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MEASUREMENT OF LASER RADIATION PARAMETERS

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Opto-acoustic measurement of the local light absorption coefficient in turbid media: 1. Monte-Carlo simulation of laser fluence distribution at the beam axis beneath the surface of a turbid medium

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***Abstract*. A new method for measuring the local light absorption coefficient in turbid media, for example, biological tissues, is proposed. The method is based on the fact that the amplitude of the excited opto-acoustic (OA) signal is proportional to the absorbed laser power density (the product of the light absorption coefficient and the laser fluence) at the medium interface. In the first part of the paper, the influence of the laser beam diameter, the light absorption and reduced scattering coefficients on the maximal amplitude of the laser fluence at the laser beam axis in the near-surface layer of the turbid medium is studied by using the Monte-Carlo simulation. The conditions are predicted under which the amplitude of the OA signal detected in a transparent medium in contact with the scattering medium should remain proportional to the light absorption coefficient of the medium under study, when the scattering coefficient in it changes more than twice. The results of the numerical simulation are used for the theoretical substantiation of the OA method being proposed.**

Keywords: *opto-acoustic diagnostics of biological tissues, light intensity, absorption coefficient, scattering coefficient, Monte-Carlo method.*

1. Introduction

Optical methods play a significant role in modern biomedical diagnostics [1, 2], where of great importance are such tomography methods as optical (see, for example, [3 – 5]) and opto-acoustic (OA) [6 – 12]. These methods are based on measuring the difference in the optical absorption and scattering in biological tissues and organs. Differences in the light absorption coefficient in a human organism are more significant than those of light scattering. However, strong light scattering reduces the efficiency of tomography methods in the *in vivo* measurement of light absorption distribution in biological tissues.

The optical properties of turbid media can be studied with these methods very conveniently and noninvasively by detecting the light backscattered from the medium [13 – 16]. Therefore, these optical measurement methods are quite widespread in biomedical studies [2, 17], the recent progress in the field of fibre optics and diode lasers making these diagnostic tools essentially inexpensive. In the last decade, significant efforts have been aimed at increasing the efficiency of these methods for *in vivo* diagnostics of optical properties of biological tissues [17 – 20]. Due to the inherent inhomogeneity of biological tissues, the measurements should be performed locally.

The methods for the local diagnostics of biological tissues with the help of fibre sources and photodetectors smaller than 600 μm in diameter were described in [18, 20]. However, the problem of acquiring local information still remains a challenge because the experimental data are fitted by the Monte-Carlo simulated dependences, which have been obtained in a semi-infinite homogeneous medium. Inhomogeneities and the layered structure of biological tissues are not usually taken into account.

The OA method of the light absorption measurement is based on the thermoelastic excitation of acoustic signals in the medium by absorption of pulsed laser radiation. The amplitude of the excited pressure pulse (OA signal) can be expressed as [21, 22]:

$$p_{\max} = \Gamma\mu_{\mathrm{a}}E_0\,\frac{I_{\max}}{I_0} = \Gamma\mu_{\mathrm{a}}E_{\max}, \qquad (1)$$

where μ_{a} is the light absorption coefficient; $\Gamma = \beta c_0^2/(2c_p)$ is the efficiency of the opto-acoustic conversion; β is the thermal expansion coefficient; c_0 is the sound velocity; c_p is the heat capacity; E_0 and I_0 are the laser fluence and the fluence rate of the incident laser beam; $E_{\max}$ and $I_{\max}$ are the maximum laser fluence and fluence rate in the medium, respectively.

When the medium is uniformly absorbing and non-scattering, the maximum laser fluence rate $I_{\max}$ inside the medium is equal to I_0. Thus, the light absorption coefficient can be determined from the amplitude of the OA signal if Γ is known.

The situation is more complex in the case of a highly scattering medium. The effect of laser fluence enhancement in the near-surface layer of a turbid medium due to strong backscattering is well known [22, 23]. Thus, the value of $I_{\max}$ can be 4 – 6 times greater than the fluence rate I_0 of the incident laser beam. The laser fluence rate amplification coefficient $k_I = I_{\max}/I_0$ depends on the diameter of the laser beam and the optical properties of the medium (light

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absorption μ_a and reduced scattering coefficients). Because the OA signal amplitude is proportional to laser fluence, it is more relevant to use the laser fluence amplification coefficient $k_E = E_{max}/E_0$. Note that $k_E \equiv k_I$ in this case, and the subscripts of these coefficients can be omitted.

