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PHOTONIC SENSORS, DEVICES, AND SYSTEMS

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Differential Mueller-matrix tomography of the polycrystalline structure of biological tissues with different damage durations

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Differential Mueller-matrix tomography of the polycrystalline structure of biological tissues with different damage durations

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ABSTRACT

The work is aimed at the development and experimental testing of the polarization method for analyzing the polycrystalline structure of the human biological tissues. the main relationships between temporary changes in the statistical structure of topographic maps of the degree of crystallization of histological sections of the internal organs of a person and variations in the magnitude of the statistical moments of the 1st - 4th orders that characterize them are revealed. It is shown that with an increase in the damage duration, the statistical parameters of linear birefringence maps change according to the following scenario — the average and dispersion values decrease, asymmetry and excess, on the contrary, increase.

Keywords: polarimetry; laser image; diagnostics; histological sections of the internal organs

1. INTRODUCTION

Determining the prescription of death, improving the accuracy of its installation in the first hours, as well as determining its cause is one of the most important problems of forensic medicine [1]. Known methods for determining the onset of the time of death are approximate and based on assessing the rate of onset of degenerative-dystrophic changes in soft tissues[2].

One of the ways to improve the sensitivity of these techniques is the application of the formalism of polarization, coherent, fractal and singular optics [3,4].

The aim of the study is to develop new forensic criteria for expanding the functionality and improving the accuracy of establishing the duration of damage to human internal organs according to the data of a multivariable digital histological study of brain, liver, and kidney tissues.

To achieve this goal, the following tasks were solved:

1. Development, substantiation and experimental testing of a complex of a new tomographic method for digital histological forensic medical research of temporary changes in polycrystalline and molecular optically anisotropic structure of tissues of internal organs with different age of damage.
2. To assess the diagnostic capabilities of the statistical analysis of the data of tomographic methods for examining samples of the brain, liver and kidney of a corpse in the forensic histological determination of the duration of damage to internal organs [5,6,7].
3. To investigate the relationship of temporal changes in the magnitude of statistical moments of the 1st - 4th orders, characterizing the distribution of the magnitude of the parameters of the tomographic method and the duration of damage.

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2. DIFFERENTIAL DECOMPOSITION OF THE MUELLER MATRIX OF BIOLOGICAL LAYERS

To describe the processes of transformation of the polarization structure of optical radiation by partial optically anisotropic layers, the following algorithm was obtained[5] in terms of the parameters of the Stokes vector $S = \{S_1;\ S_2;\ S_3;\ S_4\}$.

$$\frac{dS}{dr} = \{M\}(r)S(r), \tag{1}$$

where $\{M\}(r)$ - Mueller differential matrix; $S(r)$ - Stokes vector of optical radiation at a distance in a medium.

To represent the optical properties of an anisotropic medium using the formalism of the Mueller matrix, expression (1) takes the following form [6, 8, 9]:

$$\frac{d\{F\}(r)}{dr} = \{F\}(r)\{M\}(r), \tag{2}$$

where $\{F\}(r)$ - Mueller matrix of a phase-inhomogeneous object in the plane of the partial layer located at a distance *r*. For single scattering (non-depolarizing) layers, the symmetry of the differential matrix $\{M\}(r)$ is a combination of six polarization properties:

$$\{M\} = \begin{bmatrix} 0 & m_{12} & m_{13} & m_{14} \\ m_{21} & 0 & m_{23} & -m_{24} \\ m_{31} & -m_{32} & 0 & m_{34} \\ m_{41} & m_{42} & -m_{43} & 0 \end{bmatrix} = \begin{bmatrix} 0 & LD_{0,90} & LD_{45,135} & CD \\ LD_{0,90} & 0 & CB & -LB_{45,135} \\ LD_{45,135} & -CB & 0 & LB_{0,90} \\ CD & LB_{45,135} & -LB_{0,90} & 0 \end{bmatrix}, \tag{3}$$

where: $LD_{0,90}$ and $LB_{0,90}$ - linear dichroism and birefringence for the direction of the optical axis $\rho = 0^{\circ}$; $LD_{45,135}$ and $LB_{45,135}$ - linear dichroism and birefringence for the direction of the optical axis $\rho = 45^{\circ}$; CD and CB - circular dichroism and birefringence.

