Accurate Detection of 3D Choroidal Vasculature Using Swept-Source OCT Volumetric Scans Based on Phansalkar Thresholding

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Abstract—
Various eye ailments associated with the posterior segment of the eye, including age-related macular degeneration (AMD) and central serous chorioretinopathy (CSCR), are caused due to dysfunction of the highly vascular choroid layer. It is responsible for supplying oxygen and nutrients to the retinal outer layers and maintaining the thermal equilibrium of the eye. Clinicians hypothesize that detecting minute volumetric structural changes of the choroidal vasculature enables early diagnosis. To this end, recently introduced swept-source optical coherence tomography (SS-OCT) volume scans provide dense high-resolution imaging of the choroid. However, due to intricate structure, manual segmentation of these vessels is not feasible and clinicians seek algorithmic segmentation and attempts made earlier reported limited performance. In response, we propose a method based on adaptive Phansalkar thresholding to accurately detect choroidal vessels in OCT volumes. Specifically, it increases the contrast between vessel and non-vessel regions within each subblock of the B-Scan. On 15 SS-OCT volumes of healthy and diseased subjects, we performed subjective grading-based performance analysis on 2D and 3D vasculatures achieving 92.67% and 94% segmentation accuracy, respectively. Further, the proposed method demonstrated significant improvement over the previously reported method. Finally, we envisage that this method provides ground truth segmentation for training deep learning models.

I. Introduction

Choroid is the most vascular layer posterior to the Retinal Pigment Epithelium (RPE). It supplies oxygen and nutrients to RPE and retinal layers [1]. Choroid consists of three sublayers, Haller's sublayer consists of large vessels, Sattler's sublayer contains medium-sized vessels, and choriocapillaris has small vessels [2]. The health of the choroid is vital for the proper functioning of the retina [3]. Unfortunately, many vision-threatening eye diseases, including age-related macular degeneration (AMD) [4] and central serous chorioretinopathy (CSCR) [5] deform the structure of the choroidal vasculature. In practice, optical coherence tomography (OCT), a non-invasive imaging modality that provides volumetric sub-surface images around the fovea, is used to visualize the anomalies present in the choroid. Recent advances in OCT such as swept-source OCT (SS-OCT) imaging provides volumetric high-resolution OCT B-scans containing the finer details of the deeper structure, including the choroid [6]. A representative SS-OCT B-scan and the corresponding image with choroid layer boundary and vessel markings are depicted in Fig. 1. Clinicians assume accurate modeling of the vasculature in 3D could enable screening and quantitative assessment of those underlying diseases. However, the intricate vasculature structure makes it a challenging task to segment those vessels.

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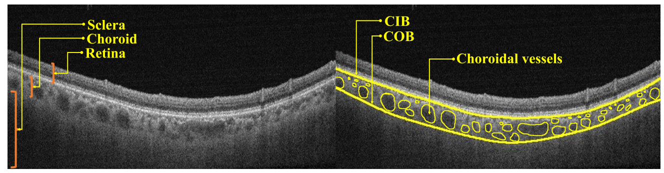

Fig. 1: Representative SS-OCT B-scan with retina, choroid, and sclera labeled image (left) and CIB, COB, and choroidal vessels demarcated image (right). Notation: CIB-choroid inner boundary, COB-choroid outer boundary.

