbs microwave signals of different frequencies in different ways. The radiation of most of the spectrum is attenuated, and for some frequencies, in the so-called «transparency windows», it is transmitted almost without loss. One of the reasons for the attenuation of radiation is the resonant absorption by water and oxygen molecules. Microwave radiation of cosmic origin is considered to be primary.

At the same time, solar radiation in the infrared range, having passed through the atmosphere, heats up living and non-living objects located on the earth's surface (water, sand, stones, etc., including those in contact with human tissue). It is known that when heated, any dielectric materials emit electromagnetic waves in a wide range of frequencies. This radiation is commonly referred to as radio-thermal radiation. It has a noise-like spectrum, and the distribution of its energy density over frequency is described by Planck's law. The maximum heating temperature of objects on the Earth's surface by solar radiation can reach 100 degrees Celsius or more. As a result, this leads to the formation of low-intensity broadband microwave radiation, which, by analogy with radiation of cosmic origin, is considered secondary.

The source of the intrinsic EMR of materials is thermal fluctuations, or the so-called thermal noise, which is characteristic of dielectric materials. Thermal noise is a consequence of the chaotic movement of electric charge carriers, which can be electrons and ions in dielectrics or holes in semiconductors. In a system that is in a balanced state, where there are no reverse processes associated with dissipation phenomena, charge carriers are in thermal equilibrium with the molecules of the substance. At the same time, the Brownian motion of charge carriers causes fluctuations in their uniform distribution in the volume of the material and causes the appearance of unbalanced charges. Unbalanced charges cause the creation of a potential difference and a corresponding current, the flow of which equalizes the potential difference. In dielectric materials that have a small number of free electrons (textile materials, materials for implantation and prosthetics, etc.), thermal noise is largely generated by fluctuating dipoles.

The man-made component of EMR includes fields and signals generated by artificially created technical means. This category includes a huge set of mobile communication equipment, special radio systems for civilian and military purposes, generators for microwave therapy, and many other technical devices. They create an uneven electromagnetic background in the environment with a power level of (10^{-9}...10^{-8}) W [5]. The result is the so-called electromagnetic pollution of the environment, which will continue to increase due to the use of

4G, 5G, and satellite systems. The level of man-made radiation power can significantly exceed the natural microwave background and, accordingly, have a significant impact on biological objects. Studies conducted by some authors have noted the harmful effects of a constant man-made electromagnetic background in the environment on the biosphere and living beings [6].

At the same time, low-intensity signals in the millimeter range can have a stimulating and therapeutic effect on living beings and the human body in the short term, which is the basis of microwave therapy.

Primary and secondary microwave radiation of natural origin is weak compared to the man-made component. Nevertheless, it constantly affects living organisms that are in the zone of their influence. The power of such radiation can be determined using special radiometric receivers [7]. The radiation level is estimated using the Rayleigh-Jeans formula:

$$P = 2\pi\beta(f,T)\frac{f^2}{c^2}kT_oS_0\varDelta f, \tag{1}$$

where $\beta(f,T)$ – is the emissivity coefficient; T – is the thermodynamic temperature of the radiation source; f – is the radiation frequency; $k = 1{,}38 \cdot 10^{-23}$ – is the Boltzmann constant; S_0 – is the surface area of the object under study, which is limited by the aperture of the receiving antenna; Δf – is the radiation frequency band to which the receiver is tuned.

The human body, which has an average temperature of 36.6°C, is also a source of EMR. The main part of it falls on the infrared part of the spectrum, but there is also microwave radiation.

Physiological processes occurring in the human body at the cellular level are regulated. In this case, the regulator is the EMR of millimeter and submillimeter wavelengths (frequency 3...3000 GHz). Radiation in this range is formed as a result of oscillations of cell membranes electrically charged due to ionic intracellular transfer. The natural frequency of oscillations of different tissues and cellular structures is different and, for example, for DNA macromolecules lies within 2...9 GHz, the frequency of oscillations of chromosomes is 0.75...15 THz, and the frequency of the human genome is about 25 THz.

In the case of the coincidence of natural frequencies of oscillations of individual cells or cellular structures with the frequency of irradiating waves of these ranges, resonance phenomena are caused, which transform weak effects of external EMR into significant bioinformational and structural changes for the body. A characteristic property of human body tissues is the ability to selectively interact only with certain frequencies of noise-like broadband radio-thermal secondary radiation.

The integral power of the microwave signal of the human body and its individual parts is in the range of 10^{-14}...10^{-13} W and depends on the state of the body. As shown by experimental studies [8], the average value of the radiation level of the palm of most respondents is in the range of (3...6)10^{-13} W.

Radiometric systems used to measure intrinsic EMR have their own temperature, different from the temperature of the objects under study. Therefore, the output signal level of the meter is determined by the temperature difference between the object under study and the measuring system:

$$\Delta P = 2\pi K_1(f)\beta(f,T)k(T_o - T_R)\Delta f, \tag{2}$$

where $K_1(f)$ – is the conversion coefficient of the antenna receiving electromagnetic radiation; T_o – is the temperature of the object; T_R – is the temperature of the radiometric system.

Based on the above equation, it can be concluded that in order to measure low-intensity electromagnetic fields and radiation, it is necessary to ensure the sensitivity of the measuring system, which is an order of magnitude higher than the level of the measuring signals.

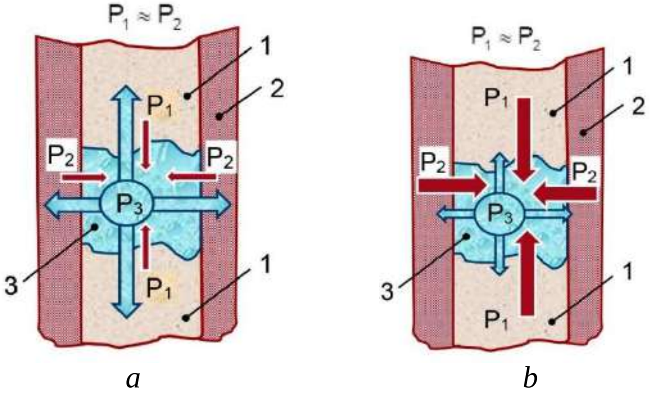
Ensuring such sensitivity of measurement systems is a complex technical task that requires fundamentally new approaches to the structural design of measurement systems and the creation of new algorithms for processing measurement information.

