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Automated choroid segmentation of three-dimensional SD-OCT images by incorporating EDI-OCT images

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ABSTRACT

Background and Objective: The measurement of choroidal volume is more related with eye diseases than choroidal thickness, because the choroidal volume can reflect the diseases comprehensively. The purpose is to automatically segment choroid for three-dimensional (3D) spectral domain optical coherence tomography (SD-OCT) images.
Methods: We present a novel choroid segmentation strategy for SD-OCT images by incorporating the enhanced depth imaging OCT (EDI-OCT) images. The down boundary of the choroid, namely choroid-sclera junction (CSJ), is almost invisible in SD-OCT images, while visible in EDI-OCT images. During the SD-OCT imaging, the EDI-OCT images can be generated for the same eye. Thus, we present an EDI-OCT-driven choroid segmentation method for SD-OCT images, where the choroid segmentation results of the EDI-OCT images are used to estimate the average choroidal thickness and to improve the construction of the CSJ feature space of the SD-OCT images. We also present a whole registration method between EDI-OCT and SD-OCT images based on retinal thickness and Bruch's Membrane (BM) position. The CSJ surface is obtained with a 3D graph search in the CSJ feature space.
Results: Experimental results with 768 images (6 cubes, 128 B-scan images for each cube) from 2 healthy persons, 2 age-related macular degeneration (AMD) and 2 diabetic retinopathy (DR) patients, and 210 B-scan images from other 8 healthy persons and 21 patients demonstrate that our method can achieve high segmentation accuracy. The mean choroid volume difference and overlap ratio for 6 cubes between our proposed method and outlines drawn by experts were −1.96µm3 and 88.56%, respectively.
Conclusions: Our method is effective for the 3D choroid segmentation of SD-OCT images because the segmentation accuracy and stability are compared with the manual segmentation.

1. Introduction

Choroid, the vascular layer of the eye, is related with the pathophysiology of many conditions, such as glaucoma [1], age-related macular degeneration (AMD) [2], and Vogt-Koyanagi-Harada [3]. With the development of high-resolution three-dimensional (3D) spectral domain optical coherence tomography (SD-OCT), enhanced depth imaging (EDI) is better for the choroidal visualization. The choroidal thickness is important and widely used for the diagnosis of the chorioretinal diseases [4–6]. The choroidal volume can be also measured and is related with the retinal diseases [7,8].

Recently, based on high resolution OCT images several automatic segmentation methods have been proposed for the measurement of choroidal thickness. A multiresolution texture based modeling in graph cuts [9], graph-searching theory [10,11] and a structural similarity (SSIM) index based method [12] were used to segment the choroid in EDI-OCT images. Zhang et al. [13] presented a graph-cut-graph-search method to segment choroidal surfaces from SS-OCT and SD-OCT. A two stage statistical model based on texture and shape [14] was presented for choroidal segmentation in a 1060 nm OCT system. A gradual intensity distance based method [15] was presented for high-definition OCT (HD-OCT) images with 20 B-scans averaging. Chen et al. [16] presented a choroidal vasculature characteristics based choroid segmentation method for EDI-OCT images with 5 B-scans averaging. Since the increase of the OCT imaging quality depends on the displacement

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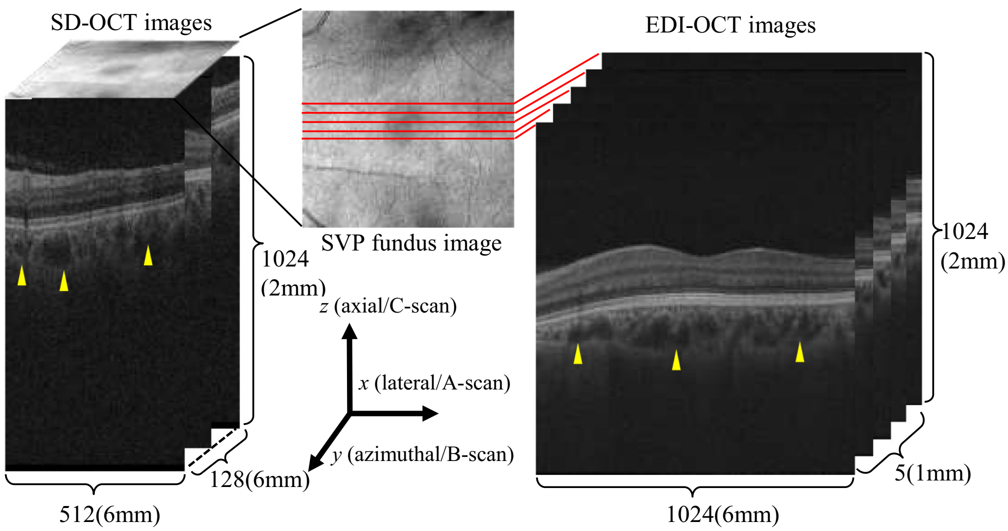

