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**Yu. USHENKO, Yu. HALIN, O. USHENKO, O. DUBOLAZOV, Yu. TOMKA,
M. GAVRILYAK, O. LYTVYNENKO, V. KYFYAK, O. VINNYCHUK, V. DVORZHAK**

METHODS AND ALGORITHMS OF POLARIZATION-CORRELATION MAPPING OF BIOMEDICAL IMAGES

Yuriy Fedkovych Chernivtsi National University, 2 Kotsjubynskyi Str. Chernivtsi, Ukraine
Bukovinian State Medical University, 2 Teatralna Square, Chernivtsi, Ukraine

Abstract. The theory of a new method of polarization-correlation mapping of biomedical images is presented. Algorithms for the determination and digital "two-point" analysis of the distributed modulus and argument of the azimuth and ellipticity of polarization-correlation maps are obtained. Computer modeling of the effectiveness of polarization-correlation analysis in the differentiation of polycrystalline structures with different levels of birefringence was carried out. An example of the application of the method in the differentiation of polarization-correlation maps of native histological brain sections with different ages of craniocerebral trauma is given.

Keywords: Polarization, correlation, azimuth, ellipticity, birefringence, statistical moments, histological section, brain, craniocerebral trauma.

Анотація. Представлено теорію нового методу поляризаційно-кореляційного відображення біомедичних зображень. Отримано алгоритми для визначення та цифрового «двоточкового» аналізу розподілених модуля і аргументу азимуту та еліптичності поляризаційно-кореляційних карт. Проведено комп’ютерне моделювання ефективності поляризаційно-кореляційного аналізу під час диференціації полікристалічних структур із різними рівнями двопроменезаломлення. Наведено приклад застосування методу для диференціації поляризаційно-кореляційних карт нативних гістологічних зрізів мозку з різними строками краніоцеребральної травми.

Ключові слова: поляризація, кореляція, азимут, еліптичність, двопроменезаломлення, статистичні моменти, гістологічний зріз, мозок, краніоцеребральна травма.

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INTRODUCTION

Recently, numerous studies in the field of laser polarimetry [1-4] widely use digital data processing methods [5-9], including polarization visualization of the optically anisotropic structure of tissue preparations of human organs [10-12]. These studies within the framework of the statistical analysis of the obtained biomedical images made it possible to determine objective criteria (markers) for identifying various types of pathological changes (precancer, cancer, sepsis, etc.) of human organs [13-20]. However, such digital markers provide the possibility of obtaining information only integrally averaged over all coordinates and scales of the biomedical image. This significantly limits the sensitivity of polarimetric techniques. A new approach [21] with the use of correlation analysis of polarization images of biological tissue preparations can be one of the promising ways of increasing the diagnostic efficiency of polarization mapping methods.

Relevance such research conditioned also and economic factors Global economic losses from injuries are substantial, reaching trillions of dollars annually. Road injuries alone cost the world economy an estimated \$1.8 trillion between 2015-2030. In 2023, work injuries cost the US economy \$176.5 billion. The total cost of fatal and nonfatal preventable injury-related incidents in 2023 was \$1,333.5 billion [22 - 27].

Our work is aimed at the development and testing of new algorithms for polarization-correlation analysis of azimuth and ellipticity of polarization maps of microscopic images of native preparations of biological tissues. The applied problem of differentiation of polarization images of histological sections of the brain with different ages of craniocerebral trauma is considered.

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1. MATERIALS AND METHODS

1.1. Algorithms of polarization- correlation analysis

The Jones matrix $\|J(LB,\rho)\|$model of formation of polarization-correlation parameters by birefringent structures is considered

$$\|J(LB,\rho)\| = \begin{Vmatrix} (cos0.5LB - icos2\rho sin0.5LB)_{11} & (sin2\rho sin0.5LB)_{12} \\ -(sin2\rho sin0.5LB)_{21} & (cos0.5LB - icos2\rho sin0.5LB)_{22} \end{Vmatrix}. \quad (1)$$

Here LB is the birefringence index; ρ- optical axis orientation.

