

Correlation properties of multiple scattered light: implication to coherent diagnostics of burned skin

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Abstract. Modeling of skin burns has been performed in this study. Autocorrelation functions of intensity fluctuations of scattered light were measured for two-layered turbid media. The first layer served as a model for motionless scatterers (optically inhomogeneous gel film) whereas the second one simulated dynamic light scattering (Brownian motion of intralipid particles in aqueous suspension). This medium was used as a model of skin burns. A theory related quasi-elastic light scattering measurements to cutaneous blood flow was used. The dependencies of statistical properties of Doppler signal on the properties of burned skin as well as on the velocity of cutaneous blood flow have been investigated. Theoretical predictions have been verified by measurements both of dynamic and stationary light scattering in model media. © 2004 Society of Photo-Optical Instrumentation Engineers.
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1 Introduction

Blood microcirculation is disturbed or cutaneous blood flow surceases completely in burned skin. The problem of precise determination of the depth of dermal burns is very important for clinical medicine. For deep burns, the presence of cutaneous blood microcirculation could be defined by mechanical inspection of wounds with the help of a thin metal needle. The appearance of blood at the puncture point within a burned skin area is assumed to be an evidence of remained cutaneous blood microcirculation in that burned layer. For the treatment of soft dermal burns, it is necessary to define the wound depth for the further removal of a burned layer. For these purposes, more accurate methods measuring the burn depth are needed instead of the needle probing procedure. For evaluation of the intensity of cutaneous blood flow, the thermal visors are often used. However, their applicability is less effective, as a rule. Thus, the development of coherent optical methods for burned skin diagnostics is the issue of a great importance.

Laser methods of medical diagnostics involve first, laser Doppler^{1,2} and laser speckle contrast analysis (LASCA) techniques,³ speckle interferometry,⁴ diffusing wave spectroscopy,⁵ analysis of processes of multiple scattering of light in turbid random media⁶ and blood flow diagnostics using Monte Carlo methods.⁷ Optical Doppler tomography is also very promising demanding in terms of diagnostics of blood microcirculation.^{8–10} Although theoretical background used in these methods is based on various approaches, the measuring procedure is similar for the variety of existing methods from the viewpoint of experimental technique. At diffraction of coherent light from the moving inhomogeneities within scattering media, temporal fluctuations of scattered

light intensity are observed. As the velocity of moving scatterers grows, a spectral bandwidth of intensity fluctuations is broadened.

The methods of burned skin diagnostics are described in detail in Ref. 11. It should be pointed out that the parameters of measured signal might be influenced, in addition to the velocity of scatterers, by the optical properties of turbid media as well as by the presence of motionless scatterers in that media.^{12,13} Thus, the problem of influence of various factors (including the depth of burned skin layers, tissue structure, tissue scattering and absorption coefficients, etc.) on the spectral bandwidth should be studied in more detail. It should be noted that the optical properties of damaged tissue are not known *a-priori*, they can vary widely and are defined, for the most part, by the type of burn (i.e., steam burn, burn caused by open fire, or plasma burn). By now, extensive investigations devoted to experimental modeling of light scattering in burned skin have not been carried out. The goal of this paper is to partially fill this gap.

2 Theoretical Background

To describe dynamic light scattering in model media, we will follow the results of Bonner and co-authors.^{1,2} We assume that the tissue matrix is stationary (since it has only motionless scatterers). Thus, the Doppler shifts in the frequency of scattered light arise only due to light scattering on moving blood cells. The formula for correlation function of temporal intensity fluctuations of light scattered by moving particles has been obtained in^{1,2}

$$g^{(2)}(\tau) = \frac{\langle i_{sc}(t)i_{sc}(t+\tau) \rangle}{\langle i_{sc} \rangle^2} = 1 + \beta [C_E(\tau)]^2, \quad (1a)$$

