УДК 681.7: 616-71

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POLARIMETRIC SYSTEM OF MUELLER-MATRIX DIAGNOSTICS OF TWO-COMPONENT BIOLOGICAL STRUCTURES WITH DECISION-MAKING SUPPORT

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Анотація. Розроблено метод та систему діагностики підповерхневих шарів двокомпонентних біологічних структур на основі вимірювання та аналізу орієнтаційних та фазових зображень матриць Мюллера оптично тонких зразків. Метод діагностики доповнено класифікаційним аналізом інформативних ознак мюллер-матричних зображень. Система діагностики має розширені функціональні можливості за рахунок введення підсистеми підтримки прийняття рішення. Виведено нечіткі моделі підтримки прийняття рішення та оцінено достовірність діагностики онкопатології шийки матки за допомогою розробленої системи.
Ключові слова: поляриметрична система, мюллер-матрична діагностика, двокомпонентні біологічні структури, підтримка прийняття рішень, біологічна тканина, нечіткі моделі.
Abstract. A method and system for diagnosing subsurface scars of two-component biological structures has been developed based on the measurement and analysis of orientation and phase images of the Mueller matrices of optically thin samples. The diagnostic method is complemented by a classification analysis of informative features of Mueller matrix images. The diagnostic system has expanded functionality due to the introduction of a decision support subsystem. Fuzzy models of decision-making support were derived and the reliability of diagnosis of cervical oncology using the developed system was evaluated.
Key words: polarimetric system, Mueller-matrix diagnostics, two-component biological structures, decision support, biological tissue, fuzzy models

DOI: 10.31649/1681-7893-2024-47-1-120-127

INTRODUCTION

The introduction of methods and systems of laser polarimetric diagnostics of biological tissues in medicine is due to the need to ensure high sensitivity of differentiation of healthy and tumor tissues. Polarized light, when interacting with biological materials, performs the function of an "instrumental probe", making it possible to quantitatively assess the microstructural optical anisotropy of biological tissues (BT) [1-3].

Many approaches are based on the analysis of the Mueller matrix of the studied biological layer, which essentially characterizes its transmission function when interacting with polarized probing radiation [4]-[5]. It contains information about the polarization-phase properties of the studied biological layer as a two-component amorphous-crystalline structure. A high sensitivity of the measured distributions of the elements of the Müller matrix of optically thin tissues in the case of a single scattering of polarizing radiation to the pathological conditions of biological tissues of various morphological origins was revealed: cancerous lesions of the skin [5], tumor processes of cervical tissues [6], stomach cancers [7] and others.

Automated systems of imaging laser Müller-polarimetry contain in their structure a digital camera with $M \times N$ pixel resolution. It allows to register two-dimensional distributions of polarization-filtered optical fields, formed during the transmission of differently polarized laser radiation through optically thin biological layers. Based on them, a complete set of 16 Mueller matrix images (MMI) of the studied biological layer is algorithmically formed.

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When performing Müller-polarimetric diagnostics of biological layers, not a complete set of elements of the Müller matrix is often used, but only distributions of individual elements from the group of orientational and/or phase elements of MMI. Thus, on the basis of statistical and correlational analysis of orientational and phase MMI of histological sections of the cervix, the reliability of cancer diagnosis was achieved at the level of 83,7% and 89,5%, respectively [8].

The study of real multi-layered biological tissues is relevant in the way of expanding the arsenal of diagnostic methods of Muller polarimetry. Modeling and quantitative analysis of MMI of two-layer optically thin BT showed the presence of diagnostic criteria for pathological conditions of different types of BT, confirmed by experimental results. A well-known method of reconstruction of the orientation and phase parameters of the subsurface layers of two-component biological layers, which, due to the variation of the polarization states of the laser probing radiation, allows to eliminate the influence of the outer layer on the MMI of the two-component tissue [10,11,12].

One of the restraining factors of increasing the reliability of the diagnosis of two-component, two-layer biological tissues in Mueller-matrix polarimetry systems is the lack of classification analysis and decision-making support [13,14,15].

The purpose of the work is to increase the reliability of the method of assessing the pathological conditions of two-component biological tissues and to expand the functionality of the system of Muller-polarimetric diagnostics of biological samples by applying methods of reconstruction of distributions of Muller-matrix images of subsurface layers of two-component biological structures, their analysis and automated decision-making support.