Taking (1) into account, the following analytical relationships between the “two-point” Stokes vector SC [21] and the parameters of the optical anisotropy of a birefringent crystal were obtained

$$\begin{pmatrix} SC_1 \\ SC_2 \\ SC_3 \\ SC_4 \end{pmatrix} = \begin{pmatrix} E^*_{x1}E_{x2} + E^*_{y1}E_{y2} \\ E^*_{x1}E_{x2} - E^*_{y1}E_{y2} \\ E^*_{x1}E_{y2} + E^*_{y1}E_{x2} \\ i(E^*_{y1}E_{x2} - E^*_{x1}E_{y2}) \end{pmatrix}; \begin{matrix} E_x = 1 - 0.5iLBcos2\rho; \\ E_y = -0.5iLBsin2\rho; \end{matrix} \quad (2)$$

$$\begin{pmatrix} SC_1 \\ SC_2 \\ SC_3 \\ SC_4 \end{pmatrix} = \begin{pmatrix} \left(1 + 0.25LB_1LB_2cos2(\rho_1 - \rho_2) + 0.5i(LB_2cos2\rho_2 - LB_1cos2\rho_1)\right) \\ \left(1 + 0.25LB_1LB_2cos2(\rho_1 - \rho_2) - 0.5i(LB_2cos2\rho_2 - LB_1cos2\rho_1)\right) \\ -0.25LB_1LB_2sin2(\rho_1 - \rho_2) + 0.5i(LB_1sin2\rho_1 - LB_2sin2\rho_2) \\ -0.5(LB_1sin2\rho_1 + LB_2sin2\rho_2) - 0.25iLB_1LB_2sin2(\rho_1 - \rho_2) \end{pmatrix} \quad (3)$$

Taking into account (1)-(3), the basic algorithms for calculating the modulus ($||$) and argument (Arg) of complex "two-point" values of azimuth (α_{12}) and ellipticity (β_{12}) of polarization are determined

$$\begin{cases} \alpha_{12} = 0.5\text{arctan}\left(\frac{E^*_{x1}E_{y2}+E^*_{y1}E_{x2}}{E^*_{x1}E_{x2}-E^*_{y1}E_{y2}}\right); \\ |\alpha_{12}| = 0.5\,\text{arctan}\left(\sqrt{\frac{C^2+D^2}{A^2+B^2}}\right); Arg(\alpha_{12}) = 0.5arctan\left(\frac{AD-BC}{AC+BD}\right); \end{cases} \quad (4)$$

$$\begin{cases} \beta_{12} = 0.5\,\text{arcsin}\left(\frac{i(E^*_{y1}E_{x2}-E^*_{x1}E_{y2})}{E^*_{x1}E_{x2}+E^*_{y1}E_{y2}}\right); \\ |\beta_{12}| = 0.5\,\text{arcsin}\left(\sqrt{\frac{F^2+H^2}{A^2+B^2}}\right); Arg(\beta_{12}) = 0.5arctan\left(\frac{AH-BF}{AF+BH}\right), \end{cases} \quad (5)$$

where

$$\begin{cases} A = ReE_{x1}ReE_{x2} + ImE_{x1}ImE_{x2} + ReE_{y1}ReE_{y2} + ImE_{y1}ImE_{y2}; \\ B = (ReE_{x1}ImE_{x2} + ReE_{y1}ImE_{y2}) - (ImE_{x1}ReE_{x2} + ImE_{y1}ReE_{y2}); \\ C = ReE_{x1}ReE_{y2} + ImE_{x1}ImE_{y2} + ReE_{y1}ReE_{x2} + ImE_{y1}ImE_{x2}; \\ D = (ReE_{x1}ImE_{y2} + ReE_{y1}ImE_{x2}) - (ImE_{x1}ReE_{y2} + ImE_{y1}ReE_{x2}); \\ F = (ImE_{y1}ReE_{x2} + ReE_{x1}ImE_{y2}) - (ReE_{y1}ImE_{x2} + ImE_{x1}ReE_{y2}); \\ H = (ReE_{y1}ReE_{x2} + ImE_{y1}ImE_{x2}) - \left(ReE_{x1}ReE_{y2} + ImE_{x1}ImE_{y2}\right). \end{cases} \quad (6)$$

1.2. Model polarization-correlation maps of birefringent networks

Two objects are considered - with the same harmonic modulation of the magnitude of birefringence LB=0,2$\pi sin\frac{2\pi}{100}m$ and different modulation periods of optical axes ρ=$\pi sin\frac{2\pi}{100}m$(A) and $\tilde{\rho}$=$\pi sin\frac{2\pi}{80}m$(B).

