Methods for assessing the impact of the energy fields of implantable wireless charging device and biotelemetric system on experimental animals

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Abstract. The article describes the influence of electromagnetic fields during testing on experimental animals (rats) of a developed experimental prototype of a device for providing wireless charging of implant batteries. The invention relates to medical implantable devices that receive transdermal energy transfer and is aimed at solving the problem of optimizing this type of energy transfer. A magnetic field of any origin affects individual organs and the biological organism as a whole. The article presents the main indicators affecting biological objects, namely: the relative magnetic permeability of the environment, the magnitude of the wave, the power that is distributed in the dielectric material with losses, the penetration depth of the electromagnetic wave and the magnitude of the wave resistance. The integration scheme of prototypes of a wireless charger and an implantable biotelemetric system is considered. The testing of the performance of a wireless charger while integrating with an implantable biotelemetric system is considered in details. The test results confirmed the compliance of these parameters with theoretical ratios and the requirements of technical specifications.

1. Introduction
The issues of the influence of electromagnetic fields on living organisms, in particular, on biological objects, are dealt with the special science of electromobiology, which incorporates the main results of many related disciplines: classical and molecular biology, biochemistry, cybernetics, electrodynamics, etc. From the point of view of medicine and electromobiology, at present, there is no doubt that the electromagnetic field of natural origin (the natural electromagnetic background of the Earth) should be considered as one of the most important environmental physical factors. Natural electromagnetic fields are absolutely necessary for normal life, and their technogenic increase or deficiency leads to serious negative, sometimes even irreversible, consequences for a living organism.

The article describes the influence of electromagnetic fields during testing on experimental animals (rats) of a developed experimental prototype of a device for providing wireless charging of implant batteries.

The invention relates to medical implantable devices that receive transdermal energy transfer and is aimed at solving the problem of optimizing this type of energy transfer.

The developed device can find application in the construction of modern implantable telemetric systems for research and applied work in the field of medicine, pharmacology, and human physiology.
The implementation of remote monitoring of the health status of a biological object faces a number of problems. Implantable devices are surgically inserted into the human body, and they autonomously monitor the functioning of individual organs and systems. Existing bioimplants must be periodically removed from the body in order to replace the energy source, and then reinstall them in the body. To a certain extent, this poses a threat to the patient’s health and worsens his quality of life. This to some extent threatens the patient’s health and worsens his quality of life [1, 2].

Thus, the priority task is the development of a wireless charger for transdermal energy supply of implantable modules, as well as the development of methods for assessing the impact of the energy fields of experimental prototypes on biological objects. In solving this urgent task, it is necessary to ensure high efficiency of wireless energy transfer regardless of the location of the implant in the patient’s body [3].

The developed modules of a wireless charger should be used in combination with an implantable bioltelemetric system to evaluate the effect of the method of wireless energy transfer based on electromagnetic induction on a biological object.

The bioltelemetric system is designed for testing on biological objects and should transmit an electrocardiogram, an electromyography, a temperature, accelerometer signals, as well as parameters received from the receiver module of the charger: the temperature of the case and receiver module, the voltage on the battery during charging, current charging.

2. Integrated experimental prototypes of the device and implantable biotelemetric system
The printed circuit boards for the bioltelemetric system’s module, the transmitting and receiving modules of the device with applied solder paste and with accessories are shown in figures 1, 2.

**Figure 1.** The printed circuit board of the receiving module of the device with applied solder paste and with accessories.

**Figure 2.** The printed circuit board of the transmitting module of the biotelemetric system with applied solder paste and with installed accessories.

Printed circuit boards of the transmitting module of the device with accessories before applying solder paste and with installed accessories in figure 3.
The experimental prototype of the device is a modular system consisting of a transmitting module that forms a force field, the parameters of which allow it to safely enter the body of a biological object, and a receiving module that converts the energy field signal into a current sufficient to charge (recharge) the implant battery (figure 4).

In the process of development and refinement of the experimental prototype of the device and the implantable biotelemetric system, technical tests of integrated experimental prototypes of the device were carried out, which made it possible to verify the joint operation of the device modules and the biotelemetric system and showed their normal functioning when working together.

The next stage was the testing of integrated experimental prototypes of the device in the simulation environment of a biological object. The appropriate program and test methodology were developed fora physiological saline, simulating the internal environment of a biological object. To this end, a procedure was carried out to cover an experimental prototype of the device with a casing preventing the penetration of moisture into the experimental prototype.

The test results showed the functioning of the experimental prototypes of the integrated experimental prototypes of the device and allowed us to start testing the integrated experimental prototypes of the device and the implantable biotelemetric system: checking the joint functioning of the experimental prototypes in biological objects (in laboratory animals).