Traditionally, for diagnosis of retinal diseases based on choroid, clinicians manually look at the B-scans and mentally synthesize the choroidal vasculature for taking a clinical opinion. However, such a manual approach is ambiguous, time-consuming, and susceptible to error. On the contrary, researchers have attempted various automated methods for segmenting vessels in 3D, both in the context of choroid [7], [8], [9] and non-choroid [10]. In particular, one of the initial attempts is based on multiscale filtering and projection of the probability cones at each voxel [11]. Although the approach appeared robust, it was exhaustive and computationally intense, where it is required to define a cone at pixel and then determine whether each voxel falls under the luminal or stromal region. Further, the quantitative accuracy of the vessel segmentation is not clear. In another attempt, a semi-supervised approach based on Niblack thresholding using openly available ImageJ tool [9]. Specifically, on each OCT B-scan, this method required manually performing denoising, histogram equalization, and Niblack binarization steps sequentially. Further, the choroid boundaries are segmented manually. The quantitative validation of this method is also unclear. In another attempt, a method motivated by the idiosyncrasies of OCT imaging involving exponential and nonlinear enhancement operations is reported [8]. They validated the method with reasonable accuracy based on healthy OCT volume scans. Recently, noting the developments of deep learning (DL) methods in image segmentation, there are also some attempts at choroid vessel segmentation using DL methods. In particular, an attempt based on ubiquitous encoder-decoder architecture, namely, RefineNet, is reported to segment choroid vessels in SS-OCT volumes [7]. However, for training the DL model, this method requires manual

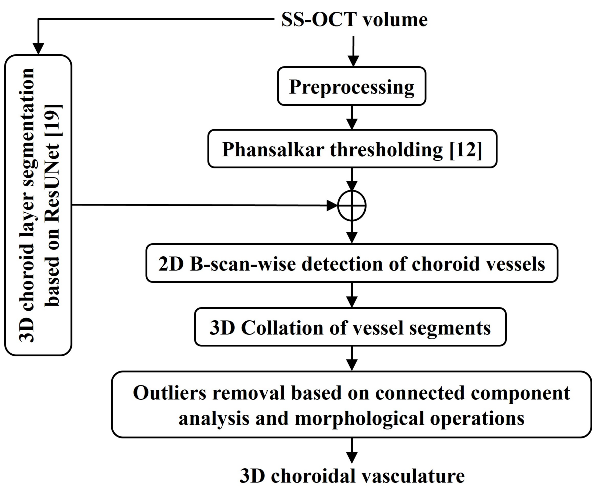

Fig. 2: Schematic of the proposed methodology.

segmentation as ground truth which is not feasible due to the complex intertwined structure of the choroidal vessels.

Against this background, we proposed an improvised method for choroid vessel segmentation based on phansalkar thresholding [10]. In particular, phansalkar thresholding works well with low-contrast and highly noisy gray-scale images based on estimating the local adaptive threshold at each pixel with a small neighborhood around it. As ground truth data is unavailable for evaluating the performance of the proposed method. Hence, our segmentation results are validated based on a subjective grading process and compared with the previously validated method [8].

The rest of the paper is organized as follows. Section II elaborates on the proposed methodology. Experiments and results are presented in Section III and finally, in Section IV, the paper is concluded with a discussion on challenges yet to be solved.

II. Proposed Approach

The schematic of the proposed algorithm is presented in Fig. 2 and the corresponding step-by-step graphical depiction is presented in Fig. 3. We now first proceed to describe the datasets considered in the work and then describe the methodology.

A. Datasets

We considered a retrospective dataset of OCT volumes that are acquired following the ethical standards of the 1964 Helsinki Declaration and informed consent from the University of Pittsburgh Ethics Committee. The volumetric OCT data were acquired using the state-of-the-art SS-OCT (Carl Zeiss Plex Elite 9000) device. Each volume consists of 1024 B-scans with a resolution of 1024x1536 ($12mm \times 12mm \times 3mm$). We consider a total of 15 SS-OCT volumes in this study, of which each 5 of them was taken from healthy, AMD, and CSCR eyes.

