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OPTOACOUSTIC MEASUREMENT OF OPTICAL PROPERTIES OF TURBID MEDIA

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Time-resolved laser optoacoustic method was developed for the measurement of the optical properties - effective light attenuation and absorption coefficients - of uniformly absorbing and scattering turbid media. The effective light attenuation coefficient is measured by exponential fitting of the leading edge of laser-induced ultrasonic transient. To determine the light absorption coefficient we investigated features of the spatial distribution of laser fluence rate beneath the surface of a turbid medium. We proved both experimentally and with Monte-Carlo simulation, that the location of the maximum of laser fluence rate depends solely on the ratio of light absorption and effective light attenuation coefficients, if the anisotropy factor of light scattering is higher than 0.8. This dependence can be employed to determine the light absorption coefficient of turbid media from the leading edge of laser-induced ultrasonic transient.

Study of the optical radiation propagation in turbid media, and particularly of the distribution of absorbing and scattering inhomogeneities, is an important scientific problem [1]. The recent interest in this problem is largely associated with the development of biological tissues optics [2]. The pattern of laser fluence rate distribution in turbid tissues and the amount of absorbed energy is very important aspect of any clinical laser treatment [3,4]. So there is a definite need for the non-invasive measurements of optical properties of biological tissues.

To solve this problem we propose the optoacoustic (OA) method, based on laser thermooptical excitation of ultrasonic waves in an investigated medium [5]. It was successfully used for the measurement of the spatial distribution of laser fluence rate in uniformly absorbing and scattering turbid media [6-9].

The aim of the present study is to demonstrate the possibility of determination of optical properties - light absorption and effective light attenuation coefficients - of uniformly absorbing and scattering turbid media from the z-axial profile of laser-induced ultrasonic transients without measurements of absolute acoustical pressure.

Let consider a uniformly light absorbing and scattering, semi-infinite medium, occupying the half-space z>0. We describe it by the averaged macroscopic parameters: the light absorption and scattering coefficients m_a and m_s respectively. In the case of scattering predominates over absorption ($m_a << m_s$) the light radiation undergoes multiple scattering in a medium. If the lifetime of photons $(m_a c)^{-1}$ (c is velocity of light in a medium) is much shorter than the duration of a laser pulse ($m_a c t_L >> 1$), the laser fluence rate in an irradiated medium can be determined with well-known light diffusion approximation at the distances $z > (2 \div 3) l^*$ (l^* is the transport mean free path of photons)[10].

Light transport theory [10] and the results of Monte-Carlo simulation [9] show that the laser fluence rate distribution in turbid media has the typical features in a subsurface region due to backscattering of light. The exponential decay of laser fluence rate inside the medium is determined by effective light attenuation coefficient $m_{eff} = \sqrt{3 m_a m_s'}$ ($m_s' = m_s(1-g)$ is the reduced scattering coefficient, g is the anisotropy factor of scattering. The maximum of laser fluence rate is located beneath the surface of irradiated medium at the distance $z_{\max} \approx l^*$. Under the condition $m_a << m_s'$ the value of $z_{\max}$ is determined solely by the transport mean free path of photons l^* and by the effective internal reflection coefficient of diffuse light from the interface, R_{eff} and does not depend on the light absorption coefficient m_a, if $g \geq 0.8$ [9]:

$$z_{\max} \approx l^*(1-R_{eff})(1-0.4R_{eff}) = \frac{(1-R_{eff})(1-0.4R_{eff})}{m'_s} . \tag{1}$$

The investigated turbid media with unknown optical properties were aqueous suspensions of titanium oxide (TiO_2) particles (average radius of particles $r_0 < 1$ μm, volume concentration $N_V = 0.2 \div 1.7\%$) and milk with 3.5% fat with different concentration of Indian black ink. The anisotropy factor for these media was assumed to be $g \approx 0.8 \div 0.9$. These media can be described by certain "effective" parameters: specific heat c_p, velocity of sound V_0, the effective coefficient of thermal expansion b^* and the thermal diffusivity c, because scattering particles do not absorb laser radiation used ($l = 1.06\, mm$ for used Nd:YAG laser) and the volume concentration of particles is less than 2-3%. If the relaxation time of the thermal field in the heat-release region $t_{th} \approx 1/(m_{eff}^2 c)$ is much longer than the laser pulse duration t_L ($t_L = 12\, ns$ for used Nd:YAG laser) the diffusion of heat during the laser pulse action may be neglected. When a short laser pulse ($m_{eff} V_0 t_L << 1$) is absorbed in a medium under study, the temporal course of laser-induced ultrasonic transient - optoacoustic (OA) signal – launching to the medium can be expressed as [5,8]:

$$p(t<0) = \frac{b^* V_0^2}{2c_p} m_a E_0 H(-V_0 t) , \tag{2}$$

where E_0 - is the incident laser fluence, $[E_0]$=J/m^2; $H(z)$ - spatial distribution of laser fluence rate in an irradiated medium.

