The physical modelling micro circulatory processes of biological tissues under the low-intensity IR-radiation

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Abstract. A physical modelling of the low-intensity IR-radiation influence on biological tissue was carried out. The deformation processes of biomembrane under the action of a non-uniform temperature field are studied. In addition to wavelength, pulse intensity and frequency the importance of pulse length has been shown for the effectiveness of laser therapy.

1. Introduction
Treatment using low-intensity laser radiation (LLR) is an effective physiotherapeutic method. In accordance with the nonresonant mechanism of influence of light exposure on microcirculation in biomembrane discovered in the 90s [1, 2] in biological tissues, temperature field inhomogeneities arise under the influence of LLR as a result of scattering processes. This leads to significant deformations of cell membranes and changes in their electrical potential. Deformations of biological membranes significantly affect the metabolic processes in cells and between them. For instance, periodic deformations of vascular wall cells in inflamed areas of biotissue facilitate circulation of liquid components.

Initially, red He-Ne lasers with a wavelength of 0.63 μm were used for LLR therapy. Radiation was injected into blood vessels using catheters [3, 4]. But according to the mechanism of radiation action, nonresonantly absorbed laser radiation can be used. Therefore, treatment of internals was performed directly through the skin by irradiation with a wavelength of 0.89 μm, falling into the transparent window of biomembranes [2, 5 and 6]. The penetration depth of GaAs laser radiation is 4 - 7 cm. Efficiency of radiation with a wavelength of 0.89 μm compared to 0.63 μm is also noted in modern studies (for example, [7, 8]). As 30 years ago, research continues to observe a strong dependence of the bio-efficiency of pulse action on the laser pulse frequency [9]. The independence of biostimulation from polarization and coherence was discovered in the 80s of the last century [10, 11], so for the treatment of LLR, the choice of the wavelength range, the spectral density and the pulse frequency are important.

2. The influence of frequency
In [1, 2] it was shown that in real conditions of laser therapy (for example, He-Ne–, GaAs-lasers) with an average power of up to several mW, a micro warming in the range of the $10^{-2}$-$10^{-1}$ K occurs, and the cell membrane deformation is up to $10^{-2}$-$10^{-1}$, and the change in their electric potential up to $10^{-3}$-$10^{1}$ mV occurs. It was shown that if the effectiveness of laser therapy is estimated by the amplitude of deformation and the electric potential of cell membranes, the efficiency is higher in case of using pulse
irradiation, and its relation of the laser pulse frequency. Maximum of efficiency determine from the ratio:

\[ \omega_{\text{max}} = \frac{10^4}{d(\mu m) + (d^4(\mu m^4) + 10^2)^{1/4}} \text{(Hz)} \]  

(1)

where \(d\) is the characteristic size of structural (optical) inhomogeneities in the biological tissue. Thus, the pulse frequency of laser irradiation must be selected depending on the morphology of biological tissue. By varying the laser pulse frequency, it is possible to exert a selective effect on various structures of biological tissues. This conclusion was confirmed by experimental studies of changes in the morphology of various tissues after laser irradiation, as well as experience in the treatment of chronic nonspecific inflammatory diseases of internals [2, 5 and 6]. For example, experimental studies of blood microcirculation in the capillaries of rat tissue under the influence of LLR showed that after laser irradiation, capillary blood flow increases and the area of the capillary bed increases. In accordance with (1), taking into account the size of the capillaries of the human heart muscle \(d \sim 10\ \mu m\), an estimate of the frequency \(\omega_{\text{max}} = 10^2\ \text{Hz}\) was obtained, at which coronary heart disease was treated. It was shown that in 98% of the examined patients there was an improvement in myocardial contractile function.

Formula (1) was obtained by jointly solving the following equations. Violation of the equality of concentrations or temperatures on both sides of the cell membrane leads to appearance of osmotic pressure on the membrane:

\[ \Delta p = nRT \left( \frac{\Delta T}{\tau} + \frac{\Delta n}{n} \right) \]  

(2)

In that case, when temperature and concentration change range near the membrane is limited by the size \(d\), the pressure leads to a lateral displacement of the membrane \(\Delta p \cong \frac{d^2}{hE}\), where \(h\) is the membrane thickness (\(d \sim 10\ \text{nm}\)), \(E\) - Young's modulus shear deformation of the double lipid layer (\(E \sim 10^5\ \text{N/m}^2\)), \(n\) - is the concentration of ions inside and outside cells (\(n \sim 140\ \text{mol/m}^3\)). Assuming the strain \(\varepsilon = \frac{x}{l}\) (\(l\) is the cell size) and using (2), the strain rate equation:

\[ \varepsilon = \left[ a \left( \frac{\Delta T}{\tau} + \frac{\Delta n}{n} \right) - \varepsilon \right] \tau^{-1} \]  

