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THE DEGREE OF MUTUAL CORRELATION OF MUELLER MATRIX ELEMENTS

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Анотація. На основі підходу до аналізу ступеня узгодженості між станами поляризації між двома точками когерентного лазерного поля, запропонованого Елісом та Догаріо, отриманий новий параметр, що характеризують кореляційну подібність між поляризаційними проявами оптично-анізотропної компоненти у різних точках біологічних тканин – ступень взаємної кореляції матриці Мюллера біологічної тканини. Здійснена експериментальна апробація запропонованого параметру у задачах диференціації орієнтаційно-фазової складової архітектоніки та фізіологічного стану біологічної тканини на основі статистичного та кореляційного підходу.

Аннотация. На основе подхода к анализу степени согласованности между состояниями поляризации между двумя точками когерентного лазерного поля, предложенного Элисом и Догарио, получен новый параметр, характеризующий корреляционное сходство между поляризационными проявлениями оптически анизотропной компоненты в разных точках биологических тканей – степень взаимной корреляции матрицы Мюллера биологической ткани. Осуществлена экспериментальная апробация предложенного параметра в задачах дифференциации ориентационно-фазовой составляющей архитектоники и физиологического состояния биологической ткани на основе статистического и корреляционного подхода.

Annotation. On the basis of the approach to the analysis of degree of consistency between the states of polarization between two points of coherent laser field proposed by Ellis and Dogario, new parameter describing the polarization correlation similarity between manifestation of optically anisotropic components in different points of biological tissues - the degree of mutual correlation Muller matrix of biological tissue have been received. An experimental parameter in problems of differentiation orientation-phase component of architectonic and physiological state of biological tissue based on statistical and correlation approach has been proposed.

Keywords: polarization, birefringence, correlation, statistics, biological tissue, skin derma

INTRODUCTION

Historically, the optical methods of biological tissues (BT) investigation may be divided into three groups:

- The specrophotometric methods [1-3], which are based on analysis of spatial (r) or time (τ) changes of radiation field intensity, scattered by BT;

- Polarizing methods are based on usage of coherency matrix of complex amplitude $\{\mathrm{K}(r,\tau)\}$ [13, 14, 20, 25, 26, 28]

$$\mathrm{K}(r,\tau)=\left\|\begin{array}{cc}\left\langle U_x(r,\tau)E_x^*(r,\tau)\right\rangle & \left\langle U_x(r,\tau)U_y^*(r,\tau)\right\rangle \\ \left\langle U_x{}^*(r,\tau)U_y(r,\tau)\right\rangle & \left\langle U_y(r,\tau)U_y^*(r,\tau)\right\rangle\end{array}\right\|, \tag{1}$$

and the analysis of the degree of polarization $P(r)$ as the factor of correlation complex orthogonal components of the electromagnetic fluctuation U_x, U_y at one of the points (r) of the scattered radiation field [16, 28]

$$P(r)=\sqrt{1-\frac{4\left[\left\langle U_x(r,\tau)U_x^*(r,\tau)\right\rangle\left\langle U_y(r,\tau)U_y^*(r,\tau)\right\rangle-\left\langle U_x(r,\tau)U_y^*(r,\tau)\right\rangle\left\langle U_y(r,\tau)U_x^*(r,\tau)\right\rangle\right]}{\left[\left\langle U_x(r,\tau)U_x^*(r,\tau)\right\rangle+\left\langle U_y(r,\tau)U_y^*(r,\tau)\right\rangle\right]^2}}. \tag{2}$$

• The correlation methods which are based on the analysis of the correlation degree J of the parallel polarization components $U_x(r_1)$, $U_x(r_2)$ of the light fluctuation at different points of object field (r_1, r_2) [20, 25, 26, 28]

$$J = \frac{\left\langle U_x(r_1,\tau)U_x^*(r_2,\tau)\right\rangle - \left\langle U_x^*(r_1,\tau)U_x(r_2,\tau)\right\rangle}{\left\langle U_x(r_1,\tau)U_x^*(r_2,\tau)\right\rangle + \left\langle U_x^*(r_1,\tau)U_x(r_2,\tau)\right\rangle}. \tag{3}$$

For actual object fields BT including its images the change both of polarization and correlation characteristics is typical [3, 13, 14, 20].