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where $i_{sc}(t)$ is a scattered intensity, β is an instrumental constant and $C_E(\tau)$ is a temporal autocorrelation function of the complex amplitude E_{sc} of scattered field

$$C_E(\tau) = \langle E_{sc} \cdot E_{sc}^* \rangle. \quad (1b)$$

As has been shown in Refs. 14 and 15

$$C_E(\tau) = P_o I_o(\tau) + \sum_{n=1}^{\infty} P_n I_n(\tau). \quad (2)$$

In the last equation, P_n is the probability that the photon reaching the detector has undergone a certain number of scattering events, N_{sc} , by the moving blood cells. I_n component describes the contribution of every photon into correlation function. Taking into account that directions of photon scattering do not correlate with the velocities of moving scatterers, Eq. (1a) for correlation function of scattered intensity may be simplified essentially¹

$$g^{(2)}(\tau) = 1 + \beta [P_o + (1 - P_o) \cdot I(\tau)]^2, \quad (3)$$

where

$$I(\tau) = [e^{-N_{sc}[1 - I_1(\tau)]} - e^{-N_{sc}}] / [1 - e^{-N_{sc}}]. \quad (4)$$

N_{sc} is the average number of photon collisions due to the moving red blood cells, P_o is the probability that a detected photon has not been scattered from moving particles, and $I_1(\tau)$ is expressed as

$$I_1(\tau) \sim 1 / [1 + \text{const} \cdot \tau^2]. \quad (5)$$

In the last expression, const is some dimensionless constant that depends both on average velocity of scatterers (that is determined both by temperature and hydrodynamic properties of media containing moving particles), size and shape of scattering particles and their velocity distribution. In general case, no explicit expression exists for const.

Let us consider the simplified case of multiple scattering in suspension of moving particles (no motionless scatterers exist within the medium). As it is known, light scattering is determined by a transport mean free path of a photon $\ell^* = (\mu_a + \mu'_s)^{-1}$ in the absorbing and scattering medium. Furthermore, we consider scattering media with the thickness that is large compared to ℓ^* . Since a scattered signal is observed in backscattering geometry, the probability that a photon has not been scattered, at least once, by a moving particle, equals zero

$$P_o \equiv 0. \quad (6)$$

Of course, it does not mean that there is no portion of photons with unshifted frequencies in the scattered light. The total frequency shift of some photons may be equal to zero in the case when the Doppler shifts (that are acquired by a photon as a result of scattering from different moving particles) compensate each other. In this case, it is appropriate to express $g^{(2)}(\tau)$ as

$$g^{(2)}(\tau) = 1 + \beta [I(\tau)]^2. \quad (7)$$

Let us define the normalized autocorrelation function of intensity fluctuation of scattered light as the following:

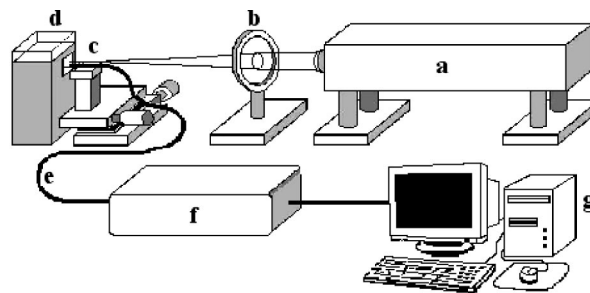


Fig. 1 The scheme of experimental setup. (a) Nd-YAG laser; (b): lens; (c): holder; (d): cuvette with scattering suspension; (e): optical fiber; (f): computer-aided correlator supplied by PMT; (g): computer.

$$C_I(\tau) = \frac{g^{(2)}(\tau) - g^{(2)}(\infty)}{g^{(2)}(0) - g^{(2)}(\infty)}. \quad (8)$$

After some algebra, using Eqs. (4), (5) and (7), the last expression can be rewritten as

$$C_I(\tau) = [I(\tau)]^2, \quad (9)$$

where $I(\tau)$ again is defined by Eqs. (4) and (5).

Equation (9) is the most important theoretical result of this paper. It allows us to describe correlation properties of intensity fluctuations and to account properly for effects of multiple scattering.

3 Experimental Technique

3.1 Experimental Setup

Experimental setup used in this study is presented in Fig. 1. It consists of argon ion laser (wavelength is 532 nm, a beam diameter is 1 mm, maximal laser power is 5 W), an attenuator, lens (focal distance is 250 mm), a cuvette with the sample, an optical detecting fiber maintained on a two-coordinate holder, photomultiplier tubes (PMT) and IBM PC/AT supplied with the digital correlator (model BI-9000AT, Brookhaven Instruments Corporation). Skin phantoms (thin agar slabs with different μ'_s and μ_a) were placed on the thermostabilizing stage at $t = 37^\circ\text{C}$ at the front edge of a cuvette filled with intralipid. The Brownian movement of intralipid particles simulated blood flow in dermal and hypodermal skin layers. Laser beam was focused onto a sample. Intensity fluctuations of scattered light formed inside the sample were detected with the help of the optical fiber at various source-detector separation distances laying basically within the range of 1–35 mm]. The amplified signal from PMT was sent to and processed by the computer-aided digital correlator. Autocorrelation functions of temporal fluctuations of scattered intensity were measured and their decay time was defined.

