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DIAGNOSTIC CAPABILITIES OF JONES MATRIX THEZIOGAPHY OF THE MULTIFRACTAL STRUCTURE OF DEHYDRATED BLOOD FILMS

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***Abstract**. The paper proposes the use of multifractal analysis by algorithmic implementation of coordinate reconstructed distributions of linear birefringence magnitude and obtaining a spectrum of fractal dimensions of dehydrated polycrystalline blood films. The results of the diagnostic application of laser Jones matrix theziography methods of multifractal structure of polycrystalline networks of dehydrated films of blood for differential diagnostics of inflammatory and pathological conditions – "norm – sepsis" are presented. For dehydrated blood films, histograms and maps of the amplitude distributions of wavelet coefficients of theziograms of optical anisotropy and multifractal spectra of theziograms of optical anisotropy of polycrystalline supramolecular networks are given. Tables of the values of the central statistical moments of the 1st – 4th orders, which the Jones matrix characterize, wavelet and multifractal parameters of theziograms of phase anisotropy of dehydrated blood films, are systematized, and the set of statistical parameters more sensitive to changes in the polycrystalline structure of biological samples – diagnostic markers – is determined. Within the framework of statistical analysis of multifractal spectra and wavelet maps, it was determined that the algorithmically reconstructed birefringence theziogram allows identifying the most sensitive markers to changes in the anisotropic optical structure of blood caused by septic manifestations.*

Keywords: Jones matrix, polarization, interferometry, blood, sepsis, theziograms

MOŻLIWOŚCI DIAGNOSTYCZNE TEZIOGAFII MACIERZY JONESA MULTIFRAKTALNEJ STRUKTURY ODWODNIONYCH ROZMAZÓW KRWI

***Streszczenie**. W artykule zaproponowano wykorzystanie analizy multifraktalnej poprzez algorytmiczną realizację współrzędnych zrekonstruowanych rozkładów wielkości liniowych dwójłomności oraz uzyskanie spektrum wymiarów fraktalnych odwodnionych polikrystalicznych rozmazów krwi. Przedstawiono wyniki diagnostycznego zastosowania metody teziografii laserowej matrycy Jonesa do określania struktury multifraktalnej sieci polikrystalicznych odwodnionych rozmazów krwi w różnicowaniu stanów zapalnych i patologicznych – „normalny – sepsa". Dla odwodnionych rozmazów krwi przedstawiono mapy i histogramy rozkładów amplitud współczynników falkowych teziogramów anizotropii optycznej oraz widma multifraktalne teziogramów anizotropii optycznej polikrystalicznych sieci supramolekularnych. Utworzono tablice wartości centralnych momentów statystycznych rzędów I–IV, charakteryzujących parametry macierzy Jonesa, falki i multifraktalne teziogramów anizotropii fazowej odwodnionych rozmazów krwi, a także określono zbiór parametrów statystycznych najbardziej wrażliwych na zmiany struktury polikrystalicznej próbek biologicznych – markery diagnostyczne. W ramach analizy statystycznej spektrów multifraktalnych i map falkowych ustalono, że algorytmicznie zrekonstruowana teziogram dwójłomności pozwala zidentyfikować najbardziej wrażliwe markery zmian anizotropowej struktury optycznej krwi spowodowanych stanami septycznymi.*

Słowa kluczowe: macierz Jonesa, polaryzacja, interferometria, krew, sepsa, teziogramy

Introduction

Recently, within the framework of numerous studies in the field of biomedical polarimetry [6, 7, 15, 20], methods for processing the obtained data - polarizing and Mueller-matrix mapping [1, 18, 20] have been widely used. as a result, several objective criteria (markers) for determining certain changes in the assessment of morphological structures in the analysis of biological tissues, which are caused by the action of necrotic and pathological conditions.

Correlation and statistical analysis of the polarization of biological samples' ellipticity and azimuth, elements of Mueller matrix coordinate distributions is the predominant algorithmic basis for determining the totality of polarimetric digital diagnostic markers of the above conditions [14, 15, 22]. In solving the problem of conducting biomedical diagnostics, there is an application multifractal analysis or multifractal scanning [8, 9, 15].