In the papers [35, 36, 28] the question about defining the degree of mutual polarization between two points of coherent radiation field was examined. It was concluded that for general case of two elliptically polarized fluctuations

$$E_{x_1} + E_{y_1}e^{-i\delta_1} \tag{4}$$

and the degree of its polarization agreement is of the next analytical form

$$|V|^2 = \frac{(E_{x_1}E_{x_2} - E_{y_1}E_{y_2})^2 + 4E_{x_1}E_{y_1}E_{x_2}E_{y_2}e^{-i(\delta_1-\delta_2)}}{(E_{x_1}^2 + E_{y_1}^2)(E_{x_2}^2 + E_{y_2}^2)}. \tag{5}$$

Ellis and Dogariu [31] called this parameter the degree of mutual polarization (DMP) of the points of field with coordinates r_1 and r_2.

On the other hand, equation (5) is a "derivative" from the matrix equation solution

$$\begin{pmatrix} S_1^* \\ S_2^* \\ S_3^* \\ S_4^* \end{pmatrix} = \begin{Vmatrix} 1 & 0 & 0 & 0 \\ 0 & f_{22} & f_{23} & f_{42} \\ 0 & f_{32} & f_{33} & f_{43} \\ 0 & f_{42} & f_{43} & f_{44} \end{Vmatrix} \cdot \begin{pmatrix} S_1^* \\ S_2^* \\ S_3^* \\ S_4^* \end{pmatrix}, \tag{6}$$

where

$$\begin{aligned} &f_{22} = \cos^2 2\rho + \sin^2 2\rho \cdot \cos\delta; \quad f_{23} = \cos 2\rho \sin 2\rho(1-\cos\delta); \quad f_{24} = \sin 2\rho \sin\delta; \\ &f_{32} = \cos 2\rho \sin 2\rho(1-\cos\delta); \quad f_{33} = \sin^2 2\rho + \cos^2 2\rho \cos\delta; \quad f_{34} = \cos 2\rho \sin\delta; \\ &f_{42} = -\sin 2\rho \sin\delta; \qquad f_{43} = -\cos 2\rho \sin\delta; \qquad f_{44} = \cos\delta. \end{aligned} \tag{7}$$

$S^0_{i=1,2,3,4}$ and $S^*_{i=1,2,3,4}$ – Stokes vector parameters, which are uniquely concerned with complex amplitudes (E_x, E_y) at the points with coordinates r_1 and r_2 through the known equations [23]

$$\begin{aligned} S_1 &= E_x E_x^* + E_y E_y^*, \\ S_2 &= E_x E_x^* - E_y E_y^*, \\ S_3 &= E_x E_y^* + E_y E_x^*, \\ S_4 &= E_x E_y^* - E_y E_x^*. \end{aligned} \tag{8}$$

On the basis of (5) and (8) one can obtain the analytical relation, which characterizes the correlation similarity of polarization manifestation of optical-anisotropic component in different points of biological tissue. Hereinafter such parameter will be called as the degree of mutual correlation (DMC) of biological tissue Mueller matrix W.

$$W = \frac{1 + A - B \cdot C}{2}, \tag{9}$$

where

$$A = \frac{f_{34}(r_1) f_{34}(r_2)}{\left[(1 - f_{44}^2(r_1))(1 - f_{44}^2(r_2))\right]^{1/2}}, \tag{10}$$

$$B = \frac{f_{24}(r_1) f_{24}(r_2)}{\left[(1 - f_{44}^2(r_1))(1 - f_{44}^2(r_2))\right]^{1/2}}, \tag{11}$$

$$C = f_{44}(r_1) f_{44}(r_2) + \left[(1 - f_{44}^2(r_1))(1 - f_{44}^2(r_2))\right]^{1/2}. \tag{12}$$

THE EXPERIMENTAL SETUP AND THE MEASUREMENT TECHNIQUE OF DEGREE OF MUTUAL CORRELATION OF BIOLOGICAL TISSUE'S MUELLER MATRIX

The traditional polarimetric scheme for measuring the MMI set of BT histological section is shown in the figure 1 [1-3, 10, 21, 24, 29].

