Automation of the Analysis of Morphometric Characteristics of the Human Eye Fundus Based on Optical Coherence Tomography Angiography Data. Basic Problems and Results

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Abstract. The paper presents the results of automated analysis of human eye fundus images obtained by optical coherence tomography angiography. A meaningful formulation of the problem is considered, and the main particular problems required for formation of a diagnostically significant feature space are determined. These problems include analysis of the retinal vascular bed, analysis of the foveal avascular zone and ischemic areas, analysis of microaneurysms, and analysis of structural characteristics of the retina by cross-sectional images. For each problem, a short formal formulation, a description of the initial data, the applied method, computational experiments, and obtained results are given. In conclusion, the possibility of combining the results of particular problems into a single diagnostic model and their implementation as part of an algorithmic software package for automated optical coherence tomography angiography image analysis is briefly considered.

Keywords: image analysis, automation of scientific research, biomedical images, ophthalmology, optical coherence tomography angiography, OCT-A, vascular bed, foveal avascular zone, microaneurysms, morphometric features.

1 Introduction

At present, the development of methods for image processing and analysis makes it possible to apply these approaches in the problems of medical diagnostics. An especially important direction is analysis of biomedical images, since they contain a large amount of visual information that requires accurate interpretation. The use of digital image processing tools makes it possible not only to improve the quality of visualization, but also to obtain quantitative characteristics of the objects under study. Thus, image processing methods become an important tool for increasing objectivity and reproducibility of medical studies [1].

One of the main objects of analysis in ophthalmological images is the vascular bed of the human eye. The state of retinal vessels reflects changes in microcirculation and can be associated with the development of various pathological processes. Changes in the density of the vascular pattern, the appearance of ischemic areas, changes in the shape of the foveal avascular zone (FAZ), and the presence of local pathological objects can serve as diagnostically significant features. Therefore, analysis of the vascular bed is one of the key problems in the study of ophthalmological images [1].

Optical coherence tomography angiography (OCT-A) is one of the modern methods for studying vascular structures of the retina. This method makes it possible to noninvasively obtain layer-by-layer images of vascular plexuses and to assess the state of the microcirculatory bed [2, 3]. Due to high resolution, OCT-A images make it possible to study small vessels, areas of rarefaction of the vascular pattern, the FAZ, and other structures that have diagnostic significance. In this regard, OCT-A images are an important initial of data for the analysis of pathological changes in the fundus [2, 3].

At the same time, visual expert assessment of OCT-A images has a number of limitations. The human visual system estimates qualitative characteristics of objects well; however, quantitative description of the same objects is quite subjective in most cases. For example, an expert can determine the presence of rarefaction of the vascular pattern or pathological changes, but accurate measurement of area, density, diameter, perimeter, and other parameters requires additional computational methods. Therefore, objective analysis of OCT-A images requires the use of methods for automatic detection and measurement of diagnostically significant structures [5, 6].

Automation of OCT-A image analysis makes it possible to move from qualitative expert assessment to quantitative description of the studied objects. Automatic calculation of morphometric characteristics makes it possible to unify measurements, reduce the influence of the subjective factor, and store processing results in a data-base. Accumulation of such data makes it possible to compare images, track changes in dynamics, and use processing results to build diagnostic models. Thus, automation of OCT-A image analysis is a necessary stage for increasing the accuracy and reproducibility of diagnostics [4, 5].

This work is devoted to the meaningful formulation and short description of a complex of problems for automated analysis of human eye fundus images obtained by OCT-A. The work considers the problems of analysis of the retinal vascular bed, the FAZ and ischemic areas, microaneurysms, and structural characteristics of the retina by cross-sectional images. All these problems are considered as related parts of one common goal: formation of a diagnostically significant feature space. Thus, the article is an introductory part of a study aimed at developing methods and software tools for automated OCT-A image analysis.

