Interactive Three-Dimensional Visualization System of the Vascular Structure in OCT Retinal Images

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Abstract. This paper proposes an automated tool for the 3D visualization of the retinal arterio-venular tree using Optical Coherence Tomography (OCT) images. The methodology takes advantage of different image processing techniques that initially segments the vessel tree and estimates its corresponding calibers. Then, the depths for the entire vessel tree are also calculated. With all this information, the 3D reconstruction of the vessel tree is achieved, interpolating with B-splines all the segments, obtaining a smooth representation that facilitates its inspection. This model allows the visualization and manipulation of the 3D vessel tree by means of graphical affine transformations, including translation, scaling and rotation. Thus, the method offers a complete and comfortable visualization of the 3D real layout of the vasculature that permits to proceed with more reliable diagnostic processes involving the retinal microcirculation analysis.

Keywords: Computer-aided diagnosis · Vascular structure
Retinal imaging · Optical Coherence Tomography

1 Introduction

Computer-aided diagnosis (CAD) systems has become one of the major research subjects in medical imaging [1]. These systems facilitate the work of clinical experts in the different diagnostic processes, facilitating and simplifying their work. Optical Coherence Tomography (OCT) is a standard imaging technique in ophthalmology that can provide non-invasive medical images with high resolution [2]. These images provide relevant medical information about the measures of the biological tissues such as retinal layers [3] and other structures [4]. Ophthalmologists use OCT scans for the analysis of the vascular tree and produce a diagnosis in different diseases like diabetes [5], hypertension [6] or arteriosclerosis [7]. Therefore, the use of automatic tools for the 3D visualization of the vessel tree is relevant as they facilitate the specialists' work, increasing their productivity and helping to establish preventive and therapeutic strategies.

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In the state-of-the-art, we can find many approaches that faced the retinal analysis in classical retinographies. Hence, different methods were proposed for the extraction and representation of the retinal vessel tree. As reference, Zhang *et al.* [8] based their proposal on the application of adaptive thresholds for the localization of the vascular structures. Mendonça and Campilho [9] employed a methodology that combines the detection of centerlines with the subsequent application of region growing to achieve the final vessel segmentation. In the case of Leandro *et al.* [10], an approach was implemented based on the continuous wavelet transform using the Morlet wavelet, integrating the information over multiple classification scales. Espona *et al.* [11] proposed a methodology based on the use of deformable contour models, incorporating domain specific knowledge such as topological properties of the blood vessels to identify them.

Only a small number of works have appeared that use OCT images to deal with the issue of the vasculature segmentation. Additionally, these few proposals consist of limited methodologies that still offer 2D representations of the retinal vasculature. Niemeijer *et al.* [12] used a 2D projection of the vessel pattern to obtain a high contrast between the vessel silhouettes and the retinal background. Guimarães *et al.* [13] employed the OCT fundus images to locate the depth of the vessels, enclosed in the study of abnormal retinal vascular patterns. Despite that, most of these works do not pay special attention to the visualization of the segmentation results, key issue that can facilitate significantly the doctor's work, specially in cases like this that involves a three-dimensional visualization.

We propose, in this work, an automated tool for the three-dimensional visualization of the retinal arterio-venular tree using OCT images. The method uses the 3D vessel coordinates as well as the corresponding calibers to render a comfortable three-dimensional visualization of the vascular structure. This interactive system provides useful information to the doctors that can be of a great utility to obtain accurate diagnosis in a large variability of pathologies.

2 Methodology

Our methodology receive, as input, a set of OCT images. These images are complemented with the corresponding near-infrared reflectance retinography of the eye fundus that is provided in combination with the OCT sections. These sections represent, in a cross-sectional view, the biological tissues such as retinal layers and other structures. Figure 1 includes an illustrative example of an OCT image.

The proposed visualization system uses the (x, y, z) coordinates and the calibers, d of the entire vasculature. The extraction of this information is organized in a set of progressive stages [14]. Firstly, the arteriovenous tree is extracted in the near-infrared reflectance retinography. Subsequently, their calibers and depth are estimated at the all the positions of the vessel structure. Using all this information, the three-dimensional reconstruction of the vessel tree is achieved interpolating with B-splines all the segments, producing a smooth representation. Following sections explain each step in more detail.

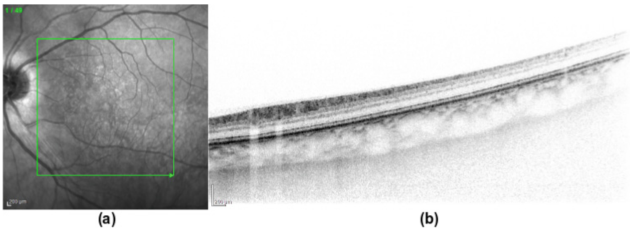


Fig. 1. Example of OCT image. (a) Near-infrared reflectance retinography. (b) OCT section.