It was illuminated by collimated ($\varnothing = 10^4$μm) He-Ne laser beam (λ = 0.6328 μm) with the power of 50μW. Polarization illuminator (quarter-wavelength plates 3, 5 and polarizer 4) formed the beam with arbitrary polarization azimuth ($0^0 \le \alpha_0 \le 180^0$) and ellipticity ($0^0 \le \beta_0 \le 90^0$). Polarization images of BT by means of microobjective 7 (focal distance - 1.5 cm, aperture - 0.2, magnification – 4x) were projected into the plane of light-sensitive area of CCD camera (overall amount of pixels – 800x600, light sensitive area size - 4000x3000 μm, deviation of photosensitive characteristics from linear no more then 15%), which provided the range of measuring the structural elements of BT with the resolution $2 - 2000\mu m$.

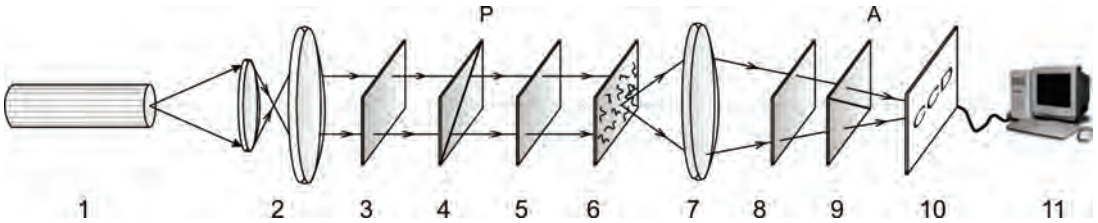

Figure 1. Polarimetric optical scheme, where 1 – He-Ne laser; 2 – collimator; 2 – immovable quarter-wave plate; 5, 8 – mechanically movable quarter-wave plates; 4, 9 – polarizer and analyzer; 6 – the research object; 7 – microscope objective; 10 – CCD camera; 11 – PC

Maximal resolution verification ($2\,\mu m$) where performed using the stage micrometer (linear scale), which image was projected into the light sensitive area of CCD camera with the help of microobjective 7. Minimal resolution ($2000\mu m$) corresponds to the situation when the light sensitive area of CCD camera is entirely filled by two equal sized structural elements (light and dark) of stage micrometer. The conditions of the experiment were chosen in such a way that it enabled to reduce the space-angular aperture filtering while forming the BT images. This was ensured by conformance of angular characteristics of indicatrices of light scattering by the BT samples ($\Omega \approx 16^0$) and angular aperture of microobjective ($\Delta\omega = 20^0$). Here Ω is the solid angle within which 98% of all the energy of light-scattered radiation is concentrated.

The BT images are analyzed by the system of quarter-wavelength plate 8 and polarizer 9. As a result, the Stokes vectors of the BT images $\left\{S^{BT}_{j=1,2,3,4}\right\}$ were determined and the ensemble of $M_{ik}(X,Y)$ was calculated in accordance with the algorithm:

$$\begin{aligned} M_{i1} &= 0.5\left[S_i^{(1)} + S_i^{(2)}\right], \\ M_{i2} &= 0.5\left[S_i^{(1)} - S_i^{(2)}\right], \\ M_{i3} &= S_i^{(3)} - M_{i1}; \\ M_{i4} &= S_i^{(4)} - M_{i1}, i = 1,2,3,4. \end{aligned} \tag{13}$$

Here indices 1 – 4 correspond to the following polarization states of illuminating beam: 1 – 0^0; 2 – 90^0; 3 – $+45^0$; 4 – $\otimes$ (right circulation).

Degree of mutual correlation of biological tissue Mueller matrix was calculated in accordance with the algorithm (9)-(12).

EXPERIMENTAL TWO-DIMENSIONAL DISTRIBUTION OF THE DEGREE OF MUTUAL CORRELATION OF THE BIOLOGICAL TISSUES MUELLER MATRIX

At the first stage as the objects of research were chosen histological sections of the sound BT of two kinds: with the arranged (muscular tissue − MT) and disarranged (dermal skin layer − DL) architectonic network.

Polarization-visualized images of such structures obtained through the cross analyzer and polarizer are represented in the figure 2.