METHOD AND SYSTEM OF DIAGNOSTIC TWO-COMPONENT BIOLOGICAL STRUCTURES

As is known from the works [1, 4], with optimal states of polarization of laser radiation transformed by the subsurface layer of a two-component biological structure (X is the Mueller matrix of the outer layer, Y is the Mueller matrix of the inner subsurface layer, Z is the Mueller matrix of a two-component biological structure, moreover $Z = Y \times X$), the measurement of their MMI becomes easier.

Thus, in the case of linearly polarized radiation, $\left(x_{ik}\left(\delta = 0\right), x_{ik}\left(\delta = \pi\right)\right)$ the elements of the MMI of a two-layer biological structure are described by expressions [4]

$$S_x = \begin{pmatrix} 1 \\ \cos\left(2\alpha_x\right) \\ \sin\left(2\alpha_x\right) \\ 0 \end{pmatrix} \Leftrightarrow z_{ik}\left(s_x\right) = \begin{cases} z_{22} = y_{22}\,; z_{23} = y_{23}\,; z_{32} = y_{32}\,; z_{33} = y_{33}; \\ z_{34} = y_{34}\,; z_{43} = y_{43}\,; z_{24} = y_{24}\,; z_{42} = y_{42}; \\ z_{44} = y_{44}. \end{cases} \quad (1)$$

If the condition is met $\left(x_{ik}\left(\delta = \pm 0,5\pi\right)\right)$, then there is the following transformation of MMI Z_{ik} of a multilayer biological object [4]:

$$S_x^{\otimes} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} \Leftrightarrow z_{ik}\left(S_x^{\otimes}\right) = \begin{cases} z_{22} = y_{23} + y_{24}\,; z_{23} = y_{23} + y_{24}; \\ z_{32} = y_{33} + y_{34}\,; z_{33} = y_{32} + y_{34}; \\ z_{34} = y_{32} + y_{33}\,; z_{43} = y_{42} + y_{44}; \\ z_{24} = y_{22} + y_{23}\,; z_{42} = y_{43} + y_{44}; \\ z_{44} = y_{42} + y_{43}. \end{cases} \quad (2)$$

In order to find the optimal state of the angle θ of rotation of the plane of polarization of the laser beam, which irradiates a two-component biological structure, it is necessary to measure and analyze the parameters of the Stokes vector in each pixel of the converted polarization image of BT for a cycle of complete rotation of the plane of polarization.

For a pixel with coordinates (x, y) , in which the condition regarding the equality of unity of the sums of squares of the second, third, and fourth parameters $S_{2;3;4}(\theta)$ of the Stokes vector is fulfilled

$$S_2^2(\theta)+S_3^2(\theta)+S_4^2(\theta)\to 1, \tag{3}$$

orientation and phase distributions of the outer (ρ_X,δ_X) and inner (ρ_Y,δ_Y) layers of the two-component biological tissue are reproduced.

The reconstruction of the orientational and phase parameters of the outer layer and subsurface layer of BT is described by the following ratios [4]:

$$\begin{cases}\rho_X^{(x,y)}=0,25\pi+\theta;\\ \rho_Y^{(x,y)}=0,5arctg\left(S_3^{(x,y)}(\theta)\Big/S_2^{(x,y)}(\theta)\right);\end{cases} \tag{4}$$

$$\begin{cases}\delta_X^{(x,y)}=\arccos\left(\pm\sqrt{1+\dfrac{1-\cos\left(\delta_Y^{(x,y)}\right)}{\cos^2\left(2\left(\rho_X^{(x,y)}-\rho_Y^{(x,y)}\right)\left(1+\delta_Y^{(x,y)}\right)\right)}}\right);\\ \delta_Y^{(x,y)}=\arccos\left[S_4^{(x,y)}(\theta)\right].\end{cases} \tag{5}$$

If necessary, expressions (4) and (5) can be used to reproduce the Mueller matrices of each layer of a two-component BT.

Having considered the theoretical basis of the method of reconstruction of the Mueller matrices of each of the layers of the two-component optically thin biological structure, we use the experimental implementation of the method in the system of Mueller-matrix diagnostics of two-component BT (Figure 1).