As one can see from the expression (2), the leading edge of OA transient $p(t<0)$ (see(2)) resembles the spatial distribution of the laser fluence rate $H(z)$ in a turbid medium (Fig.1). So the light absorption and reduced light scattering coefficients can be calculated from the absolute pressure profile of the leading edge of optoacoustic transient recorded with high temporal resolution [10].

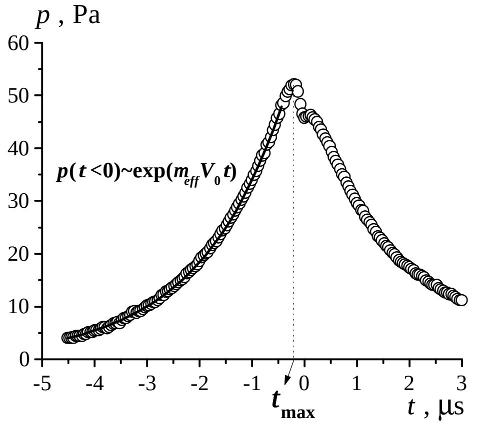

Fig.1. Temporal profile of the optoacoustic transient excited in an aqueous suspension of TiO_2 (dots - experiment, solid curve - exponential fit).

But there are the certain difficulties to use OA method to determine the optical properties of real turbid media, such as biological tissues. So, to get the absolute pressure of OA signal is practically impossible for these media, because their thermophysical properties (such as specific heat c_p and the thermal diffusivity c) are often unknown before hand. As it was mentioned above, the depth of maximum laser fluence rate location $z_{\max}$ in a turbid medium in the case of $m_a << m'_s$ is determined solely by the transport mean free path of photons l^* and by the effective internal reflection coefficient of diffuse radiation from the interface R_{eff} (see (1)). As the ratio m_a / m'_s increases the location of maximum fluence rate is assumed to move towards the turbid medium surface, since in the limit $m_a >> m_s$ all laser radiation is absorbed before to be scattered and therefore $z_{\max} = 0$ (as it takes place in uniformly absorbing and non-scattering medium). Thus the goal of our study was to obtain the dependence of maximum laser fluence rate location $z_{\max}$ ($z_{\max} = -V_0 t_{\max}$, where $t_{\max}$ is measured from temporal course of OA transient (see Fig.1), V_0 is the velocity of sound) vs. the light absorption m_a and effective light attenuation m_{eff} coefficients for turbid media. This dependence seems to be useful for determination of turbid media optical properties with the temporal profile of laser-induced OA transient solely without the measurement of absolute pressure.

To obtain the dependence of $z_{\max}$ vs. m_a and m_{eff} experimentally we added different volumes of aqueous suspension of Indian black ink particles into the fixed volume of the investigated media to vary the light absorption coefficient value. The value of the m_a of Indian black ink was known. The reduced light scattering coefficient m_s' of these media was measured with the time-resolved optoacoustic method (see [10]).

Fig.2 shows the dependence of the value $Y_1 = z_{\max} m_{eff}$ on the value $X_1 = m_a / m_{eff}$. The relative errors of determination of X_1 and Y_1 values were 3-4% è 6-7% respectively. As one can see from Fig.2, the measured values of Y_1 within inaccuracy limits can be approximated by the linear function (1) up to the value $m_a / m_{eff} \approx 0.05$. As the ratio m_a / m_{eff} increases the behavior of the dependence Y_1 changes due to the decrease of $z_{\max}$ with the growth of m_a / m_{eff} ratio. Fig.2 shows the experimental data coincide with each other within inaccuracy limits for the turbid media with different values of the reduced light scattering coefficient m_s'. It means the product $z_{\max} m_{eff}$ is the function of the m_a / m_{eff} ratio, but not of the absolute values of m_a and m_{eff}. This makes it possible to fit some single-valued function (solid curve in Fig.2) to the experimental data:

$$Y_{\text{fit}} = 0.276\left[1-\exp\left(-13.42\frac{m_a}{m_{eff}}\right)\right] \qquad (3)$$

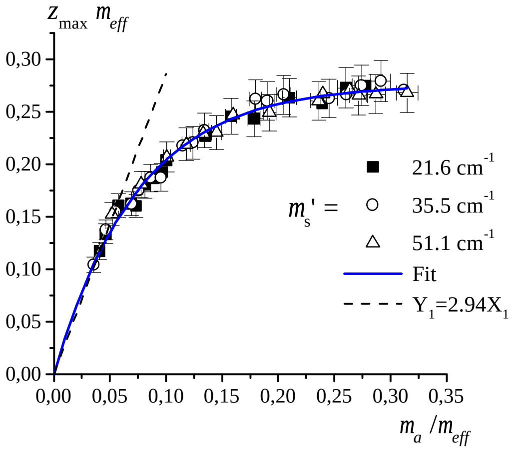

Fig.2. Dependence of the depth of maximum laser fluence rate location on the ratio of the light absorption to the effective light attenuation coefficient: dots are experimental results, solid curve is phenomenological fit (3); dashed line is the result of Monte-Carlo simulation (1).

