Mueller - matrices polarization selection of two-dimensional linear and circular birefringence images

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ABSTRACT

The optical model of polycrystalline networks of myometium is suggested. The results of investigating the interrelation between the values correlation (correlation area, asymmetry coefficient and autocorrelation function excess) and fractal (dispersion of logarithmic dependencies of power spectra) parameters are presented. They characterize the distributions Mueller marixes elements of myometrium histological sections. The criteria of differentiation of death coming reasons are determined.

Key words: Mueller matrix, correlation function, correlation area, correlation moments, power spectra , biological tissue

1. Introduction

Biological tissues and fluids represent structurally inhomogeneous optically anisotropic media with absorption. To describe the interaction of polarized light with such sophisticated systems, more general approximation based on Mueller-matrix formalism is required. Nowadays many practical techniques based on measuring and analyzing the Mueller-matrices of the samples under investigation are being used in biological and medical researches [1-6]. During recent 10-15 years a separate direction – laser polarimetry – has been formed in matrix optics [7-11]. On its basis the interconnections between the set of statistical moments of the 1^{st}-4^{th} order, correlation, fractal and singular parameters were determined, which characterize the distributions of Mueller matrix elements and the parameters of linear birefringence of fibrillar protein networks of human biological tissues. The diagnostics of pathological changes of skin derma, epithelial and connective tissues of the women's reproductive organs, etc. was realized on this basis [12- 17].

This research is focused on the search for possibilities of diagnostics of death coming due to acute coronary insufficiency by means of determining correlation [1-3] and fractal [4-8] parameters characterizing the distributions of "phase" $Z_{44}(m \times n)$ Mueller matrix elements [9-12] of myometrium tissue histological sections.

2. 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 [11-14].

It was illuminated by collimated ($\varnothing = 10^4 \mu m$) He-Ne laser beam ($\lambda = 0.6328\ \mu m$) 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 $2 - 2000 \mu m$.

Applications of Digital Image Processing XXXVI, edited by Andrew G. Tescher,
Proc. of SPIE Vol. 8856, 88562E · © 2013 SPIE · CCC code: 0277-786X/13/$18
doi: 10.1117/12.2023604

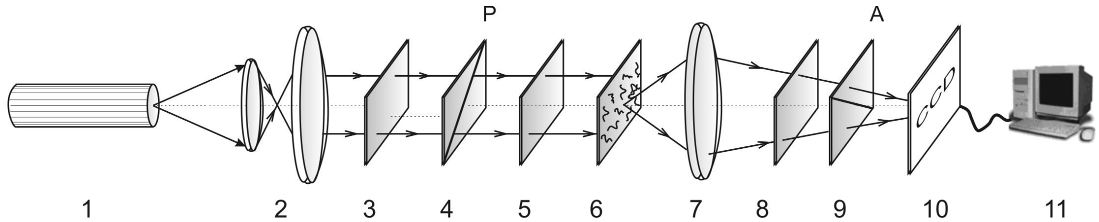

Figure 1. Polarimetric optical scheme, where 1 – He-Ne laser; 2 – collimator; 2 – immovable quarter-wave plate; 5, 8 – mechanically movable quarter-wave plates; 4, 9 – polarizer and analyzer; 6 – the research object; 7 – microscope objective; 10 – CCD camera; 11 – PC.

Maximal resolution verification (2 μm) 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 $Z_{ik}(X,Y)$ was calculated in accordance with the algorithm

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

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).

3. Diagnostic potentiality of correlation and fractal analysis of distributions of the "phase" Mueller matrix element of myometrium tissue

To find more sensitive diagnostic criteria, the correlation and fractal structure of dependencies $N(Z_{44}=0) \equiv N_0$ (Fig. 1) and $N(Z_{44}=1) \equiv N_1$ (Fig. 2) was studied [13-17].

