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OPTICAL REMODELING OF THE MYOCARDIUM IN COVID-19: INSIGHTS FROM POLARIZATION-INTERFERENCE MAPPING

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Abstract. Objective assessment of long-term structural alterations in the myocardium following COVID-19 infection remains challenging due to its predominantly subclinical course and the lack of highly sensitive morphological markers. Conventional histological methods are limited in detecting early tissue microstructural disorganization, particularly in fibrillar networks. Recent advances in optical polarimetric techniques, especially Mueller-matrix imaging, provide new opportunities for quantitative evaluation of tissue anisotropy and detection of subtle pathological and necrotic changes.

The aim of the study. To identify and assess quantitative polarimetric markers of structural anisotropy in myocardial tissue for the differential diagnosis of long-term post-COVID changes using Mueller-matrix imaging.

Materials and methods. The research was based on the analysis of native histological sections of the myocardium obtained from deceased individuals aged 18-40 years. Four representative groups were formed: a control group (no COVID-19 in the past) and two research groups with different durations after COVID-19 infection. Mueller-matrix imaging of linear birefringence (MMI LB) was applied, followed by statistical, correlation, and fractal analysis of coordinate distributions of polarization parameters. Diagnostic performance was assessed using balanced accuracy metrics.

Scientific research. The research is a part of the comprehensive research project of the Department of Internal Medicine, Clinical Pharmacology and Occupational Diseases of the Bukovinian State Medical University "Features of the comorbid course of internal organ diseases: mechanisms of mutual aggravation and ways of pharmacological correction" (state registration number 0124U002435; research period: January 1, 2024 – December 31, 2028).

Bioethics. The research materials have been reviewed and approved by the bioethics Commission of Bukovinian State Medical University (Protocol №7 dated April 16, 2026).

Results. It was found out that statistical (asymmetry Q_3, excess Q_4), correlation (correlation area SK, autocorrelation excess PSD_4), and fractal (power spectral density excess PSD_4) markers demonstrate high sensitivity to long-term post-COVID myocardial changes. The highest diagnostic performance was observed for excess-based parameters (Ac up to 95%). Differentiation between groups showed good to very good levels of balanced accuracy for most markers, with slightly lower accuracy in distinguishing later post-COVID periods. A progressive decrease in linear birefringence values and disruption of fibrillar organization were observed with increasing time since infection.

Conclusions. Mueller-matrix polarimetric analysis of myocardial tissue enables objective detection of microstructural alterations associated with long-term post-COVID effects. The identified statistical, correlation, and fractal markers demonstrate high diagnostic potential and may be used for differential assessment of myocardial remodeling. Their combined application improves diagnostic accuracy and should be considered alongside established clinical and morphological criteria in the evaluation of post-COVID cardiovascular involvement.

Key words: Mueller-matrix polarimetry; myocardium; COVID-19; birefringence; optical anisotropy.

ОПТИЧНЕ РЕМОДЕЛЮВАННЯ МІОКАРДА ПРИ COVID-19: МОЖЛИВОСТІ ПОЛЯРИЗАЦІЙНО-ІНТЕРФЕРЕНЦІЙНОГО КАРТОГРАФУВАННЯ

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Резюме. Об'єктивна оцінка віддалених структурних змін міокарда після перенесеної інфекції COVID-19 залишається складною у зв'язку з переважно субклінічним перебігом інфекційного процесу та відсутністю високочутливих морфологічних маркерів діагностики. Традиційні гістологічні методи мають обмеження у виявленні ранньої мікроструктурної дезорганізації тканин, особливо їх фібрилярних мереж. Сучасні досягнення в галузі оптичних поляриметричних методів, зокрема Мюллер-матричного зображення, відкривають нові можливості для кількісної оцінки анізотропії тканин і виявлення їх субклінічних патологічних та некротичних змін.

Мета дослідження. Виявити та оцінити кількісні поляриметричні маркери структурної анізотропії міокарда для диференційної діагностики імовірних віддалених постковідних змін за допомогою Мюллер-матричного зображення.

Матеріали та методи. Дослідження базувалося на аналізі нативних гістологічних зрізів міокарда, отриманих від померлих осіб віком 18-40 років. Було сформовано три репрезентативні групи: контрольну групу (без COVID-19 в анамнезі) та дві дослідні групи з різною тривалістю після перенесеної інфекції COVID-19. Застосовано Мюллер-матричне зображення лінійного двопроменезаломлення з подальшим статистичним, кореляційним та фрактальним аналізом координатних розподілів поляризаційних параметрів. Діагностичну ефективність оцінювали за показниками збалансованої точності.