It was noted above that millimeter-wave signals are actively absorbed by water and oxygen molecules, which are integral components of living organisms. The phenomenon of absorption of low levels of EMR is the basis of microwave resonance therapy [9]. The power level of microwave signal generators, which are used to produce therapeutic effects, is in the range of 10^{-12}...10^{-6} W. It is the effect of signals of such a low level that provides positive changes in the indicators of the patient’s body during treatment, which are recorded by laboratory tests. Taking into account the therapeutic effect of exposure to signals of this level, a number of scientists have introduced new terms for this area, such as «quantum medicine» and «bioinformation signals» [10]. In this case, the targets of microwave signals are biologically active zones that are stimulated at the cellular level with subsequent transfer of information to the level of organs and systems of the human body.

Taking into account the above mechanism of secondary microwave radiation generation and the assessment of its power level, an interesting conclusion can be drawn. It is that conventional dielectric materials in contact with human tissues at certain temperature values can generate EMR comparable in level to signals from microwave therapeutic generators. That is, materials of clothing, footwear, implants, reconstructive surgery parts and everything else that has contact with human tissue will inevitably interact by transmitting electromagnetic radiation.

Analyzing the interaction of EMR with human tissues, it is advisable to return to expression (2). In fact, the interaction process is determined by the temperature gradient between the tissue and the object with which it interacts. If the temperature of the radiation object exceeds the temperature of the human body tissue $T_O > T_T$, a positive irradiating flux of microwave radiation is formed. In the opposite case, when the temperature of the radiation object is lower than the temperature of the human body tissue $T_O < T_T$, a negative EMR flux is formed.

In Fig. 1 shows a diagram of the formation and interaction of electromagnetic fluxes between the installed bone implant 3 and the adjacent tissues of the human body – bone 1 and soft 2. If the level of intrinsic electromagnetic radiation of these tissues differs, positive (Fig. 1a) or negative (Fig. 1b) electromagnetic radiation fluxes are formed.



a *b*

Figure 1. Formation of positive
and negative electromagnetic radiation fluxes

Source: developed by the authors

Notation in the figure: P_1, P_2 – radiation power per unit surface of bone and soft tissue, respectively, P_3 – radiation power per unit surface of the implant.

The EMR powers of the bone P_1 and soft adjacent tissues P_2 are naturally physiologically consistent with each other, and the implant radiation level P_3 in the variant shown in Fig. 1a is increased, so the surrounding tissues receive constant additional radiation. In the variant shown in Fig. 1b, on the contrary, the implant absorbs the EMR of the surrounding tissues, since its radiation level is lower.

This transfer of energy in the form of microwave EMR from an object with a higher value of emissivity β_1 to an object with a lower value of β_2, subject to prolonged exposure, can both improve and worsen the course of reparative processes in the body. Such a process thereby determines the clinical effectiveness of the use of the materials under study. An increase in microwave EMR is equivalent to the onset of an inflammatory process due to excess energy at the implant site. Therefore, such studies help to select materials for implantation more efficiently.

Positive EMR fluxes increase the energy of the area they affect, while negative ones decrease it accordingly. Absorption of electromagnetic field energy by cells of a living organism in the case of a positive flow stimulates biochemical processes in cells and intercellular space. Negative fluxes, on the contrary, inhibit the course of biochemical processes at the interaction site. This is evidenced by laboratory studies conducted at the Kyiv Oncology Institute of the Ministry of Health of Ukraine on mice with irradiated sarcoma tumors [11].

This clearly demonstrates the importance of assessing both the level of intrinsic radiation of human tissues and materials in contact with tissues and their electromagnetic compatibility. An important condition for this is the availability of measuring devices that, against the background of electromagnetic pollution, allow measuring lower power radiation of a radio thermal nature.

3. Methods of measuring intrinsic electromagnetic radiation

The main problem of creating and using radiometric measuring devices capable of measuring ultra-weak EMR levels is that the measured signals have a power less than or comparable to the radiation of man-made origin and the intrinsic thermal noise of the high-frequency paths of the measuring devices. Thus, the spectral power density of the EMI of a dielectric having a temperature of 25...30 °C is in the range of $10^{-21}...10^{-19}$ at a channel bandwidth of 1 MHz. This corresponds to the power of the radiation source at the level of $10^{-13}...10^{-12}$ W. This value is much less than the background power from man-made sources received by the radiometric meter antenna and is commensurate with the intrinsic noise of the receiving antenna. Therefore, special methods of converting a useful informative signal are used to build radiometric meters. One such method is the switching-modulation conversion of the signal from the object under study.

Let's consider variants of modulation radiometric systems, which provide the ability to increase the measurement accuracy by minimizing the influence of the measuring equipment's own noise and external radiation. The functional diagram of the switching-modulation radiometric meter is shown in Fig. 2.

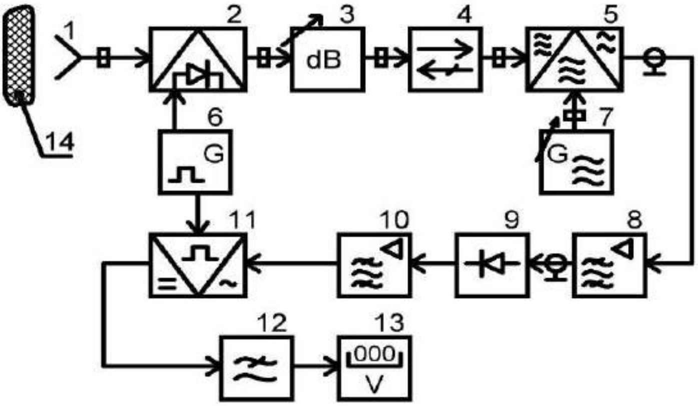


Figure 2. Functional diagram of a switching-modulation radiometer

Source: developed by the authors

The diagram shows: 1 – horn receiving antenna; 2 – microwave controlled modulator; 3 – controlled attenuator; 4 – valve; 5 – signal mixer (multiplier); 6 – clock; 7 – microwave radiation generator; 8 – band-pass high-frequency amplifier; 9 – high-frequency detector; 10 – selective amplifier; 11 – synchronous detector; 12 – low-pass filter; 13 – voltage meter; 14 – source of electromagnetic radiation.