This is evidenced by the currently insignificant number of publications [21, 22], where fractal analysis azimuth and ellipticity distributions for blood plasma facies was effectively used for healthy and cancerous tissues differential diagnosis. In particular, it was demonstrated for the first time that oncological changes are detected in transforming fractal polarization distributions of blood plasma facies' microscopic images into multifractal ones [13, 17, 21].

Thus, it can be stated that fractal properties are inherent not only in geometric morphological parameters, but also polarization manifestations of the biological tissue optical anisotropy. This fundamental result can become a starting point for a new direction for biomedical diagnostics: multifractal scanning of biological tissues optical anisotropy structure.

A promising direction for such diagnostics is the study of biological fluids. These samples are easily accessible and do not require invasive biopsy procedures. Also, a drop of biological fluid (BF) located on a horizontal plane is an informative model for the analysis of physical and chemical processes, in particular, it is possible to determine the composition of substances dissolved in the fluid, as well as the conditions of the substrate substance and external dehydration. As a result of dehydration of a BP drop, a dry film is created – "facies", a structure that reveals information about the composition and composition of substances dissolved in the BP. By removing the fluid, the researcher has the opportunity to obtain information about the state of the system at the molecular level [2, 5, 10]

The authors of the article have developed a new method for mapping the Jones matrix by analyzing the optically anisotropic structure of dehydrated blood films based on the use of multifractal analysis of coordinate distributions of linear birefringence in supramolecular networks [3, 19, 23].

The applied aspect of the study involves identifying statistical markers that characterize the spectra of fractal dimensions of birefringence maps, enabling differential diagnosis of inflammatory septic processes.

1. Brief theory of the method

It is known [1, 5, 19] that fractal properties are inherent in the polarization manifestations of optical anisotropy, which form scale-invariant distributions, or "fractal measures".

According to fractal theory, these measures of thezigrams $JT(m,n)$) are of two types: fractal JT^{h} or multifractal $JT^{F(h)}$.

For fractal distributions of thezigrams JT^{h}, there exists a single fractal dimension $h \equiv h_0$, that characterizes them.

Multifractal distributions of thezigrams for the optical anisotropy parameters of polycrystalline domains in biological fluids $JT^{F(h)}$ are characterized by a set of fractal dimensions h_r or a spectrum of singularities $F(h_r)$.

To calculate the fractal dimension h_i, a specific approach is used, which involves introducing partial functions or a generalized statistical sum.

$$Z(r,d) = \sum_{i=1}^{P(d)} JT_i^r(d) \quad (1)$$

here $P(d)$ – is the multifractal distribution of the number of fractal dimensions of the theziograms JT_i^r; $r \in R$.

As a rule, the dependence (1) has a power-law form

$$Z(r,d) \sim d^{(r-1)h_r} \quad (2)$$

where h_r is the generalized fractal dimension, which, in the case of the partial function, is written as the scaling exponent

$$\tau(r) = (r-1)h_r \quad (3)$$

here, the exponent $(r-1)$ is introduced into the exponent for automatically satisfy the equality $Z(1.d) = 1$, which corresponds to the normalization condition for the distribution $JT_i^r(d)$.

To analytically determine the dependence (h_r), the modulus maxima wavelet transform method (MMWT) is used [2, 4, 11].

The MMWT (Modulus Maxima Wavelet Transform) consists of two steps:

- Wavelet Transform $W(a,b)$ of the theziograms $JT(m,n)$ and determination of the skeleton $sup|W(a^*, x_i(a^*))|$ – the line of extreme of the amplitude modulus of coefficients of wavelet transform $W(a,b)$ at different scales a of the scanning soliton-like function $\Psi(b)$;
- Determination of the modulus of wavelet coefficients $Z(r, d, sup|W(a^*, x_i(a^*))|)$ construction of partial functions ((1)-(3)) of local maxima, and determination of the fractal dimension spectrum $F(h_r)$.