Науково-дослідна робота. Дослідження є фрагментом комплексної науково-дослідної роботи кафедри внутрішньої медицини, клінічної фармакології та професійних хвороб Буковинського державного медичного університету «Особливості коморбідного перебігу захворювань внутрішніх органів: механізми взаємообтяження та шляхи фармакологічної корекції» (номер державної реєстрації 0124U002435; термін виконання: 01.01.2024 – 31.12.2028 рр.).

Біоетика. Матеріали дослідження розглянуті і схвалені комісією з питань біоетики Буковинського державного медичного університету (Протокол № 7 від 16.04.2026 р.).

Результати. Встановлено, що статистичні (асиметрія Q_3, ексцес Q_4), кореляційні (кореляційна площа SK, ексцес автокореляційної функції PSD_4) та фрактальні (ексцес густини спектра потужності PSD_4) маркери демонструють високу чутливість до віддалених постковідних змін міокарда. Найвищу діагностичну ефективність показали параметри, засновані на ексцесі (Ac до 95%). Диференціація між групами характеризувалася добрим і дуже добрим рівнем збалансованої точності для більшості маркерів із дещо нижчими показниками при розмежуванні пізніших постковідних змін. Виявлено прогресивне зниження значень лінійного двопроменезаломлення та порушення фібрилярної організації зі збільшенням часу після перенесеної інфекції.

Висновки. Мюллер-матричний поляриметричний аналіз тканини міокарда дозволяє об'єктивно виявляти мікроструктурні зміни, пов'язані з віддаленими наслідками COVID-19. Визначені статистичні, кореляційні та фрактальні маркери мають високий діагностичний потенціал і можуть бути використані для диференційної оцінки ремоделювання міокарда. Їх комплексне застосування підвищує діагностичну точність і може використовуватися поряд із класичними клінічними та морфологічними критеріями при оцінці постковідного ураження серцево-судинної системи.

Ключові слова: Мюллер-матрична поляриметрія; міокард; COVID-19; двопроменезаломлення; оптична анізотропія.

Introduction. Recently there has been an active implementation of modern non-destructive and non-invasive optical methods for the biological tissues and fluids investigation in various fields of medicine due to their high sensitivity, informativeness and the ability to obtain objective results without altering sample structure [1, 2]. Among these approaches laser polarimetric diagnostics of the polycrystalline structure of biological layers has gained particular attention, proving to be an effective tool for high-precision and rapid differential diagnosis, especially in distinguishing benign and malignant skin neoplasms [3-5]. Further development of this approach has led to the introduction of multiparametric Mueller-matrix polarimetry, which provides comprehensive and complete information on the optically anisotropic properties of biological structures [6-7]. The implementation of these technologies has demonstrated high efficiency in forensic medicine and pathomorphology, particularly in solving doubtful tasks such as determining the cause and time of death, as well as assessing the nature of traumatic injuries [8-11]. A significant advancement has been the integration of three-dimensional (3D) scanning techniques, which expand the functional capabilities of polarimetric systems and enhance their sensitivity in detecting pathological and necrotic changes [1, 12-15].

Most of the existing and ongoing investigations are focused on the assessment of short-term morphological changes in tissues, while the identification of long-term structural alterations remains

insufficiently explored. In the context of the COVID-19 pandemic this issue has become particularly relevant, as increasing evidence indicates persistent post-infectious changes in different organs and tissues, especially in the myocardium, which may have important clinical and prognostic implications. From a clinical perspective patient who have recovered from COVID-19 increasingly present with manifestations of cardiac long-term complications, varying from subclinical or asymptomatic alterations to myocarditis, arrhythmias, and chronic heart failure manifestations. However, conventional diagnostic approaches are not always capable of detecting early or subtle structural changes in the myocardium tissue. Therefore, there is a growing need for highly sensitive methods capable of objectively identifying microstructural alterations in myocardium of post-COVID-19 individuals. In this regard application of Mueller-matrix polarimetry offers new opportunities for a deeper understanding of the pathogenesis and subclinical progression of post-COVID cardiac involvement.

The aim of the study. To substantiate and identify a set of informative markers for the differential diagnosis of cases with different durations since COVID-19 infection by applying Mueller-matrix mapping of necrotic changes in structural anisotropy (linear birefringence) of spatially organized fibrillar networks in native histological sections of the myocardium.