The principle of operation of the above scheme is as follows. The material to be tested is preheated to a temperature close to the surface temperature of the human body (approximately 37°C). This generates broadband noise-like radio-thermal radiation, the level of which depends on both the temperature and the structural features of the material under investigation. The radiation from the material is received by antenna 1 and through the microwave-controlled modulator 2 is fed to the input of the controlled attenuator 3. The modulator 2 is controlled by a clock 6. The signal modulation operation consists in the fact that in one half-period of the clock (in the absence of a positive voltage) the modulator passes the signal from the antenna to the attenuator, and in the second half-period (in the presence of a positive voltage) the modulator blocks the signal passage to the attenuator. This ensures the creation of a variable component of the useful signal (as you know, it is much easier to convert signals of variable frequency than constant signals). The attenuator allows you to set the level of the modulated signal to ensure the operation of the following circuit elements. From the attenuator, the modulated signal is sent through the ferrite valve 4 to the balance mixer 5. The task of the valve is to block the passage of the signal reflected from the mixer 5, which may occur due to load unbalance. The second input of the balanced mixer receives a signal from the microwave radiation generator 7 (heterodyne). When the signals from the antenna and the heterodyne are mixed, a difference signal of an intermediate frequency is formed, which is amplified by a bandpass amplifier 8. The balanced mixing procedure is designed to transfer the signal processing from the microwave range to the high-frequency region. The amplified signal is fed to the detector 9, from the output of which it is sent to the selective amplifier 10. The selective amplifier is tuned to the frequency of the clock, which allows at its output to obtain an amplified signal whose frequency coincides with the modulation frequency of the antenna input signal. From the output of the amplifier 10, the low-frequency signal is sent to one of the inputs of the synchronous detector 11. The output of the clock generator 6 is connected to the second input of the synchronous detector. As a result of synchronous detection, a signal with a constant component is formed, the value of which is proportional to the power of microwave radiation received by the antenna. The low-pass filter 12 separates the DC component of the useful signal from the low-frequency noise and is measured by a voltmeter 14.

One of the problems with using the described radiometric system is the cooling of the test sample during the measurement process. Cooling results in a constant change in readings and the resulting measurement error. It should be noted that in this case, the greatest interest is in the EMI level of the material for the temperature corresponding to the human body temperature.

To avoid this disadvantage, it is advisable to use a thermostat with the ability to adjust the temperature within the range near the average human body temperature. Due to this, the material placed on the surface of the heating element will always have a constant temperature. Fig. 3 shows the structural implementation of the measuring system with a thermostat.

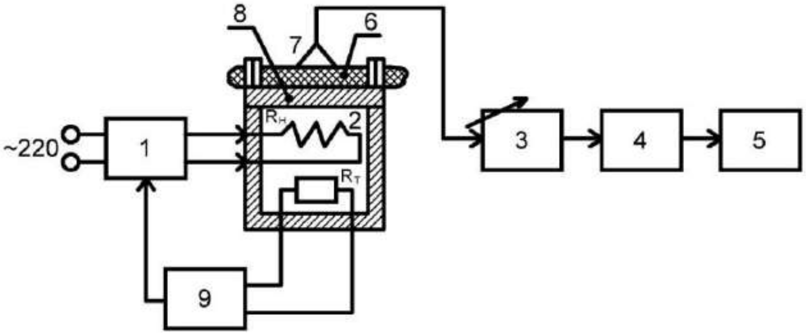


Figure 3. Radiometric system with a thermostat

Source: developed by the authors

The following notations are used in the diagram: 1 – regulated power supply; 2 – thermostat; 3 – input signal attenuator; 4 – radiometric converter; 5 – measuring device; 6 – test material; 7 – receiving antenna of the radiometer; 8 – metal plate on which the test material is placed; 9 – temperature controller; R_H – heating element; R_T – temperature sensor.

Since the thermostat maintains a constant temperature of the upper metal plate on which the test material is placed, the methodological component of the error caused by the cooling of the material is excluded. At the same time, when using a single-channel radiometer construction scheme, the radiation generated by the heated thermostat plate is added to the intrinsic EMR of the material under test. This leads to an additional error. It can be reduced by measuring the radiation of the plate without material on it and then finding the difference between the two radiation levels. However this approach does not fully compensate for the level of additional radiation. This is due to the fact that part of the heater's EMR is dissipated in the material as it passes through it. As a result, the level of radiation from the heater in the absence and presence of material is different. In addition, time-separated measurements of low EMR levels can lead to random errors due to the influence of environmental conditions.

To avoid these drawbacks, it is advisable to use a two-channel scheme for constructing a switching-modulation radiometric system shown in Fig. 4.

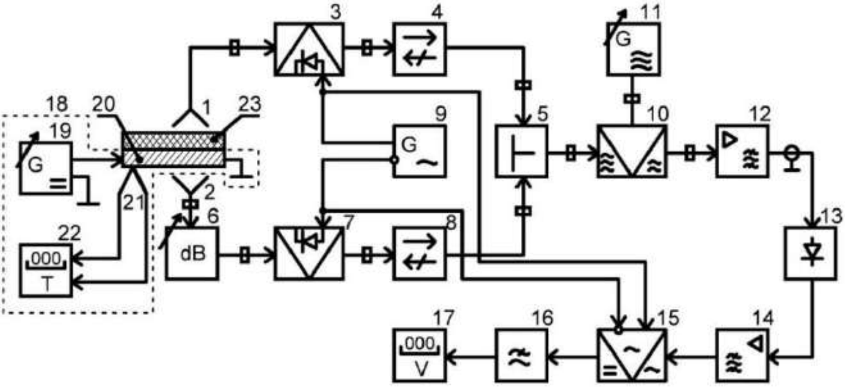


Figure 4. Two-channel diagram of the radiometric system

Source: developed by the authors

The diagram shows 1, 2 – measuring antennas; 3, 7 – microwave controlled modulators; 4, 8 – valves; 5 – waveguide tee; 6 – controlled attenuator; 9 – clock pulse generator; 10 – signal mixer (multiplier); 11 – microwave radiation generator; 12 – high-frequency bandpass amplifier; 13 – high-frequency detector; 14 – selective amplifier; 15 – synchronous detector; 16 – low-pass filter; 17 – voltmeter; 18 – heating element; 19 – heating element current setter; 20 – metal plate; 21 – temperature sensor; 22 – temperature meter; 23 – material under test.