It's necessary to note, that the values of m_{eff} and $z_{\max}$ are measured from the leading edge of OA signal $p(t<0)$ without the measurement of absolute pressure.

The function (3) can be used to determine the light absorption coefficient m_a of a turbid medium from the measured values of m_{eff} and $z_{\max}$ in the range of $m_a < 0.3m_{eff}$ (that corresponds to $m_a < 0.27m_s'$). Then the reduced light scattering coefficient m_s' can be calculated with the expression $m_s' = m_{eff}^2 / 3m_a$ in the range of such m_a / m_{eff} values, for which the light diffusion model is valid.

Thus the optical properties of uniformly absorbing and scattering turbid media can be determined from the temporal profile of laser-induced optoacoustic transients solely without the measurement of absolute acoustic pressure.

The dependence of $(z_{\max} m_{eff})$ vs. the value of m_a / m_{eff} discussed above can be obtained with Monte-Carlo simulation of the spatial distribution of the laser fluence rate in turbid media. We used the simulation data to build the dependence $Y_2 = z_{\max} m_{eff}$ vs. $X_2 = m_a / m_{eff}$ (index "2" marks the Monte-Carlo simulation of such dependence). The dependencies $Y_2\,(X_2)$ for different anisotropy factors g are shown in Fig.3. As one can see the product $z_{\max} m_{eff}$ decreases with the decrease of g at the fixed ratio of m_a / m_{eff}. When the ratio of m_a / m_{eff} is fixed, the value of $m_a / m_s' = 3(m_a / m_{eff})^2$ is fixed too.

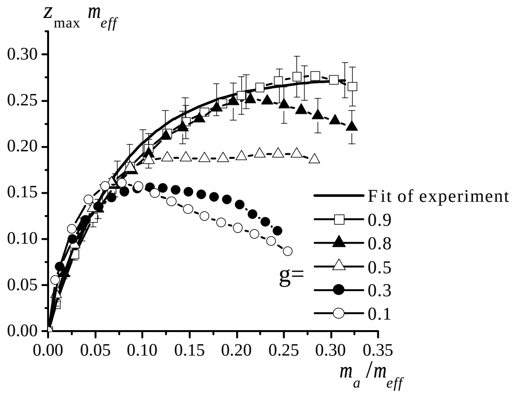

Fig.3. Comparison between the result of measurements with OA method (solid curve) and Monte-Carlo simulation (dots).

So, with the decrease of g the ratio of $m_a/m_s = m_a(1-g)/m_s'$ grows. It means the light absorption begins to predominate the light scattering and in the limit of $m_a/m_s >> 1$ the location $z_{\max} \to 0$ (as in uniformly absorbing non-scattering medium). On the other hand, the dependencies obtained numerically $Y_2(X_2)$ and experimentally $Y_1(X_1)$ coincide with each other within inaccuracy limits for the anisotropy factor values $g > 0.8$. Thus one can conclude that the dependence $Y_1(X_1)$ obtained experimentally is suitable to determine the optical properties of uniformly absorbing and scattering turbid media with the anisotropy factor $g > 0.8$. Fortunately, such values of g have most biological tissues for a wavelength $l = 1.06\, mm$, used in our experiments.

Thus it was shown both experimentally with optoacoustic method and with Monte-Carlo simulation that the product $z_{\max} m_{eff}$ is the function of the m_a/m_{eff} ratio only, but not of the absolute values of m_a and m_{eff} in the range of $m_a/m_{eff} < 0.35$, 0.8 <g < 0.9. Also the method based on time-resolved optoacoustic technique was proposed for measurements of the effective light attenuation and absorption coefficients of turbid media using both the temporal profile of laser-induced ultrasonic transient and the dependence of the product of $z_{\max} m_{eff}$ vs. the ratio of m_a/m_{eff}.

Acknowledgments

This work was partially supported by the Civilian Research and Development Foundation for the Former Soviet Union (Award # RP2-2109) and the Russian Foundation for Basic Research (Grant No. 01-02-16539).

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