

# Assessment of the Effectiveness of Laser-Acoustic Transformation

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**Abstract**—For some biotechnological technologies, there is a problem of separating living cells or destroying their membranes in order to obtain individual elements of the inner structure of the cell. This is usually done using microsurgical operations. In practice, the method of obtaining individual cell fragments without surgery using an acoustic wave is of interest. In this paper, a mathematical model and the results of modeling the process of the formation of an acoustic pressure wave in a liquid biological solution for the destruction of the membrane of a biological object is considered.

**Keywords**— *biotechnologies, laser, optoacoustic, membrane, bio-object*

## I. INTRODUCTION

The thermal mechanism for the transformation of an acoustic wave in liquid under the laser radiation is caused by thermal expansion of the medium volume heated by the radiation [1]. This mechanism is fundamental for laser radiation, when the density of optical energy released in a liquid is low compared to the heat released at the focal point. The main processes of this phenomenon in this case are described by the linear theory [2]. At low energy densities released in a liquid, the expansion rate of the heated region is small compared to the speed of sound, and linearized hydrodynamic equations can be used. In addition, in many cases, the influence of heat conduction on the generation of an acoustic wave can be neglected.

## II. PROBLEM STATEMENT

Consider the process of the formation of an acoustic wave during the absorption of laser radiation in a cultural medium. In this case, the laser beam propagating in the air is focused on the surface of the nutrient medium (or inside it), where the embryo is located. The energy of laser radiation absorbed in a liquid is transformed into thermal energy and heats the liquid, which corresponds to the laser optoacoustic effect of converting laser radiation into an acoustic wave. In this case, pulsed laser radiation of a specified duration is focused inside the liquid, forming a spherical heating region. For the case under consideration, when the acoustic wave propagates over short distances, the attenuation of the wave in the medium can be neglected, since the object is at a distance of several centimeters from the focused laser radiation. A part of the laser energy is absorbed in this

region, and the heated liquid expands during the laser pulse, which leads to the appearance of a negative pressure region. Thus, a spherical compression and rarefaction wave propagates from the point of focused radiation. To build the model, it can be assumed that the attenuation of the wave propagating in the medium from the heating region is absent, and there is also no heat loss from the heated region. It therefore follows that the acoustic pressure wave in the medium can be characterized by a non-uniform wave equation [2].

## III. METHODOLOGY OF OPTOACOUSTIC CONVERSION MODELING

Consider a model of the optoacoustic conversion of laser radiation into an acoustic wave. In this case, pulsed laser radiation of specified duration is focused inside the liquid, forming a spherical heating region of radius  $R$ . Since the distance from the point of focused laser radiation is short, as noted above, we do not take into account the energy loss in the path of radiation propagation.

To create a mathematical model, use the system of equations of hydrodynamics and electromagnetic field. By linearizing the system of equations and neglecting the viscosity effect, it is possible to obtain a non-uniform wave equation for the optical generation of sound.

As a result of the heating, the liquid expands, forming an increased pressure area, which is an optoacoustic antenna, i.e. is a source that generates an acoustic wave. In so doing, the value of the displacement vector of acoustic oscillations at the point of time  $t$  of the particle of the liquid occupying the position  $x = (x_1, x_2, x_3)$  at the initial point of time  $t = 0$  is small, and in describing this motion it is convenient to use Lagrange's motion pattern. In this case, the sought functions are the displacement  $u(x, t)$ , dynamic pressure  $p(x, t)$  and the density of the liquid  $\rho(x, t)$  related to pressure by state equation. Assuming the viscosity of the liquid in the intracellular plasma is negligible, we can use an expression, corresponding to the ideal liquid, for the stress tensor

$$N(x, t) = -p(x, t). \quad (1)$$

In this case the velocity of a fluid particle  $v(x, t)$  is equal to the partial derivative  $\frac{\partial u(x, t)}{\partial t}$ . The motion equation of such a particle through the stress tensor is written as [4]

$$\rho(x, t) \frac{\partial v_i(x, t)}{\partial t} - \sum_{k=1}^3 \frac{\partial N_{ik}(x, t)}{\partial x_k} = F_i(x, t), \quad (2)$$

where  $i=1, 2, 3$ ,  $F_i(x, t)$  is the force density acting on a fluid particle. The acceleration of liquid particle  $\frac{\partial v_i(x, t)}{\partial t}$  is equal  $\frac{\partial^2 u(x, t)}{\partial t^2}$ , then (2) can be written as

$$\rho(x, t) \frac{\partial^2 u(x, t)}{\partial t^2} + \nabla p(x, t) = \rho(x, t) \nabla U(x, t), \quad (3)$$

where  $U(x, t)$  is field potential of gravitation, i.e.