The Monte-Carlo simulation is currently the only tool which allows one to calculate the spatial distribution of absorbed laser radiation in the near-surface layer of a scattering medium (at the depths much smaller than the photon transport mean free path $l_{tr} = 1/\mu_s'$). A typical in-depth distribution of the laser fluence in a turbid medium ($\mu_s' \gg \mu_a$) for a wide laser beam with a diameter $d \gg l_{tr}$ is illustrated in Fig. 1. Due to the effect of light backscattering, the maximum of the distribution is located at a depth of $z \approx l_{tr}$ beneath the medium surface, as opposed to the case of a uniformly absorbing medium, in which the maximum of the laser fluence is located at the boundary $z = 0$. In paper [22], we studied the dependence of the laser fluence maximum position z_{max} on the ratio μ_a/μ_s' of optical coefficients. The aim of this paper is to study the dependence of the laser fluence increase at the near-surface layer of a scattering medium, characterised by the coefficient k, on the laser beam diameter and the ratio z_{max} of the medium optical coefficients. The qualitative analysis of this dependence can be found in papers [23, 24]. Although the Monte-Carlo method is very widespread in the field of turbid medium optics, the quantitative data are, to our knowledge, absent in the literature.

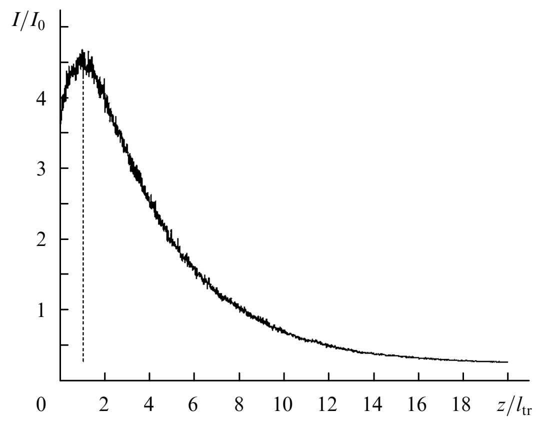

Figure 1. Typical profile of the laser fluence in-depth distribution in a turbid medium in the case when the laser beam diameter is much longer than the photon transport mean free path in the medium. The coordinate $z = 0$ corresponds to the interface between the transparent and turbid media.

2. Method

The Monte-Carlo simulation software package developed in [25] was used to calculate the spatial distribution of the laser fluence in the media under study. This software was also employed earlier [22, 26] and the simulation results were in a good agreement with the experimental data. The input parameters in the simulations were the light absorption μ_a and scattering μ_s coefficients, the anisotropy factor $g = \langle\cos\theta\rangle$ (the average value of the cosine angle θ of a singly scattered photon). The software package also made it possible to vary the laser beam diameter d at the input to the medium. The refractive index of the transparent medium $n_1 = 1.45$ was fixed and corresponded to that of PMMA. Because we studied experimentally the water solutions with small concentrations of scatterers, the refractive index of the turbid media was assumed equal to that of water ($n_2 = 1.33$). The turbid medium was treated as semi-infinite and homogeneous. The number of photons used in each simulation was 10^5. The directivity pattern of a single photon scattering act was taken into account by the Henyey–Greenstein phase function. The cross section profile of the laser beam was assumed Gaussian.

3. Simulation results

The laser fluence in-depth distributions in the media under study were simulated for different values of d and μ_a/μ_s'. A typical profile of such a distribution is shown in Fig. 1. We plotted further dependences by using the maximum values of each of the distribution.

Figure 2 presents a set of dependences of the laser fluence amplification coefficient $k = E_{max}/E_0$ on the ratio μ_a/μ_s' of the optical coefficients for different diameters d of the laser beam. Each individual curve corresponds to a fixed value of the reduced scattering coefficient μ_s (11, 17, and 24 cm^{-1}). Because the media with different reduced scattering coefficients should be equivalent from the standpoint of irradiation conditions, the laser beam diameter d was normalised to the photon transport mean free path $l_{tr} = 1/\mu_s'$. The normalised laser beam diameter d/l_{tr} was the same for the curves corresponding to a single plot (i.e., a, b, c, and d), but was varied in the range 0.5–50 from plot to plot.

If the laser beam is wide ($d/l_{tr} = 50$), the wavefront of the incident laser field can be considered plane, and the light diffusion in the turbid medium can be described in terms of a one-dimensional model along the beam axis. One can see from Fig. 2a that the amplification of the laser fluence beneath the surface of the turbid medium reaches its maximum under the following two conditions: the laser beam is wide and $\mu_a/\mu_s' \ll 1$. However, even if the laser beam is wide, the coefficient k decreases with increasing the ratio μ_a/μ_s'.

