

Automatic Detection of Retinal Vascular Bifurcations and Crossovers Based on Isotropy and Anisotropy

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ABSTRACT

The analysis of retinal blood vessels is very important in the detection of some diseases in early stages, such as hypertension, diabetes, arteriosclerosis, cardiovascular disease, and stroke. The bifurcations and crossovers are important feature points, which play important roles in the analysis of the retinal vessel tree. These feature points have been demonstrated to be important features in many visual tasks such as image registration, mosaicing, and segmentation. In this paper, a new method is proposed to detect vascular bifurcations and crossovers in fundus images. The Gaussian filter is applied to the blue channel of the original color retinal images to suppress the central reflex and reduce the candidate points. The eigenvalues and eigenvectors of Hessian matrix are then obtained in multiple scales to provide the structural and directional information. By computing the anisotropy and isotropy of neighboring image segments for each pixel in a retinal image, we define a multi-scale vessel filter which combines the responses of tubular structures and the responses of bifurcations and crossovers. Finally, the proposed method has been tested with publicly available database STARE and DRIVE. The experimental results show that bifurcations, crossovers and tubular structures can be detected simultaneously. And the proposed method performs well in detecting the bifurcations and crossovers which are in thin vessels or low contrast vessels.

Keywords: retinal vessel, feature point, bifurcation, crossover, isotropy and anisotropy

1. INTRODUCTION

The analysis of retinal blood vessels is very important in many clinical diagnosis and scientific research. Through analyzing the structures of the retinal vessel tree several pathologies, such as arterial hypertension, arteriosclerosis or diabetic retinopathy could be detected. It is believed that half of all blindness can be prevented, in part through periodic screening and early diagnosis. Automated image analysis techniques should play a central role because the huge volume of images precludes strictly manual analysis [1]. Bifurcations and crossovers are useful features in the analysis of the vascular structures. By measuring changes in select vascular branching and crossover regions the hypertension can be diagnosed earlier [2]. In registration, bifurcations and crossovers can be used as landmarks which improve the result of the registration and reduce the feature extraction computation [3] [4] [5]. In retinal vessel extraction, bifurcations and crossovers can sometimes be used as the start and end points for the vessel tracking method [6] [7] [8] [9]. Many methods have been used to find bifurcations and crossovers in a vascular tree. A. Can et al. [6] proposed a method based on center line extraction. Tsai et al. [8] proposed a model-based method for improving the accuracy and repeatability of estimating vascular bifurcations and crossovers. Yin et al. [10] proposed a Bayesian method with the Maximum a posteriori (MAP) probability criterion to identify local vessel's structure(normal, bifurcations or crossovers). D. Calvo et al. [11] combines filters and morphologic operations to obtain an adequate structure for the detection of bifurcations and crossovers. Another method proposed by R. Su et al. [12] proposed a new measurement which combines Hessian information and correlation matrix to select the candidate junction points.

In this paper, a novel method to detect bifurcations and crossovers of the retinal vascular tree is proposed. With the information of the Hessian matrix, the isotropy and anisotropy for each pixel is computed. Using the isotropy and anisotropy information a new vessel filter which combines the responses of tubular structures and the responses of bifurcations and crossovers is defined in multiple scales.

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The rest of the paper is organized as follows: in Section 2 we present the measurement of isotropy and anisotropy and define a new multi-scale vessel filter which can detect the bifurcations and crossovers of the retinal vessels. In Section 3, we apply the filter on retinal images from the STARE and DRIVE data set and illustrate the results. In Section 4, we provide a discussion about some aspects of the proposed approach and make suggestions for future work.

2. METHOD

2.1 Gaussian filter

A Gaussian filter is used to smooth an image by calculating weighted averages in a filter box. Mathematically, a Gaussian filter modifies the input signal by convolution with a Gaussian function; this transformation is also known as the Weierstrass transform. In two dimensions, a Gaussian filter can be defined as:

$$g(x,y)=\frac{1}{2\pi\sigma^2}\cdot e^{-\frac{x^2+y^2}{2\sigma^2}} \quad (1)$$

Where, x is the distance from the origin in the horizontal axis, y is the distance from the origin in the vertical axis, and σ is the standard deviation of the Gaussian distribution.