The principle of operation of the above scheme is as follows.

Antenna 1 receives the EMR from the material under test. The radiation from the heating element also partially reaches it. Antenna 2 receives the radiation generated only by the heating element. The radiation power received by antennas 1 and 2 is described by the following expressions:

$$P_1 = S_1(P_x + P_0 - \Delta P) + P_{n1}, \tag{3}$$

$$P_2 = S_2 q P_0 + P_{n2}, \tag{4}$$

where S_1 and S_2 – are the conversion coefficients of the receiving antennas 1 and 2; P_x – is the intrinsic EMR power of the material sample under test; P_0 – is the EMR power of the heating element; ΔP – is the

EMR power loss of the heating element in the material under test; q – is the attenuation level generated by the controlled attenuator; P_{n1} and P_{n2} – are the intrinsic noise power levels of the measuring antennas.

The signals (3) and (4) received by the antennas are transmitted to the microwave-controlled modulators 3 and 7, where they are periodically interrupted. The frequency of interruption (modulation) is determined by the frequency of the clock generator 9. The modulated signals pass through gates 4 and 8, after which they are sent to the inputs of the waveguide tee 5.

Microwave switches 3 and 7 are controlled by out-of-phase voltages from the clock generator 9. Due to this, a sequence of radio pulse packets received from antennas 1 and 2 is formed at the output of the waveguide tee. The frequency of this sequence corresponds to the switching frequency of the controlled modulators (modulation frequency). From the output of the tee, the packets of radio pulses are sent to one of the inputs of the mixer 10. A microwave radiation generator 11 is connected to its second input. The mixer alternately mixes the radio pulse packets with the monochromatic oscillations of the microwave generator. At the output of the mixer, signals of differential frequency are emitted, which are amplified by a bandpass high-frequency amplifier 12 tuned to a differential (intermediate) frequency. It is known that the radio-thermal radiation received by antennas is noise-like in nature and has a wide spectrum. Accordingly, the radio pulses that arrive at the first input of the mixer are broadband. After mixing them with a monochromatic signal and amplifying them with a bandpass amplifier, narrowband noise-like pulses are generated at its output, which falls into the amplifier’s bandwidth. They are sent to the high-frequency detector 13, where they are detected and averaged. As a result, the output of detector 13 generates video pulses with two amplitudes corresponding to the radiation level received by antennas 1 and 2:

$$U_1 = S_3 K_1 S_4 (P_1 + P_3), \tag{5}$$

$$U_2 = S_3 K_1 S_4 (P_2 + P_3), \tag{6}$$

where S_3 – is the steepness of the heterodyne conversion of the radio pulse frequency; K_1 – is the gain of the bandpass amplifier 12; S_4 – is the conversion steepness of the high-frequency detector; P_3 – is the power of the heterodyne conversion’s own noise.

Since the amplitudes of signals U_1 and U_2 are different, the sequence of video pulses (5) and (6) contains a variable voltage component whose frequency corresponds to the modulation frequency:

$$U_3 = \frac{U_1 - U_2}{2} = \frac{1}{2} S_3 K_1 S_4 (P_1 - P_2). \quad (7)$$

The alternating voltage U_3 is sent to the selective amplifier 9, tuned to the frequency of the clock 9 (modulation frequency). After amplification by the synchronous detector 15, the DC component of the voltage is isolated, which is smoothed by the low-pass filter 16. The output of the filter is a constant voltage:

$$U_4 = \frac{1}{2} S_3 K_1 S_4 K_2 S_5 K_3 (P_1 - P_2), \quad (8)$$

where K_2 – is the gain of the amplifier 14; S_5 – is the conversion slope of the synchronous detector; K_3 – is the transmission coefficient of the low-pass filter 16.

Taking into account the expressions describing the radiation power perceived by the antennas, we obtain:

$$U_5 = \frac{1}{2} S_3 K_1 S_4 K_2 S_5 K_3 [S_1 (P_x + P_0 + \mathit{\Delta} P) - S_2 q P_0 + P_{n1} - P_{n2}]. \quad (9)$$

The antennas used in radiometric systems usually have the same design and, accordingly, the same parameters. Therefore, the following relations are valid:

$$S_1 = S_2; P_{n1} = P_{n2} \quad (10)$$

Taking this into account, the voltage supplied to the voltmeter can be estimated:

$$U_6 = \frac{1}{2} S_1 S_3 K_1 S_4 K_2 S_5 K_3 (P_x + P_0 - \mathit{\Delta} P - q P_0). \quad (11)$$

During the measurement, the attenuator 6 sets the attenuation of the signal coming from the antenna 2. The attenuation value is chosen proportional to the thickness of the material under study. This fulfills the conditions:

$$P_0 - \mathit{\Delta} P = q P_0. \quad (12)$$

If the above condition (12) is fulfilled, the value of the voltage measured by the voltmeter 17 is determined by the equation:

$$U_7 = \frac{1}{2} S_1 S_3 K_1 S_4 K_2 S_5 K_3 P_x = S_0 P_x, \quad (13)$$

where $S_0 = \frac{1}{2} S_1 S_3 K_1 S_4 K_2 S_5 K_3$ – is the resulting conversion factor of the radiation power of the material under study into a constant voltage.