In what follows, we will use the generalized linear birefringence parameters to analyze the optical anisotropy of the polycrystalline structure of biological layers (LB):

$$LB = \sqrt{LB_{0;90}^2 + LB_{45;135}^2}\ . \tag{4}$$

3. DIGITAL HISTOLOGICAL DIAGNOSIS OF PRESCRIPTION OF LIVER DAMAGE BY LINEAR BIREFRINGENCE TOMOGRAPHY

Fragments of Fig. 1 illustrates the results of a digital tomographic histological study of the degree of crystallization of liver tissue samples [10,11,12]. Comparison of the coordinate and topographic structure of the maps of linear birefringence of histological sections of the liver showed [12-17]:

- significant variation in the degree of crystallization of liver samples;
- monotonous smoothing of fluctuations of linear birefringence with an increase in damage duration - 6 hours. (Fig. 1, fragment (2)) and 18 hours (Fig. 1, fragment (3)).

Analysis of statistical monitoring data on changes in coordinate distributions of the degree of crystallization of the substance of liver samples showed diagnostic capabilities similar to brain samples of digital tomographic histological examination of the prescription of damage - an increase in the duration and increase in the intervals of linear change, - table 1.

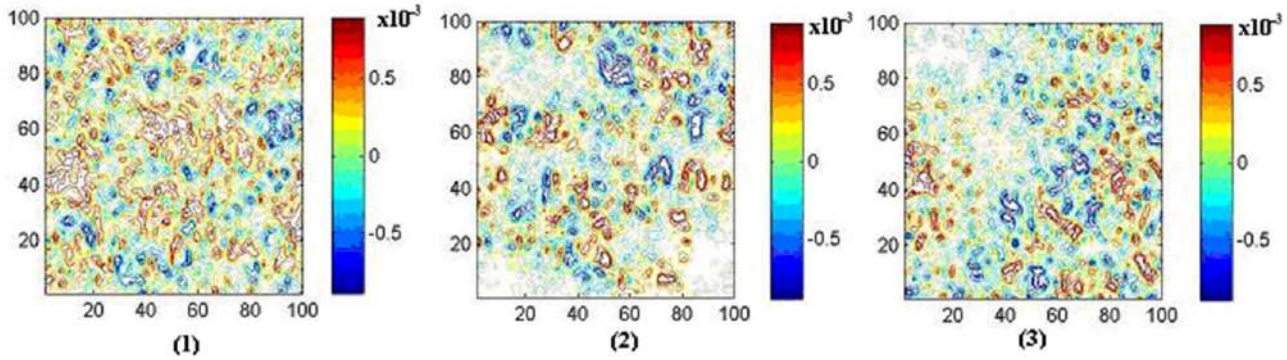

Figure 1. Maps of linear birefringence (x4) of histological sections of the liver of the dead from the control (1), research groups (6 hours - (2)) and (18 hours - (3)).

Table 1. Temporal dynamics of changes in statistical moments of the 1st - 4th orders characterizing the distribution of the magnitude of the linear birefringence (4X) of histological sections of the liver.

T, h.	2	4	6	12	18
SM_1x10^{-3}	0,49±0,021	0.38±0.018	0.27±0.012	0.16±0.007	0.13±0.08
p		$p \le 0.05$		$p \le 0.05$	
SM_2x10^{-3}	0.29±0.013	0.21±0.008	0.13±0.006	0.11±0.04	0.12±0.05
p		$p \le 0.05$		$p \le 0.05$	
SM_3	1.37±0.055	1.45±0.067	1.64±0.071	2.03±0.092	2.35±0.11
p			$p \le 0.05$		
SM_4	1.76±0.071	2.01±0.098	2.25±0.11	2.75±0.13	3.21±0.15
p			$p \le 0.05$		
T, h.	24	48	72	96	120
SM_1x10^{-3}	0.12±0.009	0.14±0.008	0.12±0.007	0.13±0.008	0.12±0.007
p			$p \le 0.05$		
SM_2x10^{-3}	0.13±0.009	0.11±0.007	0.14±0.008	0.14±0.008	0.13±0.007
p			$p \le 0.05$		
SM_3	2.73±0.12	3.05±0.14	3.11±0.15	3.12±0.16	3.18±0.14
p		$p \le 0.05$		$p \le 0.05$	
SM_4	3.72±0.16	4.18±0.19	4.31±0.21	4.49±0.21	4.64±0.22
p		$p \le 0.05$		$p \le 0.05$	