2.1 Vessel Tree Extraction and Depth Estimation

Firstly, we segment the vessels in the near-infrared reflectance retinography to obtain the (x, y) coordinates and the vessel caliber d. The retinal arteriovenous tree is extracted by means of well-established image processing techniques. The vessels can be thought as creases (ridges or valleys), where the level curves are used to calculate the crest and valley lines. Then, a method of thinning is applied to obtain the representation of each vascular segment where all the vessels are represented by one-pixel width segments, that is, their coordinates (x, y). The vascular caliber d is obtained by means of the calculation of the distance between the edges (limits of the vessel) of the crease image of each vessel coordinate. Figure 2(a) illustrates an example of the vessel tree extraction.

Once the retinal arteriovenous tree is estimated in the near-infrared reflectance retinography, we can obtain the corresponding vessel depth z in the associated OCT sections, for each coordinate (x, y). To achieve this, the vascular profiles are identified in the OCT images using two stages: (1) mapping of the (x, y) coordinates in the OCT sections and (2) depth vessel identification. Firstly, we identify the positions of the vessels in the OCT sections by the intersection of the section and the vessel tree in the near-infrared reflectance

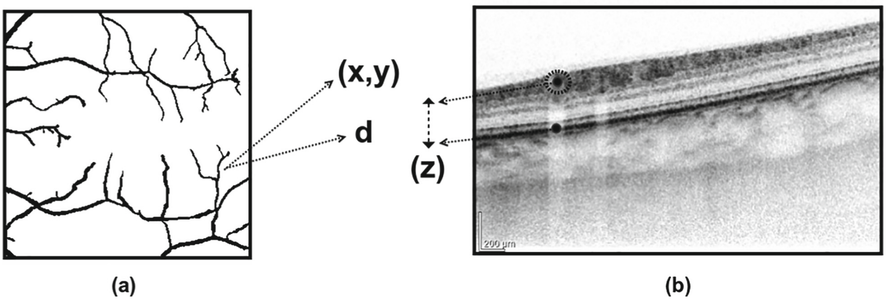


Fig. 2. Example of vessel tree extraction and depth estimation. (a) Vessel tree extraction, where (x, y) are the vessel coordinates and d is the corresponding vessel caliber. (b) Depth vascular estimation, z, in the OCT section.

retinography. This intersection identify the mapping region of the OCT section where the vessels are located. Subsequently, the vascular depth, z, is calculated in the mapped areas by the distance between the vascular profile (darkest spot in the mapping region) and the Retinal Pigment Epithelium (RPE) layer of the retina. Figure 2(b) shows an example of estimation of the vascular depth.

2.2 3D Vasculature Reconstruction

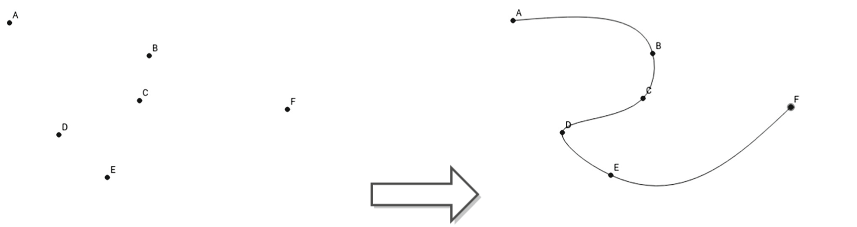
Next, we perform the three-dimensional reconstruction of the vascular structure. To achieve this, we use the information that was obtained in the previous phases: the spacial coordinates (x, y, z) and the vessel calibers, d. In a three-dimensional cartesian coordinate system ($\mathbb{R}^3$), each point P is represented by three real numbers, coordinates (x, y, z), indicating the positions of the perpendicular projections from the point to three fixed, perpendicular, graduated lines, called the axes which intersect at the origin O, which is the point with coordinates $(0, 0, 0)$. In this work, each vessel structure is represented as a segment S, where each point P_i of the vascular segment S is represented by its three-dimensional cartesian coordinates (x, y, z) and the vessel calibers d.

Firstly, we construct the vascular segment S from the points P_i representing the vascular structure with coordinates (x, y, z). For this, we a use B-spline $S(u)$, a function that has minimal support with respect to a given degree, smoothness, and domain partition, defined by:

$$S(u) = \sum_{i=0}^{n} B_{i,m}(u) P_i \qquad 2 \leq m \leq n + 1, \tag{1}$$

where P_i is the i^{th} control point of the $(n+1)^{th}$ control point of the curve and $B_{i,m}$ are the B-spline blending functions (also called the B-spline basis functions), which are basically polynomials of degree $m - 1$. In this work, the basis function $B_{i,m}(u)$ is defined by the recursion formula of Cox-de Boor [15] using an order value $m = 2$. An example of this process is shown in Fig. 3.