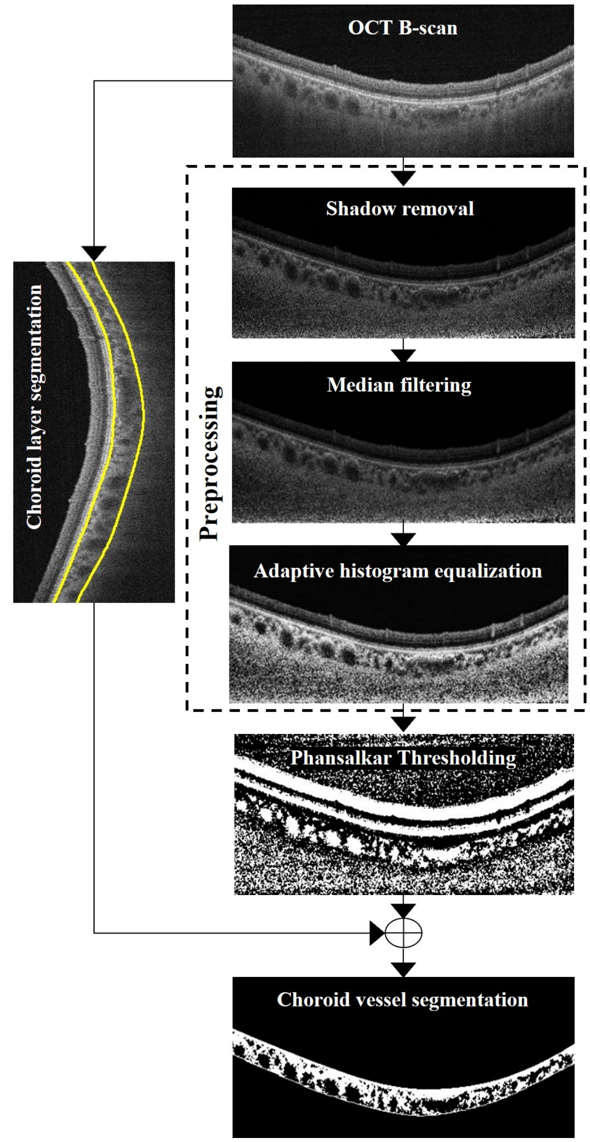

Fig. 3: Graphical depiction of the proposed methodology.

B. Preprocessing

The OCT image acquisition process introduces various artifacts including speckle noise, signal attenuation along the depth, and retinal vessel shadows cast on the underlying layers. Accordingly, we performed various preprocessing operations to mitigate their effect and improve the quality of the image. In particular, speckle noise is suppressed using median filtering with a tile size of 2×2 while the attenuation is compensated using adaptive histogram equalization with a tile size of 8×8. Finally, retinal vessel shadows are mitigated based on previously reported shadow compensation method [12].

C. Proposed method for choroid vessel segmentation

Noting the structural and intensity variation of choroidal vessels across the B-Scan, we desire a method that enhances the vessel and non-vessel structures to facilitate clear demarcation in contrast between them. Accordingly, we adopted Phansalkar local thresholding approach to segment the choroidal vessel structures accurately [10]. In particular, Phansalkar thresholding attempts to find the fine threshold separating vessel and non-vessel intensity distributions even in low-contrast B-scans.In particular, the local threshold (Th) is estimated at each pixel in B-scan considering a neighborhood window based on the statistics mean (M) and standard deviation (SD) of the neighborhood and some parameters given by.

$$Th = M(1 + p * exp(-qM) + k((SD/R) - 1)) \quad (1)$$

where p, q, k are the parameters empirically tuned to differentiate between vessel and background pixels, and R is the dynamic range of SD. Consequently, 3D morphological operations including erosion followed by dilation are performed to suppress noisy vessel components and obtain smooth choroidal vasculature estimates. We empirically used $R = 0.5$ and a window size of 40×40. Further, default values considered in Matlab are used for p, q, k.

D. Choroid layer segmentation

Towards modeling the choroidal vasculature, one of the important subtasks is to accurately delineate the choroid layer boundaries from the volumetric wide-field SS-OCT scans. In particular, as depicted in Fig. 2, the choroid layer delineation process involves the detection of (i) choroid inner boundary (CIB) and (ii) choroid outer boundary (COB). In particular, we adopted our previous approaches involving the residual encoder-decoder-based DL model [13] to obtain B-Scan wise initial boundaries and subsequently employed volumetric smoothing to smooth initial estimates volumetrically [14].