The results of computer modeling of polarization-correlation A and B maps are presented in Fig. 1.

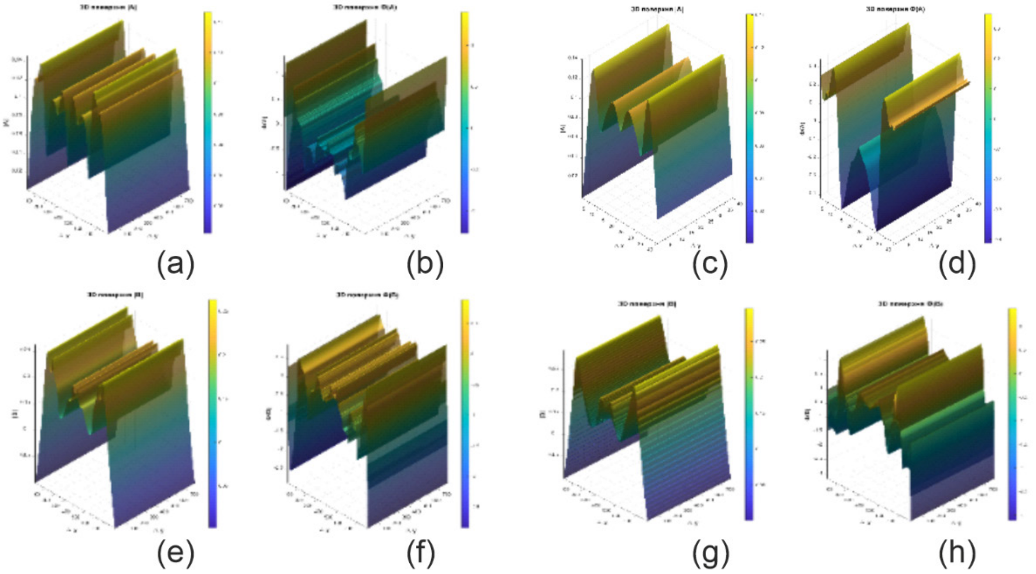

Figure 1 – Polarization-correlation maps $|\alpha_{12}|$(a, c); $|\beta_{12}|$(e, f) and $Arg(\alpha_{12})$(b, d); $Arg(\beta_{12})$(g, h) objects A (a, b, e, f) and B (c, d, g, h). Scan step $m = 1$ ($0 \leq \delta \leq 0{,}2\pi; 0 \leq \rho \leq \pi$)

The analysis of the obtained results of the computer modeling of the coordinate structure of the distributed module and the argument of the "two-point" azimuth and ellipticity of the polarization of the images of birefringent objects of type A and B demonstrated a high sensitivity to variations in the orientation of the optical axes. Quantitatively, such differences illustrate the results of statistical analysis of the polarization-correlation parameters of model objects A and B, which are shown in Table 1.

Table 1.Statistical moments of the 1st-4th orders of polarization-correlation parameters of model objects of type A and B

Objects	AND	IN	AND	IN
Parameters	$\|\alpha_{12}\|$		$Arg(\alpha_{12})$	
Average,Z_1	0.087	0.098	0.14	0.21
Dispersion,Z_2	0.00059	0.00043	0.0081	0.011
Skewness,Z_3	0.33	1.6 1	0.72	1.99
Kurtosis ,Z_4	1.99	6.4 1	1.54	9.14
Parameters	$\|\beta_{12}\|$	$\|\beta_{12}\|$	$Arg(\beta_{12})$	$Arg(\beta_{12})$
Average,Z_1	0.012	0.029	0.055	0.074
Dispersion,Z_2	0.13	0.096	0.19	0.12
Skewness,Z_3	1.12	1.17	0.92	1.071
Kurtosis ,Z_4	3.72	5.95	3.14	4.98