Fig. 1. Relationship demonstration between the EDI-OCT and SD-OCT images. The SVP fundus image is generated with the en face summed-voxel projection (SVP) from all of the SD-OCT images. The CSJ is pointed by the yellow arrowheads.

of zero delay line or the averaging of multi-B-scans, the number of B-scan is not enough to calculate the choroidal volume, such as 5 lines for the EDI-OCT images in Fig. 1 The SD-OCT images have denser scan lines than the high resolution images, but the choroid is often not well-visualized, which challenges the choroid segmentation, especially the down boundary of the choroid (namely choroid-sclera junction, CSJ) as marked with the yellow arrowheads in Fig. 1 The choroid volume is mainly obtained by manual segmentation [7,8], and Hu et al. [17] adopted a semiautomatic graph-based multi-stage segmentation method to identify the choroid for SD-OCT images with 37 B-scans. The lower contrast of the choroid boundary in SD-OCT images makes the task of automatically measuring the choroidal thickness and volume in SD-OCT images prone to difficult.

The high-definition raster OCT images are useful to improve the segmentation performance of the low-definition volumetric SD-OCT image [18]. In order to automatically measure the choroidal volume, this paper presents an automatic choroid segmentation method by combining EDI-OCT images for 3D SD-OCT images with 128 B-scans. Fig. 1 shows the relationship between the EDI-OCT and SD-OCT images, where the scan patterns of EDI-OCT and SD-OCT images are 1024 (lateral) $\times$ 1024 (axial) $\times$ 5 (azimuthal) and 512 (lateral) $\times$ 1024 (axial) $\times$ 128 (azimuthal), respectively. The EDI-OCT images with 5 B-scans averaging locate the macular center. The EDI-OCT and SD-OCT images are almost generated using a Cirrus HD-OCT device at the same time for the same eyes. The choroid in the high definition EDI-OCT images can be segmented relatively easier than that in the low definition SD-OCT images. The basic idea of the proposed method is to guide the choroid segmentation of SD-OCT images based on the choroid segmentation of EDI-OCT images. According to the choroid segmentation of EDI-OCT images, we can estimate the average thickness of the choroid and the choroidal positions near the center of the macular for SD-OCT images.

2. Methods

Fig. 2 shows the flowchart of the proposed method, where the EDI-OCT and SD-OCT images are corresponding to the same eye. The basic process of the proposed method is: ① segment inner limiting membrane (ILM), Bruch's Membrane (BM) and CSJ from EDI-OCT images and segment ILM and BM from SD-OCT images, ② align EDI-OCT and SD-OCT images based on retinal thickness (namely distance between ILM and BM) and BM position, ③ Generate CSJ feature space of SD-OCT images by embedding the choroid segmentation of EDI-OCT images based on the image registration, ④ Segment CSJ surface of SD-OCT images in the generated CSJ feature space by using a three-dimensional (3D) graph search.

The ILM layer segmentation for EDI-OCT and SD-OCT images is based on the vitreous boundary estimation [19]. The BM layers for EDI-OCT and SD-OCT images are segmented by using the retinal structure based RPE estimation [15]. The CSJ boundaries in EDI-OCT images are obtained by analyzing the choroidal vasculature characteristics, such as the gradual intensity in the axial direction near the CSJ boundary [15]. The most difficult problem for the choroid segmentation in SD-OCT images is the CSJ segmentation due to the low visibility. In the following we introduce the registration between EDI-OCT and SD-OCT images and the construction of the CSJ feature space for SD-OCT images.

2.1. Registration between EDI-OCT and SD-OCT images

Since the space distances of the B-scans in EDI-OCT and SD-OCT images are the fixed 0.047 mm (6 mm/127) and 0.25 mm (1 mm/4), respectively, we can simultaneously align the five B-scans in EDI-OCT images with the SD-OCT images to improve the robustness of the image registration. Although the spatial distance between the five EDI-OCT scans is not exactly 5 times of that between the SD-OCT images, 5 is still used as approximation in the following registration between EDI-OCT and SD-OCT images (Eq. (2)). Experimental results indicate that the approximation is acceptable because the registration results of the five EDI-OCT images are only used to facilitate the construction of the CSJ feature space of SD-OCT images. In addition, the SD-OCT images used for registration can be restricted into the center of the cube because the EDI-OCT images locate the center of the macular. According to the ILM and BM segmentation, we can calculate the retinal thickness, namely the distance between ILM and BM in the axial direction, for EDI-OCT and SD-OCT images. Let $T_i^E (i = 1, 2, \cdots, 5)$ be the retinal thickness of the ith B-scan in EDI-OCT images, and $T_i^S (i = 1, 2, \cdots, 128)$ be the retinal thickness of the ith B-scan in SD-OCT images. First, $T_i^E$was resized into the same width with T_i^S, namely the width (512) in the lateral direction. Then, we estimate the displacements in the x and y directions by optimizing the following equation: