SPECKLE PATTERN OF RADIATION SCATTERED OF SOFT BIOLOGICAL TISSUES. LIGHT FIELDS OUTSIDE TISSUE

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1. INTRODUCTION

The speckle structure of scattered light is currently used in both scientific and practical purposes for determining various characteristics of biological tissues, e.g. tissue particle sizes and blood flow rate, for diagnosing different kinds of pathologies and monitoring therapy efficiencies. However the developed techniques are constructed, generally empirically and are based on experimental data without quantitative theoretical justification. This results in incomplete use of diagnostic and other features inherent in the original speckle pattern of scattered light. So urgent is the construction of a theoretical framework of formation of interference field parameters based on radiative transfer theory and its relation to the coherence theory.

The aim of this work is to study the speckle pattern of the light field, multiply scattered soft biological tissues, and assessment of the light field outside tissue.

2. CALCULATION PROCEDURE

An analytical method of calculating the characteristics of the interference pattern formed by the repeatedly scattered light inside the multi-layer biological tissue as human skin kind at wavelengths of visible and near IR spectral ranges at laser irradiation, is described in [1,2].

The calculations assumed that the scattering particles are immobile. The simulation used a well-known analytical solutions of radiative transfer theory [3] in the presentation of the scattering function as a sum of functions having substantially different angular scales [4], for the separation of the total radiation in the coherent E_c and incoherent background E_{nc}. Calculated [5] absorption and extinction coefficients μ_{aj} and μ_{ej} as well as phase functions or a number of their integral parameters [6]. Completed research in this paper are based, in addition, the optical model of skin tissue [4, 7-9]. Examined the tissue, consisting of three macroscopically homogeneous layers: the stratum corneum, the epidermis and dermis.

The input parameters for the calculation are the wavelength λ of the laser, as well as structural and biophysical characteristics of the layers of the skin - the geometric thickness d_0 and d_1 (index j= 0, 1 and 2 denote respectively stratum corneum, epidermis and dermis), the volume concentration and blood capillaries in the dermis C_b and melanin in the epidermis C_m, the degree of oxygenation of the blood S (the ratio of the concentration of oxyhemoglobin to total hemoglobin). Dermis assumed semi-infinite (in optical terms) layer. The coefficients $\mu_{a1,2}$ can be varied by changing a wavelength of the illuminating beam, so of volume of concentrations of absorbers - respectively melanin and hemoglobin derivatives. Thus, the biological tissue model provides a direct connection between the optical determining the characteristics of the light field in the tissue and biophysical parameters

To go to the observation of the speckle pattern on the upper boundary of the surrounding (on the skin), we use the results of [3]. Here is shown that the image generated by the coherent light within the surrounding at depths $z \div z + dz$, is transferred as follows into the plane $z = 0$

$$\mathrm{d}W_j^*(z,r) = \sum_{\mathrm{i}=0}^{2} E_{i,j}(2z)\left\{1+\cos\left[\left[\frac{\pi r}{r_{i,j}(2z)}\right]+\varphi\right]\right\}\mathrm{dA}_{i,j}(z) \quad (2)$$

where r - the coordinate measured in the direction normal to z, $r_{i,j}$ - the characteristic size of the speckles, φ - random phase, $dA_{i,\mathrm{j}}$ - albedo elementary layer dz tissue. In (1) the value $j = 0$, 1 and 2 correspond to the stratum corneum, the epidermis and dermis, and $i = 0$, 1 and 2 - the direct light, a diffraction and diffusion components [1,2]. Albedo $dA_{i,\mathrm{j}}$ contains the index i, that shows in the general case albedo values may depend on the structure of the angular intensity $I_{i,\mathrm{j}}$ component. Let's mark that the representation (1) of the image speckles on the surface corresponds to the calculation of illuminance $E_{i,j}$ in the "effective" surrounding with double geometric thicknesses and coefficient also doubled the scattering and absorption of each layer [3].We write in the explicit expression for $dA_{i,j}$, assuming

that the scattering angle range $\pi/2 \div \pi$ angular directional indicator scattering structure is weak illustrated and can be replaced by $2(1 - F_j)\mu_{sj}(z)$:

$$dA_{i,j}(z) = \mu_{sj}(z)(1 - F_j)dz \int_0^{\pi/2} I_{i,j}(z,\theta)\sin\theta\, d\theta \quad (1)$$

where F_j - the share light scattered in the direction of "*forward*", and $\mu_{sj}(z)$ - an integral component of the scattering in the corresponding layer of the skin.