In another limiting case of a narrow laser beam, the maximum of the laser fluence distribution is close to the incident fluence. For example, in the case of $d/l_{tr} = 0.5$ (Fig. 2d), the coefficient $k \approx 1.2$ and remains almost constant as the ratio μ_a/μ_s' changes more than ten times. It can be explained by the fact that light diffusion cannot be described in terms of the one-dimensional model any longer. Laser radiation is diffused in all the directions with almost the same efficiency, providing a considerable light attenuation at depths smaller than l_{tr} and the absence of appreciable amplification of the laser fluence in the near-surface region of the turbid medium.

One can also see from the dependences in Fig. 2 that the curves corresponding to different values of the reduced light scattering coefficients μ_s coincide well within the wide range of μ_a/μ_s' at fixed values of the normalised laser beam diameter d/l_{tr}. This, in turn, means that the maximum laser fluence inside a turbid medium can be unambiguously determined by the two ratios d/l_{tr} and μ_a/μ_s' independently of the absolute values of these coefficients.

Figure 3 demonstrates the dependence of the laser fluence amplification coefficient k on the normalised laser

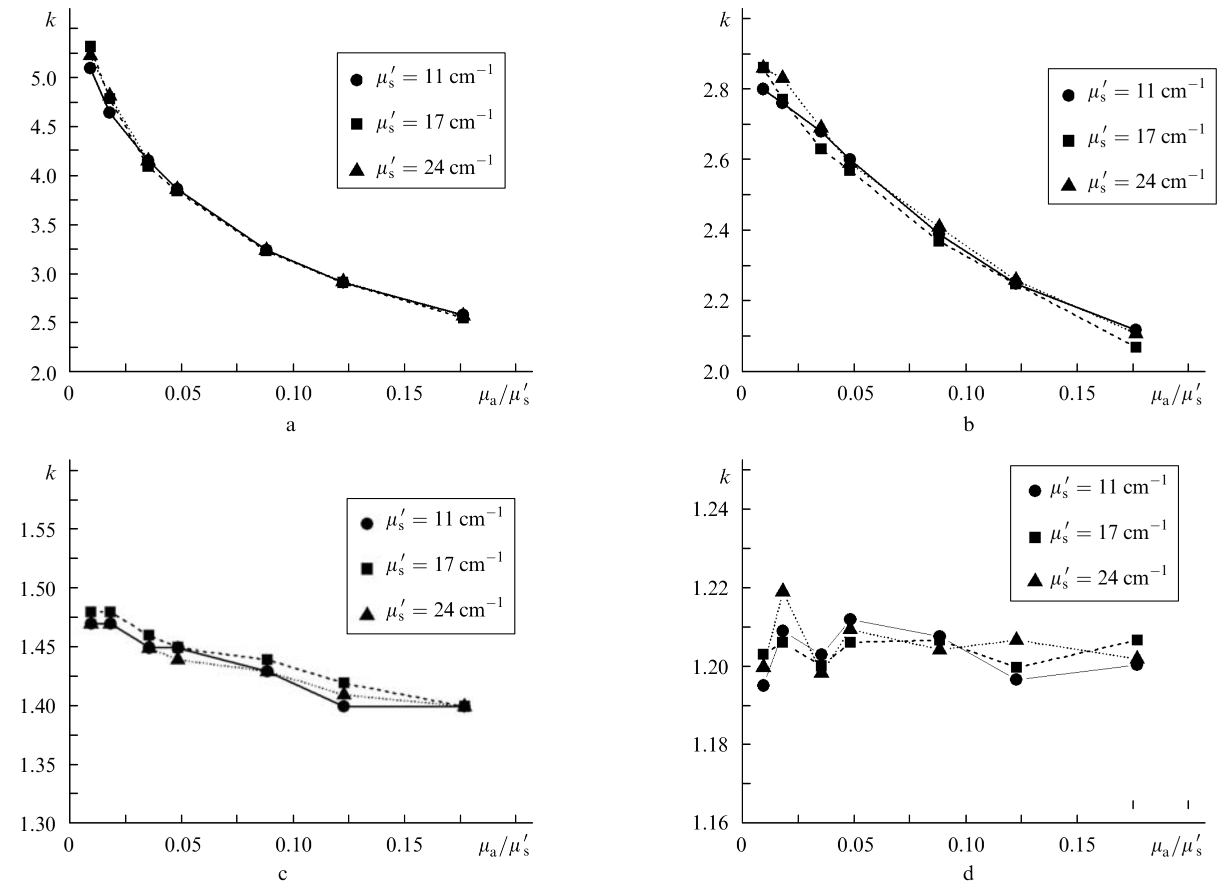

Figure 2. Dependences of the laser fluence amplification coefficient k in the near-surface layer of a turbid medium on the ratio μ_a/μ_s' for different values of laser beam diameter normalised to the photon transport mean free path: $d/l_{tr} = 50$ (a), 5 (b), 1 (c), and 0.5 (d).