Statistical moments of the 3rd and 4th orders, which characterize the skewness and kurtosis of the distributed modulus ($||$) and argument (Arg) of the complex values of the "two-point" azimuth (α_{12}) and ellipticity (β_{12}) of the polarization, turned out to be the most sensitive to changes in the orientational polycrystalline structure of model birefringent objects. The differences between the values of these statistical markers range from 2 to 5 times.

1.3. Experimental location and method of polarization-correlation mapping

Experimental measurements of the polarization-correlation mapping (PCM) field of biospeckles were carried out in the location of the Mach-Zehnder polarization interferometer (Fig . 1). A detailed description of the parameters of the optical circuit is contained in [6-8] and is not presented here.

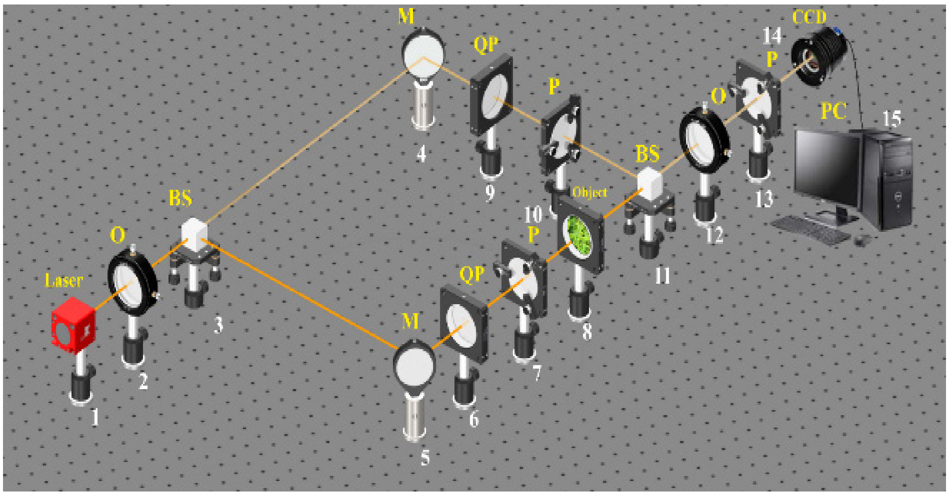

Figure 2 – Optical scheme of the Mach-Zehnder polarization interferometer

The method of measuring PCM the biospeckle field includes the following stages:

1. Using polarizing filters "QP-P"6-7 and 9-10 (Fig. 1), collinear states of linear polarization of the "illuminating" $Ir(45^0)$) and "reference" $Ref(45^0)$) laser beams are formed.
2. The digital camera CCD14 records the intensity distributions of interference patterns ($I_{x;y}^{45}(m \times n)$) for two orientations (θ=0^0; θ=90^0) of the transmission plane of the polarizer-analyzer P13
3. By means of digital two-dimensional Fourier transform [6-8] $I_{x;y}^{45}(m,n)$ the distributions of complex amplitudes $E_{x;y}^{45}(m,n)$of the biospeckle field are reconstructed

$$E_{x;y}^{45}(m,n)=\frac{1}{M \times N}\sum_{m=0}^{M\text{-}1}\sum_{n=0}^{N\text{-}1}\{I_{x;y}^{45}\exp(\text{-}i2\pi(\frac{m \times \upsilon}{M}+\frac{m \times \nu}{N}))\}; \tag{7}$$

where (υ, ν)– space frequencies; (M=1120; N=960)- pixels number.