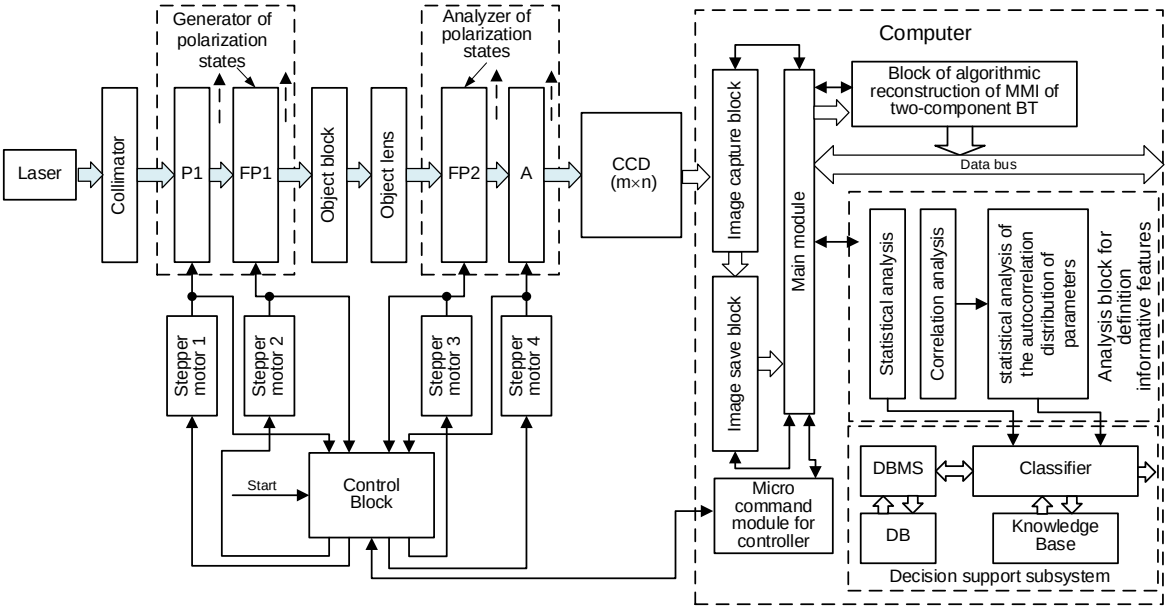

Figure 1 – Architecture of the Mueller-matrix diagnostics system of two-component biological structures with decision support

The architecture of the Müller-matrix BT diagnostics system, presented in Figure 1, contains the main blocks and elements traditional for Müller-polarimeters.

The radiation source is a semiconductor laser with a wavelength of 638 nm. Generator of polarization states (GPS) and analyzer of polarization states (APS) in the system are built on polarizer P1, analyzer A and quarter-wave phase plates FP1, FP2, which are located in frames with automated adjustment of the angle of rotation. The optical input of the GPS is connected to the output of the laser through the collimator, and the optical output is connected to the optical input of the object unit containing the test sample of the two-component bilayer biological structure. The radiation scattered and polarized by the sample is projected using an object lens

through the APS into the plane of a CCD digital camera with pixel $(m \times n)$ resolution. Control of the rotary mechanisms of the frames, in which the GPS and ASP units are located, is carried out using the control block.

The architecture of the computer software shown in Figure 1 includes the following blocks: image save block, image capture block, micro command module for controller, block of algorithmic reconstruction of MMI of two-component BT, analysis block for definition informative features and decision support subsystem.

The method of polarimetric Mueller-matrix diagnostics of two-component biological structures, implemented on the architecture of the above system, is as follows.

1. We insert the prepared two-component BT sample into the object block of the system and reconstruct its Mueller-matrix images of orientation and phase elements using the ratio (1)-(5).
2. We calculate estimates of statistical moments of the selected type of MMI, obtaining the average value $M1$, variance D, asymmetry Ax, kurtosis Ex.
3. . We calculate estimates $QM1 - QM4$ of the correlation moments of the selected type of MMI.
4. We determine the vector of features based on estimates of statistical and correlation moments of the selected type of MMI in the form $[M1, D, Ax, Ex, QM1, QM2, QM3, QM4]$.
5. For the studied sample, we calculate the functions of belonging to the class "norm" $\mu norm(M1, D, Ax, Ex, QM1, QM2, QM3, QM4)$ and to the class "pathology" $\mu pathol(M1, D, Ax, Ex, QM1, QM2, QM3, QM4)$.We use models of decision rules, which are prescribed for each specific disease using a database, a knowledge base, a decision support subsystem classifier.
6. The diagnosis recommended based on the diagnostic results is formed as follows:

   if $\mu norm(x) \geq \mu pathol(x)$, then the diagnosis "normal" is recommended;

   if $\mu norm(x) \leq \mu pathol(x)$, then the diagnosis "pathology" is recommended.