3.2 Sample Preparation

Data for reduced scattering coefficient of human skin published in literature essentially vary and may archive the values of 30–40 cm^{-1} . In preparation of the phantoms we choose the reduced scattering coefficient about $\mu'_s = 10 \text{ cm}^{-1}$ which is habitual for skin on leg.¹⁶ Titanium dioxide (TiO_2) was added to de-ionized water assuming that the TiO_2 aqueous suspension with concentration of 0.7 g/l has the required

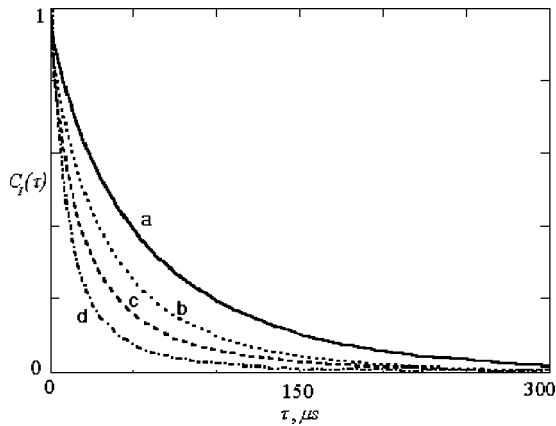


Fig. 2 Normalized correlation function of temporal intensity fluctuations, obtained for pure intralipid ($\mu_a=0\text{ cm}^{-1}$, $\mu'_s=10\text{ cm}^{-1}$) at various source-detector separations. Curve a: source-detector separation, $\Delta=2\text{ mm}$; curve b: $\Delta=3\text{ mm}$; curve c: $\Delta=6\text{ mm}$; curve d: $\Delta=9\text{ mm}$.

value of reduced scattering coefficient, i.e., $\mu'_s=10\text{ cm}^{-1}$. Further, agar with the 1% mass concentration was dissolved in the suspension. For experiments with burned skin phantoms, the India ink was added to the suspension. The 0.05% India ink suspension is assumed to have the value of absorption coefficient, $\mu_a=3.5\text{ cm}^{-1}$. The suspension was stirred by a magnetic mixer, sonicated for 15 min and boiled up to 1 min. Then, the samples of different thickness were prepared. Glass flat spacers with the thickness of 0.17 mm were used during preparation of a sample of desired thickness. The 1% intralipid aqueous solution ($\mu'_s=10\text{ cm}^{-1}$) simulated cutaneous blood microcirculation.

4 Experiments with Phantoms of Burned Skin

4.1 One-Layered Scattering Medium

Let us consider the diffraction of laser radiation in aqueous suspension of intralipid (a medium has no motionless scatterers). Light absorption in this medium is supposed to be neglected. According to experimental results, the shape of cor-

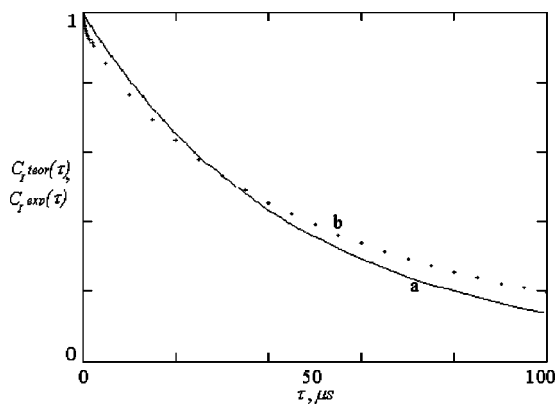


Fig. 3 Comparison of theoretical normalized correlation function $Cl_{\text{theor}}(\tau)$ of intensity fluctuations (curve a) with the same correlation function $Cl_{\text{exp}}(\tau)$, obtained in the experiment for pure intralipid (curve b).