Materials and methods. Male individuals without a documented history of chronic cardiovascular diseases aged 18-40 years who died suddenly (road traffic accidents and other accidental causes) during 2020-2025 were included in the research. Three representative groups of native histological myocardial tissue sections from deceased individuals were examined:

- control group 1 (12 samples) – no COVID-19 in anamnesis
- research group 2 (20 samples) – 6-24 months of history of COVID-19
- research group 3 (20 samples) – 24-36 months of history of COVID-19

Inclusion criteria:

- male gender; age 18-40 years old;
- sudden (unexpected) death from external causes (e.g., road traffic accidents or other accidental injuries) with a short agonal period;
- absence of documented chronic cardiovascular diseases in the medical history (including ischemic heart disease, cardiomyopathies, congenital or acquired valvular defects, chronic heart failure), confirmed by available medical records and autopsy data;
- absence of acute cardiac pathology unrelated to trauma at autopsy (e.g., acute myocardial infarction, myocarditis);
- absence of ethyl alcohol in the blood at the time of examination, confirmed by forensic toxicological analysis;
- absence of other substances capable of affecting myocardial structure (drugs, narcotics, toxins) according to toxicological screening;
- availability of complete medico-legal documentation (autopsy report, toxicology results, clinical history when available);
- high-quality native histological myocardial sections suitable for optical analysis (adequate preservation, absence of autolysis or pronounced postmortem artifacts);
- for the control group – absence of a history of COVID-19 infection (based on medical records or information obtained from relatives); for the research groups – documented history of COVID-19 infection with a defined time interval since the disease (e.g., 6-24 months, 24-36 months), verified from medical records or reliable anamnestic data.

Exclusion criteria:

- a history of confirmed chronic cardiovascular diseases (coronary artery disease, cardiomyopathies, congenital or acquired heart defects, etc.);
- evidence of acute or chronic alcohol intoxication (presence of ethyl alcohol in the blood according to forensic toxicological analysis);
- presence of other systemic diseases or conditions that may affect the morphological structure of the myocardium (endocrine disorders, severe infectious or oncological diseases);
- significant traumatic injuries of the chest or heart that may alter myocardial morphology;
- insufficient quality or unsuitability of histological material for analysis.

The research was based on the conceptual framework of multiparametric Mueller-matrix polarimetry of biological tissues [4, 6, 11], which provides an advanced approach to analyzing the optical properties of the myocardium. Native histological sections of the myocardium are considered as a complex two-component system comprising an amorphous (optically isotropic) component and a structurally organized anisotropic polycrystalline component. The amorphous component contributes to the formation of a

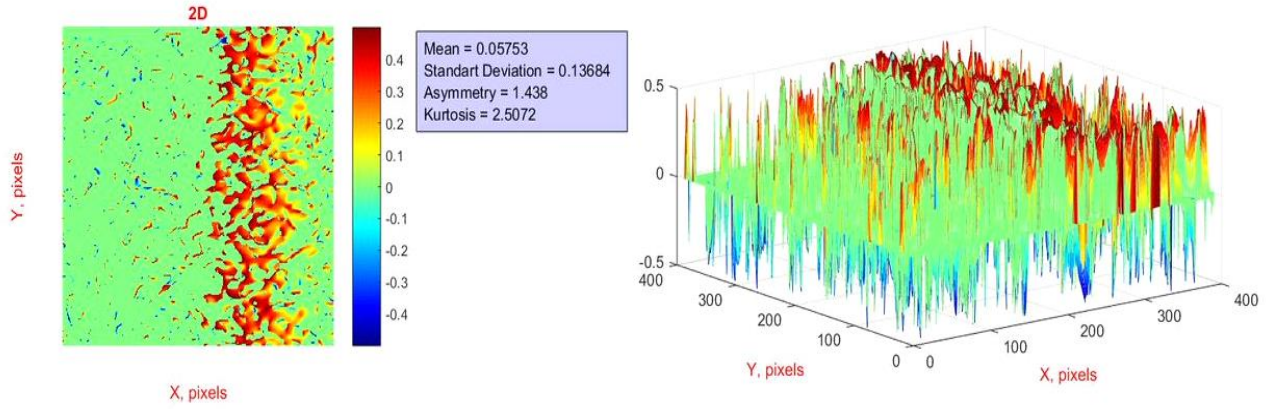
conventional microscopic image due to spatially heterogeneous light absorption, which underlies traditional histological examination. In contrast, the fibrillar structures of the myocardium form polycrystalline architectonics characterized by optical anisotropy and linear birefringence. These properties lead to alterations in the polarization state of laser beam during interaction with the tissue. To detect and quantify these effects objectively Mueller-matrix mapping is applied. This approach enables the extraction of quantitative parameters describing optical anisotropy. In particular, the use of Mueller-matrix invariants associated with linear birefringence allows for reproducible serial measurements that are independent of the orientation of myocardial samples relative to the direction of laser beam.

Scientific research. The research is a part of the comprehensive research project of the Department of Internal Medicine, Clinical Pharmacology and Occupational Diseases of the Bukovinian State Medical University "Features of the comorbid course of internal organ diseases: mechanisms of mutual aggravation and ways of pharmacological correction" (state registration number 0124U002435; research period: January 1, 2024 – December 31, 2028).