   For the argument X in the functions, the feature vector given in clause 4 is used. However, not all of the eight features can be informative, then the number of elements of the feature vector decreases.

DECISION-MAKING SUPPORT MODELS DIAGNOSTICS OF ONCOPATHOLOGY OF THE CERVIX IN THE SYSTEM

An experimental study of optically thin histological cryosections of the muscular tissue of the cervix, shielded by a layer of connective tissue, was conducted. Two groups were formed: group 1 for healthy samples (21 samples) and group 2 (21 samples) for cervical dysplasia.

Table 1 presents the results of calculating statistical and correlational estimates of orientational Z_{22} and phase Z_{44} MMI of the biological structure "muscle tissue-connective tissue".

Table 1

Ranges of changes in the signs of polarization-reproduced MMI of the two-component two-layer structure "MT-ST" for "normal" and "dysplasia"

	"Normal"	"Pathology"	"Normal"	"Pathology"
	Z_{22}^{n}	Z_{22}^{p}	Z_{44}^{n}	Z_{44}^{p}
$M1$	$0{,}31 \pm 0{,}029$	$0{,}38 \pm 0{,}03$	$0{,}25 \pm 0{,}021$	$0{,}19 \pm 0{,}012$
D	$0{,}18 \pm 0{,}015$	$0{,}09 \pm 0{,}007$	$0{,}14 \pm 0{,}011$	$0{,}08 \pm 0{,}0054$
Ax	$0{,}31 \pm 0{,}026$	$3{,}09 \pm 0{,}31$	$0{,}29 \pm 0{,}021$	$0{,}77 \pm 0{,}066$
Ex	$3{,}35 \pm 0{,}30$	$5{,}91 \pm 0{,}48$	$1{,}64 \pm 0{,}157$	$6{,}19 \pm 0{,}576$
$QM1$	$0{,}43 \pm 0{,}031$	$0{,}36 \pm 0{,}022$	$0{,}26 \pm 0{,}019$	$0{,}22 \pm 0{,}017$
$QM2$	$0{,}22 \pm 0{,}019$	$0{,}18 \pm 0{,}014$	$0{,}18 \pm 0{,}015$	$0{,}14 \pm 0{,}011$
$QM3$	$0{,}33 \pm 0{,}028$	$0{,}73 \pm 0{,}062$	$0{,}25 \pm 0{,}022$	$0{,}37 \pm 0{,}031$
$QM4$	$1{,}14 \pm 0{,}103$	$2{,}43 \pm 0{,}213$	$0{,}97 \pm 0{,}072$	$1{,}85 \pm 0{,}155$

The informativeness of the signs D, Ax, Ex, QM3, QM3 for the diagnosis of oncopathology of the cervix by orientational and phase MMI of polarization-reproduced muscle tissue of the two-component structure "muscle tissue - connective tissue" has been established.

Fuzzy logic principles are chosen to build decisive decision-making rules in this diagnostic system. This approach turned out to be the most successful for working with uncertain and incomplete data, providing flexibility and intuitiveness in building models. Fuzzy logic allows for efficient modeling of complex systems where traditional methods may not be efficient enough.

The derivation of a fuzzy decision support rule is demonstrated for the case of diagnosis of the specified disease based on the phase MMI Z_{44} analysis of two-component cervical tissue.

According to the well-known method of constructing "fuzzy" decision rules, the range of changing each of the informative parameters is divided into 5 sub-ranges. Each of the five subranges corresponds to the fuzzy terms low (L), below average (BA), average (A), above average (AA), high (H) according to the approximation function described in works [6, 9].

For each informative parameter, the experts provided a database that characterizes the classes "normal" and "cervical dysplasia" according to the vague terms "L", "BA", "A", "AA", "H".

The knowledge base with the results of the evaluations of the informative parameters of the phase MMI Z_{44} of the subsurface layer of the muscle tissue of the two-component two-layer structure in fuzzy terms is shown in Table 2 for the "normal" and "pathology" states.