The analysis of the conversion equation (13) shows that the value of the output voltage of the two-channel radiometric system is proportional to the power of the intrinsic radiative heat radiation P_x of the material under study. It should be noted that the measurement result is not affected by the power of the EMR P_0 generated by the heater plate 20. The equation also shows that the proposed signal conversion algorithm eliminates the influence of the intrinsic noise of antennas 1 and 2, as well as the intrinsic noise of the heterodyne conversion. In addition, the use of a selective amplifier 14, a synchronous detector 15, and a low-pass filter 16 eliminate the low-frequency noise of quadratic detection.

Thus, the use of the proposed two-channel radiometric system with switching-modulation signal conversion provides the ability to measure ultra-weak levels of the intrinsic EMR of the materials under study and eliminates the influence of the intrinsic noise of the elements of the high-frequency signal conversion path on the measurement result.

4. Results of experimental studies

4.1. Investigation of electromagnetic radiation of materials for dental filling

Materials from various companies are used in dentistry for root canal filling and tooth surface formation. As a rule, specialists pay attention to the strength of the final material and its aesthetic properties. At the same time, as noted above, if there is a difference in the EMR levels of the filling material and bone tissue, positive or negative EMR fluxes may occur.

Therefore, it is advisable to use such materials whose electromagnetic properties coincided or were close to the bone tissue of the tooth.

Samples of 10 materials were used for the study [12]. They are conventionally numbered from 1 to 10. The labeling of the materials used for the experiments and their manufacturers are listed below.

1 – Foredent (SPOFA, Slovenia);
2 – Endion (VOCO, Germany);
3 – Endomethazone (Septodont, France);
4 – AN Plus (Dentsply, USA);
5 – Spectrum (Dentsply, USA);
6 – Compolux (Septodont, France);
7 – Cavitan plus (SPOFA, Slovenia);
8 – tooth enamel;
9 – dentin;
10 – porous bone material.

From the above list, materials 1 to 4 are intended for filling root canals, and materials 5 to 7 are intended for restoration of the tooth surface. Samples 8 to 10 represent natural tooth material. Therefore, to evaluate the compatibility, samples 1 through 4 were compared with sample 9, and samples 5 through 7 with tooth enamel sample 8.

The experimental samples were studied using a two-channel radiometric system at a frequency of 52 GHz. The results of measuring the intrinsic electromagnetic radiation power of the studied dental materials are concentrated in the range (1,8...3,1)10^{-13} W/cm^2.

The compatibility of the filling materials and natural tissues was determined by comparing the coefficients of their emissivity $\boldsymbol{\beta_M}$, which was calculated by the formula

$$\beta_M = \frac{P_M}{P_{\mathrm{ABB}}}, \tag{14}$$

where P_M – is the radiation power of the material, recorded by the radiometric system; P_{ABB} – is the radiation power of an absolutely black body. This value is calculated by the formula:

$$P_{\mathrm{ABB}} = R(f)kT, \tag{15}$$

where $R(f)$ – is the frequency coefficient of radiation; T – is the temperature of the test sample.

The calculated values of the emissivity coefficients of materials are given in Table 1.

Table 1

EMISSIVITY OF SOME DENTAL MATERIALS

No. of sample	1	2	3	4	5	6	7	8	9	10
Emissivity coefficient β	0,71	0,6	0,46	0,41	0,46	0,51	0,48	0,46	0,67	0.58

Source: developed by the authors

A comparison of the emissivity coefficients of the filling materials and tooth tissues revealed the largest deviation in samples 4 and 9, which is about 38 %. For materials numbered 6 and 8, the difference is 10.8 %, 1 and 9 – 7.8 %. For materials numbered 5 and 8, the emissivity coefficient is the same.

These results allow a reasonable approach to the choice of materials for filling in each case, based on a quantitative assessment. When using materials, materials with similar emissivity deserve preference, since in this case, positive and negative fluxes of electromagnetic radiation are minimal. Such a test methodology deserves to be used in the development of new dental materials.

4.2. Investigation of electromagnetic radiation of medical materials implanted in the human body

Modern surgical practice widely uses implants to replace individual elements of the bone, vascular, visual system, and even entire artificial organs. In this case, materials of both natural and artificial origin are used. These can be metals, synthetic polymers, bio ceramics, and various powdered preparations for filling bone defects and soft tissue regeneration of individual injuries. Tissue extracts of animal origin, hybrid, and combined materials are widely used, for example, a metal base is covered with a material with dielectric properties that are close to human tissue in terms of characteristics [13]. Recently, studies have been conducted using promising nanomaterials [14].

The use of materials for implantation involves extensive research and testing for compatibility with human tissue. The main indicators that are paid attention to include biological tolerance, resistance to biocorrosion, chemical stability, and antimicrobial resistance. This fully applies to all types of implant materials, the classification of which is shown in Fig. 5.

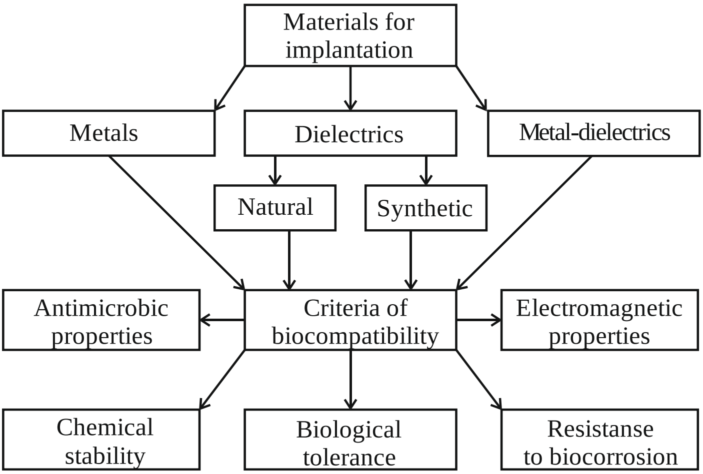


Figure 5. Classification of materials for implantation and requirements for them

Source: developed by the authors

When implants made of foreign materials are inserted into the body, an interaction occurs between them and the body tissue, in particular through electromagnetic radiation. The electromagnetic properties of materials for implantation have not been studied to date, although they can significantly affect the processes of their interaction with living organisms. The study of dielectric and composite materials has revealed another important criterion that should be considered: the electromagnetic compatibility of materials for implantation with human body tissues.