2.2 The eigensystem of Hessian matrix

Fig.1 illustrates the eigensystem of retinal blood vessel. Assuming that λ_1 and λ_2 are the two eigenvalues of the Hessian matrix H , and v_1 and v_2 are the two corresponding eigenvectors. For dark vessels in retinal images, one eigenvalue of tubular structure is positive and the other one close to zero, while both the eigenvalues of bifurcations or crossovers are positive. For light vessels in retinal images, one eigenvalue of tubular structure is negative and the other one close to zero, while both the eigenvalues of bifurcations or crossovers are negative. If one pixel is in the tubular structure, the eigenvector v_2 which corresponds to the smaller absolute value of the eigenvalue parallels the tubular vessel direction and the other eigenvector is perpendicular to the vessel direction. However, if one pixel is in the bifurcation or crossover, the two eigenvectors almost parallel the bifurcation or crossover directions. So λ_2 plays an important role in bifurcation structures or crossover structures of the retinal vessel. Therefore, λ_2 plays an important role in the detection of bifurcations and crossovers of the retinal vessels such that the whole blood vessel tree can be obtained compared to previous methods.

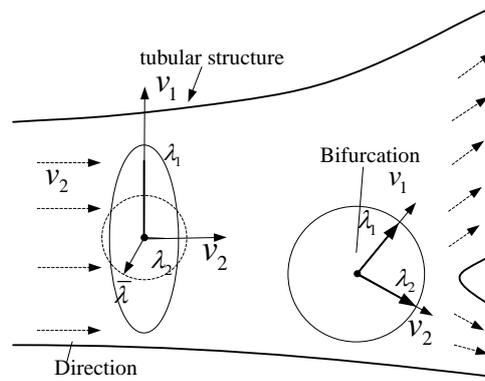


Fig. 1: the eigensystem of retinal blood vessel

2.3 Measures of isotropy and anisotropy

In diffusion tensor imaging the measures of isotropy and anisotropy from diffusion tensor is very useful to recognize different local structures of soft tissues. The most commonly used invariant indices are the relative anisotropy (RA), the fractional anisotropy (FA), and the area ratio (AR) [13] [14]. Here we introduce new measures of isotropy and anisotropy from multi-scale hessian matrix which can be used to detect the vascular bifurcations and crossovers from fundus images. First, we decompose matrix H into isotropic part and anisotropic part:

$$H = IS + AN = \langle H \rangle I + (H - \langle H \rangle I). \quad (2)$$

where, $IS = \langle H \rangle I$ is the isotropic part of H ; and $AN = H - \langle H \rangle I$ is the anisotropic part of H ; and I is the identity matrix. $\langle H \rangle$, where

$$\langle H \rangle = \frac{\text{Trace}(H)}{2} = \frac{H_{xx} + H_{yy}}{2} = \frac{\lambda_1 + \lambda_2}{2}. \quad (3)$$

Above, H_{xx} and H_{yy} are the diagonal elements of H ; λ_1 and λ_2 are the eigenvalues of H . Then we can obtain the magnitudes of the isotropic and anisotropic parts just as the magnitude of a vector, where

$$\text{Magnitude of } H = \sqrt{H : H} = \sum_{i=1}^2 \sum_{j=1}^2 H_{ij}^2. \quad (4)$$

Because the Hessian matrix is a real symmetric matrix, we can obtain the magnitudes of the above matrixes, defined respectively as:

$$\sqrt{H : H} = \sum_{i=1}^2 \sum_{j=1}^2 H_{ij}^2 = \lambda_1^2 + \lambda_2^2. \quad (5)$$

$$\sqrt{IS : IS} = \frac{\sqrt{2}}{2} (\lambda_1 + \lambda_2). \quad (6)$$

$$\sqrt{AN : AN} = \sqrt{\frac{(\lambda_1 - \lambda_2)^2}{2}}. \quad (7)$$

Then we obtain measures of the relative anisotropy (RA) and the fractional anisotropy (FA):

$$RA = \frac{\sqrt{AN : AN}}{\sqrt{IS : IS}} = \frac{|\lambda_1 - \lambda_2|}{\lambda_1 + \lambda_2}. \quad (8)$$

$$FA = \frac{\sqrt{2} \times \sqrt{AN : AN}}{\sqrt{H : H}} = \frac{|\lambda_1 - \lambda_2|}{\sqrt{\lambda_1^2 + \lambda_2^2}}. \quad (9)$$