3. Assessment of the influence of energy fields on biological objects during testing on laboratory animals

The question of extrapolating the results of experiments on animals to humans should be approached with extreme caution. It is known that for each organism there is a set of frequencies inherent in fluctuations in the parameters of the external environment to which it reacts most acutely. Calculation and analysis of resonant frequencies for organs and systems reveals their good compliance with the experimentally identified frequencies of the body’s greatest response to external influences [11]. For
example, bioefficiency for humans of frequencies 0.05-0.06, 0.1-0.3, 80 and 300 Hz is explained by the resonance of the circulatory system, and frequencies 0.02-0.2, 1-1.6, 20 Hz by the resonance of the heart. The sets of biologically active frequencies do not coincide in different animals [11].

For example, resonant heart frequencies for humans give 20 Hz, for a horse – 10 Hz, and for a rabbit and rats – 45 Hz [6]. Thus, the presented experimental data on animals showed the unidirectionality of morphofunctional changes both under disturbances of the Earth’s GMF and under the influence of artificial magnetic fields of various intensities.

The most vulnerable to exposure to magnetic fields is the nervous system. 3 syndromes of disturbed nervous regulation due to chronic exposure to electromagnetic fields were distinguished: 1) asthenic; 2) asthenovegetative or vegetovascular dystonia syndrome; and 3) hypothalamic.

Long-term exposure to maximum permissible doses of radiation leads to an increase in the waves of the alpha range of the bioelectric activity of the brain during and after the shutdown of electromagnetic field.

The result of chronic exposure to electromagnetic field of high and ultrahigh frequencies is a change in the cardiovascular system: lowering blood pressure, bradycardia, slowing down intraventricular conduction, as well as an imbalance in the content of potassium, calcium and sodium ions in the blood.

Types of physical interaction of permanent magnetic fields with biological systems

- Electrodynamic interaction by conduction currents
- Magnetic-mechanical effects
- Effects on the electronic spin state of intermediate reaction products

Figure 5. Types of physical interaction of permanent magnetic fields with biological systems.

The following three types of physical interaction of constant magnetic fields with biological systems are distinguished (figure 5):

- Electrodynamic interaction with conduction currents (for example, with the current electrolyte solution). The magnetic field as a result of the emergence of the Lorentz force acts on moving carriers of an electric charge. This leads to the induction of the electric potential (the so-called potential of the flow) and current. The “flow potentials” in animals and humans are usually associated with contraction of the heart ventricles and the release of blood into the aorta. Lorentz interaction also leads to the emergence of a magneto-hydrodynamic force directed opposite to the bloodstream. It is believed that the decrease in blood flow in the aorta reaches 10% under the action of a magnetic field of 15 T.

- Magnetic-mechanical effects, including the orientation of magnetic anisotropic structures in homogeneous fields and the displacement of paramagnetic and ferromagnetic materials in magnetic field gradients. Particular attention in the mechanisms of interaction is the emergence of forces and torques acting on endogenous and exogenous metal objects.

- The effects on the state of the electronic spin of intermediate reaction products.

When exposed to external electric and magnetic fields of ultra-low frequencies, electric fields and currents are induced in the body. Using measurements, the relationship between external fields and the induced electric field and the current density in the body or other parameters due to the influence of these fields was revealed.

Interactions of electromagnetic fields with a biological object are determined by:
radiation parameters (frequency or wavelength, oscillation coherence, propagation velocity, wave polarization);

- physical and biochemical properties of a biological object, as environment for the propagation of electromagnetic fields (dielectric constant, electrical conductivity, electromagnetic wavelength in the tissue, penetration depth, reflection coefficient from the air-tissue boundary).

The processes of interaction of electromagnetic fields with a living cell, a living organism are quite complex and are currently not fully investigated.

The main force field planned for use in the device is magnetic. A magnetic field of any origin affects individual sites and the biological organism as a whole. Data analysis shows that a static magnetic field of increased tension acting on a biological object causes disorder in the nervous, endocrine, autonomic, cardiovascular and other systems [9]. The dynamics of changes in heart rate, with various kinds of effects on the body of biological objects, is an informative and affordable indicator of assessing the functional state of the body of biological objects. A variational analysis of the function of the heart rhythmogram enables a quantitative and differentiated assessment of the degree of tension or tone of the sympathetic and parasympathetic departments of the autonomic nervous system, their interaction in various functional states, as well as the activities of the subsystems that control the work of various organs [8].

As a rule, experiments on the influence of the magnetic field are performed on rabbits and rats, due to the availability of these biological objects. During the tests, animals were placed between two Helmholtz coils in accordance with figure 6. Each coil contains 2000 turns of copper wire. The current flowing through the coils is 10 A. The coils are located at the distance of 30 cm from each other. To ensure room temperature in the space between the coils, a water cooling system has been developed.

During the experiment, the animal is placed in a special container or jar to reduce mobility (figure 6).