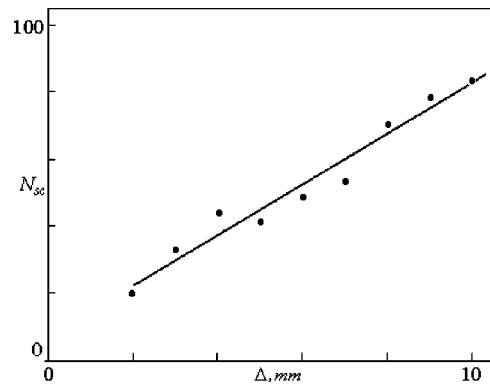


Fig. 4 Dependence of a number of scattering events, N_{sc} on source-detector separation, Δ obtained for pure intralipid ($\mu_a=0\text{ cm}^{-1}$, $\mu'_s=10\text{ cm}^{-1}$).

relation function of intensity fluctuations of scattered light is close to the exponential function (Fig. 2). The shape of a theoretical correlation function depends on the two parameters [see Eqs. (3)–(5)], namely, on const and a mean number of scatterers, N_{sc} which, in turn, can be roughly estimated from the formula

$$N_{sc} = \Delta / \ell^* = \Delta \mu'_s, \tag{10}$$

where Δ is a distance between the centers of the incident laser beam and the detector, called a “source-detector separation,” ℓ^* is a transport mean free path, $\mu'_s = 1/\ell^* = \mu_s(1-g)$ is a reduced scattering coefficient, μ_s is a scattering coefficient, g is a mean cosine of scattering angle.⁵ As was mentioned above, const is determined entirely by characteristics of dynamic medium, namely, by the velocities of moving particles and their scattering properties.

Let us perform a fitting procedure of a theoretical expression for correlation function to its experimentally obtained curve, using these two parameters. As a criterion for the best fitting, we use a minimal value of standard deviation of theoretically calculated values from experimentally measured quantities. The calculations showed that the best correspondence of experimental data with theoretical curve of normalized correlation function might be achieved at $\text{const}=9.737$

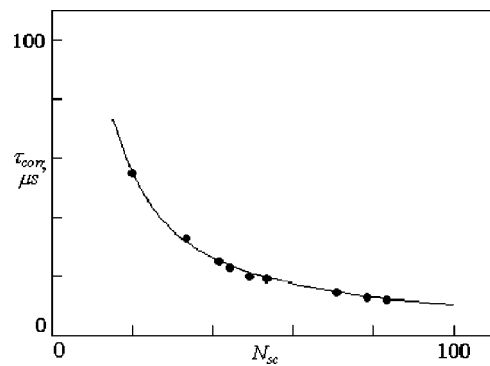


Fig. 5 Dependencies of decay time, τ_{corr} of experimental normalized correlation function of intensity fluctuations on the number of scattering events, N_{sc} . Data obtained for intralipid aqueous suspension ($\mu_a=0\text{ cm}^{-1}$, $\mu'_s=10\text{ cm}^{-1}$).