The wavelet analysis of the theziograms $JT(m,n)$ is based on an analytical transform consisting of decomposing the distribution into a basis constructed from a soliton-like function (wavelet) using multiscale variations a and coordinate shifts b

$$W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} JT(x) M\left(\frac{x-b}{a}\right) dx \quad (4)$$

here a – is the scaling parameter, b – is the spatial coordinate, and M – is the soliton-like (wavelet) function.

In the following, we focus on exploring the possibility of scanning and determining the exponents $\tau(r)$ (4), which characterize $JT_i^r(d)$ using the skeletons $sup|W(a^*, x_i(a^*))|$.

This analytical procedure is based on utilizing a construction of partial functions according to the following equation

$$Z(r,d) = \sum_{l \in L(a)} (sup|W(a^*, x_i(a^*))|)^r \quad (5)$$

According to [12, 19], the following dependencies are determined $Z(r,d) \sim d^{\tau(r)}$, where the fractal dimensions $\tau(r)$ for each r are computed from the slope of the dependency of the exponents $\ln Z(r,d)/\ln d$.

Variations of r in the construction $\sum_{l \in L(a)} (sup|W(a^*, x_i(a^*))|)^r$ allow us to obtain:

- for fractal distributions $JT_i^r(d)$ the dependencies $\tau(r)$, are linear – $(h(r) = {d\tau}/{dr} = const)$;
- for multifractal distributions $JT_i^r(d)$ linear dependencies $\tau(r) = rh - D(h)$ with fractal dimensions $h(r) = {d\tau}/{dr}$ are absent. Instead, there exists a range of dimensions characterized by the multifractal spectrum $F(h(r))$.

In our case, we studied the multifractal spectra of theziograms JT based on partial functions $Z(r, d, sup|W(a^*, x_i(a^*))|)$ using the skeletons of amplitude modulus maxima of the wavelet transform $sup|W(a^*, x_i(a^*))|$ These were applied to different types of optical anisotropy in supramolecular networks of biological fluid phases, where $Z(r, d, sup|W(a^*, x_i(a^*))|) \Leftrightarrow \ln Z(r,d)/\ln d$.

To obtain coordinate polarization distributions, an experimental setup is used, the detailed description of which is provided in [8, 12, 19].

The obtained multifractal spectra $F(h_j)$ of Jones matrix theziograms $JT(m,n)$ were analyzed statistically using algorithms for deterring of statistical central moments of the 1st to 4th orders, namely: the mean (Z_1), variance (Z_2), skewness (Z_3) and kurtosis (Z_4). These moments characterize the distributions of linear birefringence in the supramolecular networks of blood film samples.

2. Multifractal analysis of layered theziograms of phase anisotropy in dehydrated blood drop films

To conduct a comprehensive study, two groups of dehydrated blood drop film samples from rats were formed:

- healthy animals – control group 1, consisting of 17 samples.
- septically affected animals – experimental group 2, consisting of 17 samples.

Figure 1 shows the results of the wavelet analysis of Jones matrix-reconstructed theziograms of linear birefringence.

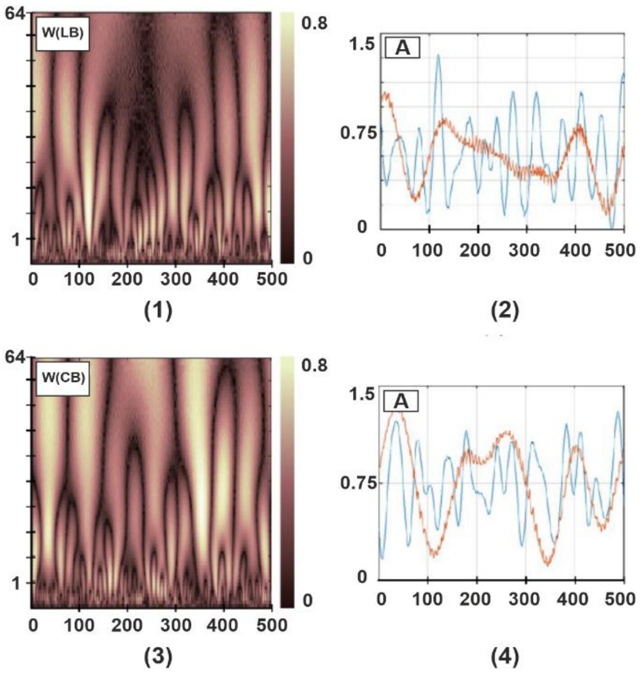

Fig. 1. Maps of wavelet coefficients $W(a,b)$ (left column) and linear multiscale dependencies of the wavelet coefficient amplitudes of the theziograms of linear birefringence in dehydrated blood films from healthy rats (top row) and septic rats (bottom row). Blue lines – μ_k (a = 15); red lines – μ_k (a = 55)