Bioethics. The research materials were reviewed and approved by the Bioethics Committee of the Bukovinian State Medical University (Protocol №7, dated April 16, 2026).

Results. The results of the experimental studies are presented in Fig. 1 (control group 1), Fig. 3 (research group 2 – 6-24 months since COVID-19), and Fig. 5 (research group 3 – 24-36 months since COVID-19). A series of coordinate distributions (fragments (1)) of random values of the matrix parameter of structural anisotropy – Mueller-matrix invariants of linear birefringence (MMI LB) – as well as their three-dimensional maps (fragments (2)) are shown.

Figures 2 (control group 1), 4 (research group 2 – 6-24 months since COVID-19), and 6 (research group 3 – 24-36 months since COVID-19) illustrate the results of correlation (fragments (1), (3)) and fractal (fragments (2), (4)) transformations of the topographic maps of MMI LB of spatially structured fibrillar networks in native histological sections of the myocardium from deceased individuals in the control and main research groups.



1 2

Fig. 1. 2D (fragment (1)) and 3D (fragment (2)) Mueller-matrix images of linear birefringence of fibrillar networks in native histological sections of the myocardium from a deceased individual in control group.

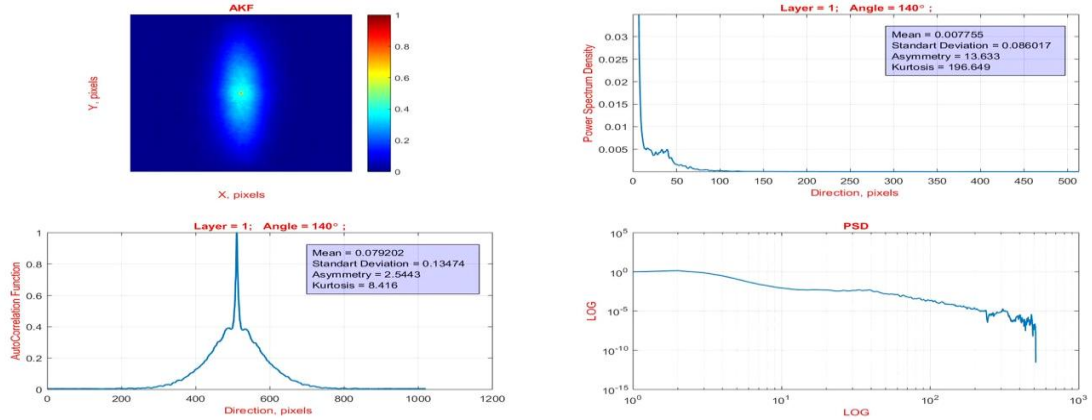
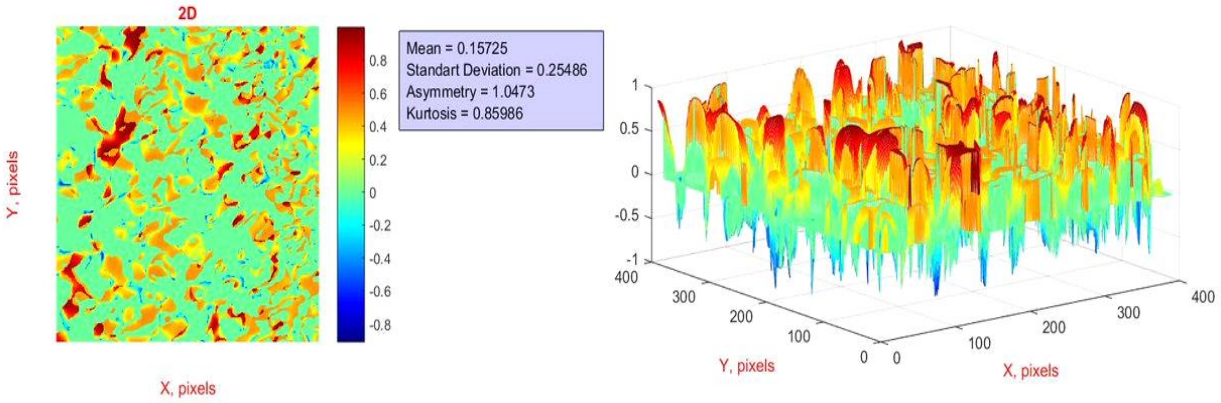


Fig. 2. Autocorrelation (fragments (1), (3)), spatial-frequency (fragment (2)), and fractal (fragment (4)) characteristics of the Mueller-matrix image of linear birefringence of a native histological section of the myocardium from a deceased individual in control group.



1 2

Fig. 3. 2D (fragment (1)) and 3D (fragment (2)) Mueller-matrix images of linear birefringence of fibrillar networks in native histological sections of the myocardium from a deceased individual in research group 1.

