Energy Fields' Impact on Biological Objects

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***Abstract*—The paper deals with the impact on biological objects of the energy fields of the devices, which provide wireless charging of implant batteries and wireless power supply of non-accumulator implants. The device is intended for use in the area of medicine, pharmacology and human physiology. Implantable small-sized devices are introduced into the body surgically and autonomously monitor and control the functional state of individual organs and systems. Power sources have become the main limiting factor for increasing the service life of the implant. The main force field used in the device is magnetic. The magnetic field of any origin has an impact on individual areas and the biological organism as a whole. The article presents the main indicators that affect biological objects, namely: the relative magnetic permeability of the medium, the magnitude of the wave power that propagates in a dielectric material with losses, the depth of penetration of the electromagnetic wave and the magnitude of the wave resistance. Analysis of the data proves that the static magnetic field of increased intensity acting on a biological object causes disordering in the nervous, endocrine, vegetative, cardiovascular and other systems.**

I. Introduction

Due to the miniaturization of electronic devices while expanding their functional qualities, researchers receive new technologies for exploring and controlling the state of biological objects in a wider range of parameters. First of all, this applies to technologies based on the use of wireless implanted devices. In practice, the implementation of their capabilities faces a number of challenges.

Implantable small-sized devices are introduced into the body surgically for the purpose to monitor and control the functional state of individual organs and systems autonomously. However, the currently existing implantable devices must be periodically removed from the body of the monitored object to replace the power supply source, and then re-installed in the body.

Power sources have become the main limiting factor for increasing the period of the implant's use. They are also an obstacle to further miniaturization of implanted devices. Mostly in currently used implantable devices, such as electric cardiac stimulators (ECS), the battery takes 85-90 % of the volume of the device. The same trend continues for the mass of the device.

The possibility of contactless and safe implant's charging can significantly reduce the volume and weight of the power source, replacing single cells with batteries. Using modern lithium-based batteries with maximum specific energy, low self-discharge and long service life, it is possible to achieve the service life of the implanted device comparable to the life of the controlled organism.

The average power consumption of modern battery devices is in the following ranges: for ECS is 10 ... 50 mW (depending on heart rate), sacred neurostimulators is 50...100 mW, implantable infusion pumps is 0.1...1 mW. Among the devices equipped with a wireless channel of energy transfer without a built-in battery, it is possible to result following examples of power consumption: RFID sensor of arterial blood pressure – 10 mW [1], a stimulator of spinal cord – 3...15 mW, a cochlear implant – 20 to 40 mW [2], telemetric 64-channel implantable corticogram recorder – 100 mW [3], 100-channel interface brain-computer – 120 mW (equipped with the inductive wireless power transmission (WPT) requiring forced cooling of the biological object's (BO) tissues by water compresses to maintain adequate temperature) [4].

The battery service life of electric cardiac stimulators (ECS) can be up to 12 years [5]. Similar implanted devices are mainly charged on Li/I_2 batteries with a specific energy consumption of about 210 W·h/kg or more capacious $Li/Ag_2V_4O_{11}$ elements with 270 W·h/kg. The work period of Li-Ion batteries is also limited due to degradation of their capacity and power output. The higher is the frequency of charge and discharge cycles, the more variable and wide is the range of charge values and the higher is the temperature during the operation of the battery, the faster its service life is depleted [6]. Batteries for medical use produced by companies Quallion and Xcellion (different models with capacity from 40 mAh to 220 mAh) are designed for more than 1000 cycles of full charge and discharge while maintaining at least 80% of the initial capacity or 10 years of service [7].

The issue of battery life was investigated during the stress test [8], when the same type of Li-Ion batteries was operated in different ranges of charge level (SoC – state of charge), that is, the available capacity was not used entirely. Capacity degradation up to 90 % of the initial value was achieved in 1000 cycles at the charge level range of 25 ... 100 %, 2100 cycles at 25 ... 85 %, 2900 cycles at 25 ... 75 % and 4600 cycles at 45 ... 75 %. The performance of the parameters ΔSoC and the number of cycles showed an increase as ΔSoC declined. Thus, it is possible to increase the functionality of implanted devices and achieve the required service life by selecting a higher capacity battery, reducing ΔSoC, using pulsed charge methods [9] and maintenance based on analytically calculated SoC values [10].