This article consists of an introduction, five sections, and a conclusion. Section 1 presents the meaningful formulation of the research problems and describes the clinical problem of automating OCTA image analysis. Sections 2–5 briefly consider the main particular problems of the study: analysis of the retinal vascular bed, analysis of the foveal avascular zone and ischemic areas, analysis of microaneurysms, and analysis of structural characteristics of the retina based on cross-sectional images. The conclusion summarizes the obtained results, describes the possibility of integrating the features into a common diagnostic model, and briefly outlines the use of the developed methods in the software package for automated OCTA image analysis.

2 Meaningful Formulation of the Research Problems

2.1 Clinical Problem of Automating OCT-A Image Analysis

Intravital examination of the retinal and choroidal vascular beds is widely used by the medical community for diagnostics of vascular and nonvascular pathology [2, 3]. Examination of the retinal vasculature can reveal a wide range of diseases, such as hypertension, diabetes mellitus, atherosclerosis, cardiovascular diseases, and stroke [1, 6].

Early assessment of pathological changes in vessels of the microcirculatory bed in diabetic retinopathy makes it possible to perform screening in a timely manner, track development of the disease, and start therapy at early stages [6-8]. This, in turn, contributes to reducing the risk of severe proliferative forms of the disease and decreasing the number of complications.

Diabetic retinopathy is a chronic progressive disease affecting retinal micro vessels and developing in patients with diabetes mellitus. A serious problem in treatment of diabetic retinopathy is its asymptomatic progression. Patients often remain unaware of the gradual development of retinal vascular dysfunction. Manifestations of the disease usually occur at late stages or when clinically significant macular edema appears [6, 7].

The development of diabetic retinopathy is based on microcirculatory changes; therefore, methods that make it possible to visualize the retinal vascular plexuses are important for its diagnostics. One of such methods is OCT-A, which makes it possible to noninvasively obtain high-resolution layer-by-layer images of the vascular bed. With OCT-A, such changes as microaneurysms, neovascularization, ischemic areas, and rarefaction of the vascular pattern can be detected and quantitatively assessed [2, 3, 9]. Thus, OCT-A is an important initial of data for objective assessment of pathological changes in the retinal vascular network.

At present, based on an image obtained using an OCT-A device, a researcher subjectively assesses the state of the retinal vascular plexuses and their qualitative characteristics, for example, the presence of ischemic areas, the density of the vascular pattern, the presence of microaneurysms, and the severity of structural changes. The presence of software that makes it possible to assess the indicated parameters of the obtained images will make it possible to obtain an objective assessment of the state of the retinal vascular plexuses and to track its changes in dynamics [4, 5, 10].

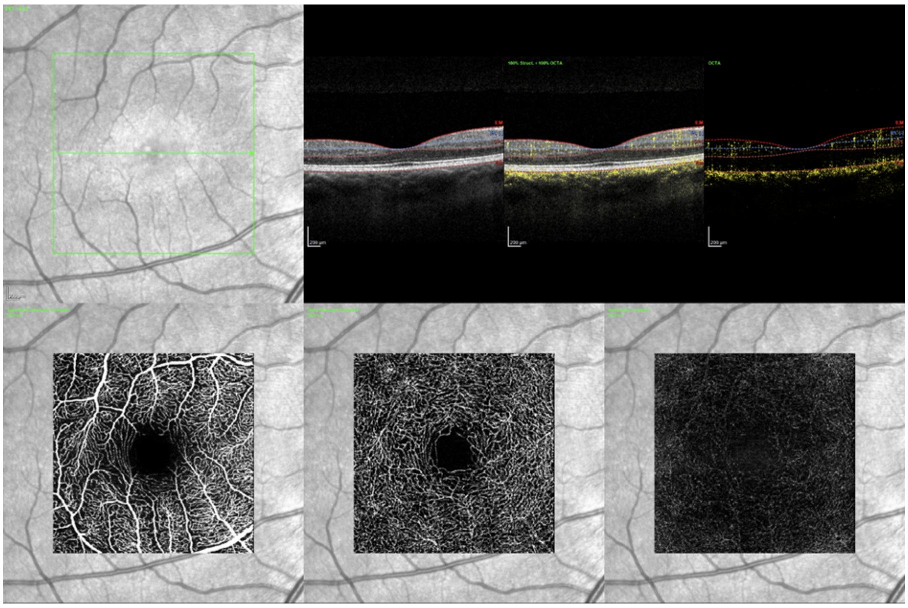

Fig. 1. Example of an initial OCT-A image of the human eye fundus.