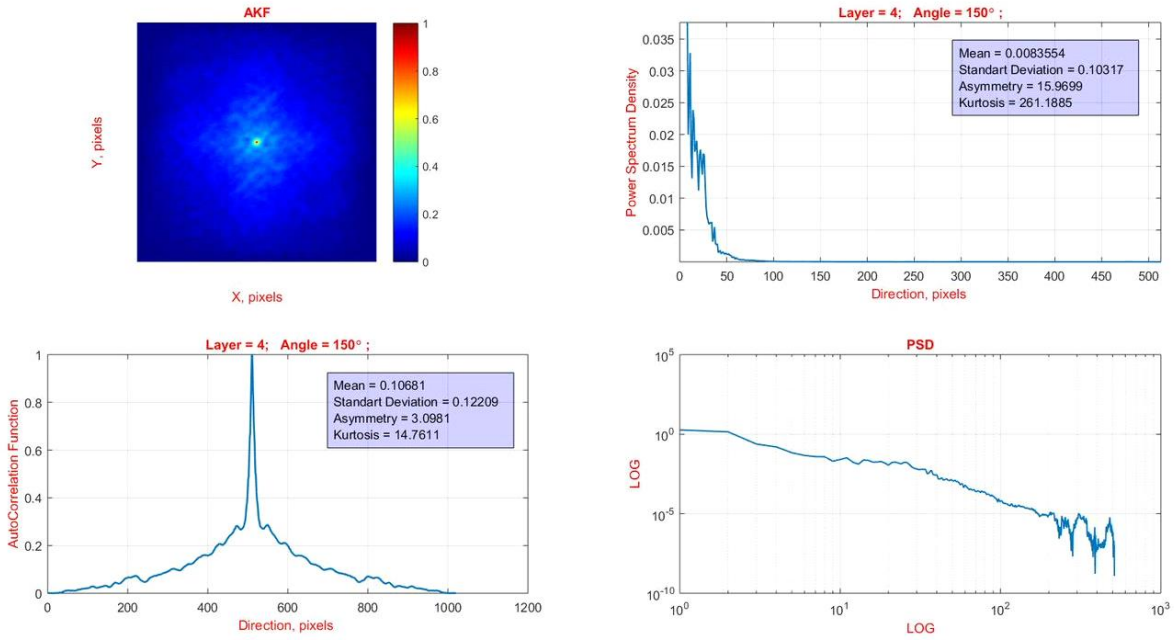


Fig. 4. Autocorrelation (fragments (1), (3)), spatial-frequency (fragment (2)), and fractal (fragment (4)) characteristics of the Mueller-matrix image of linear birefringence of a native histological section of the myocardium from a deceased individual in research group 1.

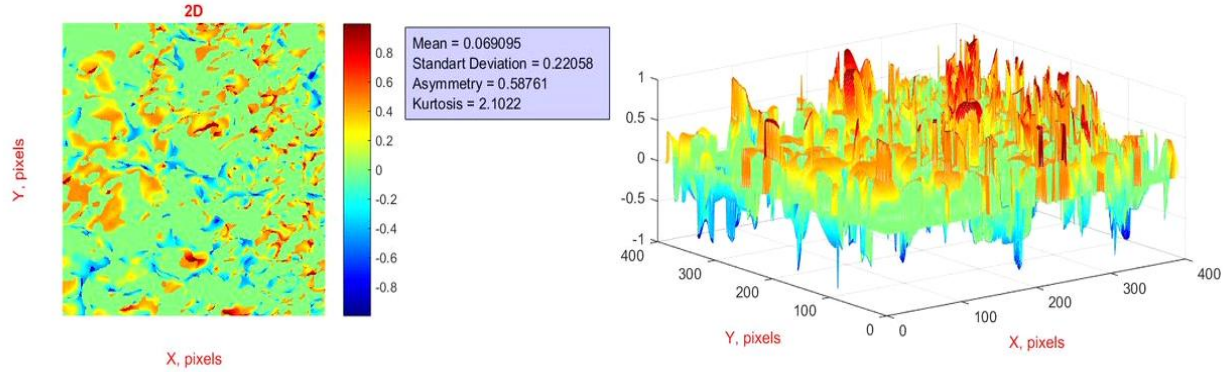


Fig. 5. 2D (fragment (1)) and 3D (fragment (2)) Mueller-matrix images of linear birefringence of fibrillar networks in native histological sections of the myocardium from a deceased individual in research group 2.