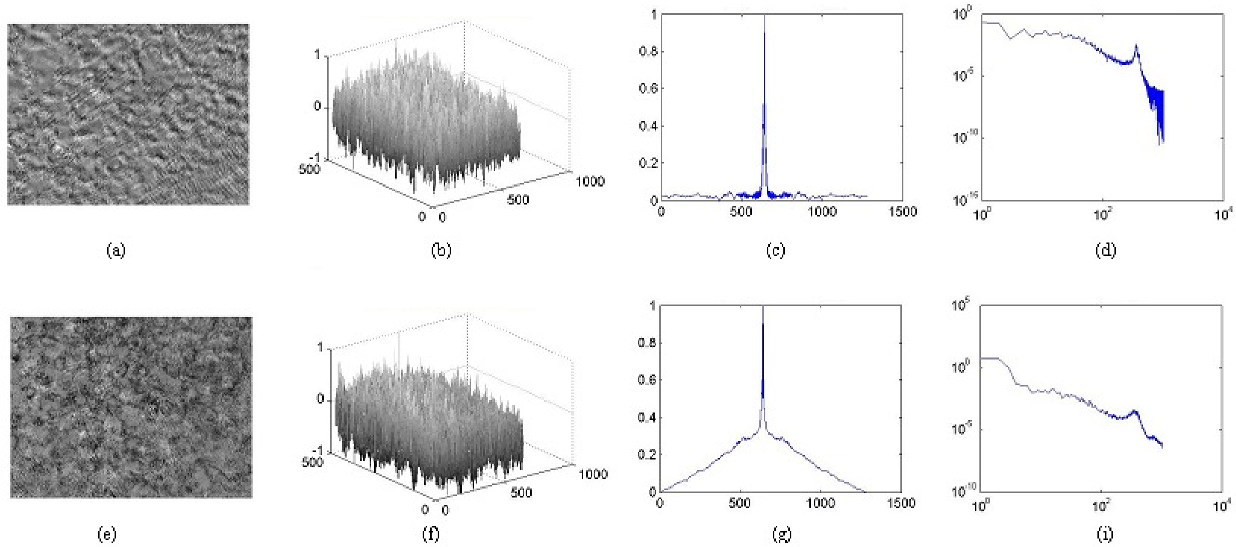

Figure 2. Statistical, correlation and fractal structure of extreme values dependencies of myometrium phase matrix element $Z_{44} = 0$.

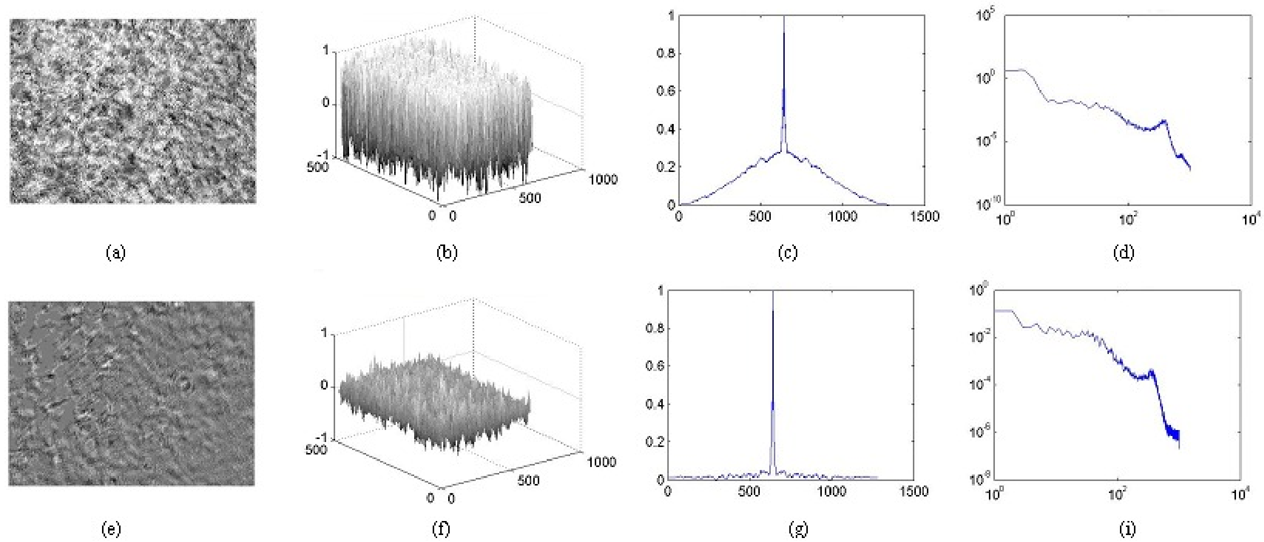

Figure 3. Statistical, correlation and fractal structure of extreme values dependencies of myometrium phase matrix element $Z_{44} = 0$.

This approach enables to study the statistical manifestations of myometrium myosin fibrils birefringence at its two extreme levels – the minimal, optically isotropic ($N(Z_{44} = 1) \equiv N_1$) level and maximal, optically anisotropic ($N(Z_{44} = 0) \equiv N_0$) one.

As a result of investigating the dependencies of extreme values amount $N(Z_{44} = 1) \equiv N_1$ and $N(Z_{44} = 0) \equiv N_0$ a sufficient diagnostic sensitivity differentiation of group 1 and group 2 was revealed.

Thus, for group 2 the increase (by one order of a value) of the amount of extreme values $Z_{44} = 0$ of myometrium tissue Mueller matrix phase element (Fig. 2, fragments (c) and (d) respectively) occurs. This fact testifies to sufficiently higher level of optical anisotropy of myosin fibrils at group 2 if compared with that of group 1.

Besides, at group 2 it is accompanied by transformation of fractal dimensions $N(Z_{44}=0)\equiv N_0$ into statistical ones – for the corresponding logarithmic dependencies of power spectra no stable slope of approximating curve is observed (Fig. 1, fragments (g) and (h)).

On the contrary, birefringence degradation of group 1 myometrium is vividly manifested in the increase (by one order of a value) of the amount of another extreme level $Z_{44}=1$ of myometrium tissue Mueller matrix phase element (Fig. 3, fragments (c) and (d) respectively). At that the value of correlation area $S(Z_{44}=1)$ of distribution $N(Z_{44}=1)\equiv N_1$ sufficiently decreases (Fig. 3, fragments (e) and (f)).