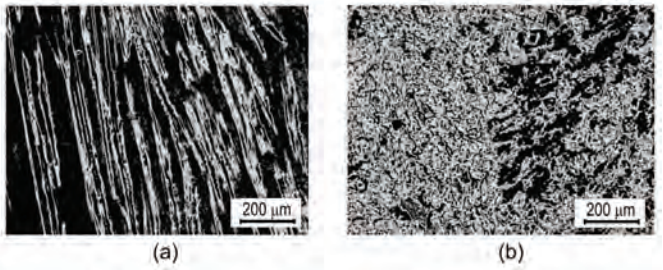

Figure 2. Architectonics of the muscular tissue (a) and the dermal layer (b) in crossed polarizer and analyzer

At the series of figures 3 and 4 the coordinate (fragments (a)) and statistic (fragments (b)) distributions of the DMC values of the Mueller matrices of the MT (fig. 3) and the DL (fig. 4) are shown.

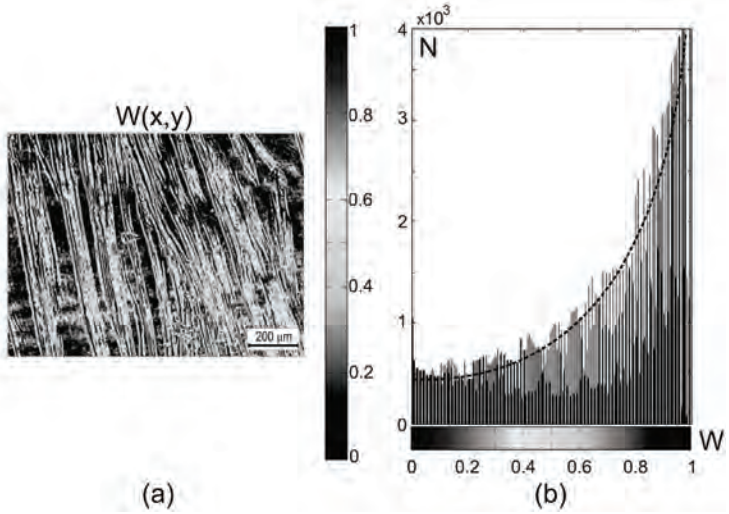

Figure 3. The DMC of the Mueller matrix of the MT

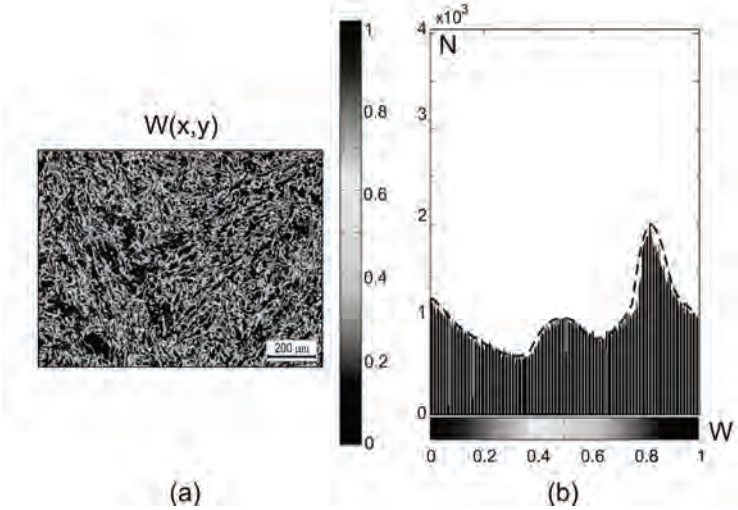

Figure 4. The DMC of the Mueller matrix of the DL

The analysis of the obtained experimental data discovered:

- irrespective of the type of the chosen BT coordinate distributions of the DMC of their Mueller matrices represent the set of the local areas ($W(x, y) \approx const$) with the range of the value changes from 0 to 1.0;
- the coordinate distribution of the DMC values of the Mueller matrices of the MT are characterized by the large-scale areas, the sizes of which correlate with the fibril sizes and are situated within the limits from $20\mu m$ to $100\mu m$ (fig.2 (a)). The extreme values ($W \approx 1$) prevail in the bar chart of the random value $W(x, y)$ (fig.3 (b));
- the coordinate structure of the DMC of the DL Mueller matrix consists of the small-scale areas ($2\mu m - 40\mu m$) (fig.2 (b)) with the sufficiently equiprobable values $W(x, y)$ (fig.4 (b)).