2.2 Features of the Initial Data and Limitations of Expert Analysis

OCT-A images are images of retinal tissues divided into several layers. In the study, images obtained using Spectralis HRA+OCT devices with the OCT Angiography module from Heidelberg Engineering were used, as well as images obtained using other types of equipment at later stages of development of the algorithmic software package [4, 10].

The initial images have a number of features that complicate their automatic analysis. These features include the presence of noise and artifacts, differences in vessel brightness, nonuniform background, differences in image quality, and the need to analyze different retinal layers. An additional problem is the complexity of analyzing borderline cases, in which the vascular pattern already differs from the normal state, but pathological changes are not expressed clearly enough [4, 5].

The FAZ in the normal state may differ in diameter and shape, but it usually tends to have a rounded shape. The vascular pattern can also differ, but its density and brightness depend on the presence or absence of pathological changes. Rarefaction of the vascular pattern means worsening of retinal blood supply, that is, hypoperfusion leading to ischemia. An increase in the vascular pattern and its brightness may be a manifestation of formation of new pathological vessels.

2.3 Meaningful Formulation of the Main Research Problem

The main problem of the study is to develop methods for automatic calculation of morphometric characteristics on the basis of which it is possible to assess pathological changes in the vascular bed and retinal structures of the human eye.

This problem is not a single separate problem of image segmentation. To solve it, it is necessary to consider several related subproblems. Each of them is responsible for extracting a certain type of diagnostically significant information. As a result of solving these problems, a common feature space is formed, which can be used for image classification and support of diagnostic analysis [4, 5].

To assess the state of the vascular bed and adjacent structures, the following problems are solved: 1) localization of the FAZ in OCT-A images; 2) quantitative assessment of the FAZ area; 3) visualization of the complex of vessels forming the retinal vascular plexuses; 4) quantitative assessment of vascular density; 5) visualization of components of the vascular skeleton; 6) quantitative assessment of diameter, perimeter, complexity, and connectivity of the vascular network; 7) search for local pathological objects potentially corresponding to microaneurysms; 8) analysis of structural characteristics of the retina by cross-sectional images.

2.4 Determination of Particular Research Problems

To solve the main research problem, the following particular problems were determined: 1) analysis of the retinal vascular bed; 2) analysis of the foveal avascular zone and ischemic areas; 3) analysis of microaneurysms; 4) analysis of structural characteristics of the retina by cross-sectional images; 5) combining particular features into a single diagnostic model.

Each problem has its own formulation, its own stages of image preprocessing, feature sets, and computational experiments. At the same time, the problems are not independent. The results of analysis of the vascular bed are used in analysis of the FAZ, ischemic areas, and microaneurysms. Structural characteristics of the retina supplement vascular features and make it possible to expand the diagnostic description of the image.

3 Problem of Analysis of the Retinal Vascular Bed

3.1 Formal Formulation of the Problem

The problem of analysis of the retinal vascular bed consists in automatic detection of vascular structures in OCT-A images and calculation of quantitative features describing the state of the vascular network [4,5].

Let an image of a retinal layer obtained by OCT-A be given. It is necessary to construct processed representations of this image, including a binary image of vessels, an image of the vascular skeleton, and an image of vessel perimeter. On the basis of these representations, it is necessary to compute a set of morphometric features characterizing the vascular bed.

In this sense, the problem consists in replacing subjective expert assessment of the vascular pattern with a quantitative description that can be used to compare normal, pathological, and borderline states.