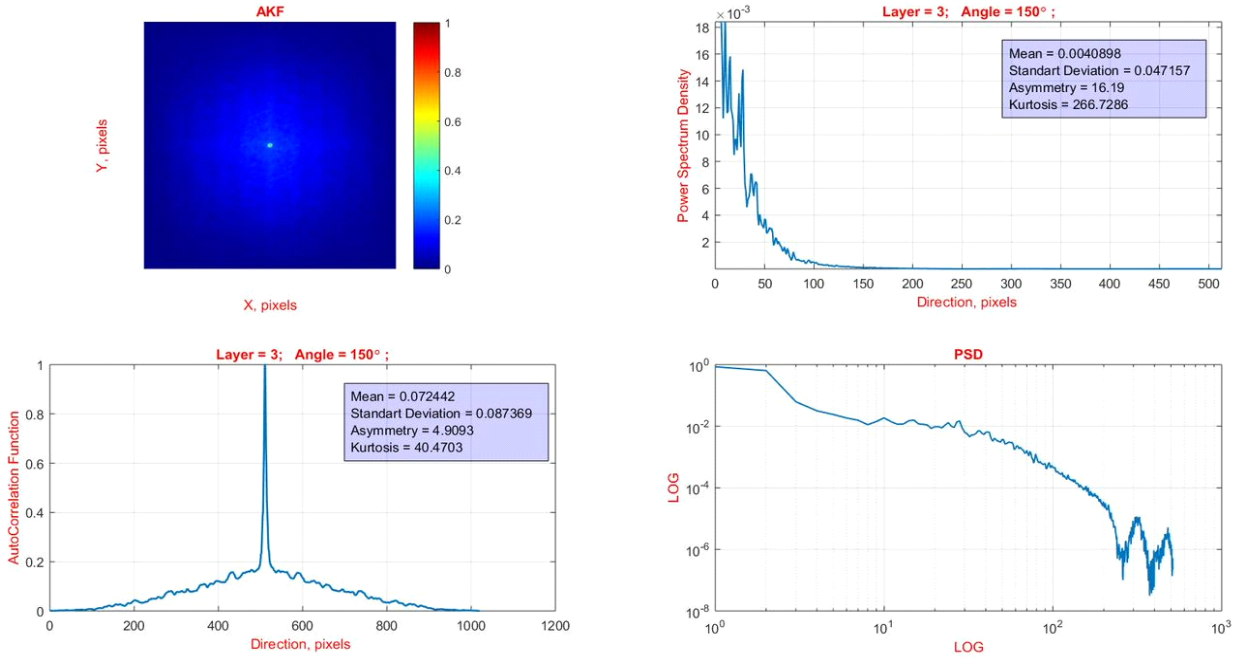


Fig. 6. Autocorrelation (fragments (1), (3)), spatial-frequency (fragment (2)), and fractal (fragment (4)) characteristics of the Mueller-matrix image of linear birefringence of a native histological section of the myocardium from a deceased individual in research group 2.

Based on a comparative evaluation of the experimentally obtained coordinate distributions of random values of the structural anisotropy matrix parameter, together with the results of algorithmic correlation and scale self-similarity analyses, it was found that the spatial, statistical, correlation, and self-similar features of the reconstructed maps of MMI LB in fibrillar networks of native myocardial histological sections are case-specific across all representative control and study groups.

Comparative analysis of the prognostic data and the results of algorithmic processing of MMI LB revealed a correlation concordance between them, increasing with longer time since COVID-19 (Tables 1 and 2).

Table 1

Statistical markers characterizing Mueller-matrix images of linear birefringence in fibrillar networks of myocardial samples from deceased individuals with a history of COVID-19

	Control group 1	Research group 2	Research group 3
Mean, Q_1	0,18±0,008	0,14±0,006	0,11±0,005
$p_{1,2}<0,05$, $p_{1,3}<0,001$, $p_{2,3}<0,05$			
Dispersion, Q_2	0,08±0,003	0,06±0,003	0,04±0,002
$p_{1,2}<0,05$, $p_{1,3}<0,001$, $p_{2,3}<0,05$			
Asymmetry, Q_3	1,12±0,053	1,29±0,057	1,41±0,068
$p_{1,2}<0,001$, $p_{1,3}<0,001$, $p_{2,3}<0,05$			
Excess, Q_4	1,73±0,083	1,97±0,044	2,73±0,058
$p_{1,2}<0,001$, $p_{1,3}<0,001$, $p_{2,3}<0,001$			

The most sensitive quantitative statistical markers were identified:

- Asymmetry (Q_3), characterizing the distribution of the matrix parameter of structural anisotropy MMI LB in fibrillar networks of experimental native histological myocardial sections, with a diagnostically significant range of statistically significant change ($p<0,001$), demonstrating a predicted increase from 1.12 to 1.41;
- Excess (Q_4), characterizing the sharpness (peak) of the histogram of random values of MMI LB, with a diagnostically significant range of statistically significant change ($p<0,001$), demonstrating a predicted increase from 1.73 to 2.73.

