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Integral estimating an impact peril by sequence of ultra-wideband electromagnetic pulses on human organism

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Impact peril for warm-blooded organisms produced by a sequence of ultra-wideband electromagnetic sub-nanosecond pulses, used in various scientific and technological applications, is assessed by calculation methods of radiophysics and classical mechanics. Threshold values of the sequence parameters whose long time excess can be perilous for human have been determined.

Keywords: ultrashort electromagnetic pulse (USEMP), electromagnetic impact, warm-blooded organism, free and bound charges.

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Introduction

Upon an emergence of radio communication and further spread of more powerful and higher-frequency radio transmission systems of the various kinds, many countries got interested in a problem of perilous electromagnetic radiation for human. There exists a large number of articles, monographs, textbooks, manuals published to solve, at quite different levels of complexity, the tasks of penetration, absorption and influence (including the negative one) of the electromagnetic waves on functioning of various human organs and human health as a whole. These studies in Russia [1], Canada [2] and some other countries resulted in working out the regulations for maximum permissible levels of the narrow-band electromagnetic radiation impact on humans within the frequency range from 30 kHz to 300 GHz.

Preamble [2] said that the safety code updated in 2015 (SAFETY CODE 6) does not cover all possible situations, and other interpretations may be applied to the area of fast development of the technologies. For instance the current rapid spread of cell communication made the researchers of [3–6] deeper study the influence of the narrow-band electromagnetic oscillations used in this area on the human brain. Another example is the last decades' emergence of sources of powerful ultrabroadband electromagnetic radiation [7–9] as a sequence of ultrashort electromagnetic pulses (USEMP), whose spectrum may extend from dozen–hundred MHz to several GHz.

The powerful USEMPs are widely used for radiolocation of small-sized and hidden (by a wall, forest, ice, an earth surface) objects as well as for studying the immunity of automated and robotized systems to the electromagnetic impacts. The Russian standard [10] regulates the use of USEMPs with duration from 0.2 to 1 ns, the rate repetition of $F \geq 1$ kHz and the peak strength of the electric field E_p within the object location up to 30 kV/m and over. Pulses with approximately similar parameters are stated in international standards [11].

USEMP sequences differ from the narrow-band electromagnetic impacts differ in the large amplitude of the electric field E_p exceeding dozen kV/m, short-time impact of each pulse (not over several nanoseconds) and the large width of its energy spectrum. No maximally permissible levels of such impacts for human yet exist. This article, based on the energy approach of [12], attempts to make preliminary estimates by two different methods.

1. Radiophysical method

In the far zone the instantaneous value of the USEMP power to the human body, whose abris (mid-section) equals σ can be described by the standard formula

$$P_{\text{fal}}(t) = \frac{\sigma}{Z_0} E^2(t),$$

wherein $E^2(t)/Z_0$ — the Poynting vector; $E(t)$ — the time dependence of the USEMP electric field intensity within the human location; $Z_0 = 120\pi$ — the wave resistance of the space [13]. One of possible dependences of the USEMP electric field $E(t)$ in its relative form shown in Fig. 1 for clarity.

It is convenient to describe in energy units the fast-changing electromagnetic field incident on the object. At that, the USEMP full energy incident on the object is

$$\Theta_{\text{fal}} = \frac{\sigma}{Z_0} \left[\int\limits_{-\infty}^{\infty} E^2(t)dt = E_p^2 \tau_e \right], \tag{1}$$

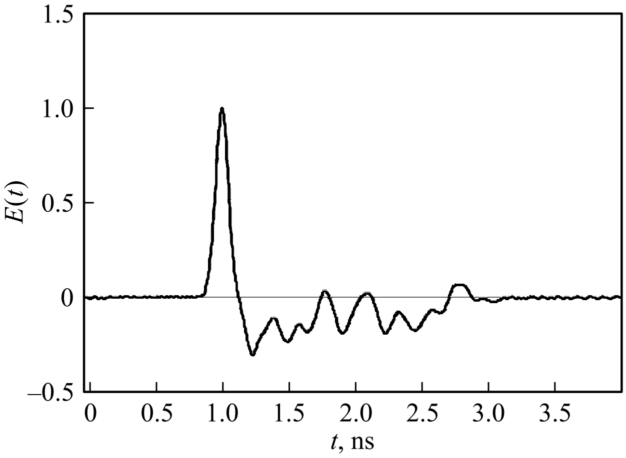

Figure 1. One of the possible USEMP forms.

where E_p — the USEMP peak value, and

$$\tau_e = \frac{1}{E_p^2} \int\limits_{-\infty}^{\infty} E^2(t)dt \qquad (2)$$

— the USEMP equivalent duration. In fact, an identity can be received in the square brackets when substituting (2) in (1). The formula (1) matches the sing-alternating USEMP to the rectangular video pulse of duration τ_e, whose amplitude is E_p. In particular, the pulse in Fig. 1 has the equivalent duration not exceeding 0.15 ns.