E. Subjective grading

Due to the non-availability of the ground truth annotation for validating the algorithmically estimated choroid vessel segmentation, we perform the subject evaluation on 2D and 3D segmentation with the help of a trained expert to manually grade the accuracy of segmentation. In particular, for 2D evaluation, the grader looks at the B-scan and corresponding vessel segmentation (see Figure. 4) and scores for its accuracy on a scale of 0-100. In particular, We considered five randomly picked B-scans per volume. The average among each type of eye (healthy, AMD, and CSCR) gives the respective representative score. Further, for 3D evaluation, the grader looks at 3D vasculatures obtained by the proposed and previous methods and scores on a scale of 0-100 for their accuracy. The average scores of all volumes are taken for comparison.

III. Experiments and Results

On 15 SS-OCT volumes (5-healthy, 5-CSCR, and 5-AMD eyes), the proposed methodology is tested against the previously validated exponential enhancement (EE) method [8]. Figures 4 and 5 depict a visual comparison of 2D and 3D choroid vasculatures. 2D segmentations clearly indicated that the improvement of Phansalkar thresholding accurately detected the vessel segments. Further, it can be noticed in Fig. 5 that the encircled spots on the 3D vasculature of the EE method indicate the regions where the proposed method performed better. Further, as alluded earlier, we have designed a subjective grading framework based on 2D and 3D vessel segmentation to evaluate accuracy. The scores provided by the grader based on the accuracy of vessel segmentation in 2D B-scans and for 3D vasculature were recorded for both methods. The average score represents the overall accuracy of each method. The mean 2D and 3D subjective grading scores for the Phansalkar-based vasculature are observed to be 92.67% and 94% while for the exponentiation enhancement method, they are observed to be 77.67% and 73.33%, respectively, buttressing the efficiency of the proposed method.

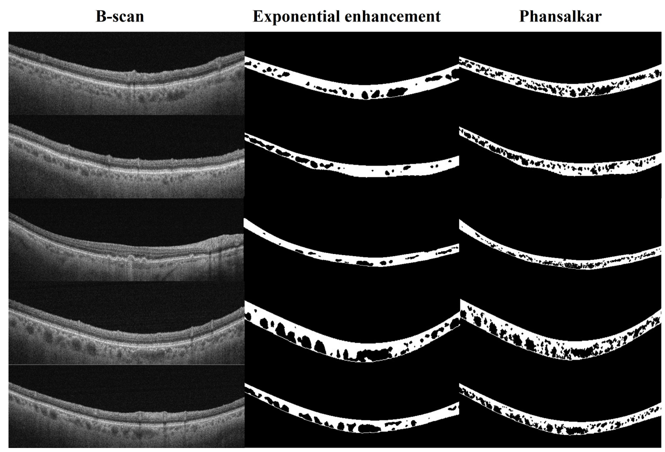

Fig. 4: Visual comparison of choroid vessel segmentation based on previous [8] and proposed method using 2D B-scans.

IV. Discussion

The proposed method based on Phansalkar thresholding significantly improves the performance of choroidal vessel segmentation over the previously reported EE method. Consequently, it has the potential to enable quantitative analysis of vasculature models based on accurate vessel-level biomarker quantification for precisely screening ocular disorders such as AMD and CSCR. We believe that the proposed method can be used in deeper analysis of choroid including choroid vessel tracing and vessel diameter variation maps. Further, the proposed method can be leverage to produce ground truth segmentations required for training deep learning models including encoder-decoder architectures to further improve the semgentation accuracy.