The results of the comparative investigation of the value and change ranges of correlation area $S(N_0)$, $S(N_1)$; dispersion $Q_2(N_0)$, $Q_2(N_1)$; excess $Q_4(N_0)$, $Q_4(N_1)$ and statistical moments of the 1st-4th order $M_{j=1;2;3;4}(N_0)$, $M_{j=1;2;3;4}(N_1)$ of power spectra $J(N_0)$, $J(N_1)$ logarithmic dependencies $\log J(N_0)-\log d^{-1}$ i $\log J(N_1)-\log d^{-1}$ of the extreme values $Z_{44}=0$ and $Z_{44}=1$ amount of Mueller matrix phase element $Z_{44}(m\times n)$ of group 1 and group 2 myometrium are presented in Table 1 ($N(Z_{44}=0)\equiv N_0$) and Table 2 ($N(Z_{44}=1)\equiv N_1$).

Table 1. Correlation and fractal parameters of the dependencies of extreme values $N_0(Z_{44}=0)$ amount of coordinate distributions $Z_{44}(m\times n)$ of myocardium tissue for group 1 and group 2

Parameters	Group 1	Group 2
$S(Z_{44})$	$0{,}29\pm0{,}016$	$0{,}31\pm0{,}014$
$Q_2(Z_{44})$	$0{,}21\pm0{,}024$	$0{,}23\pm0{,}029$
$Q_4(Z_{44})$	$0{,}13\pm0{,}015$	$0{,}11\pm0{,}012$
$M_1(Z_{44})$	$0{,}62\pm0{,}066$	$0{,}51\pm0{,}057$
$M_2(Z_{44})$	$0{,}23\pm0{,}034$	$0{,}48\pm0{,}054$
$M_3(Z_{44})$	$0{,}14\pm0{,}015$	$1{,}05\pm0{,}16$
$M_4(Z_{44})$	$0{,}31\pm0{,}042$	$2{,}97\pm0{,}36$

Table 2. Correlation and fractal parameters of the dependencies of extreme values $N_1(Z_{44}=1)$ amount of coordinate distributions $Z_{44}(m\times n)$ of myocardium tissue for group 1 and group 2

Parameters	Group 1	Group 2
$S(Z_{44})$	$0{,}21\pm0{,}023$	$0{,}04\pm0{,}0037$
$Q_2(Z_{44})$	$0{,}32\pm0{,}041$	$0{,}01\pm0{,}003$
$Q_4(Z_{44})$	$0{,}54\pm0{,}061$	$18{,}11\pm2{,}04$
$M_1(Z_{44})$	$0{,}56\pm0{,}062$	$0{,}29\pm0{,}035$
$M_2(Z_{44})$	$0{,}19\pm0{,}023$	$0{,}81\pm0{,}093$
$M_3(Z_{44})$	$0{,}31\pm0{,}045$	$4{,}75\pm0{,}76$
$M_4(Z_{44})$	$0{,}43\pm0{,}054$	$9{,}83\pm1{,}41$

4. Conclusions

The obtained data of experimental investigation of statistical structure of extreme values amount distributions of Mueller matrix phase elements of both types of myometrium tissue indicate the objective possibility of differentiation of different states.

Statistical moments of the 2nd-4th order $M_{j=2;3;4}(N_0)$, $M_{j=2;3;4}(N_1)$ of power spectra $J(N_0)$, $J(N_1)$ logarithmic dependencies $\log J(N_0)-\log d^{-1}$ and $\log J(N_1)-\log d^{-1}$ of $N(Z_{44}=0)\equiv N_0$, $N(Z_{44}=1)\equiv N_1$

distributions of extreme values $Z_{44} = 0$ and $Z_{44} = 1$ amount of Mueller matrix phase element $Z_{44}(m \times n)$ of group 1 and group 2 myometrium tissue proved to be the most informative.

The following difference ranges between statistical parameters of distributions $N(Z_{44} = 0) \equiv N_0$ characterizing optically anisotropic component of myometrium with group 1 and group 2 – dispersion $M_2(N_1)$ (increase by 2.03 times); asymmetry $M_3(N_0)$ (increase by 8 times) and excess $M_4(N_0)$ (increase by 9.7 times) were determined.

For statistical moments that describe distributions $N(Z_{44} = 1) \equiv N_1$ of optically isotropic component of group 1 and group 2 myometrium the following was determined: dispersion $M_2(N_0)$ (increase by 4.4 times); asymmetry $M_3(N_1)$ (increase by 15 times) and excess $M_4(N_1)$ (increase by 21.4 times).

Moreover, the group of correlation parameters demonstrates sufficient changes: correlation area $S(N_1)$ decreases by 5 times; dispersion $Q_2(N_1)$ decreases by 32 times, while excess $Q_4(N_1)$ increases by 35 times.

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