Table 2

Base of estimations of informative parameters of Z_{44} of the subsurface layer of muscle tissue of a two-component biological structure in fuzzy terms

Diagnosis	D	AX	EX	QM3	QM4
Normal	H AA	L	L	L BA	L BA
Pathology	L	H AA	H AA	AA H	AA H

Note that membership functions $\mu^{L}(r), \mu^{BA}(r), \mu^{A}(r), \mu^{AA}(r), \mu^{H}(r)$ on the interval [0;1] determine each of the five terms. Their selection can be implemented, for example, according to the graphically represented dependencies shown in work [6]. Then the membership functions $\mu norm(D, Ax, Ex, QM3, QM4)$ and $\mu pathol(D, Ax, Ex, QM3, QM4)$ the classes "norm" and "pathology", respectively, are models of decision rules for fuzzy terms.

Based on the membership functions $\mu^{L}(r), \mu^{BA}(r), \mu^{A}(r), \mu^{AA}(r), \mu^{H}(r)$ of fuzzy terms, we define the function $\mu pathol(D, Ax, Ex, QM3, QM4)$ as follows:

$$\begin{aligned}
&\mu pathol(D, Ax, Ex, QM3, QM4) = (\mu^{L}(D) \wedge \mu^{H}(Ax) \wedge \mu^{H}(Ex) \wedge \mu^{H}(QM3) \wedge \mu^{H}(QM4)) \vee \\
&(\mu^{L}(D) \wedge \mu^{H}(Ax) \wedge \mu^{H}(Ex) \wedge \mu^{H}(QM3) \wedge \mu^{AA}(QM4)) \vee (\mu^{L}(D) \wedge \mu^{H}(Ax) \wedge \mu^{H}(Ex) \wedge \\
&\mu^{AA}(QM3) \wedge \mu^{H}(QM4)) \vee (\mu^{L}(D) \wedge \mu^{H}(Ax) \wedge \mu^{H}(Ex) \wedge \mu^{AA}(QM3) \wedge \mu^{AA}(QM4)) \vee \\
&(\mu^{L}(D) \wedge \mu^{H}(Ax) \wedge \mu^{AA}(Ex) \wedge \mu^{H}(QM3) \wedge \mu^{H}(QM4)) \vee (\mu^{L}(D) \wedge \mu^{H}(Ax) \wedge \mu^{AA}(Ex) \wedge \\
&\mu^{H}(QM3) \wedge \mu^{AA}(QM4)) \vee (\mu^{L}(D) \wedge \mu^{H}(Ax) \wedge \mu^{AA}(Ex) \wedge \mu^{AA}(QM3) \wedge \mu^{H}(QM4)) \vee \\
&(\mu^{L}(D) \wedge \mu^{H}(Ax) \wedge \mu^{AA}(Ex) \wedge \mu^{AA}(QM3) \wedge \mu^{AA}(QM4)) \vee (\mu^{L}(D) \wedge \mu^{AA}(Ax) \wedge \mu^{H}(Ex) \wedge \\
&\mu^{H}(QM3) \wedge \mu^{H}(QM4)) \vee (\mu^{L}(D) \wedge \mu^{AA}(Ax) \wedge \mu^{H}(Ex) \wedge \mu^{H}(QM3) \wedge \mu^{AA}(QM4)) \vee \\
&(\mu^{L}(D) \wedge \mu^{AA}(Ax) \wedge \mu^{H}(Ex) \wedge \mu^{AA}(QM3) \wedge \mu^{H}(QM4)) \vee (\mu^{L}(D) \wedge \mu^{AA}(Ax) \wedge \mu^{H}(Ex) \wedge \\
&\mu^{AA}(QM3) \wedge \mu^{AA}(QM4)) \vee (\mu^{L}(D) \wedge \mu^{AA}(Ax) \wedge \mu^{AA}(Ex) \wedge \mu^{H}(QM3) \wedge \mu^{H}(QM4)) \vee \\
&(\mu^{L}(D) \wedge \mu^{AA}(Ax) \wedge \mu^{AA}(Ex) \wedge \mu^{H}(QM3) \wedge \mu^{AA}(QM4)) \vee (\mu^{L}(D) \wedge \mu^{AA}(Ax) \wedge \mu^{AA}(Ex) \wedge \\
&\mu^{AA}(QM3) \wedge \mu^{H}(QM4)) \vee (\mu^{L}(D) \wedge \mu^{AA}(Ax) \wedge \mu^{AA}(Ex) \wedge \mu^{AA}(QM3) \wedge \mu^{AA}(QM4)).
\end{aligned} \tag{6}$$