3.2 Initial Data and Formation of the Feature Space

Images of retinal vascular layers were used to solve the problem. The initial image is presented in color, but the areas of interest are presented in a monochrome form. Therefore, at the first stage, separate images of retinal layers are selected from the full image and then used to calculate features [4].

To solve the problem of vascular bed analysis, a set of features was formed in accordance with the requirements formulated by experts [4, 5]. The features were divided into several subgroups: 1) features based on grouping pixels of different brightness; 2) features based on quantitative analysis of the vascular network; 3) features based on analysis of the vessel skeleton and perimeter.

The first group includes features of bright vessels, dull vessels, and non-vessel areas. This group of features makes it possible to take into account not only the presence of vessels, but also their brightness characteristics. This is important because the brightness of the vascular pattern can change depending on the pathological state.

The quantitative analysis features include vessel area density, vessel skeleton density, vessel diameter index, vessel perimeter index, and vessel complexity index. These features make it possible to describe the vascular network from different points of view: by area, length, thickness, boundary, and structural complexity [4, 5].

3.3 Method for Solving the Problem

The method for solving the problem consists of two main stages: preliminary image processing and direct formation of features on the basis of the initial image and the obtained processed variants.

The aim of image preprocessing is to improve image quality, filter it, and reduce the influence of various noise and artifacts that arise during image acquisition on further calculation of morphological features. At the preprocessing stage, the image is converted into a form convenient for subsequent analysis. For this purpose, filtering, binarization, removal of small noise components, construction of the vessel skeleton, and construction of the vessel perimeter are applied [4].

The binary image is used to estimate the area of the vascular bed. The vessel skeleton is used to estimate the vascular framework and vessel length without taking into account their diameter. The perimeter image is used to estimate the complexity of vascular structure and boundaries of vascular objects.

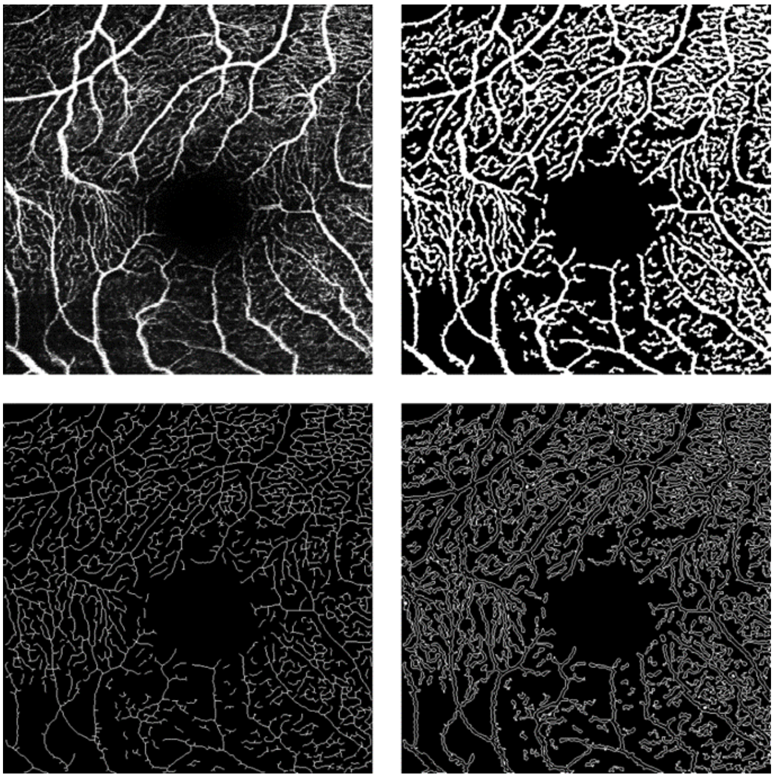

Fig. 2. Example of stages of vascular bed image processing: initial image of a retinal layer; binary image; skeleton image; perimeter image.