4. The results of the digital Fourier transform (relations (7)) are used to obtain complex amplitude distributions according to the following algorithms

$$E_x^{45}(m,n) \rightarrow |E_x^{45}(m,n)|(m,n); \tag{8}$$

$$E_y^{45}(m,n) \rightarrow (|E_y^{45}(m,n)|\exp(i(\delta_x^{45}\text{-}\delta_y^{45})))(m,n). \tag{9}$$

5. In order to isolate the single-scattered component ($E_{x;y}^{single}$), layer-by-layer ($\Delta\delta_{xy}^{45}$=$0.1rad$) phase scanning of the object field (8), (9) was carried out.
6. In each phase plane, the amplitude distributions $E_y^{45}(\delta_x^{45}, m, n)$are scanned using double iterations $\Delta x \in [\text{-}(n\text{-}1), (n\text{-}1)]$and $\Delta y \in [\text{-}(m\text{-}1), (m\text{-}1)]$with a discrete step Δ=$1pix$.
7. For each such step, coordinate distributions of the module are calculated $|\alpha_{12}|(E_{x;y}^{single})$; $|\beta_{12}|(E_{x;y}^{single})$ and the argument of $Arg(\alpha_{12}(E_{x;y}^{single}))$; $Arg(\beta_{12}(E_{x;y}^{single}))$ "two-point" azimuth and ellipticity of polarization.

1.4. Experimental polarization-correlation maps of native histological slices of the brain

We conducted a study of the diagnostic effectiveness of the PCM method of microscopic images of native histological sections of the brain in differentiating the history of traumatic brain injury (TBI) of the dead.

Two groups of samples were studied:

- History of TBI – 12 hours (21 samples, group 1);
- The history of TBI is 18 hours (21 samples, group 2).

On the series of fragments of fig. 3 and fig. 4 presents "two-point" polarization maps in the phase plane δ_{xy}^{single}=0.25π of biospeckle fields of samples from both groups.

The analysis of the data obtained from the experimental polarization-correlation mapping of microscopic images of native histological slices of the brain demonstrated a correlation with the data of analytical modeling (Fig. 1) in the task of detecting changes in optical anisotropy.

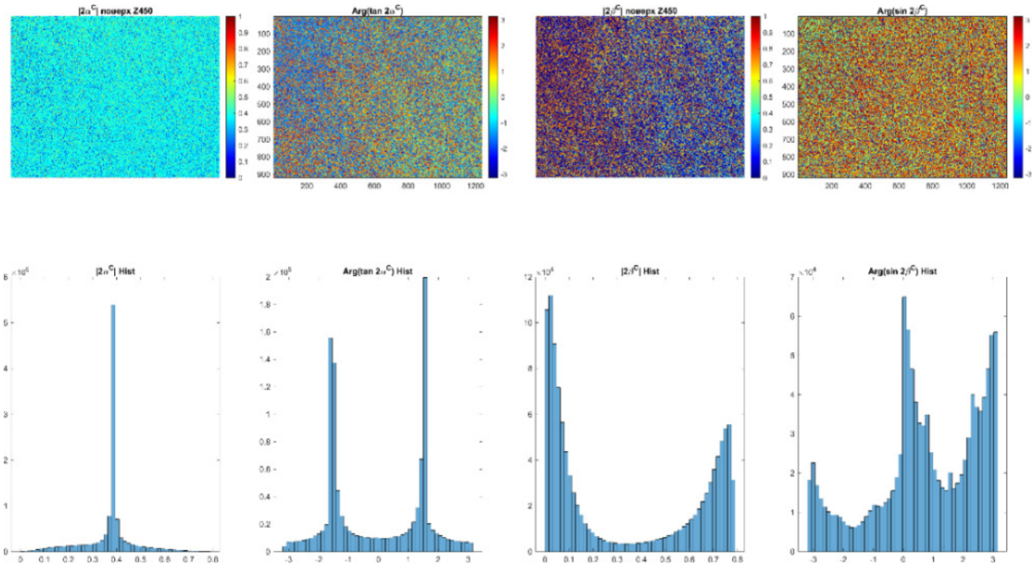

Figure 3 – Polarization-correlation maps of the module (a , c) and argument (b , d), as well as histograms of the distributed values of the real e , g) and imaginary (i , h) parameters of the "two-point" azimuth α_{12}(a , b , e , i) and ellipticity β_{12}(c , d , g , h) of the microscopic image of the native histological section with a history of craniocerebral trauma 12 hours