To find an image of speckles formed by the entire thickness of the biological tissue, it must be integrated (1) with respect to z, taking into account (2) and add background W_{nc}, incoherent light generated at the surface of the skin:

$$W(r) = \int_0^{\infty} dW_j^*(z,r) + W_{nc} = \sum_{j=0}^{2} W_j(r) + W_{nc} \quad (3)$$

The formulas for calculating the W_{nc} are given in [4, 5, 11]. Note that to calculate W_{nc} as described in [4, 5, 11] you need to be in "*good*" tissue for the incoherent background, optical properties which are different from the tissue introduced above for coherent light [10]. Below W values normalized to the power density of light incident on the surface. The provisions of the plots on the horizontal axis of the accident because of the random nature of the phase φ in (1).

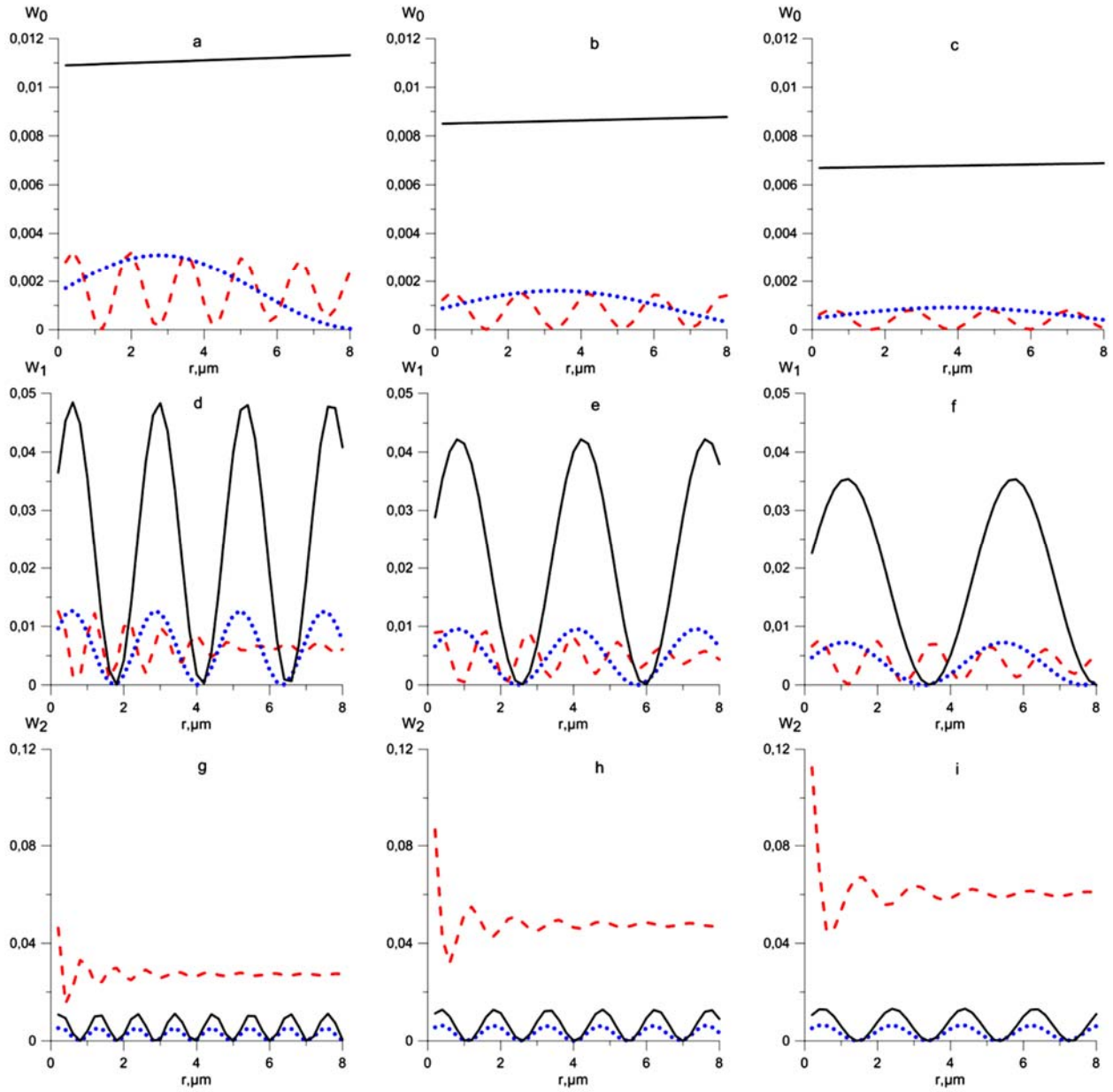

Figure 1. *The contribution of direct light W_0 (solid curves) a diffraction W_1 (dotted) and diffusion W_2 (dashed) components of the stratum corneum (a, b, c), the epidermis (d, e, f) and dermis (j, h, i) in speckle pattern on the skin surface when λ = 600 nm (a, d, g), 700 nm (b, e, h) and 800 nm (c, f, i).*

3. EXAMPLES OF SIMULATED SPECKLE STRUCTURE OUTSIDE BIOTISSUE

Fig. 1 shows the radial irradiance distribution $W_j(r)$ at wavelengths $\lambda = 600$, 700 and 800 nm, generated by the three components ($i = 0$, 1, and 2) coherent light on the skin surface, the back-scattered throughout the thickness of the stratum corneum (a,b,c) epidermis (d,e,f) and dermis (g,h,i). The calculations were performed for the following values of structural and biophysical parameters of tissue: the thickness of the stratum corneum and epidermis $d_0 = 20$ mm and $d_1 = 100$ mm (hereinafter, these parameters remain fixed), the degree of oxygenation of the blood $S = 0.75$, the volume of melanin concentration in the