$$U(x, t) = -ge_3, \quad (4)$$

Finally we have:

$$\rho(x, t) \frac{\partial^2 u(x, t)}{\partial t^2} = -\nabla p(x, t) - \rho(x, t) ge_3. \quad (5)$$

In the process of movement in the oscillating liquid there are the pressure drops. We will neglect the temperature fluctuations associated with the pressure drops. In addition, temperature fluctuations occur due to the heating of the liquid by the laser beam, which is intensely (almost completely) absorbed in a small neighborhood of the point of entry of the beam into the liquid.

Using the equation of the thermal conductivity and the van der Waals equation of state for a fluid, we finally get

$$\frac{\partial^2 \rho(x, t)}{\partial t^2} - \frac{\mu R_g T_0}{(\mu - b\rho_0)^2} \Delta \rho(x, t) = -\frac{\rho_0 R_g}{\mu - b\rho_0} \cdot \frac{1}{a^2} \cdot q(x, t), \quad (6)$$

where  $\mu$  is molar mass of liquid,  $R_g$  is universal gas constant,  $b$  is the excluded volume of molecules in the total mass of 1 mole,  $\rho_0$  is the density of liquid at rest,  $a$  is associated with surface forces and does not play a significant role.

Here it is taken into account the fact that the change in the density of the liquid, caused by its thermal expansion and the density increment corresponding to the change of pressure during the movement of the liquid, are insignificant compared to  $\rho_0$ .

This equation describes the process of propagation of sound vibrations in a liquid. The right side of the equation is a function that is finite for all its arguments. The coefficient  $\frac{\mu R_g T_0}{(\mu - b\rho_0)^2} = v_c^2$  has the meaning of the square of the sound wave velocity in a liquid.

Finally we get

$$\frac{\partial^2 \rho}{\partial t^2} - v_c^2 \Delta \rho(x, t) = f(x, t), \quad (7)$$

where  $f(x, t) = Aq(x, t)$ ,  $A = \frac{\rho_0 R_g}{\mu - b\rho_0} \cdot \frac{1}{a^2}$ .

Considering the relationship of pressure with density in the van der Waals equation for a fluid, we get

$$\Delta p - (1/v_c^2) (\partial^2 p / \partial t^2) = -kc^{-1} (\partial W / \partial t) \quad (8)$$

where  $v_c$  is the sound wave velocity,  $k$  is the coefficient of volume change,  $c$  is the specific heat capacity,  $W$  is the energy of radiation, absorbed in the volume  $G = R^3$  and converted to heat.

To solve this equation, it is necessary to specify the initial and boundary conditions with respect to  $p$ , as well as an explicit form of the function  $\partial W / \partial t$ .

Specify the initial and boundary conditions as follows

$$p(r, \tau_f = 0) = 0, \quad p(r, \tau_f \rightarrow \infty, t) = 0 \quad (9)$$

where  $\tau_f$  is the starting point of the leading edge of the laser pulse. The connection  $W(t)$  is similar to the connection  $P(t)$ , in this case it is the power of laser radiation, since the proposed model of an acoustic wave corresponds to a diverging spherical wave.

Solving equation (8), we can consider two variants of interaction of laser radiation with the medium. Considering the different sizes of the heated region  $G$  and the distance that the wave propagates from the beginning of the leading edge of the laser pulse treatment and its duration, for the case in which the pulse duration is small, the acoustic wave does not propagate beyond the boundaries of the heated region, since the pressure increases only within the heated interval where  $v\tau \leq R$ .