The results of the statistic moments of the 1st-4th orders calculation (the average value M, dispersion σ, skewness coefficient A and kurtosis coefficient E), which characterize the coordinate distributions (fig.3 (a)) and (fig.4 (a)) of DMC values of Mueller matrix of the MT and DL samples, are given in the table 1.

Table 1

Statistic moments of the 1st-4th orders of the DMC distribution of the MT and DL Mueller matrices

Statistic moment	MT (36 samples)	DL (34 samples)
M	0.78 ± 0.069	$0.081 \pm 0{,}0074$
σ	0.012 ± 0.0093	0.11 ± 0.088
A	18.3 ± 1.54	9.64 ± 0.102
E	30.6 ± 2.79	88.7 ± 6.49

From the data presented in table 1 one can conclude:

- the change of the distribution of organic crystals optical axes orientation of MT and DL architectonic network of the human-being is revealed in the change of the values of all statistic moments which characterize the corresponding DMC distribution of the Mueller matrix of such samples;
- the differences in the statistical moments values of the 1st and 2nd orders reach the one order of magnitude;
- the values of the asymmetry and the kurtosis coefficients of the DMC distributions of the Mueller matrices differ in 2-3 times.

THE CORRELATION ANALYSIS OF THE DMC DISTRIBUTION OF THE BT MUELLER MATRICES

The effectiveness of the correlation analysis of the DMC distribution of the MT and DL samples Mueller matrix is illustrated in the figure 5, where the autocorrelation functions (ACF) are depicted.

As the diagnostic criteria were chosen:

- the half-width (L) of ACF;
- the dispersion (Ω) of the ACF log-log power spectra values.

From the obtained results it was established that for the well-ordered birefringent architectonics of the MT samples the bigger half-width of the corresponding ACF of the DMC coordinate distribution (fig.5 (a)) is typical (~2 times) in contrast to disordered DL network.

The dispersion values of the log-log distribution of the ACF power spectrum values of the DMC distribution of the MT and DL Mueller matrix differ approximately in 3 times.

The received experimental data concerning the correlation criteria L and Ω were statistically generalized within the limits of two groups of samples MT (25 samples) and DL (28 samples) (table 2).

Table 2

Correlation criteria of the DMC coordinate distributions of MT and DL Mueller matrices.

Correlation criteria	MT (21 samples)	DL (23 samples)
L, x10^{-3} μm	0.52±0.047	0.29 ±0.023
Ω, x10^{-3} μm	0.18±0.021	0.06±0.0043

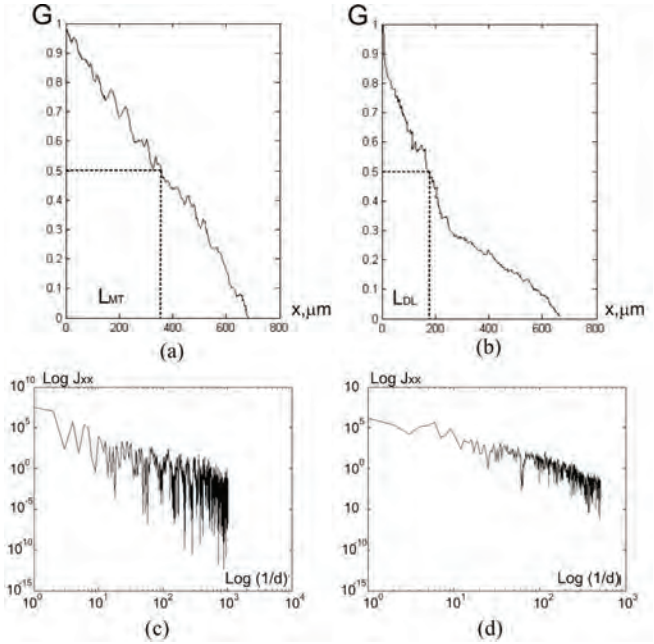

Figure 5. The autocorrelation functions and log-log power spectra of the DMC coordinate distributions of MT (a) and DL (b) Mueller matrix

So, the statistical and correlation approaches to analysis of two-dimensional DMC distribution of Mueller matrix of real BT samples revealed their effectiveness in differentiation of BT optical properties.