3.4 Computational Experiments

To check applicability of the method, computational experiments were carried out to assess informativeness of the formed feature space. On the basis of the selected features, classification of images of patients with and without pathology was carried out, as well as analysis of borderline cases [4, 5].

During the experiments, different variants of image preprocessing were compared. It was shown that too aggressive image cleaning makes it possible to remove noise better and detect bright vessels, but can lead to loss of information about dull vessels. This negatively affects feature calculation and further classification. Therefore, when choosing an image preprocessing method, it is necessary to take into account not only visual quality of the binary image, but also the influence of processing on subsequent feature formation [5].

3.5 Obtained Results and Conclusions for the Problem

As a result of solving the problem of vascular bed analysis, a basic set of features was formed that makes it possible to quantitatively describe the state of the vascular network in OCT-A images. These features became the basis for subsequent problems of analysis of the FAZ, ischemic areas, microaneurysms, and construction of a general diagnostic model.

The most stable features were those based on the vessel area, the vessel skeleton, and the perimeter of the vascular network. Features of bright and dull vessels also proved to be important, since they made it possible to take into account differences in brightness of the vascular pattern. At the same time, it was shown that the quality of features significantly depends on the selected preprocessing variant.

The problem of vascular bed analysis is the basic problem of the whole study. Its results are used both as an independent initial of diagnostic information and as a basis for solving other particular problems.

4 Problem of Analysis of the FAZ and Ischemic Areas

4.1 Formal Formulation of the Problem

The problem of analysis of the FAZ and ischemic areas consists in automatic detection of image areas corresponding to the absence or significant decrease of the vascular pattern and calculation of quantitative characteristics of these areas [4, 5].

Let an OCT-A image of a retinal layer and the results of vascular bed detection be given. It is necessary to determine the FAZ area, as well as areas corresponding to ischemic changes, and to calculate features describing their area, shape, and relative position.

In a meaningful sense, this problem is a continuation of the problem of vascular bed analysis. If in the previous problem the presence of vessels and their structure are analyzed, then in this problem the main attention is paid to areas of absence of vessels or significant rarefaction of the vascular pattern.

4.2 Initial Data and Formation of the Feature Space

For solving this problem, the same OCT-A images of retinal vascular layers are used, as well as the results of binarization and detection of vascular structures. On the basis of the binary image, it is possible to detect areas not occupied by vascular objects. Some of these areas correspond to the FAZ, and some may correspond to ischemic areas or other dark areas.

The FAZ in the normal state can have different diameter and shape, but it usually tends to have a rounded form. A change in the FAZ area and the appearance of additional areas of rarefaction of the vascular pattern can be considered diagnostically significant features [2-5].

The feature space of this problem includes: 1) FAZ area; 2) relative FAZ area; 3) features of FAZ shape; 4) area of dark zones; 5) features characterizing ischemic areas; 6) ratio of the area of ischemic areas to the image area.

4.3 Method for Solving the Problem

The method for solving the problem is based on the results of image preprocessing and vascular network detection [4, 5]. After construction of the binary image, areas corresponding to absence of vascular structures are determined. Then large dark areas that can correspond to the FAZ and ischemic areas are detected.

To assess the FAZ, a geometric description of the selected area is used. The area is calculated and, if necessary, its perimeter and shape characteristics are estimated. For analysis of ischemic areas, the total area of large nonvascular areas, as well as their distribution in the image, is estimated.

When solving this problem, it is important to separate the normal avascular area from pathological areas of vascular pattern rarefaction. This requires the use of both geometric features and information about the location of the area in the image.

4.4 Computational Experiments

Computational experiments were aimed at checking how features of the FAZ and ischemic areas can supplement features of the vascular bed. For this purpose, features of this group were included in the general feature space and used in image classification [4, 5].

Special attention was paid to borderline cases, since it is in these cases that changes in the FAZ and vascular density may be expressed insufficiently clearly. In such cases, features of the FAZ and ischemic areas can provide additional information; however, accuracy of their detection depends on the quality of the initial image and preprocessing results.