The results of the information analysis using statistical markers Q_3 and Q_4 are given in Table 2.

Table 2

Balanced accuracy of statistical markers for the differential diagnosis of long-term effects of COVID-19

Sample	Myocardium samples		
Groups	***"1 – 2+3"***		
	Se, %	*Sp, %*	*Ac, %*
Mean, Q_1	a=15; b=10	c=40; d=10	**73**
Dispersion, Q_2	a=15; b=10	c=43; d=7	**75**
Asymmetry, Q_3	a=23; b=2	c=47; d=3	**94**
Excess, Q_4	a=23; b=2	c=48; d=14	**95**
Groups	***"2 – 3"***		
Mean, Q_1	a=35; b=12	c=32; d=18	**67**
Dispersion, Q_2	a=38; b=15	c=33; d=17	**71**
Asymmetry, Q_3	a=45; b=5	c=44; d=6	**89**
Excess, Q_4	a=46; b=4	c=44; d=6	**90**

It was established that the differentiation of cases with a history of COVID-19 and control group is characterized by a good level of accuracy, whereas the differentiation between two and three years demonstrates a satisfactory level of accuracy.

Table 3 presents the results of the correlation and fractal transformation of maps of Mueller-matrix invariants of linear birefringence of fibrillar networks in native histological myocardial sections. Comparative analysis of prognostic and experimentally obtained results of diagnostic efficiency using algorithms of correlation and fractal transformation of coordinate distributions of MMI LB of myocardial fibrillar networks identified the most sensitive digital markers of long-term effects of COVID-19:

- Excess (Q_4), the value of which characterizes the sharpness of the peak of the autocorrelation functions of MMI LB, with a diagnostically range of statistically significant change ($p<0,001$), showing an increase from 11,9 to 32,3;
- Correlation area (SK) of the autocorrelation function of MMI LB, with a statistically significant range of change ($p<0,001$), showing a decrease from 0,194 to 0,097;
- Excess (PSD_4) of the power spectral density of the autocorrelation distribution of MMI LB, with a statistically significant range of change ($p<0,001$), showing a decrease from 266,4 to 138,3.

Table 3

Correlation and fractal markers characterizing MMI LB

Sample	Myocardium samples		
	Control group 1	Research group 2	Research group 3
Marker	***Correlation***		
Excess, Q_4	11,9±0,5	14,8±0,6	32,3±1,9
$p_{1,2}<0,05$, $p_{1,3}<0,001$, $p_{2,3}<0,001$			
Area *SK*	0,194±0,008	0,162±0,007	0,123±0,006
$p_{1,2}<0,05$, $p_{1,3}<0,001$, $p_{2,3}<0,05$			
Marker	***Fractal***		
Excess, PSD_4	266,4±12,25	208,7±10,31	138,3±6,32
$p_{1,2}<0,001$, $p_{1,3}<0,001$, $p_{2,3}<0,001$			

Table 4

Balanced accuracy of correlation and fractal markers markers for the differential diagnosis of long-term effects of COVID-19

Sample	Myocardium samples		
Groups	***"1 – 2+3"***		
	Se, %	*Sp, %*	*Ac, %*
Excess, Q_4	a=24; b=1	c=48; d=2	**95**
Excess, PSD_4	a=24; b=1	c=48; d=2	**95**
Area *SK*	a=21; b=4	c=43; d=7	**91**
Groups	***"2 – 3"***		
Excess, Q_4	a=49; b=1	c=45; d=5	**94**
Excess, PSD_4	a=49; b=1	c=44; d=6	**93**
Area *SK*	a=47; b=3	c=42; d=8	**89**

The results of the information analysis, including the determination of operational characteristics of diagnostic performance within the framework of evidence-based medicine for the MMI LB method applied to representative samples of myocardial tissue from deceased individuals, demonstrated the following levels of diagnostic efficiency in differentiating long-term effects of COVID-19 (Table 4):

- Correlation markers Q_4 and SK: diagnosis ("control group 1 – research groups 2, 3") demonstrated a good level of balanced accuracy for SK (Ac=91%) and a very good level for Q_4 (Ac=95%); differentiation (one year – two years) showed a satisfactory level for SK (Ac=89%) and a very good level for Q_4 (Ac=94%);
- Fractal marker PSD_4: diagnosis ("control group 1 – research groups 2, 3") demonstrated a very good level of balanced accuracy (Ac=95%).
- Differentiation (one year – two years) demonstrated a very good level of balanced accuracy (Ac=93%)

Research results discussion. Within the proposed framework of structural optical anisotropy of myocardial fibrillar networks, long-term alterations following COVID-19 can be interpreted as the consequence of persistent, often subclinical, yet pathogenetically significant injury to cardiac tissue. Accumulating clinical and morphological evidence indicates that even after viral clearance, a proportion of patients exhibit sustained endothelial dysfunction, microvascular disturbances, and residual inflammatory activation. This imbalance between injury and repair processes creates the conditions for gradual myocardial remodeling.