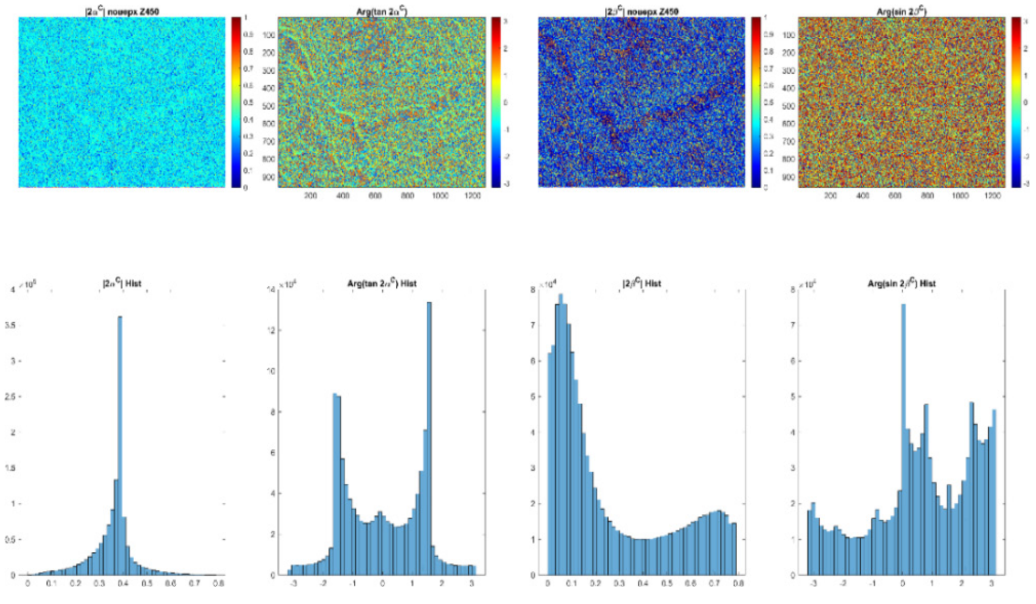

Figure 4 – Polarization-correlation maps of the module (a, c) and argument (b , d), as well as histograms of the distributed values of the real (e , g) and imaginary (i , h) parameters of the "two-point" azimuth α_{12}(a , b , e , i) and ellipticity β_{12}(c , d , g , h) of the microscopic image of the native histological section with craniocerebral trauma is 18 hours old

We established an individual coordinate and statistical (Table 2) structure of maps of the module and argument of "two-point" polarization parameters of microscopic images of native histological sections of the brain with different ages of traumatic brain injury.

The statistical moments of the 3rd and 4th orders, which characterize the skewness and kurtosis of the distributed modulus ($||$) and argument (Arg) of the complex values of the "two-point" azimuth (α_{12}) and ellipticity (β_{12}) of the polarization, turned out to be the most sensitive to changes in the polycrystalline structure of brain tissue samples. The differences between the values of these statistical markers reach 2 times.

Table 2. Polarization-correlation maps

	$\lvert\alpha_{12}\rvert(\delta_{xy}^{single}, m, n)$		$\lvert\beta_{12}\rvert(\delta_{xy}^{single}, m, n)$	
$\bar{Z}_i$	**12 hours**	**1 8 hours**	**12 hours**	**1 8 hours**
$\bar{Z}_1$	0.23 ±0.02	0.41±0.02	0.41±0.03	0.61±0.04
$\bar{Z}_2$	0.11±0.001	0.16±0.01	0.29±0.02	0.45±0.03
$\bar{Z}_3$	1.41±0.07	0.76±0.04	0.47±0.03	0.21±0.02
$\bar{Z}_4$	2.43±0.2	1.06±0.06	0.65±0.04	0.33±0.04
	$Arg(\alpha_{12}(\delta_{xy}^{single}, m, n))$		$Arg(\beta_{12}(\delta_{xy}^{single}, m, n))$	
$\bar{Z}_i$	Normal	Precancer	Normal	Precancer
$\bar{Z}_1$	1.03±0.06	1.49±0.07	1.02±0.06	1.78±0.2
$\bar{Z}_2$	0.76±0.04	1.18±0.05	0.73±0.04	1.08±0.05
$\bar{Z}_3$	0.88±0.05	0.61±0.04	0.87±0.04	0.41±0.03
$\bar{Z}_4$	1.45±0.08	0.99±0.05	1.32±0.07	0.67±0.04