4.5 Obtained Results and Conclusions for the Problem

As a result of solving the problem of analysis of the FAZ and ischemic areas, features were obtained that make it possible to take into account not only the state of vessels, but also areas of their absence. These features are an important supplement to vascular bed features, since they make it possible to assess the degree of ischemia and changes in the macular zone.

The successful solutions include the use of information about large dark areas and their area. Partially successful solutions are related to full automation of accurate detection of FAZ boundaries, since the shape and size of this area can differ significantly in different patients. In addition, in cases of severe pathology, boundaries of ischemic areas may be unclear.

The problem of analysis of the FAZ and ischemic areas is the second basic problem of the study. It logically follows from the problem of vascular bed analysis and expands the description of the image by analysis of areas without vessels.

5 Problem of Analysis of Microaneurysms

5.1 Formal Formulation of the Problem

The problem of analysis of microaneurysms consists in searching for local pathological objects potentially corresponding to microaneurysms and in forming features associated with their number, area, and position relative to the vascular network.

Microaneurysms are small saccular protrusions of retinal vessel walls. They are often observed in patients with diabetes mellitus, hypertension, and atherosclerosis. Microaneurysms are one of the early signs of diabetic retinopathy, and their number may indicate progression of the disease [3, 6, 9].

Let an OCT-A image be given, as well as a binary image of the vascular network and an image of the vessel skeleton. It is necessary to detect objects that, according to their geometric, brightness, and topological characteristics, may correspond to microaneurysms and to calculate features characterizing their density [5].

5.2 Initial Data and Formation of the Feature Space

To solve the problem, initial OCT-A images, binarized images of the vascular network, and images of the vessel skeleton are used [5]. This is due to the fact that a microaneurysm should be analyzed not only as a separate bright object, but also as an object located in a certain way relative to the vascular network.

The following characteristics are considered for feature formation: 1) number of detected candidate objects; 2) area of detected objects; 3) shape of objects; 4) elongation and compactness of objects; 5) intersection of objects with the binary image of vessels; 6) connection of objects with the vascular skeleton; 7) density of potential microaneurysms.

The feature of density of potential microaneurysms is calculated as the ratio of the area of objects assigned to potential microaneurysms to the area of the vascular image or to the number of white pixels of the binary image [5].

5.3 Method for Solving the Problem

The method for solving the problem consists of searching for candidate objects and their sequential filtering [5]. At the first stage, an algorithm for searching local maxima is used. The detected maxima are combined into objects, which then pass through several filtering stages.

Filtering is performed according to the following rules: 1) filtering by size: too small and too large objects are removed; 2) filtering by shape: objects that are too elongated are removed; 3) filtering by intersection with the binary image: the object must sufficiently intersect with the vascular image; 4) filtering by position relative to vessels: connection of the object with the vascular skeleton is checked.

For the remaining objects, the number of connections with the vessel skeleton and the angle between the connections are analyzed. If an object is connected with the skeleton in such a way that it may correspond to a local vessel expansion or bend, it is considered as a potential microaneurysm.

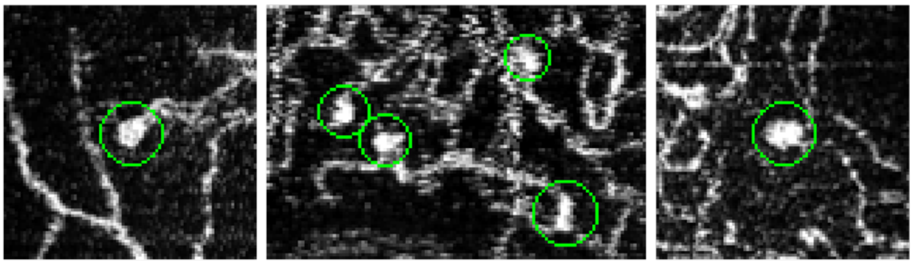

Fig. 3. Example of searching for objects potentially corresponding to microaneurysms.