epidermis and blood in the dermis $C_m = 0.08$, and $C_b = 0.08$. As can be seen from fig. 1, the contribution of the stratum corneum to the total interference pattern is small and in many cases can be ignored. For the epidermis and dermis values W_1 и W_2 , on the contrary, are comparable. With increasing wavelength (fig. 1 h, i) contribution of dermal to the total W_2 interference pattern increases markedly, while the value of W_1 decreases a little. This is associated with a significant (approximately an order of magnitude) decrease in blood absorption index at $\lambda = 800$ nm in compare with 600 and 700 nm. The absorption of the melanin does not change very much, but at the same time there is a decrease in scattering index of the epidermis. [4]

Fig. 2 shows the total (by index i) contributions from the three components of each layer in the interference pattern on the surface, as well as integrated speckle pattern W (3) of the backscattered light. Usually blood diagnostic tasks by speckle parameters of reflected radiation is interesting a component of the dermis in full interference pattern. As is evident from fig. 2 (a) this component at 600 nm is largely hidden epidermis. Therefore, when the characteristics of erythrocytes $\lambda = 600$ nm is more convenient to determine the variable component of the speckle pattern caused by the motion of the particles in blood flow. However, consideration of this issue is beyond the scope of this research. When $\lambda = 700$ nm (fig. 2b) the value of the components of the dermis and epidermis is about the same. When $\lambda = 800$ nm (fig. 2 c) the contribution of the dermis exceeds the optical signal from the epidermis, which can be the basis for the creation of non-invasive diagnostic methods for blood pulse irradiation the tissue surface. This will be the subject of study in the future.