beam d/l_{tr} at different values of the ratio μ_a/μ_s'. As is expected, the maximum laser fluence in the turbid medium increases with increasing d/l_{tr} and reaches the limit at $d/l_{tr} \gg 1$, where the one-dimensional light diffusion is realised. The laser fluence amplification coefficient also depends on the ratio μ_a/μ_s'. In the case of $\mu_a/\mu_s' \ll 1$, it reaches the absolute maximum $k_{max} \approx 5-6$ and decreases when the relative contribution of absorption increases. Finally, when $\mu_a/\mu_s' \gtrsim 1$, the laser fluence amplification coefficient is $k \to 1$ because the medium is not strongly scattering any longer. The maximum value of the laser fluence is located at the medium surface.

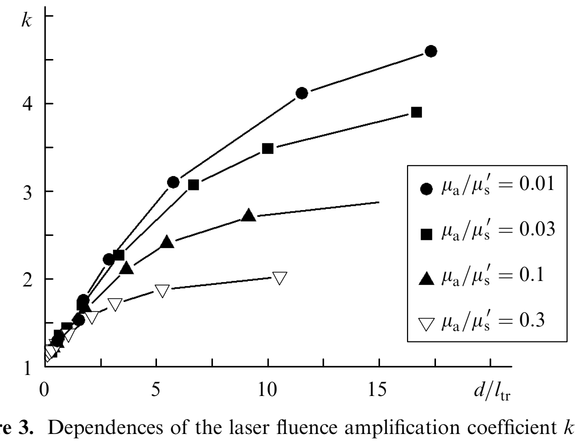

Figure 3. Dependences of the laser fluence amplification coefficient k in the near-surface layer of a turbid medium on the laser beam diameter d normalised to the photon transport mean free path l_{tr} for different ratios μ_a/μ_s'.

Note another important feature in the behaviour of the curves in Fig. 3. When the beam diameter is in the order of the photon transport mean free path $d/l_{tr} \lesssim 1$, the curves corresponding to different values of μ_a/μ_s' coincide within a 10 % error at $0.01 < \mu_a/\mu_s' < 0.3$, while the coefficient k linearly increases as a function of the normalised beam diameter. This can be explained by the fact that in the case of a narrow laser beam, the light diffusion across the beam affects the in-depth light attenuation more than the light absorption.

The dependences of the maximum absorbed laser power density $\mu_a E_{max}$ on the light absorption coefficient μ_a at different laser beam diameters is shown in Fig. 4. For definiteness, the fluence of the incident laser beam is $E_0 = 1$ mJ cm^{-2} for all the plots. Similarly to Fig. 2, each individual curve is plotted for a fixed value of μ_s (11, 17, and 24 cm^{-1}), the laser beam diameter d varying from plot to plot. The presented dependences are important because according to (1), the amplitude of the OA signal excited in the medium is proportional to $\mu_a E_{max}$. Thus, the curves represented in Fig. 4 also describe the dependences of the excited OA signal amplitude on the light absorption coefficient μ_a.

The function $\mu_a E_{max}(\mu_a)$ is nonlinear (see Fig. 4a) for all three values of μ_s' when $d/l_{tr} \gg 1$. This is explained by the fact that the laser fluence amplification coefficient k below the scattering medium surface decreases with increasing the light absorption coefficient μ_a (see Fig. 2).