V. Acknowledgments

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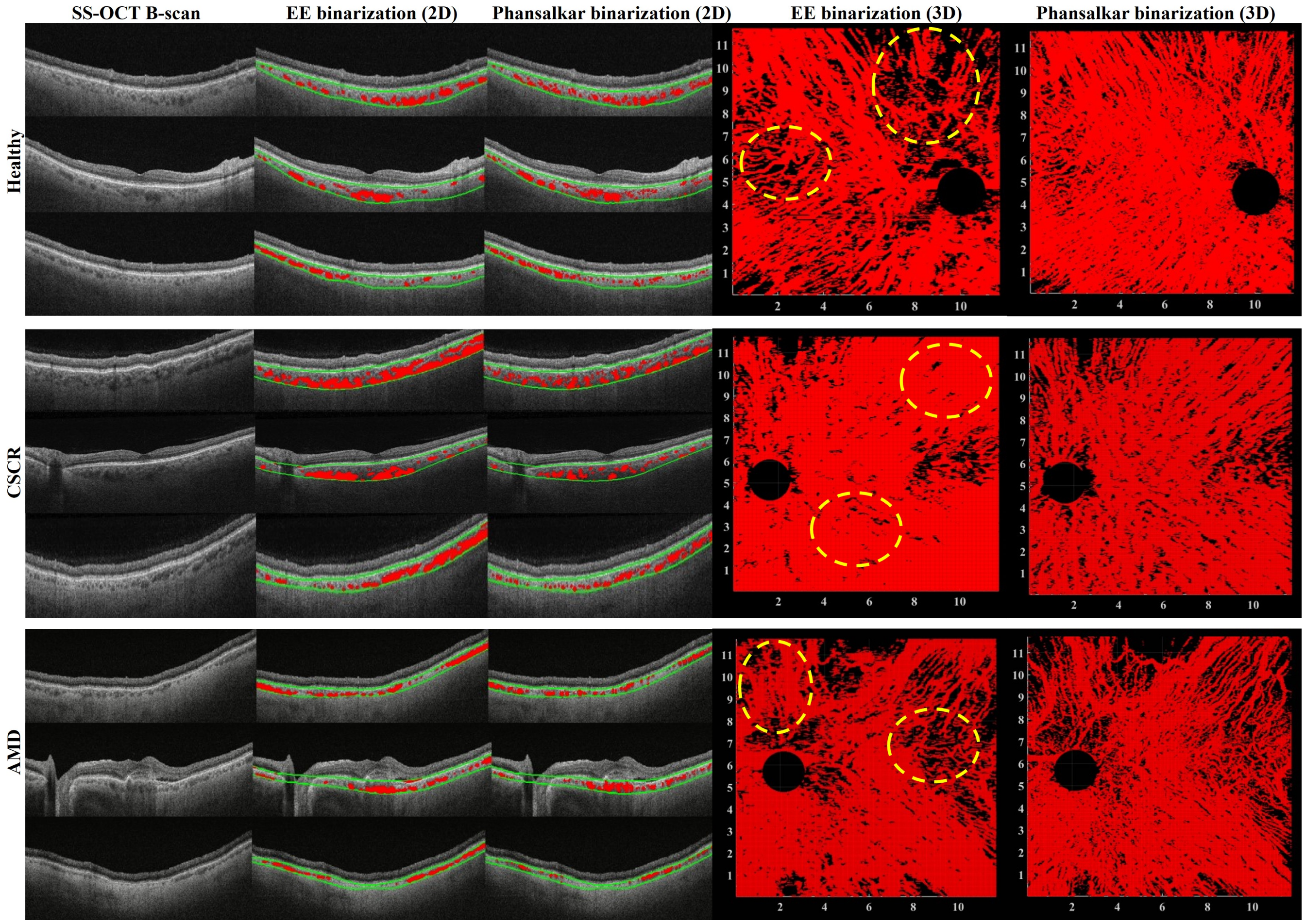

Fig. 5: Choroid vessel segmentation: EE vs Phansalkar (encircled regions indicate places of improvement).

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