Simultaneously, the area ratio, AR :

$$AR = \frac{A(\text{ellipse})}{A(\text{circle})} = \frac{\lambda_1 \times \lambda_2}{\left(\frac{\lambda_1 + \lambda_2}{2}\right)^2}. \quad (10)$$

where, $A(\text{ellipse})$ is the area of the eigenellipse and $A(\text{circle})$ is the area of a circle whose radius is the mean value of λ_1 and λ_2 .

2.4 A new multi-scale vessel filter

In order to detect vessels at a variety of widths in a retinal image, it is vital to use a multiple scale scheme. In this paper, we propose a new multi-scale vessel filtering based on isotropy and anisotropy such that we can easily detect the bifurcations and crossovers of the retinal vessel. For tubular structures which are anisotropic mediums, $\lambda_1 \gg \lambda_2 \approx 0$, $RA \approx 1$, $FA \approx 1$, $AR \approx 0$, and for bifurcations or crossovers which are symmetric isotropic mediums, $\lambda_1 \approx \lambda_2$, $RA \approx 0$, $FA \approx 0$, $AR \approx 1$. So we define $L_s(x, y)$ as the local responses of tubular structures and $B_s(x, y)$ as the local responses of bifurcations and crossovers:

$$L_s(x, y) = RA \times E^\alpha(\lambda_s(x, y)) = \frac{|\lambda_{s,1} - \lambda_{s,2}|}{\lambda_{s,1} + \lambda_{s,2}} \times \bar{\lambda}_s^{-\alpha}(x, y), \quad (11)$$

or,

$$L_s(x, y) = FA \times E^\alpha(\lambda_s(x, y)) = \frac{|\lambda_{s,1} - \lambda_{s,2}|}{\sqrt{\lambda_{s,1}^2 + \lambda_{s,2}^2}} \times \bar{\lambda}_s^{-\alpha}(x, y), \quad (12)$$

$$B_s(x, y) = AR \times E^\alpha(\lambda_s(x, y)) = \frac{\lambda_{s,1} \times \lambda_{s,2}}{\left(\frac{\lambda_{s,1} + \lambda_{s,2}}{2}\right)^2} \times \bar{\lambda}_s^\alpha(x, y). \quad (13)$$

where, $\bar{\lambda}_s(x, y)$ is the mean eigenvalue, which characterizes the overall mean-squared structure. The parameter α determines how strictly the structure can be adapted to return a well filtered value. In our study, α is set to 0.5.

In order to detect bifurcations and crossovers of vessels at a variety of widths in a retinal image $I(x, y)$, we compute anisotropy measure and isotropy measure at each pixel, and then linearly combine the anisotropy response and the symmetric isotropy response across multiple scales,

$$V_s(x, y) = \max_{s_{min} < s < s_{max}} s^\gamma \times (L_s(x, y) + \eta B_s(x, y)). \quad (14)$$

Where, s is the scale; γ is a normalization factor; s_{min} and s_{max} are the minimal scale and the maximal scale respectively. η is a positive weight, which controls the influence of isotropy.

3. RESULTS

3.1 Importance of the Gaussian filter

The proposed method has been tested with publicly available database STARE and DRIVE.