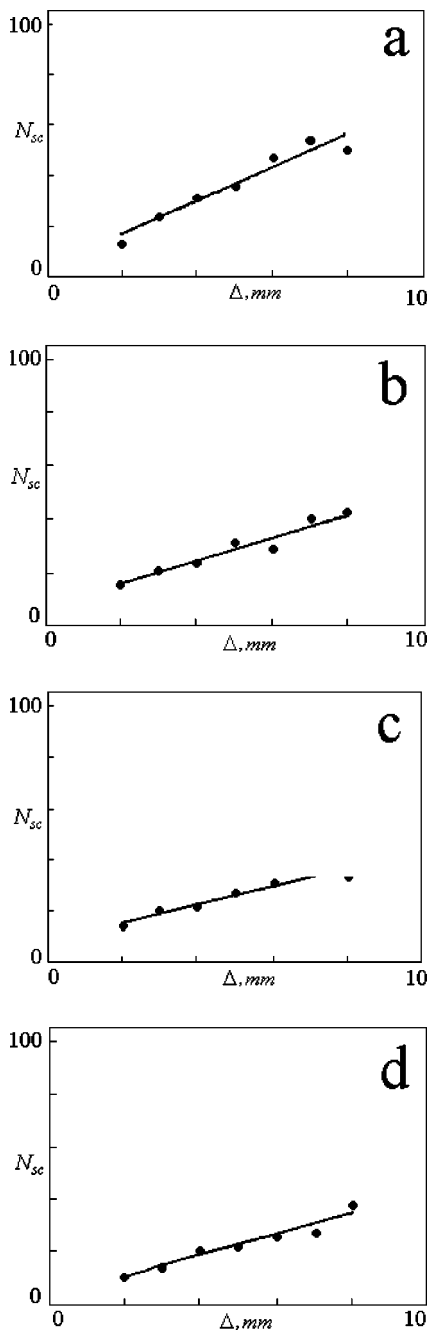


Fig. 6 Dependencies of a number of scattering events, N_{sc} on source-detector separation, Δ . The case of nonabsorbing media. Dots: number of scatterers formally calculated from experimental correlation function using Eqs. (4), (5) and (9). Solid line: results of linear interpolation. (a): $H=0.5$ mm; (b): $H=1.5$ mm; (c): $H=2.0$ mm; (d): $H=2.5$ mm.

$\times 10^{-4}$ (Fig. 3). In this case, the error of fitting is less than 3%. Equations (4), (5) and (9) allow us to define the average number of scatterers from experimentally obtained normalized correlation function of intensity fluctuations.

Experimental study has shown that the dependence of a number of scatterers, N_{sc} as a function of source-detector separation is in a good agreement with theoretical estimations [see Eq. (10)] as well. This dependence is close enough to

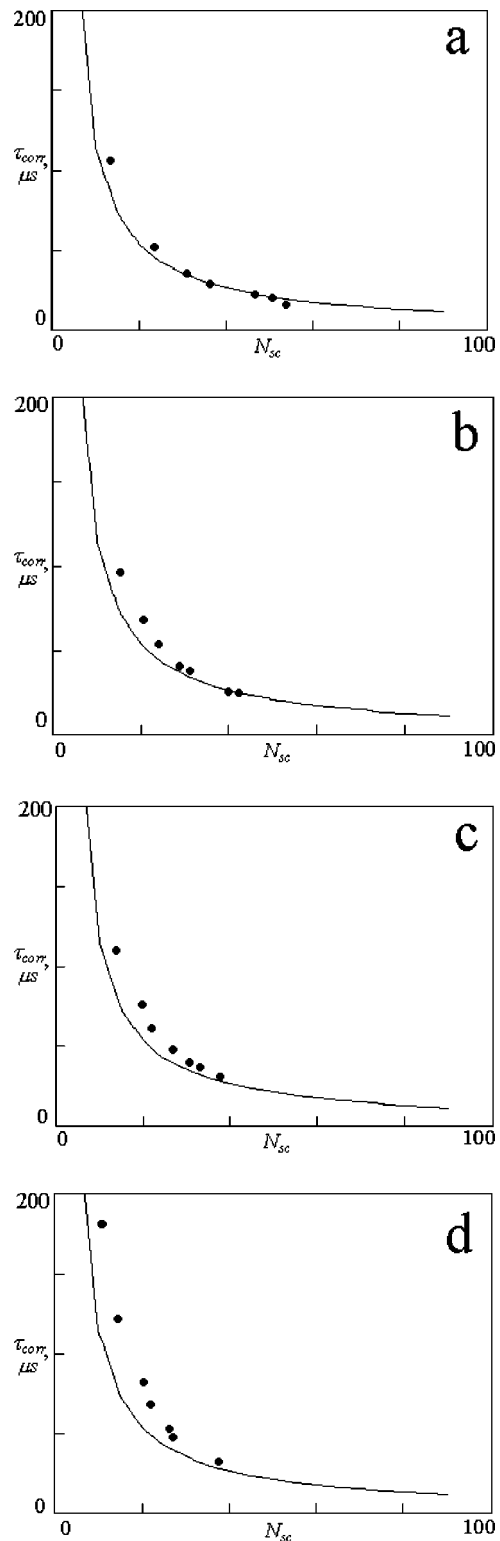


Fig. 7 Dependence of decay time, τ_{corr} , of correlation function of scattered intensity fluctuations on a number of scattering events, N_{sc} . Data obtained for gel with thickness, H , of 0.5 mm (a), 1.5 mm (b), 2 mm (c), and 2.5 mm (d).

linear (Fig. 4). This is supported by the fact that the value of cross-correlation coefficient is close to unity ($K=0.979$), whereas the value of a Durbin–Watson criterion described

elsewhere in Ref. 17 is close enough to 2. Thus, the hypothesis of linear dependence of a number of scattering events on source-detector separation should be accepted for the case of light scattering in intralipid suspensions (with no motionless scatterers).