Using the Parseval equality [14], from (1) the USEMP energy incident on a warm-blooded object (WBO), will be found, expressed via its energy spectrum:

$$\Theta_{\text{fal}} = \int\limits_{-\infty}^{\infty} P_{\text{fal}}(t)dt = \frac{\sigma}{Z_0} \int\limits_{-\infty}^{\infty} E^2(t)dt = \frac{\sigma}{Z_0} \int\limits_{0}^{\infty} 2S_E^2(f)df. \qquad (3)$$

Here $2S_E^2(f)$ — a square of the spectrum module

$$|\dot{S}_E(\omega)| = \left| \int\limits_{-\infty}^{\infty} E(t)\exp(-j\omega t)dt \right|$$

of the USEMP electric field strength within the object location, and expressed via the physical frequency $f \geq 0$. Fig. 2 shows the energy spectrum of the pulse in Fig. 1, as normalized to its maximum value. It is clear that the bulk spectrum is concentrated within the frequency range from 100 MHz to 3 GHz. The density of the energy spectrum averaged across this range is approximately 0.3.

Taking into account (1), the equation (3) for the energy of a single USEMP incident on WBO takes the form

$$\Theta_{\text{fal}} = \frac{\sigma}{Z_0} \left[\int\limits_{-\infty}^{\infty} E^2(t)dt = 2\int\limits_{0}^{\infty} S_E^2(f)df = E_p^2\tau_e \right]. \qquad (4)$$

Let us evaluate. The introduction has provided the USEMP parameters used in practice. Out of them the ones will be selected that are cumulatively close to the limit values: the duration of 0.2 ns, the repetition rate $F = 1$ kHz, the peak strength of the electric field at the object location $E_p = 10^5$ V/m. Let the warm-blooded object, which outline has an area $\sigma = 0.7\,\text{m}^2$ be irradiated by such a USEMP sequence. Using the formula

$$\Theta_{\text{fal}} = \frac{\sigma}{Z_0} E_p^2 \tau_e$$

from (4), by substituting the values of the selected parameters, obtain the energy $\Theta_{\text{fal}} \approx 3.7 \cdot 10^{-3}$ J of a single USEMP. When multiplying it by the pulse repetition rate, obtain the power $P_{\text{fal}} = \Theta_{\text{fal}}F \approx 3.7$ W of the USEMP sequence incident on WBO.

The mechanisms of impacting WBO by USEMP and continuous electromagnetic waves (i.e. UHF oscillations) can be different in their nature, so it is not quite correct to make a comparison between the outcome of one or another kind. At the same time, both of them have a common mechanism, i.e. a thermal one, whereas there are even marginal rates for the continuous effects. Therefore, we compare the two kinds in terms of thermal impact.

Under long-term impact of the USEMPs passing with the frequency $F = 1$ kHz, the density of the power incident on WBO is $P_{\text{fal}}/\sigma \approx 0.53\,\text{mW/cm}^2$. This values turns out to be approximately four times less than the maximum permissible level $P_{\text{fal}}/\sigma \approx 2\,\text{mW/cm}^2$ of the continuous electromagnetic radiation of the frequency range $(0.1 \leq f \leq 5)$ GHz, affecting the human [15,16] for 6 min. It is clear from Fig. 2 that the same range also comprises the spectrum of the USEMPs under consideration. Hence, in terms of the energy the frequency components of the USEMP spectrum affect the organism on average in the same way as the UHF oscillations, and it is quite acceptable to compare the results of these two exposures.