These examples prove that the existing energy intensity of batteries meets the needs of only a part of the numerous types of implants. For devices shown for life-time use, with an average power consumption of tens or hundreds of milliwatts, alternative solutions are required.

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II. Structure and Purpose of the Device

Creation of a device for wireless implanted batteries' charging and wireless non-batteries power supply is aimed to be implemented in the field of medicine, pharmacology and human physiology. It is assumed that they will be used to create a charging system of sealed devices' power sources (batteries, capacitors) designed for implantation in biological objects and working in conditions of immersion in liquids and in other conditions, excluding the possibility of frequent depressurization of the device housing, which is integrated into the receiving module of the charging system. The developed device should provide a safe for the biological object charging procedure (charging) built into the implant power supply (battery, capacitor), as well as wireless power supply of non-battery implants. The receiving module of the charging system is designed for integration into the technical means implanted into the biological object: telemetry, neuro and myostimulants, infusion pumps of drugs, etc.

III. Parameters of the Receiving Module Operation

Power supply of the computing unit and other devices of the transmitting circuit (TC) will be carried out using the energy storage. A battery (with battery power supply) or a supercapacitor (with non-battery power supply) is selected to be the energy storage in the receiving module of the device. To ensure the operation of an implant, the output voltage of the device should provide the charge (recharging) of the battery or capacitor (supercapacitor), which serves as an energy storage device. Apart from the function of the charging the rectifier ensures the protection of downstream elements of the device's receiver module from excessive voltages on the output of the rectifier, which occurs when the location of the receiving circuit (RC), is very close to the TC. This is shown in Fig. 1 by the "output voltage limitation" element.

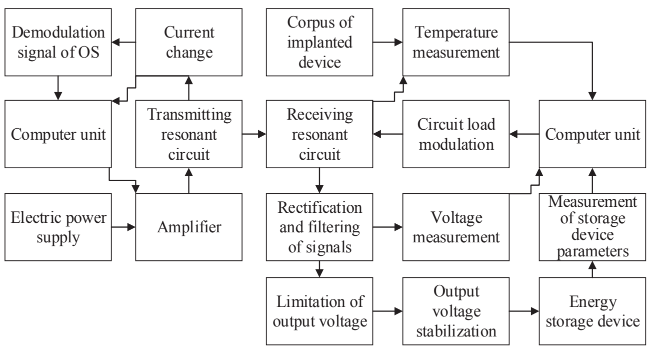

Fig. 1. General structure of the experimental prototype of the device

To ensure the required temperature and energy parameters of the receiving module of the device, their evaluation and transmission of corrective information to the transmitting module of the device is required, which is carried out by the computing unit with the measuring channels specified in Fig. 1.

The use of magnetic field's force requires normalization of electromagnetic field's (EMF) power, and, in particular, the level of thermal impact on the biological object (BO). In addition to the specific action of electromagnetic fields on body tissues, expressed in their heating due to the flow of the induced conduction currents and displacement [11], the negative impact can have a heat capacity that is allocated to the hardware part of the system converting the energy of the implant [12, 13, 14, 15]. Therefore, there is a proposal to introduce into the structure of the experimental prototype the measurement of such parameters as: the temperature of the receiving module of the wireless energy transmission (WET) to be able to respond quickly to an unexpected temperature increase; the temperature of the implanted device case to assess the efficiency of heat dissipation by the BO's tissues and the degree of thermal effect on them; the voltage at the output of the rectifier to prevent the release of additional heat on the limiting and stabilizing components and protect the latter from failure by adjusting the power of the EMF; voltage and current of the energy storage device to control the charging process. All these parameters can be included in the feedback of the automatic power adjustment of the transmitting module of the device, which requires the introduction of a data transmission channel.

To provide communication between the receiving and transmitting modules of the device, a load modulation method for the emitted magnetic force field is used.