Paper [13] investigated the EMC of materials for implantation used to replace bone defects, in dental implantation, etc. In the course of the study, the EMR level of materials with a temperature close to the human temperature was determined. The results were compared with the level of intrinsic radiation of human tissues.

In metal implants, due to the presence of a skin layer, intrinsic microwave radiation is practically absent. At the same time, dielectric materials generate their own EMR when heated to human body temperature. As mentioned above, the electromagnetic energy fluxes generated by implants in relation to human body tissues can be neutral, positive, or negative. This is especially important for human cells that are able to respond to low-intensity EMF. The radiation (electromagnetic) characteristics of implants may differ significantly from those of living tissues. When the fluxes of the implant and the body tissue are equal, full electromagnetic compatibility occurs. Significant deviation from it, in one direction or another for a long time, can cause a violation of the electromagnetic state of nearby cells and the appearance of complications in the tissues near the implanted material.

Samples of 10 implant materials were used for the study. They are conventionally numbered from 2 to 11. The labeling of the materials used for the experiments is indicated below:

1 – H – the average value of a person’s own electromagnetic radiation (H – human);

2 – Osteoplast K;

3 – Bone powder. Bone powder (ground tubular bone of animal origin);

4 – Osteoplast T;

5 – Polihemostat (powder);

6 – Calcium salt of orthophosphoric acid $Ca_3(PO_4)_2$;

7 – Calcium salt with the addition of silver ions $Ca_3(PO_4)_2$+Ag;

8 – Bioactive glass (500 microns)

9 – Bioactive glass (1000 microns);

10 – Biomin GT-700;
11 – Biomin GT-500.

Before each experiment, the respondents' own EMR was measured under the same conditions.

According to the determined levels of electromagnetic radiation of materials, the relative emissivity coefficient K was calculated by the formula:

$$K = \frac{P_M}{P_H}, \tag{16}$$

where P_M – is the radiation power of the material under study; P_H – is the average human EMF power level. The research results are presented in Table 2.

Table 2

EMISSIVITY OF SOME MATERIALS FOR IMPLANTATION

Sample No	1	2	3	4	5	6	7	8,9	10	11
Emissivity, K	1,0	0,98	0,95	0,92	0,90	0,14	0,13	0,13	<0,01	<0,01

Source: developed by the authors

In the process of researching these materials for implantation, a number of features related to the human body and the properties of some materials were identified. A number of materials have approximately the same emissivity (difference within 10 %) as the human body. This probably results in a very small transfer of energy in the form of microwave radiation from a body with a higher level (healthy tissues) to a body with a lower level. Thus, materials that have a relative emissivity coefficient slightly lower than the level of human emissivity (Osteoplast K, Osteoplast M, Osteoplast T, Polyhemostat) are likely to be more compatible with human tissues in terms of electromagnetic compatibility. Implants based on such materials create virtually coincident positive EMR fluxes from implants to body tissues, and their use can lead to increased treatment efficiency.

On the contrary, known materials (calcium salt of orthophosphoric acid with the addition of silver in various amounts, Biomin GT-500, Biomin GT-700, bioactive glass) have a low relative emissivity coefficient (difference from the human body by one or two orders of magnitude), which can cause the formation of a negative microwave flux.

In turn, the presence of a negative microwave flux from living tissues to the implanted material can cause chronic inflammation and pain.

Thus, in order to improve the prediction of engraftment and long-term successful use of implants, as well as to increase the effectiveness of treatment, it is necessary to take into account the level of electromagnetic radiation of the materials used and their electromagnetic compatibility with human tissue.

4.3. Investigation of electromagnetic radiation of clothing materials

Clothing materials, like the implantable materials discussed above, are in contact with human skin for a long time. Depending on the purpose, style and other features, such materials can be fabrics, leather, film materials, etc. Since these materials are dielectrics and heat up when in contact with the surface of the human body, they also generate their own electromagnetic radiation. Therefore, in addition to the generally accepted methods [1] for assessing the properties of clothing materials, it is important to assess the electromagnetic compatibility of clothing materials with the surface tissues of the human body.

It is advisable to assess the level of EMR of clothing materials having a temperature close to the average human temperature by the level of spectral power density of radio-thermal radiation in the millimeter wavelength range. The middle of the millimeter range corresponds to the oscillation frequency of 52 GHz. The two-channel switching-modulation radiometric system discussed above was used for the measurements.

The spectral power density is determined by the formula:

$$G_M(f,T) = \frac{P_M}{\Delta f}, \tag{17}$$

where Δf – is the frequency band in which the measurements are made.

For the radiometric system described above, the frequency range is determined by the bandwidth of the intermediate frequency amplifier and is 100 MHz.

In the course of experimental studies, 14 types of textile materials made of natural, chemical, and mixed fibers were used. Designation of research objects:

1 – H is the average value of the human electromagnetic radiation level (H – human);

2 – cloth made of wool fibers (100 %);

3 – cloth made of flax fibers (100 %);

4 – cloth made of wool and silk fibers (70 % + 30 %);

5 – cloth made of wool and silk fibers (45 % + 55 %);

6 – cloth made of cotton fibers (100 %);
7 – cloth made of silk fibers (100 %);
8 – cloth made of viscose fibers (100 %);
9 – cloth made of cotton and polyester fibers (65 % + 35 %);
10 – cloth made of cotton and polyester fibers (60 % + 40 %);
11 – cloth made of cotton and polyester fibers (55 % + 45 %);
12 – cloth made of cotton and polyester fibers (47 % + 53 %);
13 – cloth made of viscose and polyester fibers (55 % + 45 %);
14 – cloth made of polyester fibers (100 %);
15 – cloth made of polyamide fibers (100 %).

The results of measuring the power spectral density of the tested materials are shown in Table 3.