In the case when the acoustic wave goes beyond the heated region  $v\tau \geq R$ . In this case, the resulting pressure in the medium under the influence of focused laser radiation forms the front of the acoustic pressure wave, which propagates to a greater distance from the focusing point. Since the medium in which the process of converting optical radiation into an acoustic wave occurs corresponds to a solution of the nutrient medium with a biological object placed in it, according to the options considered, it is appropriate to generate a pulse of a shorter duration. Hence, since the first option corresponds to a shorter pulse, and the second one to corresponds a pulse of longer duration, according to (8), the expression for the limiting case of a short pulse will be in a form

$$p(\tau_{\min}) \approx (kW/cr)(v_c/R)^2 \quad (10)$$

The equation for a pulse of longer duration corresponding to the case in question is as follows

$$p(\tau_{\max}) \approx (kW/cr)(1/\tau)^2 \quad (11)$$

From these expressions (10) and (11), it follows that the ratio of acoustic pressures makes it possible to estimate the value of the pressure of an acoustic wave on the membrane of a biological object, i.e.

$$\frac{p(\tau_{\min})}{p(\tau_{\max})} \approx (v_c \tau / R)^2. \quad (12)$$

From the expression (12) it follows that with a known value of the absorbed energy  $W$  with solution parameters ( $\beta, c, v$ ) for the case of a longer laser pulse, the pressure of the acoustic wave will be  $R/v\tau$  times less in comparison to a short duration because the pressure in the liquid arising under the action of the optical-acoustic effect, propagates in a larger volume  $R^3$ .

The energy of an acoustic wave can be estimated as  $W_c = (p^2 \sim P^2 \sim W^2)$ , from where the coefficient of conversion of laser radiation into sound is proportional to the laser power. However, the laser pulse interaction time, depending on its duration, is a necessary condition for the destruction of the cell membrane, which is located at a certain distance from the point of application of the focused radiation. The conversion coefficient of laser radiation into an acoustic pressure wave is equal to

$$\delta = \frac{W_c}{W} \quad (13)$$

To determine the maximum pressure of an acoustic wave in a solution arising from local heating by focused laser radiation, it is necessary to take into account the volume density of the absorbed radiation energy, which should not exceed the latent heat of evaporation of the liquid, at which heating does not change the phase state of the medium. In this case, such an approach ensures the absence of heating of a biological object located in a liquid solution.

#### IV. EXPERIMENT

The performed calculations show that at a distance of five centimeters from the point of application of focused radiation to a biological object, the temperature of the medium does not exceed the temperature of the liquid around the object for specified laser radiation energy [3].

The value of the acoustic pressure on the membrane corresponds to the values obtained for its rupture in paper [4].

In Fig. 1 the dependences of the pressure amplitude values  $p(r,0)$  at the point  $r=5$  cm on the radiation energy  $W$  of a Nd laser, calculated for radiation pulse durations  $\tau$ : 1) 10; 2) 20; 3) 50 ns are shown. Fig. 2 shows the dependences of the characteristic time constant of the compression wave  $Q$  [3] at the point  $r=5$  cm on the radiation energy  $W$  of a Nd laser calculated for radiation pulse durations  $\tau$ : 1) 10; 2) 20; 3) 50 ns.

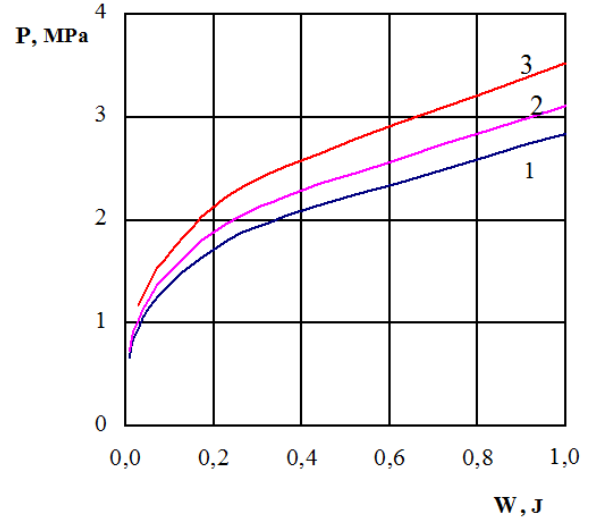


Fig. 1. Dependence of the values of the pressure amplitude  $P$  on the radiation energy of a Nd laser