A key mechanism underlying these changes is microcirculatory impairment, leading to tissue hypoxia. Against this background, increased vascular permeability promotes the development of interstitial edema, which mechanically disrupts the spatial organization of cardiomyocytes and intercellular structures. Concurrently, infiltration of the myocardium by immunocompetent cells maintains a local inflammatory response, accompanied by the release of pro-inflammatory cytokines, activation of oxidative stress pathways, and damage to cellular membranes.

Under these conditions, cardiomyocytes undergo degenerative alterations, including disruption of sarcomere organization, loss of myofibrillar alignment, and the appearance of vacuolization and fragmentation of intracellular components. With more pronounced injury, these processes may progress to necrosis. At the same time, reparative mechanisms are activated, often involving remodeling of the extracellular matrix, particularly changes in collagen fibers, which further affect the spatial organization of the tissue.

The degree of optical anisotropy in myocardial tissue is largely determined by the ordered arrangement of fibrillar structures, primarily myofibrils and collagen fibers. Disruption of this organization due to edema, inflammation, and degenerative-necrotic processes leads to a reduction in optical anisotropy. This is manifested as a decrease in linear birefringence, which may be considered a sensitive indicator of disorganization within the fibrillar architecture.

In parallel, the topographic hierarchy of the polycrystalline organization of the myocardium is altered: a relatively ordered structural system is replaced by a more heterogeneous and fragmented distribution of optically active components. Thus, the observed changes in optical parameters reflect deeper morphological and functional disturbances arising from the combined effects of hypoxia, microvascular dysfunction, and persistent inflammation, which are characteristic of post-COVID myocardial involvement.

From a clinical perspective, the changes identified are of significant importance for understanding the course of post-COVID cardiac damage in the patients. Even in the absence of pronounced clinical symptoms, microstructural disorganization of the myocardium, associated with oedema, inflammation and impaired microcirculation, may underlie subclinical cardiac dysfunction. This manifests as reduced contractility, impaired diastolic function, a predisposition to arrhythmias, and the possible development of chronic heart failure in the long term. The data obtained suggest that changes in optical anisotropy, in particular a reduction in linear birefringence, may be considered as potential early markers of myocardial structural remodelling even before the onset of clinically significant manifestations. This opens up prospects for the development of highly sensitive diagnostic approaches aimed at the early detection of post-COVID heart damage, patient risk stratification, and the timely implementation of preventive and therapeutic measures. Furthermore, understanding the mechanisms underlying the disruption of myocardial structural organization justifies the need for long-term cardiological follow-up of patients who have had COVID-19, even in cases of mild disease course. In practical terms, this may help to optimize rehabilitation approaches, personalize treatment and prevent the progression of cardiovascular complications in this category of patients.

Conclusions.

1. The obtained results demonstrate that the Mueller-matrix polarimetry method, based on invariants of linear birefringence, enables objective detection of myocardial microstructural alterations associated with long-term effects of COVID-19, which is of particular importance for the early identification of subclinical cardiac involvement.

2. The identified statistical, correlation, and fractal digital markers (asymmetry, excess, correlation area SK, and spectral characteristics) exhibit high diagnostic informativeness and may be used to differentiate the severity and duration of post-COVID myocardial changes, thereby providing a basis for patient risk stratification.

3. The integrated application of these markers is important and necessary, as it enhances the accuracy of intergroup differentiation and should be considered alongside currently established criteria and risk factors, thereby contributing to the development of high-sensitivity approaches for monitoring, prognostication, and personalized management of patients with post-COVID cardiovascular involvement.

Author declaration. The authors declare the absence of conflicts of interest, plagiarism, and external sources of funding in relation to this article. AI-assisted tools, including DeepL (version 2026) and ChatGPT (GPT-5.3), were used solely to improve the clarity, grammar, and academic style of the manuscript. These tools were applied for language editing and translation purposes only. No AI tools were used for data analysis, data interpretation, or generation of scientific results. All aspects of study design, data acquisition, analysis, and interpretation were performed by the authors, who take full responsibility for the accuracy and integrity of the work.

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Author contribution.

Nataliia Pavliukovych – literature review, data collection, performance of comparative data analysis, statistical analysis, and preparation of the manuscript for publication

Oleksandr Ushenko – organization of the research process, coordination of data acquisition, verification of results, and final approval of the version to be published.

Oksana Khukhlina – development of the conceptual framework of the study, participation in data interpretation and critical revision of the manuscript for important intellectual content.

Oleksandr Pavliukovych – literature review, data collection, verification of results.

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