The following characteristics of the duration and number of time intervals of linear and statistically significant (0.05) changes in the eigenvalues of the set of statistical moments of the 1st - 4th orders were experimentally determined:

- the average within the representative groups of liver samples of linear birefringence distributions up to 12 hours with a dynamic range of 0.33;
- dispersion of the scatter of random values of the degree of crystallization within representative groups of liver samples up to 12 hours with a dynamic range of 0.16.
- asymmetries in the distributions of linear birefringence within the representative groups of liver samples — the diagnostic interval lasts up to 48 hours from two linear sections 1 hour - 24 hours and 24 hours - 48 hours with a dynamic range of 1.68;
- excess — linear birefringence distributions within representative groups of liver samples — diagnostic interval up to 48 hours. of the two linear sections 1 hour - 24 hours and 24 hours - 48 hours with a dynamic range of 1.98.

The results of polarization tomography of digital histological studies of large-scale (40x) topographic maps of linear birefringence of histological sections of the liver are shown in fig. 2.

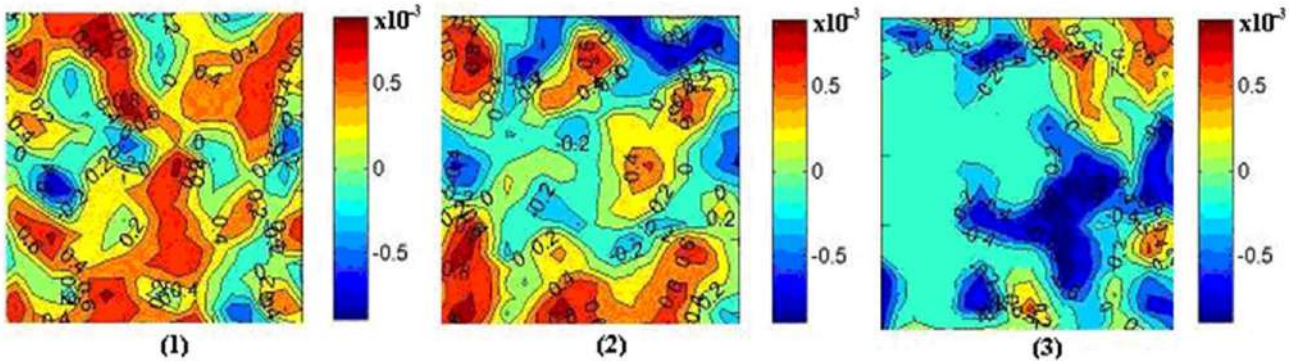

Figure 2. Maps of the distributions of linear birefringence (x40) of histological sections of the liver of the deceased from the control group (1), research groups with different damage durations (6 hours - (2)) and (18 hours - (3)).

A statistical analysis of the temporal changes in the topographic distributions of the degree of crystallization is given in the data series of table 2. Tables 3 to 5 show time intervals and accuracy of the method for reconstructing the polycrystalline structure of histological sections of tissues.

Table 2. Temporal dynamics of changes in statistical moments of the 1st - 4th orders characterizing the distribution of the magnitude of the linear birefringence (40X) of histological sections of the liver.

T, h.	***2***	***4***	***6***	***12***	***18***
SM_1x10^{-3}	0.48±0.014	0.43±0.011	0.38±0.009	0.28±0.007	0.18±0.005
SM_2x10^{-3}	0.29±0.009	0.23±0.008	0.17±0.006	0.11±0.004	0.05±0.002
SM_3	1.53±0.055	1.74±0.067	1.93±0.071	2.21±0.092	2.54±0.11
SM_4	1.87±0.071	2.08±0.098	2.29±0.11	2.78±0.13	3.31±0.15
T, h.	***24***	***48***	***72***	***96***	***120***
SM_1x10^{-3}	0.08±0.003	0.03±0.001	0.02±0.001	0.03±0.002	0.02±0.001
SM_2x10^{-3}	0.02±0.001	0.25±0.001	0.23±0.001	0.24±0.0012	0.23±0.0012
SM_3	2.92±0.13	3.29±0.15	3.67±0.16	3.35±0.15	3.42±0.12
SM_4	3.73±0.17	4.16±0.18	4.87±0.21	4.63±0.21	4.79±0.21

Table 3. Time intervals and accuracy of the method for reconstructing the polycrystalline structure of brain tissue sections.