Above mentioned set of registered parameters is characterized by the volume within several tens of bytes and the frequency of digitization at the level of several tens of Hz. The low frequency of digitization is associated with the low-frequency nature of the perturbing factor, namely, changes in the distance between the TC and the RC as a result of the movement of the object wearing the implant. To implement a transmission channel of such data volume providing feedback, it is proposed to use the load modulation approach of the receiving resonant circuit, by analogy with RFID systems. In contrast to the dedicated transceiver radio channel, the implementation of the proposed approach requires a minimum set of components on both the receiving and transmitting sides, taking into account the presence of TC and RC, replacing the transceiver antenna. It should be noted that this method of data transmission does not require the power supply to the RC inductor, which formally does not make it an actively emitting antenna and, accordingly, does not require additional consumption of energy stored on the built-in implant storage. I.e. when transmitting parameters, the receiving resonant circuit does not act as a transmitter. In principle, load modulation can be carried out both by active and reactive resistance (Fig. 2). The data signal on the receiving side can be demodulated from the current measurement signal in the transmitting resonant circuit. It does not need to interrupt the transmission of energy from the RC to the TC. The possible drawdown of the charging current during load modulation will not have a significant impact on the time of recharging the energy storage device, due to the small volume and low frequency of the transmitted data, which suggests a short-term, periodic mode of data transmission.

The results of the temperature measurement and the set of parameters will be transmitted by modulating the load circuit in the receiving module of the device, which will lead to the modulation of the current in the transmitting module of the device. After the corresponding demodulation feedback signals will be transmitted to the computing device (Fig. 2).

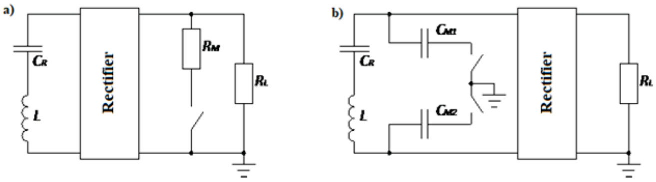

Fig. 2. Different approaches of load modulation by resistance: a) active resistance; b) reactive resistance

IV. INFLUENCE OF EXTERNAL MAGNETIC FIELD ON BIOLOGICAL OBJECT

The degree of a magnetic field's influence on a biological object depends on the maximum intensity in its working space of a magnetic device or in the zone of influence of an artificial magnet. Any subjective sensations are not caused by permanent magnetic fields. Under the action of variable magnetic fields some characteristic visual sensations are observed, the so-called phosphenes, which disappear at the time of termination of exposure.

At constant work in conditions of permanent magnetic field exposure, exceeding the maximum permissible levels, there is a risk of disorders of the nervous, cardiovascular and respiratory systems, digestive tract, changes in the blood. In conditions of predominantly local effects may develop vegetative and trophic disorders, usually in body areas under the direct influence of the magnetic field (most often hands). They are manifested by a feeling of itching, pallor or cyanosis of the skin, swelling and compaction of the skin, in some cases hyperkeratosis (cornea) develops.

Hence, it might be concluded that it is necessary to control the main physiological parameters in the analysis of the external force fields' impact on a biological object. At the first stage, it will be the main indicators of the cardiovascular system, as providing the vital activity of the body. Further research will show the influence of external impact on the reproductive and hematopoietic systems of the body. Such research will be carried out when testing experimental prototypes of the device for charging the implant battery.

We shall consider the effect of magnetic (electromagnetic) field on the characteristics of the cardiovascular system [3]. Let's start the analysis with considering the influence of the Earth's magnetic field during solar storms as the most fully described in the available information. In this case, the levels of variation of the magnetic field are much less than the variations of the magnetic field of the antenna of the device's transmitting module. The spectral characteristics of the magnetic field also differ.

In the brain and adrenal glands there are areas sensitive to the magnetic field. Under its influence, in particular in the blood the adrenaline content increases, as well as deviations in the mental status of some people (irritability, depression) are observed [16].

Microcirculation and rheological properties of blood change noticeably: capillary blood flow becomes not constant, but intermittent, aggregation of blood elements increases, the risk for ischemia of the heart and brain appears.

V. THE ELECTROMAGNETIC FIELD'S PHYSICAL PROPERTIES

The electromagnetic field, penetrating into a biological object, interacts with charged particles, causing them to oscillate.

The biological object is proposed to be considered as a dielectric medium. Molecules of dielectric medium can be non-polar and polar [2...5]. When an external electric field is applied, non-polar molecules are polarized, that is, the symmetry of their charges is broken, and the molecule acquires some electric moment. Under the influence of an external electric field in polar molecules not only changes the magnitude of the electric moment, but also the rotation of the axis of the molecule in the direction of the field. At ultrahigh frequencies, heat generation is possible even in the absence of current's conductivity [6], [7].