The analysis of the obtained data revealed:

- individual modulation and coordinate heterogeneity of the values of amplitude $\mu_k(a=15)$ and $\mu_k(a=55)$ of the coefficients of wavelet μ_k of distributions of the wavelet coefficients $W(\mu_k, b)$ on the maps of linear LB birefringence in blood films from rats in group 1 and group 2 are shown in Fig. 1, right columns,
- for structural birefringence (LB), the maximum amplitude and variations in the magnitude of wavelet coefficients μ_k are present at all scales of the scanning soliton-like function (MHAT) in the theziograms of blood film samples from healthy rats (Fig. 1).

The comparison of the results of statistical analysis of the amplitude distributions of coefficients of multiscale wavelet $A(\mu_k)$ in the theziograms of phase anisotropy in dehydrated blood films from rats in both groups revealed the following patterns.

Firstly, for the blood samples from healthy rats, the statistical moments of the 1st and 2nd orders, determined for different scales a of the scanning soliton-like MHAT function in the wavelet maps of the linear LB birefringence theziograms, are 1.45 to 1.55 times greater than the corresponding statistical parameters that characterize the scale-selective structure $W(LB, \mu_i, b)$ of the theziograms of structural anisotropy in the blood films from septic rats, as shown in table 1.

Table 1. Statistical parameters of the amplitude distributions of coefficients wavelet $A(\mu_k)$ in the LB theziograms of blood dehydrated films from rats (healthy (group 1) and septic (group 2))

Linear birefringence LB						
a_i	$a_{min} = 15$		$Ac, \%$	$a_{max} = 55$		$Ac, \%$
Z_i	Group 1	Group 2		Group 1	Group 2	
Z_1	0.57±0.031	0.39±0.016	91.2	0.46±0.024	0.36±0.019	88.2
Z_2	0.68±0.035	0.45±0.024	94.1	0.54±0.029	0.41±0.024	91.2

As a result, the maximum balanced accuracy of differential wavelet diagnostics reaches the following levels:

The wavelet maps $W(LB, \mu_i, b)$ of linear birefringence LB – $Ac(Z_{i=2}(\varphi = \pi/8)) = 94.1\%$ – a very good level.

Figure 2 shows the multifractal spectra $F(LB, h)$, *f* the linear birefringence theziograms $T(LB, m \times n)$, determined by the method of analyzing the modulus of extremum amplitudes of wavelet coefficients.

The analysis of the algorithmically reproduced multifractal structure of the distributions of birefringence linear in the polycrystalline network of dehydrated blood film samples from septic and healthy rats revealed significant differences (up to 2–2.5 times) between the values of the central statistical moments of the 1st to 4th orders of structural anisotropy (table 2).

$$\begin{pmatrix} Z_{i=1;2}(F(h, LB), \text{group 2}) > Z_{i=1;2}(F(h, LB), \text{group 1}) \\ Z_{i=3;4}(F(h, LB), \text{group 2}) < Z_{i=3;4}(F(h, LB), \text{group 1}) \end{pmatrix}$$

Table 2. Statistical characteristics of the distributions of fractal dimensions of the theziograms of linear LB birefringence in the combined network of dehydrated blood film

$F(h)$			
T	LB		$Ac, \%$
Z_1	1.39±0.065	1.52±0.078	88.2
Z_2	0.27±0.016	0.43±0.022	97.1
Z_3	1.12±0.064	0.62±0.034	94.1
Z_4	1.89±0.092	0.97±0.049	97.1