5.4 Computational Experiments

Computational experiments were aimed at checking the possibility of using microaneurysm features to expand the general feature space. Special attention was paid to analysis of false detections, since small bright objects in OCT-A images can correspond not only to microaneurysms, but also to noise, vessel fragments, vessel intersections, or image artifacts.

The experiments showed that a simple search for bright local objects is insufficient. It is necessary to take into account the shape of the object, its size, and its connection with the vascular network. It is the addition of filtering rules that makes it possible to reduce the number of false objects and obtain a feature that can be used in further classification [5].

5.5 Obtained Results and Conclusions for the Problem

As a result of solving the problem, a method for searching for objects potentially corresponding to microaneurysms was developed. The obtained feature of density of potential microaneurysms made it possible to expand the feature space and add local pathological characteristics to it.

Successful solutions include the use not only of brightness features, but also of information about the connection of an object with the vascular skeleton. Partially successful solutions are those based only on local maxima, since they provide a large number of false detections. The main limitations of the problem include dependence of the result on the quality of the initial image, accuracy of binarization, and complexity of the vascular pattern.

Thus, the problem of analysis of microaneurysms is an important superstructure over the basic problem of vascular bed analysis. It makes it possible to move from a general assessment of vascular density to the search for local pathological objects.

6 Problem of Analysis of Structural Characteristics of the Retina by Cross-Sectional Images

6.1 Formal Formulation of the Problem

The problem of analysis of structural characteristics of the retina by cross-sectional images consists in detecting and quantitatively describing additional morphological characteristics that can be associated with pathological changes in the retina [5].

If the problems of analysis of the vascular bed, FAZ, ischemia, and microaneurysms are mainly based on OCT-A images of vascular layers, then this problem is aimed at analysis of cross-sectional images of the retina. Such images make it possible to take into account structural features of tissues and retinal layers that can serve as additional diagnostic features.

Let a cross-sectional image of the retina be given. It is necessary to detect regions or layers of interest and to calculate features characterizing their brightness, shape, width, density, and other structural parameters.

6.2 Initial Data and Formation of the Feature Space

Cross-sectional images of the retina obtained during OCT/OCT-A examination are used as initial data for this problem. On such images, various structural changes can be observed: changes in layer thickness, presence of hyperreflective dots, signs of cystoid macular edema, disorganization of inner retinal layers, and other changes.

The following groups of features can be used to form the feature space: 1) brightness features of layers; 2) features of width or thickness of the analyzed areas; 3) features of structural density; 4) shape features of the detected areas; 5) features describing image inhomogeneity.

This group of features does not replace vascular features, but supplements them. The main meaning of this problem is to take into account not only the vascular pattern, but also the structural state of the retina.

6.3 Method for Solving the Problem

The method for solving the problem includes detection of a region of interest in a cross-sectional image, preliminary image processing, and calculation of structural characteristics. Depending on the image type and data quality, filtering, threshold processing, boundary detection, and calculation of statistical brightness characteristics can be applied.

At the first stage, the image is prepared for analysis [5]. Then areas corresponding to inner or outer retinal layers are detected. After this, features describing brightness, width, density, and shape of the detected structures are calculated.

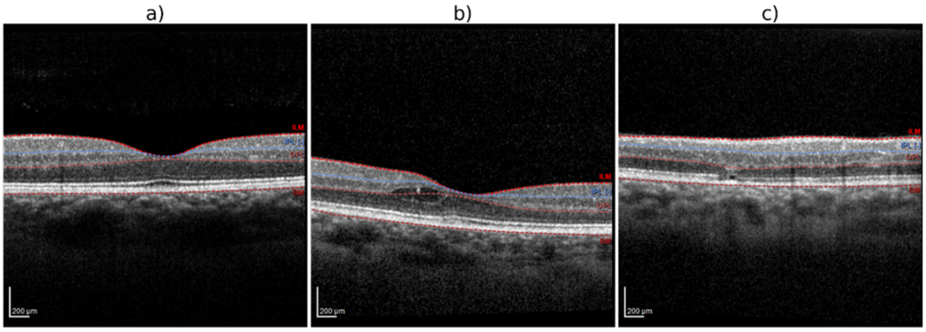

Fig. 4. Example of a cross-sectional image of the retina and regions of structural analysis.