In this case, the dielectric medium is represented as consisting of oscillators, each of which interacts with the electric field, which makes forced oscillations [6], [7].

It is known [6] that under the action of an external magnetic field, the electron shell of an atom begins to move around the direction of the field at a certain angular velocity. In variable magnetic fields, in addition, there is a reorientation of the magnetic axis of the atom. These phenomena are similar to "internal friction", and lead to the release of heat in the medium.

We assume that the medium being heated is isotropic and the material equations of the medium can be written as:

$$\begin{cases} D = \varepsilon * \varepsilon_0 * E \\ B = q * q_0 * H, \\ J = s * E \end{cases} \quad (1)$$

where ε_0 and q_0 are the absolute dielectric and magnetic permeabilities, J is the density of conduction current, E and H are the intensities of electric and magnetic fields, D and B are the dielectric and magnetic inductions, ε is the relative permittivity of the medium, q is the relative magnetic permeability of the medium, s is the conductivity of the medium.

Let the electromagnetic field changes in time according to the harmonic law:

$$\begin{cases} E = E_n * g^{\alpha\omega t} \\ H = H_n * g^{\alpha\omega t}, \end{cases} \quad (2)$$

where ω is the angular frequency.

The value of the relative permittivity of the medium q is defined as:

$$\varepsilon = \frac{\varepsilon_i^{'}}{\varepsilon_0} - J\frac{\varepsilon_i^{''}}{\varepsilon_0}, \quad (3)$$

where $\varepsilon_i^{'}$ and $\varepsilon_i^{''}$ are the real and imaginary parts of the absolute permittivity of the medium.

The value of the relative magnetic permeability of the medium q is defined as (4):

$$q = \frac{q_i^{'}}{q_0} - J\frac{q_i^{''}}{q_0}, \quad (4)$$

where and $q_i^{'}$ and $q_i^{''}$ are the real and imaginary parts of the absolute magnetic permeability of the medium.

Heat loss power in a biological object:

$$P_{hl} = \frac{1}{2}\int_{\vartheta} s * E * E_c * d * \vartheta + \frac{1}{2}\int_{\vartheta} \omega * \varepsilon_i'' * E * E_c * d * \vartheta + \frac{1}{2}\int_{\vartheta} \omega * q_i'' * E, * E_c * d * \vartheta \quad (5)$$

where E_c and H_c are the integrated values of the amplitudes of the electric E and magnetic H field vectors in a biological object.

VI. Application of electromagnetic radiation to the device operation

Since the electromagnetic radiation used for contactless battery charging has the frequency of less than 1 MHz, it is not ionizing, and the main factor affecting the biological object is the heating of the conductive structure of the device's receiving module to the temperature above 40 degrees.

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

Considering the distance between both transmitting and receiving modules of the charging device and the principle of operation (coupled circuits) the main field for the transmission of energy for charging the battery, is the magnetic field.

The specific power of heat losses in a biological object from (5) can be represented as:

$$P_{sp} = \frac{s}{2} * E^2 + \frac{\omega * \varepsilon_i^{''}}{2} * E^2 + \frac{\omega * q_i^{''}}{2} * H^2. \quad (6)$$

The first term expresses the volume power density, released in the medium with the flow of the conduction current in it according to the Joule-Lenz law.The second and the third components determine the density of the power released in the medium due to the displacement of the dielectric D and magnetic B induction, as well as the electric E and magnetic H fields.

In biological objects, the real and imaginary parts of the absolute magnetic permeability are represented as: $q_i^{'} = 1$; $q_i^{''} = 0$. In this case, the third term in (6) is zero.

The paper [18] describes the test of electrodes of the developed device with the size of 25x25 mm with an air gap of 0.1...1 mm, which, depending on the frequency, was equivalent to the capacity between electrodes of less than 1x1 mm, when a skin layer with a thickness of 1 mm would be used as a dielectric.

The output power at the frequency of 0.5 MHz at distances of 0.2 and 0.8 mm was 30 mW and 12 mW, respectively. And at the frequency of 10 MHz it was 2.2 mW and 0.6 mW.