Dependence of decay time of ACF of intensity fluctuations on the number of scattering events is presented in Fig. 5. Correlation time (dots) was calculated from experimentally measured correlation functions. Theoretical curve (solid line) was derived from Eqs. (4), (5) and (9); N_{sc} was estimated using Eq. (10). Clearly, theoretical estimations are in a good agreement with the experimental data. Standard deviation of experimental data from theoretical values is less than 1%. Thus, the approach proposed in Refs. 1 and 2 might be applied effectively for the quantitative description of coherent light transport in highly scattering dynamic media.

4.2 Two-Layered Scattering Medium

In the present study, the applicability of the theoretical approach described was verified for the case of light scattering in a two-layered medium simulated with the 1% aqueous solution of intralipid, that resembles moving scatterers, and gel films containing TiO_2 particles immersed into agar, that was used as a model for motionless scatterers. Aqueous suspension of intralipid and gel had the same scattering properties, namely, $\mu_a = 0$ and $\mu'_s = 10 \text{ cm}^{-1}$. The thickness H of a scattering gel film varied within the range of 0.5–2.5 mm. Dependence of a number of scattering events, N_{sc} on source-detector separation, Δ for various thickness H of a gel film is presented in Fig. 6. As can be seen, theoretical dependence predicted is close to a linear function at all values of N_{sc} . Furthermore, the slope of experimental curves decreased with the increase of the thickness of agar film simulating a motionless layer. This phenomenon might be described in terms of light transport through the turbid media. The volume concentration of TiO_2 in gel was chosen in certain way that the scattering properties of agar film were equivalent to the ones of intralipid aqueous solution. So, the value of optical scattering coefficient remained constant ($\mu'_s = 10 \text{ cm}^{-1}$) whereas optical absorption, μ_a , was assumed to be zero. In this case, motionless scatterers extruded the moving scattering particles out of the perfused volume, leading to the reduction of a number of scattering events. This resulted in the narrowing of a Doppler spectral bandwidth. Thus, decay time of ACF of intensity fluctuations grew with the thickness of steady medium. It should be noted that a theoretically evaluated number of scattering events is linearly proportional to source-detector separation, Δ .

The curve of the dependence of decay time on a number of scattering events drops monotonously that is in a good agreement with Eqs. (4), (5), and (9) (see Fig. 7). Standard deviation of experimental data from theoretical values is calculated to be less than 5% in this case.

5 Conclusions

The dependence of the value of Doppler broadening of scattered light on the scattering properties of inhomogeneous media has been analyzed. It has been found that the deviation of experimental data from theoretical values is less than 3% for purely scattering media with no absorption. The applicability

of a theoretical model developed by Bonner and Nossal for the study of multiple optical scattering in dynamic media is demonstrated.

It has been shown theoretically and experimentally that decay time of intensity fluctuations of scattered field reduced monotonously with the decrease of a number of scattering events in a medium. It has been deduced also that the motionless scatterers (that were used as a model of burned skin) may essentially influence the Doppler spectral bandwidth.

There is a very simple physical explanation for this phenomenon. Static layer extrudes moving particles from the probing volume. Of course, motionless scatterers do not produce additional Doppler shift in the scattered light, but they affect the number of dynamic scatterers participating in the process of formation of Doppler signal. As the thickness of the burned layer of the skin is larger, the number of moving erythrocytes in the investigated volume is smaller; as a result, the spectrum of scattered intensity fluctuations becomes narrower.

In perspectives, the results of experimental study, which are presented in this paper, might be used as a basis for blood microcirculation diagnostics as well as for estimation of the depth of burned skin *in vivo*. The number of dynamic scatterers in the probing volume (at fixed value of source-detector separation) can be easily measured on the nonburned part of the skin of the patient. Comparison of this value with the number of scatterers obtained with the analogous burned part of the skin allows one to judge the thickness of the layer with motionless scatterers, i.e., the depth of burn.

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