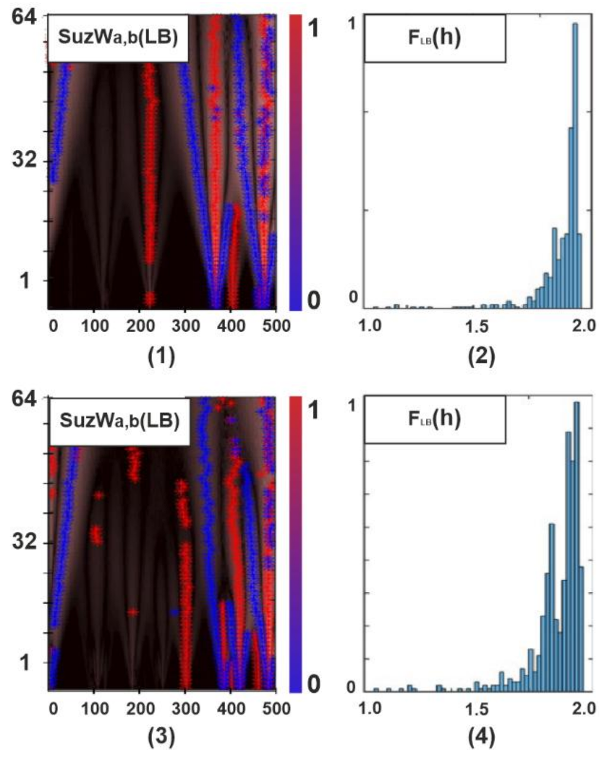

Fig. 2. Fractal dimension spectra of the theziograms T of linear LB birefringence in the combined network of dehydrated blood films from healthy (fragment (1)) and septic (fragment (2)) rats

Within the framework of multifractal analysis, the following was revealed:

- Physical scenarios of "pathological" changes in the of multifractal spectra structure:

$$\left(Z_{i=1;2}(F(h, LB), \text{group 2}) > Z_{i=1;2}(F(h, LB), \text{group 1})\right)$$

and

$$\left(Z_{i=3;4}(F(h, LB), \text{group 2}) < Z_{i=3;4}(F(h, LB), \text{group 1})\right)$$

which characterize the set of theziograms of polycrystalline networks of dehydrated blood films from rats.

- Within the framework of informational analysis, the following maximum levels of accuracy balanced for differential sepsis diagnostics were established;
- Wavelet analysis – wavelet maps $W(LB, \mu_i, b)$ of linear LB birefringence – $Ac(Z_{i=2}) = 94.1\%$ - a very good level;
- Multifractal analysis – multifractal spectra $F(LB, h)$ of linear birefringence – $Ac(Z_{i=2;4}) = 97.4\%$ – an excellent level.

3. Conclusion

A new technique of laser polarization-interference Jones-matrix theziography of birefringence in supramolecular networks of dehydrated blood films has been developed.

The paper proposes the use of multifractal analysis by algorithmic implementation of coordinate reconstructed distributions of linear double-change magnitude and obtaining a spectrum of fractal dimensions of dehydrated polycrystalline blood films.

Within the framework of statistical analysis of multifractal spectra and wavelet maps, it was determined that the algorithmically reconstructed birefringence theziogram allows identifying the most sensitive markers to changes in the anisotropic optical structure of blood caused by septic manifestations.

Very good (wavelet analysis – 94.1%) and excellent (multifractal analysis – 97.4%) accuracy of differential diagnostics for experimental samples of dehydrated blood films from healthy and septic subjects was achieved.

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Ethics approval and consent to participate

This study was conducted in accordance with the principles of the Declaration of Helsinki, and in compliance with the International Conference on Harmonization-Good Clinical Practice and local regulatory requirements. Ethical approval was obtained from the Ethics Committee (protocol No 7, 16.05.2024) of the Bukovinian State Medical University (Chernivtsi, Ukraine).

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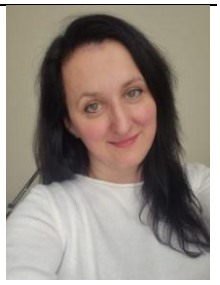

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