6.4 Computational Experiments

Computational experiments were aimed at assessing whether structural features of the retina can supplement features of vascular analysis. For this purpose, these features were considered as an additional part of the general feature space.

A feature of this problem is that structural features may be less directly related to the vascular bed, but at the same time reflect changes accompanying the pathological process. Therefore, they may be useful in the analysis of complex and borderline cases.

6.5 Obtained Results and Conclusions for the Problem

As a result of solving the problem of analysis of structural characteristics of the retina, additional features describing the state of cross-sectional images were selected. These features can be used together with vascular features, features of the FAZ, ischemic areas, and microaneurysms.

Successful solutions include the formulation of the problem itself as an additional initial of diagnostic information. Partially successful solutions are associated with automatic detection of structures in low-quality images, since in these cases the boundaries of layers may be expressed unclearly.

The problem of analysis of structural characteristics of the retina by cross-sectional images expands the field of the study and makes it possible to move from analysis of only the vascular bed to a more complex description of the retinal state.

7 Integration of Results of Particular Problems and Short Description of the Algorithmic Software Package

7.1 Combination of Features of Particular Problems

The considered problems are parts of the general problem of automated OCT-A image analysis. Each of them forms its own group of features: 1) the problem of vascular bed analysis forms features of vessel density, skeleton, diameter, perimeter, and complexity; 2) the problem of FAZ and ischemia analysis forms features of avascular and ischemic areas; 3) the problem of microaneurysm analysis forms features of local pathological objects; 4) the problem of analysis of structural characteristics of the retina forms additional features of cross-sectional images.

Combination of these groups of features makes it possible to form a common feature space reflecting different levels of OCT-A image analysis: vascular, avascular, local pathological, and structural [4, 5]. This approach is important because pathological changes can manifest themselves not only in one parameter, but also in a combination of several characteristics: decrease in vascular density, increase in the FAZ, appearance of microaneurysms, and changes in brightness and structure of retinal layers.

7.2 Use of Features in a Diagnostic Model

On the basis of the formed feature space, diagnostic models intended for image classification can be built. In the study, two-class and three-class formulations of the problem were considered [4, 5].

In the two-class formulation, images are divided into normal and pathological. This formulation is simpler and makes it possible to assess the basic ability of features to distinguish healthy and pathological states of the vascular bed.

In the three-class formulation, a borderline class is additionally selected. This formulation is more complex, but closer to the real clinical problem, since some images cannot be unambiguously assigned either to the normal state or to pronounced pathology.

Analysis of borderline cases is of special interest, since it is associated with early detection of pathological changes.

7.3 Short Description of the Algorithmic Software Package

The developed methods were implemented as part of an algorithmic software package for automated OCT-A image analysis [10]. The software package provides loading of initial images, their processing, calculation of features, and visualization of intermediate and final results.

At later stages of the work, the software package was expanded. New interface variants were developed, the possibility of remote work was implemented, and support for images obtained using different types of equipment was started. However, in this article, the software part is considered only briefly, since the main emphasis is placed on the meaningful formulation of the problems and short description of methods for their solution [10].

8 Conclusion

A meaningful formulation of the complex problem of automated analysis of OCT-A images of the human eye fundus was considered. It was shown that this problem is not reduced to one image processing operation, but includes several related particular problems.

It was shown that the results of particular problems can be combined into a single feature space, which is used to build a diagnostic model. This approach makes it possible to take into account different manifestations of the pathological process reflected in vascular, avascular, local, and structural features.

Further work is related to a more detailed description of the combined diagnostic model, comparison of different feature compositions, analysis of computational experiments, and development of the algorithmic software package for automated OCT-A image analysis.

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