![Figure 6. Registration of telemetric data of an experimental animal during charging.](image_url)

To record an electrocardiogram, subcutaneous electrodes are used. Each electrocardiogram is recorded for 150 minutes: 30 minutes before exposure of the magnetic field to the animal; 60 minutes during exposure and 60 minutes after exposure. The heart rate value is calculated by analyzing the recorded data.

4. The mathematical justification of the influence of the electromagnetic field on the laboratory animal

An electromagnetic field, penetrating a biological object, interacts with charged particles, causing them to oscillate.
A biological object is proposed to be considered as a dielectric environment. Molecules of a dielectric environment can be nonpolar and polar [5]. When an external electric field is applied, nonpolar molecules are polarized, that is, the symmetry of the arrangement of their charges is broken, and the molecule acquires some electric moment. Under the action of an external electric field, polar molecules not only change the magnitude of the electric moment, but also rotate the axis of the molecule in the direction of the field. At ultrahigh frequencies, heat generation is possible, even in the absence of a conduction current [6, 7].

In this case, the dielectric environment seems to consist of oscillators, each of which interacts with the electric field, and therefore makes forced oscillations [6, 7].

It is known [6] that under the influence of an external magnetic field, the electron shell of an atom begins to move around the direction of the field with a certain angular velocity. In alternating magnetic fields, a reorientation of the magnetic axis of the atom also occurs. These phenomena are similar to “internal friction”, and lead to the release of heat in the environment.

The environment subjected to heating is isotropic and the material equations of the environment can be written in the form:

\[
\begin{align*}
D &= \varepsilon \varepsilon_0 E \\
B &= q q_0 H , \\
J &= s E,
\end{align*}
\]

(1)

where \(\varepsilon_0\) and \(q_0\) are the absolute dielectric and magnetic permeabilities; \(J\) isthe conductivity current density; \(E\) and \(H\) are the electric and magnetic field strengths; \(D\) and \(B\) are the dielectric and magnetic inductions; \(\varepsilon\) isthe relative dielectric constant of the environment; \(q\) isthe relative magnetic permeability of the environment; \(s\) isthe conductivity of the environment.

In this case, the electromagnetic field changes in time according to the harmonic law:

\[
\begin{align*}
E &= E_n g^{\omega \alpha \varepsilon} \\
H &= H_n g^{\omega \alpha \varepsilon},
\end{align*}
\]

(2)

where \(\omega\) is the angular frequency of oscillations.

Heat loss power in a biological object:

\[
P_{hl} = \frac{1}{2} \int_0^\infty E \ast E_c \ast d * \vartheta + \frac{1}{2} \int_0^\infty \omega \ast \varepsilon_i \ast E \ast E_c \ast d * \vartheta + \frac{1}{2} \int_0^\infty \omega \ast q_i \ast E \ast E_c \ast d * \vartheta,
\]

(3)

where \(E_c\) and \(H_c\) are the complex values of the amplitudes of the electric \(E\) and magnetic \(H\) fields’ intensity vectors in a biological object.

5. The use of electromagnetic radiation for the operation of the device

One of the important conditions for interaction with biological objects is the polarization of the electromagnetic wave, which determines the position of the vectors \(E\) and \(H\) in space. The horizontal or vertical arrangement of the vector \(E\) determines the electromagnetic wave, respectively, as horizontally or vertically polarized. The magnetic field intensity is estimated by the energy flux density in the frequency range from 0.3 GHz to 3000 GHz and the electric component \(E\) and magnetic \(H\) in the frequency range from 3 Hz to 3 MHz.

The effect of the interaction of the electromagnetic field with the biological environment will depend on the field energy absorbed over a certain time, i.e. radiation doses. It is based on the conversion of field’s energy into heat, which is carried out by two classical mechanisms determined by the dielectric characteristics of biological material: induction of currents and rotation/movement of molecules.
The force acting on an electric charge depends not only on where it is located, but also on how fast it moves. Each point in space is characterized by two vector quantities that determine the force acting on any charge. There is an electric force giving that part of the force that is independent of the speed of the charge. To explain the origin and transfer of forces acting between resting charges, the concept of an electric field is introduced. When an electric charge appears in some place in space, an electric field arises around it. The main property of this field is that on every other charge placed in this field, a force acts. If we replace this charge with another, then the force acting on this charge will change in proportion to the magnitude of the charge. For an electric field, the principle of superposition is valid – the field of a system of charges can be defined as the sum (of course, a vector) of electric fields from each of the charges. To quantify the electric field, a special physical quantity is used – the electric field $E$. The electric field at a given point is measured by the force acting on a single positive charge placed at this point. In a different way, tension is a value equal to the ratio of the force acting on a positive test charge placed at a given point in the field to this charge. The unit of electric field is 1 V/m (volt per meter).