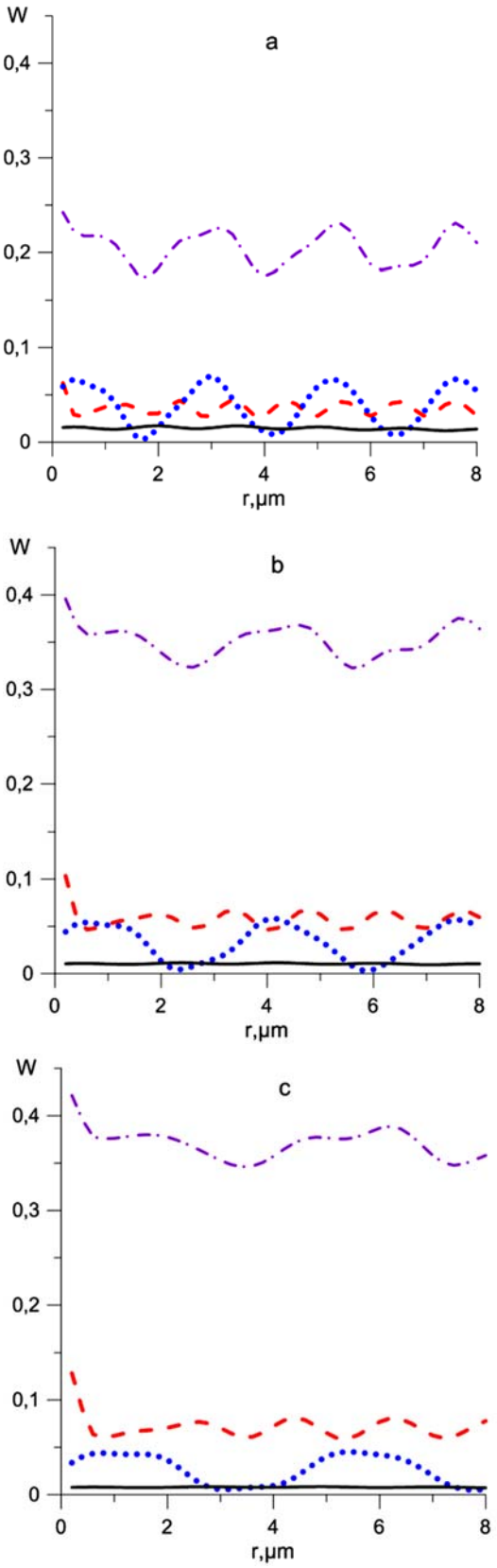

Figure 2. *The contribution of the stratum corneum (solid curves), the epidermis (dotted) and dermis (dashed) to the total speckle light (dash-dot) on the skin surface when λ = 600 nm (a), 700 nm (b) and 800 nm (c).*