Table 3

SPECTRAL POWER DENSITY OF TEXTILE MATERIALS

Sample No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Power spectral density, G_M	5,2	4,3	4,1	4,0	3,9	3,8	3,6	2,8	2,4	2,2	2,1	1,9	1,7	1,5	1,3

Source: developed by the authors

The analysis of the data in Table 3 shows that materials made from natural fibers, such as wool, linen, cotton, and silk, generate an EMR level close to the radiation level of the surface tissues of the human body. Therefore, in terms of electromagnetic compatibility, these materials are compatible with human tissue. It should also be noted that these materials do not interfere with the electromagnetic interaction of human surface tissues with the environment. This is due to the electromagnetic coherence of the materials with human tissue. From a physical point of view, this is explained by the fact that the emission coefficients, and, accordingly, reflection and absorption, are close in value to the corresponding coefficients of the surface tissues of the human body.

The data in Table 3 also show that an increase in the percentage of chemical fibers in the composition of the materials under study causes a significant decrease in the level of intrinsic EMR. This leads to a deterioration in the electromagnetic interaction of the human body with the environment and the occurrence of negative reactions of the body in case of prolonged contact with such materials.

The presented results of studies of the radiating ability of clothing materials made of natural and artificial fibers generally confirm the subjective assessment of people using products made of materials of different origins accumulated over the years. The advantage of the proposed method is the availability of a numerical estimate of the compatibility index, which makes it possible to obtain an objective assessment of the material. This does not take into account the influence of factors that change the psychological state of a person and affect the results of subjective assessment.

4.4. Study of the emissivity of minerals and semiprecious stones

Minerals are used in such a highly specialized heat treatment technology as lithotherapy. In addition, minerals and semi-precious stones are often used as jewelry that is placed on the surface of the body. Heating of minerals, like other dielectric materials, leads to the formation of low-intensity microwave electromagnetic radiation. Paper [7] presents the results of a study of the emissivity of a number of minerals. The electromagnetic radiation level was measured at a frequency of 60 GHz at a temperature of objects close to the average human body temperature. Fig. 6 shows the distribution of radiation intensity of the studied materials in comparison with the radiation level of humans and water.

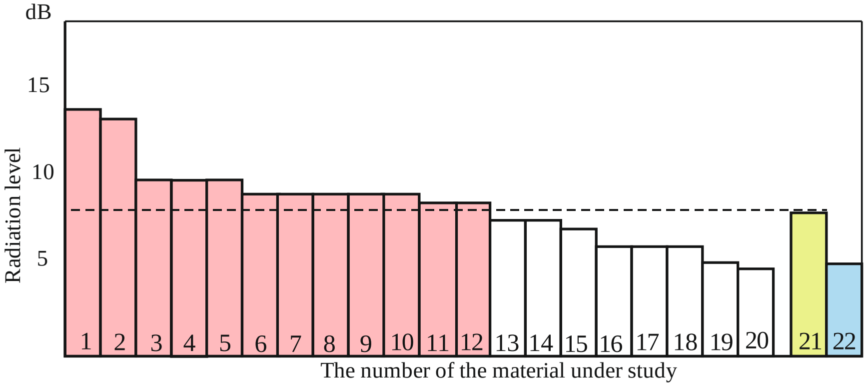


Figure 6. Intrinsic radiation level of minerals,
human surface tissues and water

Source: developed by the authors

The studied materials have the following digital indexing: 1 – jade; 2 – onyx; 3 – agate; 4 – shell rock; 5 – large fragment of bone tissue; 6 – amethyst; 7 – amber; 8 – red jasper; 9 – pyrite; 10 – small fragments of bone tissue; 11 – quartz (single crystal); 12 – chalk; 13 – sulfur; 14 – fluorite; 15 – flint; 16 – amazonite; 17 – rock crystal; 18 – calcite (feldspar); 19 – topaz; 20 – morion (quartz). Number 21 indicates the level of intrinsic radiation of the human palm, 22 – the level of electromagnetic radiation of water at a temperature close to the temperature of the human body.

The results of measurements of the intrinsic EMR level presented in Fig. 6 show that the studied materials can be divided into two groups. The radiation level of the first group (above the dotted line) is higher than the radiation level of the human palm. These minerals include jade, onyx, agate, amethyst, amber, and jasper. When in contact with the human body and at a temperature equilibrium, they are able to generate microwave radiation that is excessive for the surface tissues of the human body. This creates a positive flow of EMR. Thus, these minerals provide energy support to the body during lithotherapy sessions or when worn by a person. The second group of materials under study has an EMR level lower than the radiation level of the human palm (below the dotted line). The materials in this group include sulfur, fluorite, silicon, amazonite, rock crystal, calcite, topaz, and morion. At the same temperature as the human body, they form a negative flux of electromagnetic radiation. Water has the same property. There is a hypothesis that such materials should be used in the treatment of inflammatory processes, but it requires additional research.

4.5. Investigation of electromagnetic radiation of physiotherapeutic materials

In physiotherapy, heat treatment is one of the most common procedures that use a variety of dielectric materials, including minerals, peat, sand, therapeutic mud, and some oil field materials such as naphthalene, ozocerite, and paraffin. Among the group of materials for physiotherapy, ozocerite, and paraffin should be singled out, which, alone or in a mixture, are most often used in physiotherapy procedures. The high heat capacity, heat retention capacity, and lowest thermal conductivity of ozokerite determine the high efficiency of its use in physiotherapy procedures. The factors that influence the treatment area are considered to be thermal, mechanical, and chemical [13]. The therapeutic effects that arise in this case, first of all, include anti-inflammatory and vasodilating effects, as well as acetylcholine-like, estrogen-like, and chemical effects of ozokerite.

Heat therapy technologies involve preheating the material (applicator), applying it to the patient's skin surface, and keeping it cool for a period of time to the patient's body temperature. Usually, the temperature of the applicator does not exceed 50°C. At the same time, as follows from expressions (1,2), an increase in the temperature of the material leads to the appearance of low-intensity microwave electromagnetic radiation, which, along with other factors, has an effect on the human body and needs to be studied.

Work [13] investigated the electromagnetic radiation of an ozokerite applicator, the process of its formation, and changes in the microwave field during a physiotherapy procedure.

From the point of view of physics, the process of heat treatment should be considered as a violation of thermodynamic equilibrium in a system that includes a section of each human surface and the applied applicator. The exchange of energy in any system whose parts have different temperatures is known to be carried out through the processes of heat conduction, convection, and radiation. In our case, convection can be ignored, and the energy exchange between the applicator surfaces and the patient's skin is mainly due to the phenomena of thermal conductivity and electromagnetic radiation.