So, the thermal impact on the human by the USEMP with parameters $E_p = 10^5$ V/m, $\tau_e \approx 0.2$ ns, $F = 1$ kHz and the irradiation duration of $\Delta t < 6$ min turns out to be four times less than the maximally permissible level $P_{\text{fal}}/\sigma \approx 2\,\text{mW/cm}^2$ as regulated for the continuous UHF oscillations. By increasing one or several USEMP parameters so that

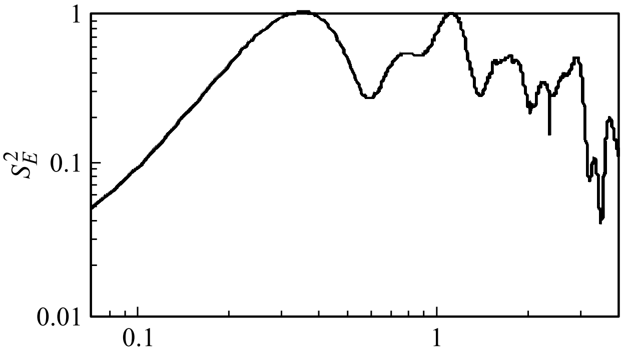

Figure 2. Normalized energy spectrum of USEMP.

the product $E_p^2\tau_e F = 10^{10}\cdot 2\cdot 10^{-10}\cdot 10^3 = 2\cdot 10^3$ grows $N = 4$ times, approach this maximally permissible level $P_{\text{fal}}/\sigma \approx 2\,\text{mW/cm}^2$. Thus, the value of the product

$$\Pi = NE_p^2\tau_e F = 4\cdot 10^{10}\cdot 2\cdot 10^{-10}\cdot 10^3 = 8\cdot 10^3\,\text{V}^2/\text{m}^2 \qquad (5)$$

of main parameters of the USEMPs sequence continuously affecting the human for $\Delta t = 6$ min can be regarded as a threshold, whose exceedance can be perilous for human's health.

2. Mechanical method

Only charged particles can react to the impact of the electromagnetic field. Under a continuous impact of the electromagnetic wave, the human tissues suffer dipole molecules rotation or free charges oscillation with the frequency f_0 of the field variation. Both the processes are accompanied by thermal losses, that depend on the dielectric conductivity of the tissues [16], their electric conductivity and the frequency f_0. The ratio between these two kinds of the losses is expressed by the complex dielectric permittivity.

$$\varepsilon = \varepsilon' - j\varepsilon''.$$

where ε' — the relative dielectric permittivity measured at the frequency f_0; $\varepsilon'' = \gamma/2\pi f_0\varepsilon_0$ — the loss coefficient accounting for transformation of the wave energy to heat as caused by electrical conductivity; γ —the active specific electrical conductivity measured at the frequency f_0; ε_0 — the vacuum electric constant. The loss coefficient ε'' is structured to show that under the impact of the energy of the continuous electromagnetic wave the charged particles will oscillate around their centers of gravity with the frequency f_0 of the wave oscillations.

Beside the transformation to heat, the energy of the electromagnetic or electric field affects a rate of biochemical reactions and the diffusion processes in the biological tissues, that can result in unpredictable consequences. For instance under the impact of single-pole electric pulses of the nanosecond duration with the amplitude of the electric field from $E = 10^5$ V/m to $E = 10^7$ V/m and above the biological membranes can change [17] their permittivity leading to higher transmembrane transfer of ions (i.e. electroportation) as well as charged and neutral molecules. However, USEMP is not a single-pole electric video pulse, it is an alternating-sign pulse (Fig. 1), whose changing amplitude averaged across the time of its existence is zero: the impact of these alternating-sing pulses with the peak values $E_p \le 10^7$ V/m does not lead to the electroportation and the phenomena related thereto [17].

Concentration of free electrons in the human tissues is negligible. The free charged particles are ions of various chemical elements, whereas the cells predominantly contain potassium ions, and the intercellular solutions contain sodium ions [18]. To simplify the calculations, an evaluation will be performed in regard to the efficiency of USEMP impact on the potassium ion located in vacuum (rather than in a cell) without obstacles to its motion.

Equation of the motion of the free particle of the mass m, carring the charge e and staying in the electric field $E(t)$, is as follows

$$\frac{d^2x}{dt^2} = \frac{e}{m}E(t). \qquad (6)$$

Let us replace USEMP with its energetically-equivalent video pulse of the typical equivalent duration $\tau_e \approx 0.2$ ns. The equation solving reveals that at the end of the video pulse with the peak field strength $E_p = 10^5$ V/m the potassium ion will have the speed

$$\dot{x} \approx \frac{e}{m_{\text{K}}}E_p\tau_e = 50\,\text{m/s}$$

(the initial speed of ion is assumed equal to zero) and be shifted by the distance of $x \approx 10^{-8}$ m, approximately equal to three interatomic distances in the aqueous solution and one and a half order less than the average size of the human cell. At the same time, the kinetic energy gained by the ion $W_{\text{K}} = 0.5m_{\text{K}}\dot{x}^2 \approx 8.1\cdot 10^{-23}$ J turns out to be two orders less than its thermal energy $3/2kT \approx 6.4\cdot 10^{-21}$ J (here $k = 1.38\cdot 10^{-23}$ J/K — the Boltzmann's constant, $T \approx 310$ K — the temperature of the human body).