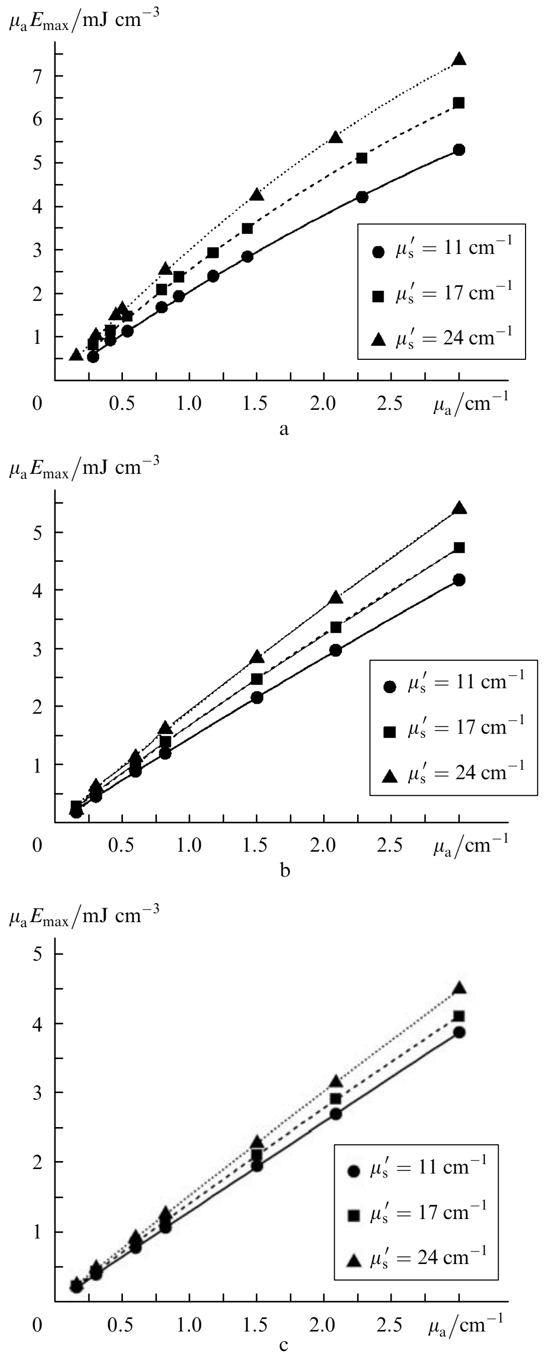

Figure 4. Dependence of the maximum laser energy density absorbed in a turbid medium on the light absorption coefficient for the different values of the laser beam diameter: $d = 3$ (a), 1 (b), and 0.5 mm (c).

When the laser beam diameter is decreased down to $d/l_{tr} \sim 1$ (Fig. 4b), the diffusion of light across the laser beam affects the in-depth distribution of the laser fluence, leading to a decrease in the coefficient k. Nevertheless, the near-surface amplification of the laser fluence is still present, and the curves corresponding to different values of μ_s do not coincide.

In the limiting case $d/l_{tr} \ll 1$, the dependences corresponding to different values of μ_s should coincide. For example, at $d = 0.5$ mm, the difference between the slopes of the curves does not exceed 8 % and the laser fluence amplification, in this case, is in the order of 25 %.

4. Discussion and conclusions

Let us analyse the obtained results from the standpoint of their use in the OA method measuring the light absorption coefficient in turbid media.

If the laser beam is wide, the maximum absorbed laser energy density $\mu_a E_{max}$, which is proportional to the OA signal amplitude, depends both on the light absorption and scattering coefficients. Therefore, the amplitude of the OA signal cannot be used for measuring the light absorption in turbid media. On the other hand, Fig. 2d clearly shows that if the laser beam is narrow ($d/l_{tr} \ll 1$), the maximum laser fluence inside the medium differs less than by 25 % from that of the incident laser beam. In this case, the three-dimensional light diffusion regime is realised and the maximum of the laser fluence distribution is located at the surface of the medium, as in the case of a uniformly absorbing, nonscattering medium.

One can see from Fig. 3 that at $d/l_{tr} \lesssim 1.5$, the dependences of the laser fluence amplification coefficient on the normalised laser beam diameter coincide within a 10 % error for the ratios $0.01 < \mu_a/\mu_s' < 0.3$ under study. If the laser beam is narrow, the maximum absorbed laser energy density increases linearly with increasing the light absorption coefficient (Fig. 4c) and the slopes of the curves differ no more than by 8 % in the case of the two fold increase in the reduced light scattering coefficient μ_s.

Thus, the numerical simulation performed in this work clearly demonstrates that the maximum laser fluence in an arbitrary turbid medium is unambiguously determined by two ratios d/l_{tr} and μ_a/μ_s'. Within the range of the optical properties typical of biological tissues in the visible and near-IR regions, it is possible to choose the laser beam diameter so that the maximum absorbed laser energy density, which is proportional to the OA signal amplitude [21, 22], be linearly dependent on the light absorption coefficient and independent of the light scattering coefficient. This conclusion is of practical importance in the problem of OA diagnostics of biological tissues. Because the amplitude of the excited OA pulse is proportional to the density of the light energy absorbed in the medium [21, 22], it allows one to develop the OA method for the direct *in vivo* measurements of the light absorption coefficient in turbid media, especially in biological tissues, when the efficiency of the OA conversion Γ is known. The substantiation of this method is presented in the second part of this paper.

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