(3)

where \(\tau\) - diffusion time scale through the membrane, \(a = \frac{nRTd^2}{hIE}\). The temperature change temperature \(\Delta T\) is related to the difference in absorption coefficients on different sides of the membrane and it is described by the equation:

\[ \Delta T = bI(t) - \frac{\Delta T}{\tau_T} \]  

(4)

where \(b = \frac{a}{c\rho}, a\) - difference of absorption coefficients in the field of \(d\) and outside it, \(c\) and \(\rho\) - heat capacity and density of the medium, \(I(t)\) - radiation flux density, \(\tau_T\) - time of temperature relaxation \(\tau_T = \frac{d^2}{k}\) (\(k \sim 1.5 \times 10^{-7}\ \text{m}^2/\text{s}\) - thermometric conductivity). Diffusion of sodium and potassium ions from external areas (not through the membrane), as well as the displacement of the membrane, accompanied by diffusion of water through it, leads to a change in the concentration difference on both sides of the membrane under conditions of uneven heating.
where \( \tau_D = \frac{a^2}{D_{NaK}} \) - diffusion time scale of Na\(^+\), K\(^+\) ions in the medium. In the case of continuous exposure to laser radiation under the assumption \( \tau_D \gg \tau_T \left( \frac{T_0}{\tau_T} \sim 10^2 \right) \) at long times, the solution of the system (3-5) gives \( \varepsilon \equiv \frac{abI_0\tau_T}{T} \). This is a deformation under continuous irradiation.

To estimate the dependence of \( \varepsilon \) on the frequency of sending laser pulses, we set \( I(t) = I_0(1 - \sin(\omega t)) \). The solution of the equations at large times:

\[
\varepsilon \approx \frac{a b I_0}{T} \left\{ \frac{\tau_T \tau_D \sin(\omega t) + \arctg \frac{1 - \omega^2 \tau_D (\tau_T + \tau_b)}{\tau_D \omega (1 - \omega^2 \tau_T \tau_b)}}{[1 - \omega^2 \tau_D (\tau_T + \tau_b)] + \omega^2 \tau_D^2 (1 - \omega^2 \tau_T \tau_b)^2} \right\} \]

The frequency when the largest oscillation amplitude is realized is found from the condition \( \frac{d\varepsilon}{d\omega} = 0 \).

\[
\omega_{\text{max}} \approx \frac{1}{(\tau_D \tau_T)^{1/2} (\tau_T^2 - \tau_b)^{1/4}}
\]

From (7), taking into account the dependencies of characteristic times on \( d \), we obtain the relation (1).

3. The influence of pulse duration
The pressure on the membrane \( \Delta p \) at temperature and ion concentration differences occurs as a result of different permeability of the membranes for water (characteristic diffusion time through the membrane is \( \tau_b \sim 10^{-4} \) s) and for ions (\( \tau_i \sim 10^0 - 10^2 \) s) [5]. Therefore, the effectiveness of the impact depends on the duration of the pulses. The pulse duration of laser therapeutic devices on GaAs-laser diodes is from 100 to 300 ns. For short pulse \( \tau_L \), when \( \tau_b \gg \tau_L \), the temperature relaxation time can be estimated as \( \tau_T = \frac{a^2}{k} \). For large sizes \( d > 4 \text{ \mu m} \), the time of temperature relaxation exceeds the time of membrane deformation, and the assessments are valid. The size of 5 - 11 \text{ \mu m} corresponds to the microcirculation systems in various organs.

For smaller sizes associated with cellular structures the temperature field relaxes faster than deformations of biological membranes. In the approximation of the pulse effect the intensity \( I(t) = I_0(1 - \sin(\omega t)) \) substitution can only be used to estimate the frequency dependence of the strain. Absolute values of membrane deformation will obviously decrease with decreasing pulse duration. The optimal porosity appears to be 2. Lasers have a very large one.

4. Conclusion
The effectiveness of biological action or therapeutic effect of low-intensity IR-radiation, in accordance with the established non-resonant mechanism of light effect on microcirculation in biomembrans, depends on the frequency of pulse irradiation and the duration of the pulses. To stimulate microcirculation processes in cellular structures, the pulse duration should exceed the time of establishing osmotic pressure on membranes. Besides a value of the porosity should be about 2. Therefore, instead of laser diode sources traditionally used in laser therapy, it is proposed to use IR LEDs with a pulse duration of 100 ms. LEDs are no less effective for bio-structure and capillary-vascular structures with an obvious cost advantage.
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