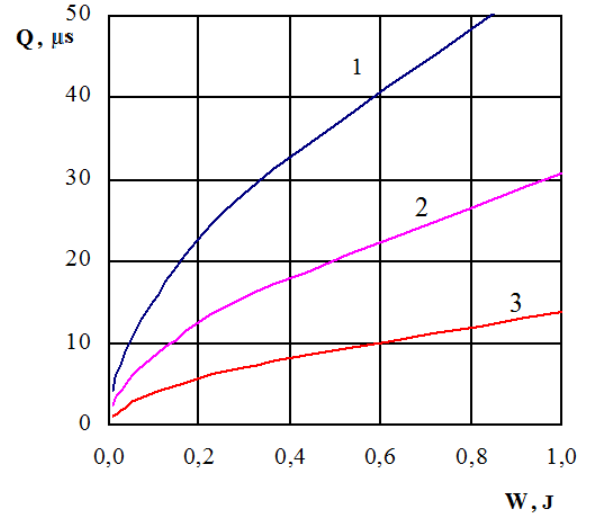


Fig. 2. Dependences of the characteristic time constant of the compression wave  $Q$  on the radiation energy of a Nd laser

Fig. 3 shows the results of calculating the amplitude at different points of the compression wave, performed for different values of the radiation energy of a neodymium laser with the pulse duration  $\tau = 10$  ns.

With typical parameters of laser pulses for the effective action of compression waves on biological objects, these latter should be located at distances of about 1-10 cm from the breakdown point, where the pressure amplitude is in the range from several hundred to several thousand kPa, as can be seen in Fig. 3.

In Fig. 4. the calculations of the characteristic time constant of the compression wave  $Q$  on the distance  $r$ , calculated for the same conditions as in Fig. 3 are given. The calculated duration of a pressure pulse, determined by the  $1/e$  level, may be in the range of microseconds to one hundred microseconds, depending on the parameters of the laser pulse, such as its energy and duration.

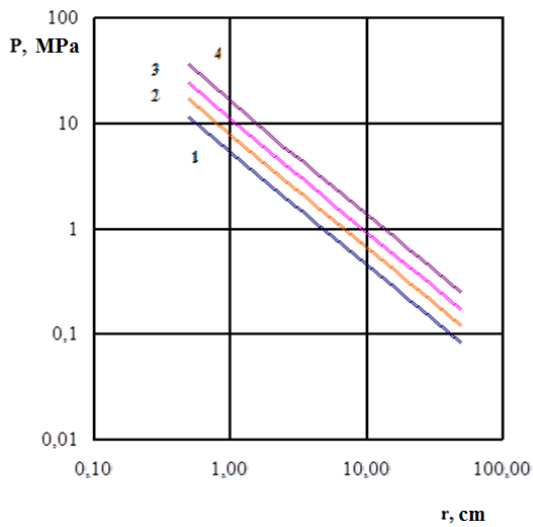


Fig. 3. Dependence of the pressure amplitude  $P(r,0)$  on the distance to the center of the optical breakdown  $r$  calculated for a Nd laser pulses with the duration  $\tau=10$  ns and the following energies  $W$ : 1) 0,03; 2) 0,1; 3) 0,3; 4) 1,0 J

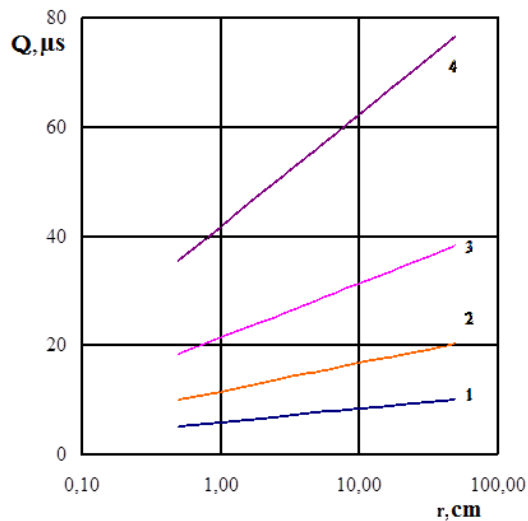


Fig. 4. Dependence of the characteristic time constant of the compression wave  $Q$  on the distance  $r$ , calculated for a Nd laser radiation pulse with a duration  $\tau=10$  ns and the following energies  $W$ : 1) 0,03; 2) 0,1; 3) 0,3; 4) 1,0 J