The second stage of experimental investigations was the ascertainment of the possibility of BT physiological state diagnostics on the basis of DMC measurement of the corresponding Mueller matrices.

THE DIAGNOSTICS OF BT PHYSIOLOGICAL STATE ON THE BASIS OF STATISTICAL AND CORRELATION ANALYSIS OF THE DMC DISTRIBUTIONS OF THEIR MUELLER MATRICES

Two groups of BT samples were chosen as the objects of investigation:

- sound and degeneratively changed (osteoporosis) shin osseous tissue (OT);
- sound and dystrophic changed skeletal muscular tissue (MT).

The choice of such objects is conditioned by the following factors:

- optical mechanisms of changes of organic crystals structure of such tissues are different;
- for the osseous tissue the decrease of organic crystals birefringence (washing out of bone-salt crystals (hydroxyl apatite) [11, 14]) with permanent orientation of optical axis of birefringent collagenous fibrils occurs – "phase scenario";
- for MT disordering of optical axes directions of organic crystals (myosin fibrils) with permanent birefringence occurs – "orientation scenario".

Figures 6 and 7 present the DMC coordinate distributions of Mueller matrix of sound (fragment (a)) and degeneratively-distrophic changed (fragments (b)) BT of both types.

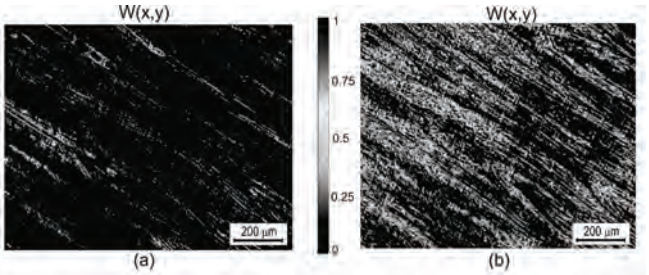

Figure 6. Two-dimensional distributions of the DMC ($W(x, y)$) of the sound (a) and degeneratively changed (b) OT Mueller matrix

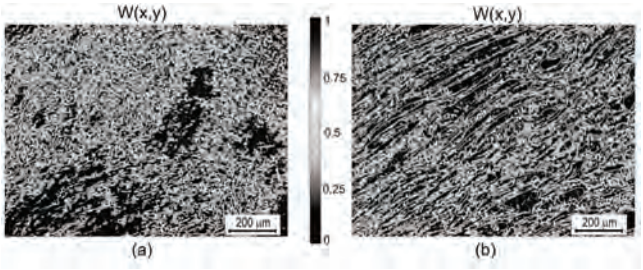

Figure 7. Two-dimensional distributions of the DMC ($W(x, y)$) of the sound (a) and degeneratively changed (b) MT Mueller matrix

Tables 3 and 4 present the set of statistic moments values, which characterize the DMC of OT (table 3) and MT (table 4) Mueller matrix.

Table 3

Statistic moments of the 1st-4th orders of the DMC of OT (sound and degeneratively changed) Mueller matrix

Statistic moments	OT (sound, 21 samples)	OT (degeneratively changed, 18 samples)
M	0.89 ± 0.075	0.41 ± 0.036
σ	0.023 ± 0.0019	0.093 ± 0.0081
A	8.35 ± 0.68	3.41 ± 0.27
E	21.5 ± 2.07	36.9 ± 3.15

Table 4

Statistic moments of the 1st-4th orders of the DMC of MT (sound and dystrophic changed) Mueller matrix

Statistic moments	MT (sound, 19 samples)	MT (dystrophic changed, 18 samples)
M	0.62 ± 0.057	0.49 ± 0.038
σ	0.11 ± 0.098	0.14 ± 0.012
A	32.65 ± 2.98	21.14 ± 1.83
E	81.6 ± 7.91	43.8 ± 3.72

Figure 8 and figure 9 illustrate the ACF of the parameter $W(x, y)$ of Mueller matrix of both types BT.