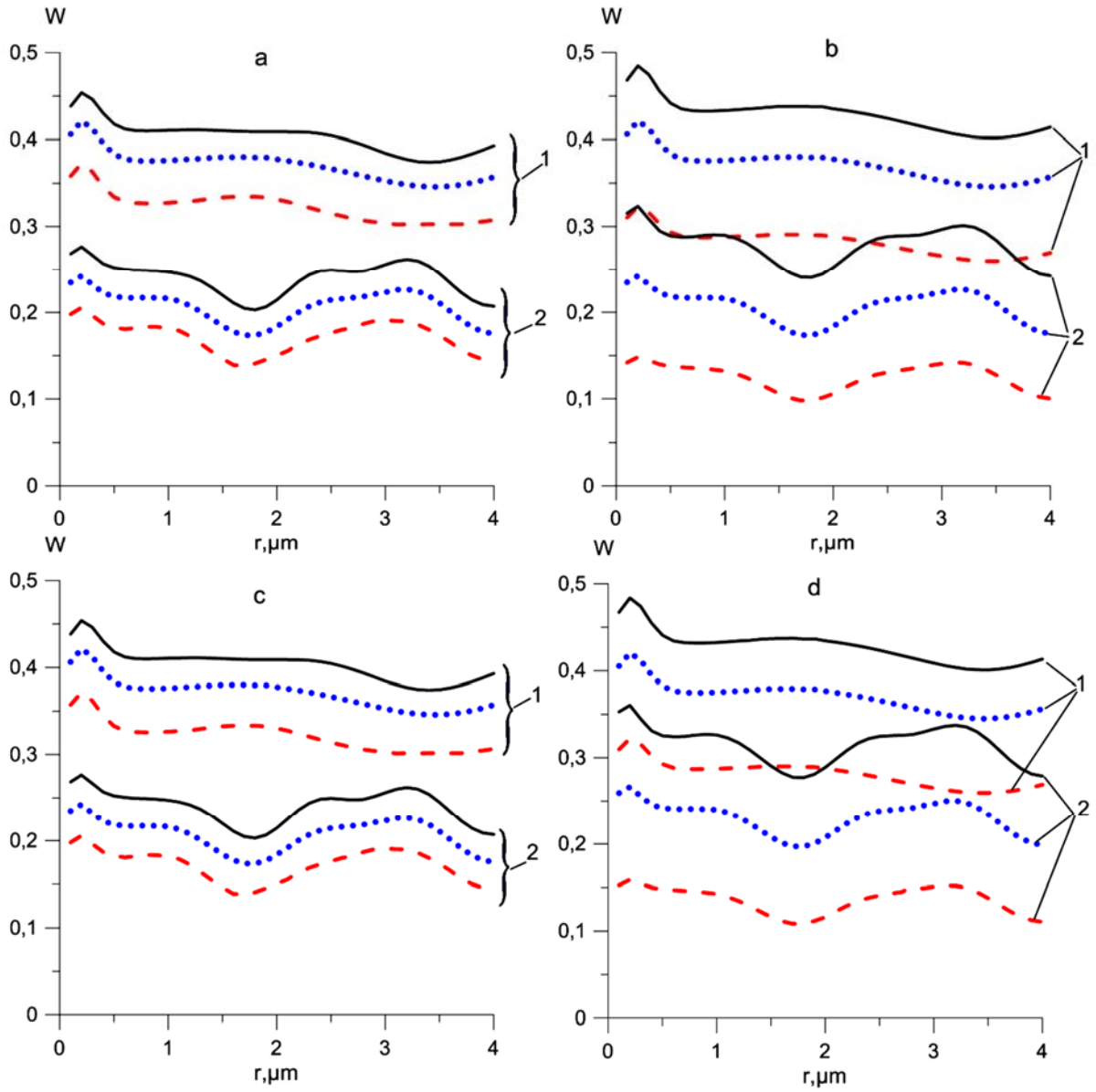

Figure 3. Full structure of the speckle light at the skin surface.
1 - λ = 800 nm, 2 - 600 nm, S = 0,75 (a, b) and S = 0,97 (c, d);
a, c - Cm = 0.08, Cb = 0.04 (solid), 0.08 (dotted) and 0.16 (dashed);
b, d - Cm = 0.04 (solid), 0.08 (dotted) and 0.16 (dashed), Cb = 0.08.

Let's examine the dependence of the full speckle pattern of light on the surface of the skin tissue on the biophysical parameters - the degree of oxygenation of blood S, C_m volume concentration of melanin in the epidermis and the dermis capillaries C_b.

As previously noted, the total value of light field W on the skin surface is bigger at a wavelength of 800 nm. Fig. 3 (b, d) varies the volume concentration of melanin in the epidermis C_m, which acts as a spectral filter with fixed value $C_b = 0.08$ for various values of the degree of blood oxygenation $S = 0.75$ (fig. 3 b), and $S = 0.97$ (fig. 3 d). By increasing melanin concentration C_m in the range of 0.04 to 0.16 total luminance value of W decreases. Epidermis simply attenuates light penetrating in the depth of the medium, the attenuation being the more noticeable, the more concentration fm is.

Fig. 3 (a, c) correspond to the variable (ranging from 0.04 to 0.16) volume concentration C_b of blood capillaries in the dermis at a fixed $C_b = 0.08$.

With increasing C_b contribution of light scattering of red blood cells in the total attenuation of the dermis growing, so full value of the W light speckle pattern is reduced.

We note that while simultaneous increasing the volume concentration of melanin C_m in the epidermis and the dermis capillaries C_b integrated speckle pattern W) backscattered light decreases even faster because of the weakening of the epidermis (which becomes the greater noticed, in case C_m is bigger) and reducing incoherent background due to growth tissue absorption.

It should be noted that the light field on the W skin practically does not depend on the extent of blood oxygenation S under $\lambda = 800$ nm (curve 1 in fig. 3) and increases (curves 2 in fig. 3) $\lambda = 600$ nm is stronger (2 the solid curve in fig. 3 b, d), the smaller is the value of volume concentration of melanin C_m in the epidermis (0.04 versus 0.08 and 0.16). The presented analytical method of estimating the parameters of the speckle pattern observed in the reflected light from the multilayer biological tissue has important scientific and practical applications: it allows without the use of complicated and cumbersome numerical algorithms to calculate the characteristics of the light field on the tissue surface. This can be the basis for the creation of new and improvement of the known methods for studying the interaction of light with biological tissues [11]. Analytical disposition of calculation method provides simplicity of use by various categories of researchers who do not specialize in computer technology and programming. This will expand the number of consumers, including medical practitioners, biologists, etc.

4. CONCLUSION

The results described above are valid for mobile scattering particles under their pulse illumination, when the pulse duration is essentially smaller than the characteristic time of the particle movement. The scatterers obviously can be considered as “frozen” or immobile in this case.

In future is planning to develop received results in case of moving scatterers and construction parameters of the analytical relations between the speckle pattern and different characteristics of moving particles (e.g., red blood cells) and the surrounding in which they move. It is obvious that the functionality of the optical speckle methods of diagnosis of biological tissues in this care significantly enhances.

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