For comparison, at the same conditions the sodium ion will have the kinetic energy gained by the field $W_{\text{Na}} \approx 1.4\cdot 10^{-22}$ J, that is 50 times less than the thermal one. Even the proton's gained energy of $W_{\text{P}} \approx 3.1\cdot 10^{-21}$ J is approximately twice less than its thermal energy. If the equation (6) were integrated outside the equivalent duration of the video pulse, and using the form of the real USEMP (Fig. 1), then the maximum deviations of ions from the initial position would decrease and the energy gained by them would drop several times. Thus, the evaluations of the kinetic energy of the particles received by replacement of the USEMP with the energy-equivalent video pulse could be overestimated. But this overestimation can be slight: like, Fig. 1 shows the duration of the first ejection $E(t)$, which is commensurate with the equivalent duration of $\tau_e \approx 0.2$ ns of the entire pulse.

It should be also taken into account that at the electromagnetic wave penetration to the body the field strength $E(t)$ reduces and the impact efficiency drops.

3. Discussion

Evaluations obtained show that in the warm-blooded organisms ions of light chemical elements are the most sensitive to impact of ultrashort electrical pulses. In vacuum, the energy gained by them from the field is proportional to the square of the field E_p^2, the square of the pulse duration τ_e^2 and inversely proportional to the mass. For the proton, this energy is maximum and under impact of the single pulse with the parameters $E_p = 10^5$ V/m, $\tau_e \approx 0.2$ ns turns out to be comparable with its thermal energy.

Within a living body, the dynamics of the ion motion is not the same as in vacuum: at the given values of the parameters E_p and τ_e of the video pulse the energy gained from the external field is still the same, and a part of this energy is imparted to other particles when colliding with them, thereby making uncertain the direction of the ion motion [19]. The portion of the delivered energy will be the smaller, the smaller the mass of the ion in relation to the mass of the particles, it collides with, and the lower frequency of the collisions. In other words, inside the organism body the ion will maintain the laws of proportionality of its kinetic energy to the magnitudes E_p^2, τ_e^2, m_i^{-1}, which are valid in vacuum. At the same time, the part of the gained energy is transferred to the particles, it collides with. This leads to the temperature increase. The energy gained by the proton decreases weaker in collisions than that for the heavier ions.

With at least a fourfold increase in the electric field of the E_p video pulse or the product $E_p^2\tau_e F$ at the energy of protons and the light ions will prevail over their thermal energy, which can affect the diffusion processes and the rate of biochemical reactions occurring with their participation. In this case, the thermal threshold (5) reached in the previous section via other methods is approached.

Generalizing received results, may arrive to the conclusion that generally a threshold value characterizing the USEMP degree of peril is a product of its main parameters $\Pi \approx NE_p^2\tau_e F \approx 8 \cdot 10^3\,\mathrm{V^2/m^2}$, whose excess can become unsafe for the human at the time of irradiation over several minutes.

Conclusion

Physically, there should not be expected any sizable reaction of humans and other warm-blooded biological species to short-time (about one minute) impact of the electromagnetic pulses of a sub-nanosecond duration with the peak strength of the incident electric field $E_p \leq 10^5\,\mathrm{V/m}$ and the repetition rate $F \leq 1\,\mathrm{kHz}$. This is explained by the fact that the concentration of free electrons and holes inside the human body is negligible, while at fields of $E_p \approx 10^5\,\mathrm{V/m}$, the mechanism of transferring the energy of ultrashort pulse to free and bound charged ions is ineffective because of their large mass and the short duration of the alternating-sign pulse.

However, with the increase of the amplitude, the duration, the repetition rate and the irradiation time the dynamics of the physical processes in the living body is changes quickly and the USEMP impact can become perilous for human. Physics does not answer the question what is this peril; the answer to it may be delivered by biophysics and physicians through their conclusions made as resulted in experimental studies.

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Conflict of interest

The authors declare that there exists no conflict of interest.

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