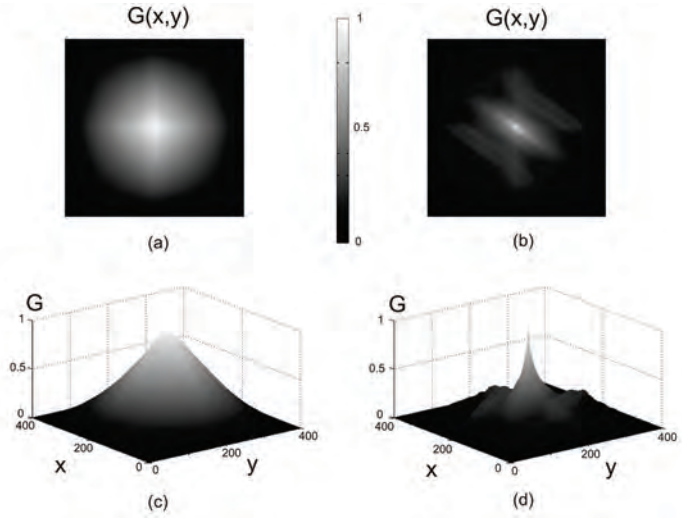

Figure. 8. Two-dimensional autocorrelation functions $G(x, y)$ of parameter $W(x, y)$ of sound (a) and degeneratively changed (b) OT. Parts (c, d) correspond to three-dimensional representation of $G(x, y)$

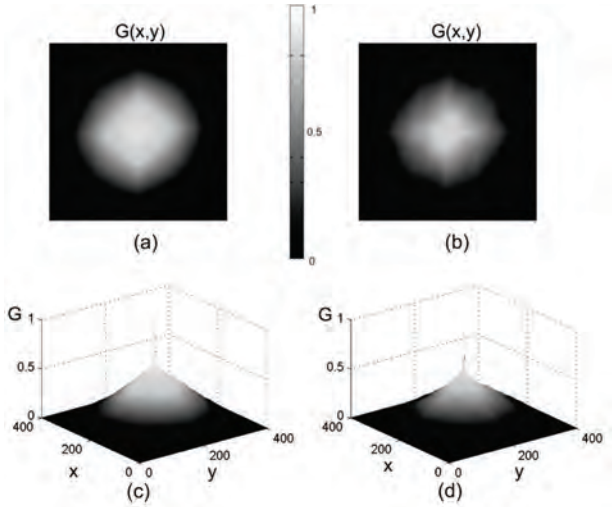

Figure. 9. Two-dimensional autocorrelation functions $G(x, y)$ of parameter $W(x, y)$ of sound (a) and dystrophic changed (b) MT. Parts (c, d) correspond to three-dimensional representation of $G(x, y)$

The statistic analysis of the DMC coordinate distribution ($W(x, y)$) (tables 3 and 4) has detected the following:

- for sound and degeneratively changed OT the differences between the average and dispersion, the skewness and the kurtosis are of 1,5 - 4 times.
- for various conditions of MT the differences between statistic moments of the 1st-3rd orders are within of 30-50%, the values of the kurtosis coefficient of the $W(x_i, y_i)$ distribution differs practically in 2-2.5 times.

Table 5

Correlation parameters of DMC coordinate distribution of BT Mueller matrices

	OT			MT	
	sound	pathology		sound	pathology
$L \cdot 10^3$, μm	0,6 ± 0,04	0,34 ± 0,03	$L \cdot 10^3$, μm	0,25 ± 0,02	0,13 ± 0,01
Ω	≈ 0	0,01 ± 0,001	Ω	0,07 ± 0,005	0,005 ± 0,0001

The comparative analysis of correlation parameters has detected the essential distinctions in the values of half-width and dispersion of BT ACF oscillation (table 5).

CONCLUSIONS

The degree of mutual correlation of Mueller matrix has been used for the first time for analysis of biological tissues optical properties. Such parameter characterizes the correlation similarity of polarization presentations of optical anisotropy of different areas organic crystals birefringent network.

It has been determined that physical reason of dispersion increasing and, *vice versa*, the skewness and the kurtosis decreasing of coordinate distribution of the degree of mutual correlation of biological tissue Mueller matrix caused by the increasing of distribution of organic crystal optical axes orientations because of dystrophic changes.

The inverse processes of statistic moments of the 2nd-4th orders value changes correspond to increasing of the phase shifts dispersion, which caused by dystrophic changed biological tissue organic crystals.

Thereupon the early (pre-clinical) discrimination between the optical properties of sound and degeneratively-dystrophic muscular and osseous tissues has been performed.

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