To solve the problem of RFID tags shielding by metal skeletal prostheses causing data transmission errors, the article [19] considered the possibility of using capacitor coupling for the implementation of a standard power and data exchange protocol at the frequency of 13.56 MHz in the 0.19% NaCl medium.

When placing the steel plate (80x50x6 mm) behind the receiving electrodes (10x10,5 mm) and round transmitting electrodes with diameters of 20 mm and the gap of 10 mm, a decrease in the output voltage by only 25% was noted, which allowed to assert the possibility of successful use of capacitor coupling to solve this problem (Fig. 3).

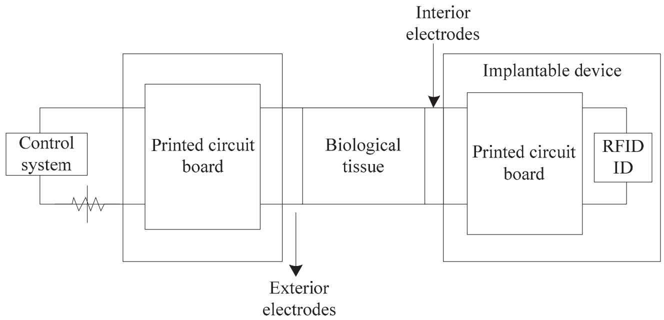

Fig. 3. Use of capacitor coupling for the implementation of a standard power and data exchange protocol

At the same time, stable data exchange with RFID tag at the distance of 25 mm filled with several layers of pig skin is demonstrated. Significantly higher frequencies (402 MHz) were used in the article [20]. Copper PCB electrodes 20x19 mm in size were made on the printed circuit board and spaced by 7 mm. Simulation medium placed between the plates of the receiving and transmitting parts, possessed the characteristics of the skin (ε_r = 46,7, σ = 0,69 Cm / m at 402 MHz) and was made by mixing 42 g of distillate with 2 g of salt, 56 g of sugar and 1 g of agarose.

The reactance of capacitors was leveled by connecting resonant inductances to them. The measured efficiency of energy transfer to the load of 50 Ohms at the gaps of 4.6 mm, 5.6 mm and 6.6 mm was 68.3%, 67.2% and 66.1%, respectively.

In the case of using a narrow-band amplifier class E (Fig. 4), provided by the standard circuit output LC filter plays the role of a resonant transmitting circuit.

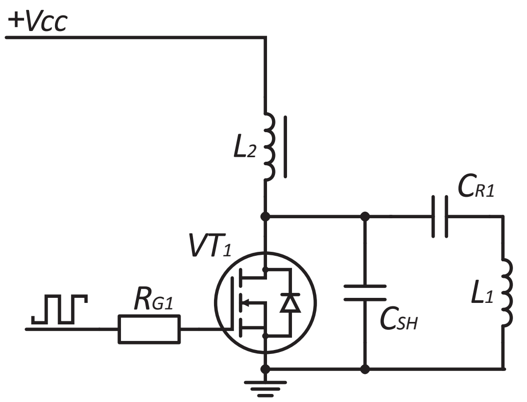

Fig. 4. Diagram of a power amplifier operating in key mode (class E)

The correct mode of operation of the circuit requires zero voltage and the derived voltage at the drain VT1 at the moment of switching the transistor (the so-called mode ZVS-zero-voltage-switching). This is achieved by selecting the CSH and L1 values at a fixed duty cycle of the incoming signal (usually 50 %). In this feature lies the main drawback of the scheme: to adjust the power through the use of pulse width modulation (PWM) it is required either to enter an array of switched capacitances into the scheme [23], [24], or to introduce a load-correcting reactance circuit based on a variable-capacitance diode [12]. On the contrary, in the absence of the need to adjust the output power, the scheme requires a relatively small number of components and has a simple implementation, which, of course, can be attributed to its advantages.

If it is necessary to adjust the output power and/or the operating frequency variation over a wide range, a half-bridge class *D* amplifier circuit may be preferable (Fig. 5).