CONCLUSIONS

1. A new algorithmic method of polarization-correlation mapping of optical fields is proposed.
2. Enhanced Read Performance: Direct access to consolidated data provided substantial improvements in data retrieval efficiency, particularly beneficial for time-series analytics.
3. Columnar Storage Optimization: The denormalized structure leveraged the advantages of columnar storage in Azure Synapse, achieving superior compression ratios and improved query performance.
4. Temporal Query Efficiency: The embedding of temporal attributes directly in the fact table significantly enhanced the performance of time-based filtering and aggregation operations.

Ethics approval and consent this participate

This study was conducted according to 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 #7, 16.05.2024) of the Bukovinian State Medical University (Chernivtsi, Ukraine), and written informed consent was obtained from all subjects before study initiation.

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USHENKO YURII – D.Sc., Professor, Head of Computer Science Department, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine**, *e-mail: y.ushenko@chnu.edu.ua***

HALIN YURIY – PhD student, Computer Science Department, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine**, *e-mail: y.halin@chnu.edu.ua***

USHENKO OLEXANDER – D.Sc., Professor, Department of Printing, Multimedia and Optical Technologies, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine**,**
e-mail: o.ushenko@chnu.edu.ua

DUBOLAZOV OLEXANDER – D.Sc., Professor, Department of Printing, Multimedia and Optical Technologies, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine**,**
e-mail: a.dubolazov@chnu.edu.ua

TOMKA YURIY – Ph.D., Associate Professor of Computer Science Department, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine, ***e-mail: y.tomka@chnu.edu.ua***

GAVRILYAK MIKHAILO – Ph.D., Associate Professor of Correlation Optics Department, Yuriy Fedkovich Chernivtsi National University, Chernivtsi, Ukraine, ***e-mail: m.gavrylyak@chnu.edu.ua***

LYTVYNENKO OLEXANDRA – Ph.D., Department of Forensic Medicine and Medical Law, Bukovinian State Medical University, Chernivtsi, Ukraine, ***e-mail: office@bsmu.edu.ua***

KYFYAK VICTORIA – Ph.D., Associate Professor at the Department of Business and Human Resource Management, Yuriy Fedkovich Chernivtsi National University, Chernivtsi, Ukraine,
e-mail: v.kyfyak@chnu.edu.ua

VINNYCHUK OLENA – Ph.D., Associate Professor at the Department of Economic and Mathematical Modelling, Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine,
e-mail: o.vinnychuk@chnu.edu.ua

DVORZHAK VALENTYNA – Ph.D., Assistant professor of Computer Science Department, Yuriy Fedkovich Chernivtsi National University, Chernivtsi, Ukraine, ***e-mail: v.dvorzhak@chnu.edu.ua***

Ю.О. УШЕНКО, Ю.О. ГАЛІН, О.Г. УШЕНКО, О.В. ДУБОЛАЗОВ,
Ю.Я. ТОМКА, М. С. ГАВРИЛЮК, О.В. ЛИТВИНЕНКО,
В.В. КИФЯК, О.Ю. ВІННИЧУК, В.В. ДВОРЖАК

МЕТОДИ ТА АЛГОРИТМИ ПОЛЯРИЗАЦІЙНО-КОРЕЛЯЦІЙНОГО КАРТОГРАФУВАННЯ БІОМЕДИЧНИХ ЗОБРАЖЕНЬ

Чернівецький національний університет імені Юрія Федьковича
Буковинський державний медичний університет