Statistical moments	Interval, h		Accuracy, min.	
Increase	4x	40x	4x	40x
Average	1-24 24-48	1-24 24-72	45 55	35 45
Dispersion	1-24 24-48	1-24 24-72	45 55	35 45
Asymmetry	1-24 24-72	1-24 24-120	35 50	25 45
Excess	1-24 24-72	1-24 24-120	35 50	25 45

Table 4. Time intervals and accuracy of the method for reconstructing the polycrystalline structure of liver tissue sections.

Increase	4x	40x	4x	40x
Average	1-24 24-48	1-24 24-72	45 55	35 45
Dispersion	1-24 24-48	1-24 24-72	45 55	35 45
Asymmetry	1-24 24-72	1-24 24-120	35 50	25 45
Excess	1-24 24-72	1-24 24-120	35 50	25 45

Table 5. Time intervals and accuracy of the method for reconstructing the polycrystalline structure of kidney tissue sections.

Increase	4x	40x	4x	40x
Average	1-24 24-48	1-24 24-72	45 55	35 45
Dispersion	1-24 24-48	1-24 24-72	45 55	35 45
Asymmetry	1-24 24-72	1-24 24-120	35 50	25 45
Excess	1-24 24-72	1-24 24-120	35 50	25 45

An analysis of the results of a large-scale polarization reconstruction of the degree of crystallization of liver samples revealed similar patterns (but with a different range of eigenvalues) to digital tomographic histology of brain samples — an increase (from 2 to 8 times) in the time duration for determining the age of liver tissue damage based on detection linear intervals of change in the magnitude of statistical moments of the 1st - 4th orders (average, dispersion, asymmetry and excess), which characterize the topographic linear birefringence maps of representative choosing samples from the control and research groups [18,19]:

- the average distribution of the degree of crystallization is two linear intervals of 1 hour – 24 hours. and 24 hours - 48 hours and a range of variation of the eigenvalues of 0.045;
- dispersion of the distribution of the degree of crystallization – a linear interval of 24 hours and a range of variation of the eigenvalues of 0.27;
- asymmetry of the distribution of the degree of crystallization – two linear intervals of 1 hour - 24 hours. and 24 hours - 72 hours and a range of variation of the eigenvalues of 2.14;
- excess of the distribution of the degree of crystallization – two linear intervals of 1 hour – 24 hours and 24 hours – 72 hours and a range of variation of the eigenvalues of 2.99

CONCLUSION

By applying the method of digital histological research to the original algorithmic reproduction of maps of the degree of crystallization of the substance of tissues of the internal organs of a person with different damage durations, changes in the morphological and biochemical structures of the tissues of the brain, liver and kidney were studied for the first time over a time interval from 1 hour to 120 hours.

For the first time, the main relationships between temporary changes in the statistical structure of topographic maps of the degree of crystallization of histological sections of the internal organs of a person and variations in the magnitude of the statistical moments of the 1st - 4th orders that characterize them are revealed.

It is shown that with an increase in the damage duration, the statistical parameters of linear birefringence maps change according to the following scenario — the average and dispersion values decrease, asymmetry and excess, on the contrary, increase.

The time ranges of linear change in the variation of the magnitude of the statistical indicators of the tomographic method of digital histology and the accuracy of determining the prescription of damage are established.

Small-scale crystallization maps (4x):

- average – 48 hours, accuracy 45 minutes – 55 minutes;
- dispersion – 48 hours, accuracy 45 minutes – 55 minutes;
- asymmetry – 72 hours, accuracy 35 minutes – 50 minutes;
- excess – 72 hours, accuracy 35 minutes – 50 minutes

Large-scale crystallization maps (40x):

- average – 72 hours, accuracy 35 minutes – 45 minutes;
- dispersion – 72 hours, accuracy 35 minutes – 45 minutes;
- asymmetry – 120 hours, accuracy 25 minutes – 45 minutes;
- excess – 120 hours, accuracy 25 minutes – 45 minutes.

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