Based on the membership functions $\mu^{L}(r), \mu^{BA}(r), \mu^{A}(r), \mu^{AA}(r), \mu^{H}(r)$ of fuzzy terms, we define the function $\mu norm(D, Ax, Ex, QM3, QM4)$ as follows:

$$\begin{aligned}\mu norm(D, Ax, Ex, QM3, QM4) = (\mu^{H}(D) \wedge \mu^{L}(Ax) \wedge \mu^{L}(Ex) \wedge \mu^{L}(QM3) \wedge \mu^{L}(QM4)) \vee \\ (\mu^{H}(D) \wedge \mu^{L}(Ax) \wedge \mu^{L}(Ex) \wedge \mu^{L}(QM3) \wedge \mu^{BA}(QM4)) \vee (\mu^{H}(D) \wedge \mu^{L}(Ax) \wedge \mu^{L}(Ex) \wedge \\ \mu^{BA}(QM3) \wedge \mu^{L}(QM4)) \vee (\mu^{H}(D) \wedge \mu^{L}(Ax) \wedge \mu^{L}(Ex) \wedge \mu^{BA}(QM3) \wedge \mu^{BA}(QM4)) \vee \\ (\mu^{AA}(D) \wedge \mu^{L}(Ax) \wedge \mu^{L}(Ex) \wedge \mu^{L}(QM3) \wedge \mu^{L}(QM4)) \vee (\mu^{AA}(D) \wedge \mu^{L}(Ax) \wedge \mu^{L}(Ex) \\ \wedge \mu^{L}(QM3) \wedge \mu^{BA}(QM4)) \vee (\mu^{AA}(D) \wedge \mu^{L}(Ax) \wedge \mu^{L}(Ex) \wedge \mu^{BA}(QM3) \wedge \mu^{L}(QM4)) \vee \\ (\mu^{AA}(D) \wedge \mu^{L}(Ax) \wedge \mu^{L}(Ex) \wedge \mu^{BA}(QM3) \wedge \mu^{BA}(QM4)).\end{aligned} \quad (7)$$

If $\mu norm(D, Ax, Ex, QM3, QM4) \geq \mu pathol(D, Ax, Ex, QM3, QM4)$, then the recommended diagnosis is "norm", otherwise the diagnosis will be "pathology ".

The results presented in Table 3 were obtained for assessing the reliability of the diagnosis of cervical oncology based on the analysis of orientational and phase MMI of its two-component biological structure "muscle tissue-connective tissue" for each sample from a sample of 42 samples. This Table 3 has special designations: for truly sick (TP), for truly healthy (TN). Testing errors are indicated by false positive (FP) and false negative (FN) diagnostic test results.

Table 3

Reliability of the Mueller-matrix diagnosis of the two-component biological structure "muscle tissue" - connective tissue" of the cervix in the developed system

Parameter	Test results, pieces				Reliability of the diagnostic method,%
	TP	FN	TN	FP	
Vector of informative signs of orientation MMI	18	3	18	3	85,7%
Vector of informative signs of phase MMI	20	2	19	1	92,8%

The analysis of Table 3 demonstrates an increase in the reliability of the Mueller-matrix diagnosis method of two-component, two-layer biological structures in comparison with the analogue [4]. The reliability of the diagnosis in the developed system increased by 2% when using orientation MMI and by 3,3% when using phase MMI.

CONCLUSIONS

The method of Müller-matrix polarimetric diagnosis of two-component, two-layer biological structures has been improved due to the introduction of classification analysis of informative features of Müller-matrix images of samples, which allows to increase the reliability of diagnostics.

The architecture of the polarimetric system for the Mueller-matrix diagnosis of two-component biological structures was improved by introducing a decision support subsystem, which expanded its functionality.

Fuzzy models of decision-making support in the diagnosis of cervical oncopathology have been developed based on the phase MMI analysis of the subsurface layer of muscle tissue of the two-component biological structure "muscle tissue" - "connective tissue". An increase in the reliability of the diagnostic method was obtained by 2% and 3,3%, respectively, when diagnosing by orientational MMI and phase MMI of two-component BT.

Дослідження виконано за підтримки гранту Національного фонду досліджень України 2022.01/0135.

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Надійшла до редакції 10.05.2024р.

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ПОЛЯРИМЕТРИЧНА СИСТЕМА МЮЛЛЕРОВО-МАТРИЧНОЇ ДІАГНОСТИКИ ДВОКОМПОНЕНТНИХ БІОЛОГІЧНИХ СТРУКТУР З ПІДТРИМКОЮ ПРИЙНЯТТЯ РІШЕНЬ

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