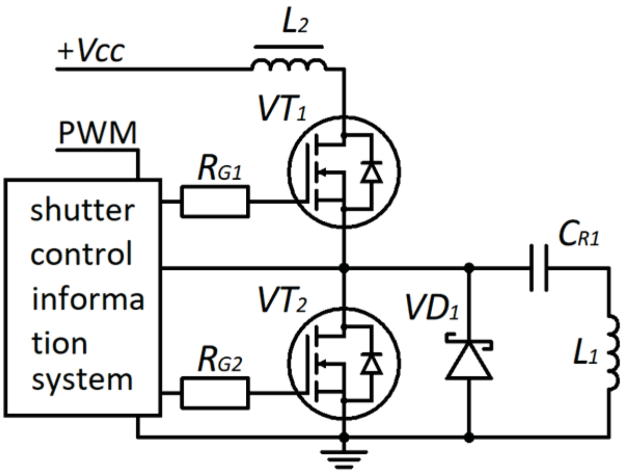

Fig. 5. Power amplifier circuit operating in key mode (class D)

It is necessary to take into account the peculiarities of its implementation, connected with the necessity of antiphase switching of transistors VT1 and VT2 and with the obligatory introduction of a time delay between their breaks to avoid the flow of through-currents. PWM duty cycle can vary in the range of 10 ... 50%. The output power is non-linearly dependent on the PWM signal duty cycle, which usually requires the introduction of feedback.

Finally, it is deduced the general feature of the key amplifier circuits to be the potential occurrence of harmonic oscillations (with a frequency higher than the main resonance) on the parasitic components of the circuit when switching transistors, which can lead to additional heat losses and noise of the spectrum of the generated EMF.

VII. Design of references assessment of the energy fields' impact on biological objects

The main force field planned to be used in the device is magnetic. The magnetic field of any origin has an impact on individual areas and the biological organism as a whole. Data analysis shows that the static magnetic field of increased intensity acting on a biological object causes disordering in nervous, endocrine, vegetative, cardiovascular and other systems [25]. The dynamics of the heart rate changes, with various kinds of effects on the body of biological objects, is an informative and accessible indicator of the evaluation of the functional state of the body of biological objects. Variance analysis of the functions of the heart tachogram gives the possibility of quantitative and differentiated assessment of the degree of tension or tone of the sympathetic and parasympathetic divisions of the autonomic nervous system (ANS), their interactions in different functional states, as well as activities of subsystems that control the operation of various organs [26].

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

During the experiment the animal is placed in a special machine to exclude any sudden movements. Subcutaneous electrodes are used for electrocardiogram registration. Each electrocardiogram is recorded for 150 minutes: 30 minutes before the exposure of the magnetic field on the animal; 60 minutes during the exposure and 60 minutes after the exposure. The heart rate is calculated by analyzing the recorded data (Fig. 6).

The experiment resulted in fact that during the first 30 minutes of ECG registration (without magnetic field exposure) the heart rate was 270 beats per minute. During the exposure of the magnetic field strength of 21 MT, heart rate decreased, reaching the minimum in 45 minutes. The value of the heart rate decline was about 13% of the initial value and was confirmed by statistical analysis.

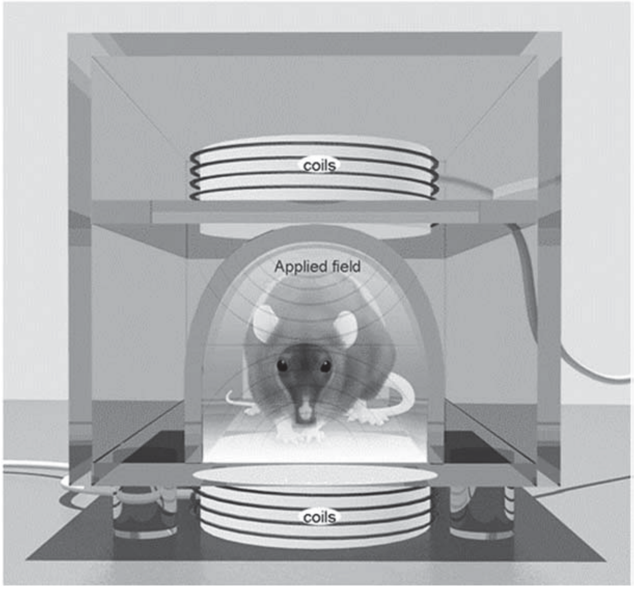

Fig. 6. Experiment of magnetic field's influence on a biological object

From the macroscopic point of view, heat release in the medium due to conduction and polarization currents is indistinguishable from each other. Mathematically, this fact can be expressed by recording the relative permittivity of the medium taking into account its conductivity in the form of (6, 7):