The noted factors should be taken into account when using the pressure of a compression wave, created by laser breakdown in a liquid, on biological objects.

Fig. 5 and Fig. 6 show, respectively, the dependences of  $P(r,0)$  and  $Q$  on the pulse duration of a neodymium laser radiation  $\tau$ , calculated for different energies  $W$  at the point  $r = 1$  cm, which is also of interest for practical use.

It can be seen from the figures that in the compression wave that propagates in a liquid during optical breakdown, the dependence of pressure on the pulse energy is more pronounced than on its duration. At the same time, the characteristic time constant  $Q$  essentially depends on both quantities.

## V. CONCLUSIONS

The paper considers a mathematical model and a method of implementing an optoacoustic laser effect for rupturing the membrane of a microbiological object in order to study

individual fragments of its internal structure. The values of the parameters of laser radiation for the destruction of the bio-object pellucid zone are determined. The elements obtained this way, without the use of microsurgical intervention, ensure sterility by microscopic examination of individual bio-elements.

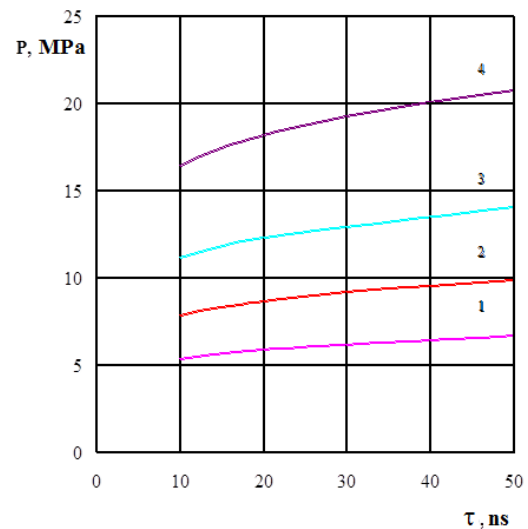


Fig. 5. Dependence of the pressure amplitude  $P(r,0)$  at the point  $r = 1$  cm on durations  $\tau$  of a Nd laser radiation pulses, calculated for the following energies  $W$ : 1) 0,03; 2) 0,1; 3) 0,3; 4) 1,0 J

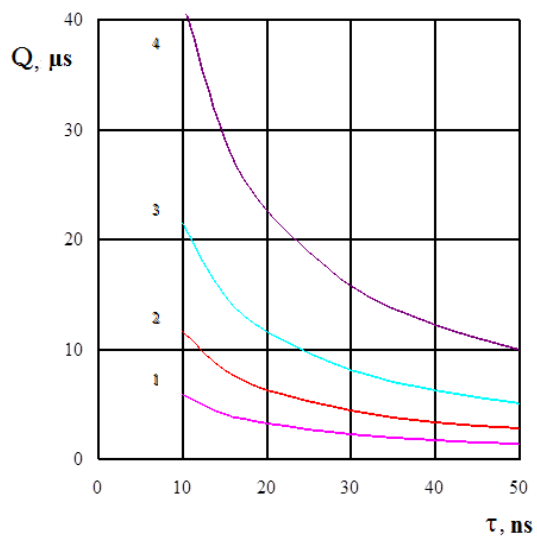


Fig. 6. Dependence of the characteristic time constant of the compression wave  $Q$  at the point  $r = 1$  cm on the durations  $\tau$  of a Nd laser radiation pulses, calculated for the following energies  $W$ : 1) 0,03; 2) 0,1; 3) 0,3; 4) 1,0 J

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