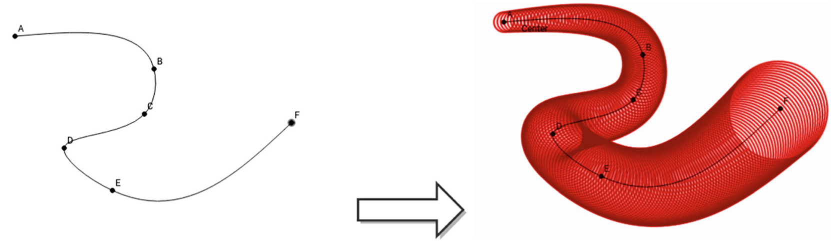
Once all the curves $S(u)$ are obtained for all the points P_i that represent the vascular coordinates, we can perform the three-dimensional reconstruction of the



(a) (b)

Fig. 3. Example of the three-dimensional representation process. (a) Set of points (x, y, z) of the plane. (b) Interpolation with B-spline curves between the set of points.

arterio-venular tree. To achieve this, we use the vascular calibers, d, associated to the points P_i. The vessels are reconstructed as tubular shapes (following the tubular vessel structure) centering on the B-spline curve $S(u)$ with a diameter size equivalent to the caliber d. Subsequently, a post-processing is applied offering a smooth representation of the vessel structure and, therefore, minimizing abrupt transitions between consecutive coordinates of the vessel. Figure 4 illustrate this three-dimensional representation process over a curve.



(a) (b)

Fig. 4. Example of the three-dimensional representation process. (a) Interpolation with B-spline curves between points. (b) Three-dimensional tube along a spline.

This model allows the visualization and manipulation of the three-dimensional vessel tree by means of graphical affine transformations, including translation, scaling and rotation. Under the use of clinicians, these operations are applied over all the identified vessel coordinates, rendering the new set of coordinates and the corresponding calibers, for the user visualization. The application of any affine transformation is indicated by the user interactively with the system.

Translation: To achieve the translation operation within a three-dimensional space, we use of a matrix T (Eq. 2), where D_x, D_y and D_z represent the coordinates to move respectively in the x, y and z directions.

$$T(x, y, z) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ D_x & D_y & D_z & 1 \end{bmatrix} \tag{2}$$

Scaling: We obtain the scaling operation using a matrix S (Eq. 3), where k, l and m represent the scaling factors applied respectively in the x, y and z directions.

$$S(k, l, m) = \begin{bmatrix} k & 0 & 0 & 0 \\ 0 & l & 0 & 0 \\ 0 & 0 & m & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

Rotation: To perform the rotation operation on the x, y or z axes, we use the following matrices R_x, R_y and R_z (Eqs. 4, 5 and 6, respectively), where α denotes the angle of rotation.

$$R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos(\alpha) & sin(\alpha) & 0 \\ 0 & -sin(\alpha) & cos(\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$$R_y(\alpha) = \begin{bmatrix} cos(\alpha) & 0 & -sin(\alpha) & 0 \\ 0 & 1 & 0 & 0 \\ sin(\alpha) & 0 & cos(\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

$$R_z(\alpha) = \begin{bmatrix} cos(\alpha) & sin(\alpha) & 0 & 0 \\ -sin(\alpha) & cos(\alpha) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

3 Experimental Results

The proposed method was tested using a dataset of 392 OCT retinal images that were taken with a confocal scanning laser ophthalmoscope, Spectralis®OCT (Heidelberg Engineering), that offers the near-infrared reflectance retinography combined with the corresponding OCT sections. These sections were obtained from both left and right eyes, all centered on the macula, with a resolution of 1520×496 pixels. In order to test the performance of our system, this automated tool has been evaluated by an expert who has validated its functionality and usefulness. Figure 5 illustrates the proposed methodology, where an example can be observed with the main graphical transformations that this automatic visualization tool allows.

(a) (b) (c)

Fig. 5. Example of interactive three-dimensional visualization of the vessel tree. (a) Initial visualization. (b) Rotation operation. (c) Scaling operation.

4 Discussion and Conclusions

In this paper, we presented a new interactive three-dimensional visualization system of the vascular structure in OCT retinal images. Our proposal offers a complete set of information for a three-dimensional analysis of the arterial vessel tree, aiding the clinical experts to identify the vascular alterations that may lead to the early detection of various types of pathologies, such as diabetes, hypertension or arteriosclerosis.

The proposed methodology exploits different techniques to identify the vessel structure and estimate their calibers, using the near-infrared reflectance retinography images. Subsequently, the depth of the vascular profiles is obtained in the OCT sections. The three-dimensional reconstruction is performed using B-splines to interpolate all the vessel points, obtaining a smooth representation of the vascular structure. This automatic tool allows the clinical experts to visualize and manipulate the retinal vessel tree by means of the main graphical transformations, such as translation, scaling and rotation. The implemented tool was tested by an expert clinician, validating its well-functioning as well as stating its utility in the analysis of the retinal vasculature for the early diagnosis of different diseases.

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