$$\hat{\varepsilon} = \varepsilon^{'} - J * \varepsilon^{''}, \tag{7}$$

where

$$\varepsilon^{'} = \frac{\varepsilon_i^{'}}{\varepsilon_0}, \tag{8}$$

$$\varepsilon^{''} = \frac{\varepsilon_i^{''}}{\varepsilon_0} + \frac{s}{\omega * \varepsilon_0}, \tag{9}$$

where $\varepsilon^{'}$ and $\varepsilon^{''}$ are the real and imaginary parts of the relative dielectric permittivity in regard with the conductivity of the biological medium.

Referring to point (9) the expression (6) takes the form:

$$P_{sp} = \frac{\omega * \varepsilon_0 * \varepsilon^{''}}{2} * E^2, \tag{10}$$

where E is the intensity of the electro-magnetic field in V/m, P_{sp} is the specific heat loss power in W/m^3.

The higher is the frequency of the electromagnetic field, the greater is the specific power of heat losses. When choosing the wavelength of the microwave energy source, it should be

$$Q = s_{sp} * f^2 * E^2 * t, \tag{18}$$

taken into account that with increasing frequency the depth of penetration of the electromagnetic wave into the dielectric with losses decreases (6, 7).

The value of the imaginary part of the medium's relative permittivity depends not only on the frequency of oscillations of the electromagnetic field, but also on humidity and temperature (1, 6).

The magnitude of the wave power that propagates in a dielectric material with losses (along the "y" axis is described by the expression (11):

$$P(y) = P(0) * e^{-2*\varphi*y}, \tag{11}$$

where P_0 is the electromagnetic field power included in the dielectric material, P_y is the electromagnetic field power at a distance of "y" from the material surface; φ is the value of constant decay is given by (13):

$$\varphi = \frac{\pi}{\lambda} * \frac{\varepsilon''}{\sqrt{\varepsilon'}}, \tag{12}$$

where λ is the wavelength in free space.

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 in "e" times, is determined by the ratio (1, 6):

$$L = \frac{\lambda * \sqrt{\varepsilon'}}{2 * \pi * \varepsilon''}. \tag{13}$$

The structure of the human body is multi-layered and each layer reflects microwave energy.

Let the value of RF power propagate through the medium, which is characterized by the real part of the relative permittivity through the biological object $\varepsilon_1^{'}$.

The value of the wave resistance:

$$y_1 = \sqrt{\frac{q_1^{'} * q_0}{\varepsilon_1^{'} * \varepsilon_0^{'}}}, \tag{14}$$

y_1 enters another medium, which represents the load, which is characterized by $\varepsilon_2^{'}$. The value of the wave resistance is:

$$y_2 = \sqrt{\frac{q_2^{'} * q_0}{\varepsilon_2^{'} * \varepsilon_0^{'}}}. \tag{15}$$

In this case, the reflection coefficient R can be calculated by the formula:

$$R = \frac{y_2 - y_1}{y_2 + y_1}. \tag{16}$$

If we assume that in the biological medium the relative magnetic permeability of the medium is $q_1^{'} = q_2^{'} = 1$, then:

$$R = \frac{\sqrt{\varepsilon_1'} - \sqrt{\varepsilon_2'}}{\sqrt{\varepsilon_1'} + \sqrt{\varepsilon_2'}}. \tag{17}$$

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

where Q is the amount of heat released in a biological object, s_{sp} is the conductivity of a biological object, f is the electromagnetic field frequency, E is the electric field intensity, t is time.

VIII. CONCLUSION

The main issues of the article are focused on specifics of implanted devices (ID) power supply, which include: the service life of batteries and the level of energy consumption of modern devices, permissible weight and size characteristics of ID, priority areas of implantation. As a result of the research, the ranges of possible values of specific power were determined: wireless power transmission is 0.1...100 mW/cm^2, energy conversion of specific sources for the biological object is 0.0001...0.1 mW/cm^2, isotope power sources is below 0.0001 mW/cm^2.

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