Since the electromagnetic radiation used for wireless charging of the battery has a frequency of less than 1 MHz, it is non-ionizing and the main factor affecting the biological object is the heating of the conductive structure of the receiving module of the device to temperatures above 40 degrees.

Therefore, the main parameters, by which the power is estimated, are the heating of the receiving module and the obtaining sufficient power to charge the battery of the implantable device.

Given the distance between the receiving and transmitting modules of the charger and the principle of operation (coupled circuits), the main field that provides energy transfer for charging the battery is a magnetic field.

The specific power of heat loss in a biological object from (3) can be represented in the form:

$$P_{sp} = \frac{s}{2} E^2 + \frac{\omega \varepsilon_i''}{2} E^2 + \frac{\omega q_i''}{2} H^2.$$  \hspace{1cm} (4)

The first term expresses the volumetric power density released in the environment when the conduction current flows in it according to the Joule-Lenz law. The second and third terms determine the density of power released in the environment due to the displacement of the dielectric $D$ and magnetic $B$ inductions, as well as the electric intensity vectors $E$ and magnetic $H$ fields.

In biological objects, the real and imaginary part of absolute magnetic permeability is represented as: $q_i' = 1; q_i'' = 0$. In this case, the third term in (4) is equal to zero.

The output power at a frequency of 0.5 MHz at distances of 0.2 and 0.8 mm was 30 mW and 12 mW, respectively. At a frequency of 10 MHz – 2.2 mW and 0.6 mW.

The frequency can be changed by replacing the division coefficient of the clock frequency of the microcontroller, however, its final result should be equal to 880 kHz.

The power of the force field is changed by changing the duty cycle of the pulse signal supplied by the microcontroller to the input of the amplifier, from the output of which the signal is fed to the transmit antenna circuit of the transmitter module of the experimental prototypes of the device. Thus, the power can vary from zero to the maximum value, which is determined by the feedback signal coming from the receiving module of the experimental prototypes of the device with a speed of at least 1200 baud. The power must be sufficient to provide a charging current of at least 40 mA with a battery voltage of at least 4.1 V.

The penetration depth $L$ of the electromagnetic wave, i.e. the distance from the surface of the material, at which the power of the electromagnetic field decreases by an “e” time, is determined by the relation [1, 6]:

$$L = \frac{2\pi \sqrt{\varepsilon_i}}{2\pi \varepsilon_{i}^{\gamma}}.$$ \hspace{1cm} (5)

The structure of any biological object is multilayer, and microwave energy is reflected from each layer.
If we assume that in a biological environment the relative magnetic permeability of the environment is \( q_1' = q_2' = 1 \), then:

\[
R = \sqrt{\varepsilon_1' - \sqrt{\varepsilon_1'}} \sqrt{\varepsilon_1' + \sqrt{\varepsilon_2'}}
\]  
(6)

The amount of heat \( Q \) released in the biological environment is determined by:

\[
Q = s_{sp} \ast f^2 \ast E^2 \ast t,
\]  
(7)

where:
- \( Q \) is the amount of heat released in the biological object, \( J \);
- \( s_{sp} \) is the specific conductivity of a biological object;
- \( f \) is the frequency of the electromagnetic field;
- \( E \) is the electric field strength;
- \( t \) is the time.

The issues of dosimetry of electromagnetic fields are very complex, because the amount of absorbed energy is determined not only by the intensity and frequency of the field, but also by the size, shape of the object, its location relative to the \( E \) and \( H \) vectors, internal structure, surrounding space, the presence of grounding and many other factors. As a characteristic of the amount of absorbed energy, the electromagnetic field (specific absorbed power) is used.

The penetration depth and wavelength in the tissues of the human and animal bodies depend on the content of water in them and at its high concentration these values are less than in the opposite case. Heating of biological material is the main mechanism for converting the energy of an electromagnetic field of high intensity. A change in a body temperature can serve as a mechanism for triggering various negative reactions, the level of change of which depends on the thermoregulatory and metabolic characteristics of a particular functional system of the body. Any increase in temperature by its nature is associated with a change in the heat balance between the rate of energy input into the object and its removal.

6. Conclusions

In the process of testing it was found that the test objects (integrated experimental prototypes of the device and the implantable biotelemetric system) confirmed the joint functioning. The measurement results are entered into protocols, in which the measured electromagnetic field’s intensity levels are given in the examined frequency range. For all results, measurement errors are given, determined either by the technical characteristics of the measuring instruments, or by the difference in the readings of the instruments in a series of consecutive measurements in the same places (depending on which of these values is greater). Based on the measurement results, conclusions are drawn on whether or not each of the surveyed jobs meets the sanitary standards’ requirements. For all results, measurement’s errors are also given, determined either by the technical characteristics of the measuring instruments, or by the difference in the readings of the instruments in a series of consecutive measurements in the same places (depending on which of these values is greater).

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