In Fig. 7 shows two arbitrary objects, or the applicator and the patient's body, which are in thermal contact. In the state when thermodynamic equilibrium is disturbed ( ), and the power of the heat fluxes , are not balanced, the direction of energy transfer depends on the temperature ratio. For example, in the case when the patient's temperature is higher than the applicator's temperature (the applicator is cooling), the heat flux will be directed away from the patient's skin, and it can be considered negative in relation to the person (Fig. 3b)

$$\Delta P = P_A - P_H < 0. \tag{18}$$

If, on the contrary, the applicator is heating, as in the case of heat therapy, the flux will be directed towards the patient and can be considered positive (Fig. 3c).

$$\Delta P = P_A - P_H > 0. \tag{19}$$

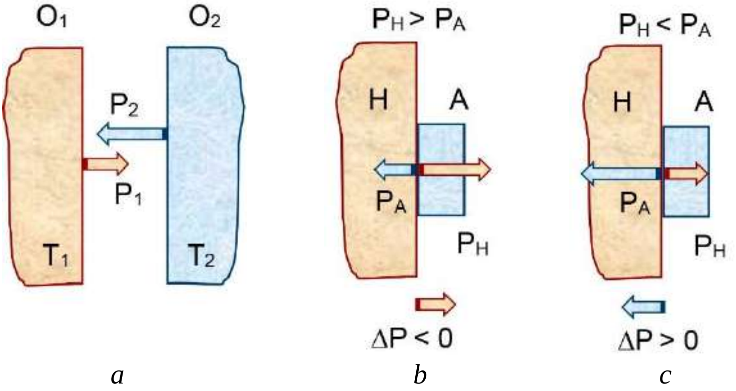


Figure 7. Distribution of energy fluxes between an arbitrary tangential object, option (a) and the applicator and the patient's body:
(b) with negative electromagnetic radiation flux;
(c) with positive electromagnetic radiation flux

Source: developed by the authors

The figure shows: P – patient's body; A – applicator; P_H – patient's electromagnetic radiation flux; P_A – applicator's electromagnetic radiation flux

Measurements of electromagnetic radiation power were performed at a frequency of 52 GHz with an analysis bandwidth of 100 MHz. For comparison, the average value of the intrinsic radiation power density of the human palm of the three respondents was determined, which was $2{,}25 \cdot 10^{-14}$ W/cm^2.

The absolute values of the electromagnetic radiation level were determined using a certified reference noise generator, which is part of the radiometric system. According to the results of measurements at the maximum therapeutic temperature of 50°C (Fig. 8), it is clear that the radiation level of pure ozokerite is slightly higher than that of the human palm. At the same time, the radiation level of pure paraffin at the same temperature does not exceed 20 % relative to the radiation level of human skin. This can cause the formation of a negative flux of electromagnetic radiation, the intensity of which increases with an increase in the percentage of paraffin in the mixture with ozokerite.

From the graph of the temperature dependence of the intrinsic radiation power of pure ozokerite during its cooling, shown in Fig. 8, it can be seen that a change in temperature can lead to a change in the redistribution of electromagnetic energy between the applicator and the skin. Thus, in the temperature range from 50 to 46°C, a positive flux ($\Delta P > 0$) is formed on the graph, and in the temperature range from 45°C to 36°C, a negative flux of microwave radiation is formed, at which ($\Delta P < 0$).

Experimental studies have shown that ozokerite, paraffin and their mixtures generate low-intensity electromagnetic radiation in the millimeter range. This factor, in combination with thermal effects, enhances the therapeutic effect.

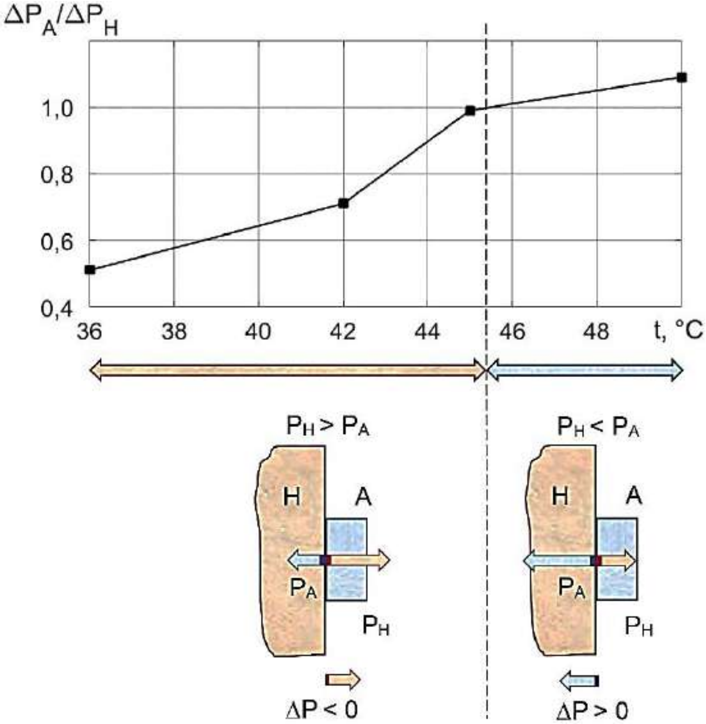


Figure 8. Dependence of relative power on temperature and distribution of electromagnetic energy flux for an ozokerite applicator during cooling

Source: developed by the authors

Conclusions

The results of theoretical and experimental research presented in the work allow us to state that when in contact with the tissues of the human body, the materials generate electromagnetic radiation, in particular, in the microwave range. This radiation is radio thermal in nature. Its level depends on the temperature of the material and its internal structure. At the same time, there is an interaction of the electromagnetic radiation of the tissues of the human body with the radiation of the material in contact with the tissue. Since the levels of radiation are different, their long-term interaction can cause both positive and negative effects on the human body. Taking this into account, when developing materials in contact with human tissues, it is necessary to study their electromagnetic properties. When using contact materials, it is also necessary to take into account their electromagnetic compatibility with the human body.

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