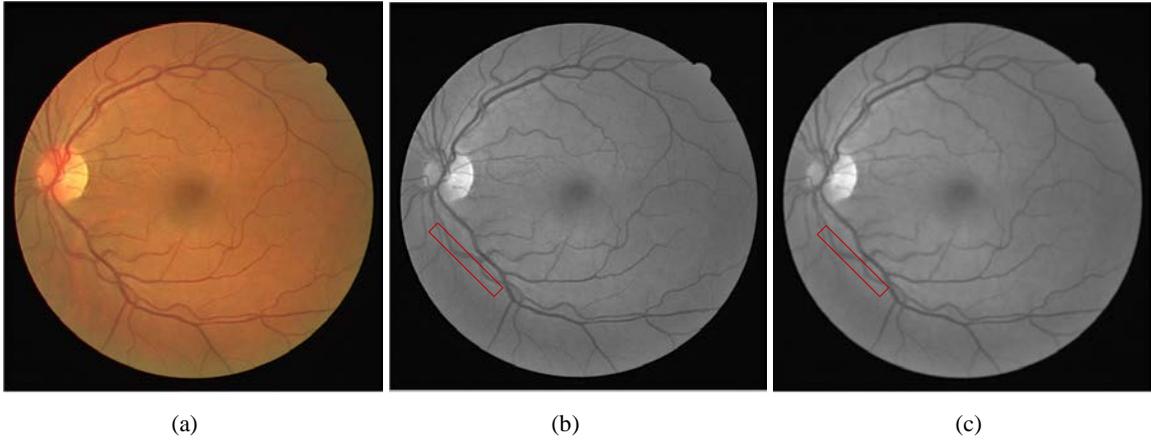


Fig. 2: (a) an original retinal image, (b) gray level image, (c) gray level image after Gaussian filter, the “central reflex” is suppressed

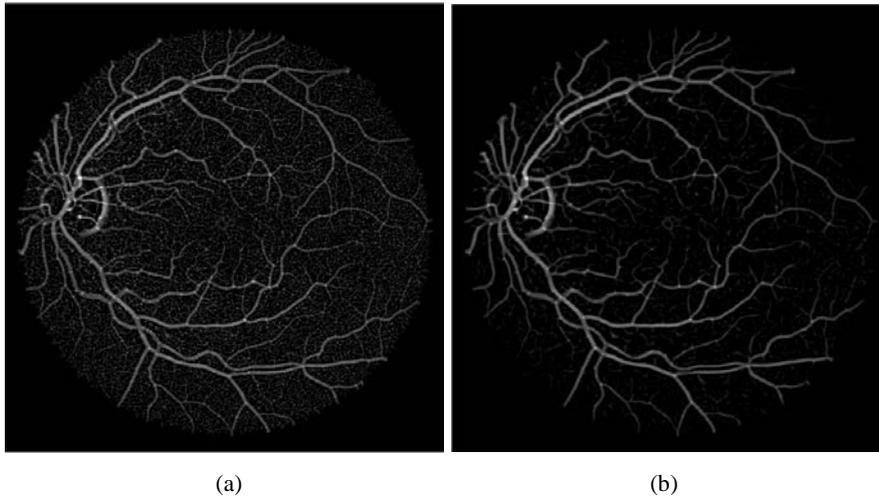


Fig. 3: (a) result without Gaussian filter, (b) result with Gaussian filter.

Here we use a 4×4 Gaussian filter with the standard deviation $\sigma=2$ to smooth the noise of the gray level image and suppress the influence of central reflex of the retinal vessels. Fig.2 (a) shows an original retinal image from the database DRIVE. Fig.2 (b) shows that the vessel's central reflex is serious in the gray level image. Fig.2 (c) shows that Gaussian filter can suppress the influence of the vessel's central reflex. Fig.3 (a) shows that there are many false candidate feather points in the final result which without using Gaussian filter. Fig.3 (b) shows that the Gaussian filter can reduce the false candidate feather points.

3.2 Results

As can be seen in Fig. 4, when $\eta=1$, the tubular structure is detected while the bifurcations and crossovers are not obvious. When $\eta=3$, the bifurcations and crossovers are obvious. So the weight η is important in our method. In Fig. 4 (b), the bifurcations or crossovers being detected correctly are in the center of the red circles and the yellow rectangle mark the false detection. From the enlarged figures (Fig. 4 (c) and Fig. 4 (d)), we can see the bifurcations and crossovers are marked with the highest intensity in the center of the red circles by the proposed method. The experimental results demonstrate the effectiveness of the proposed approach.

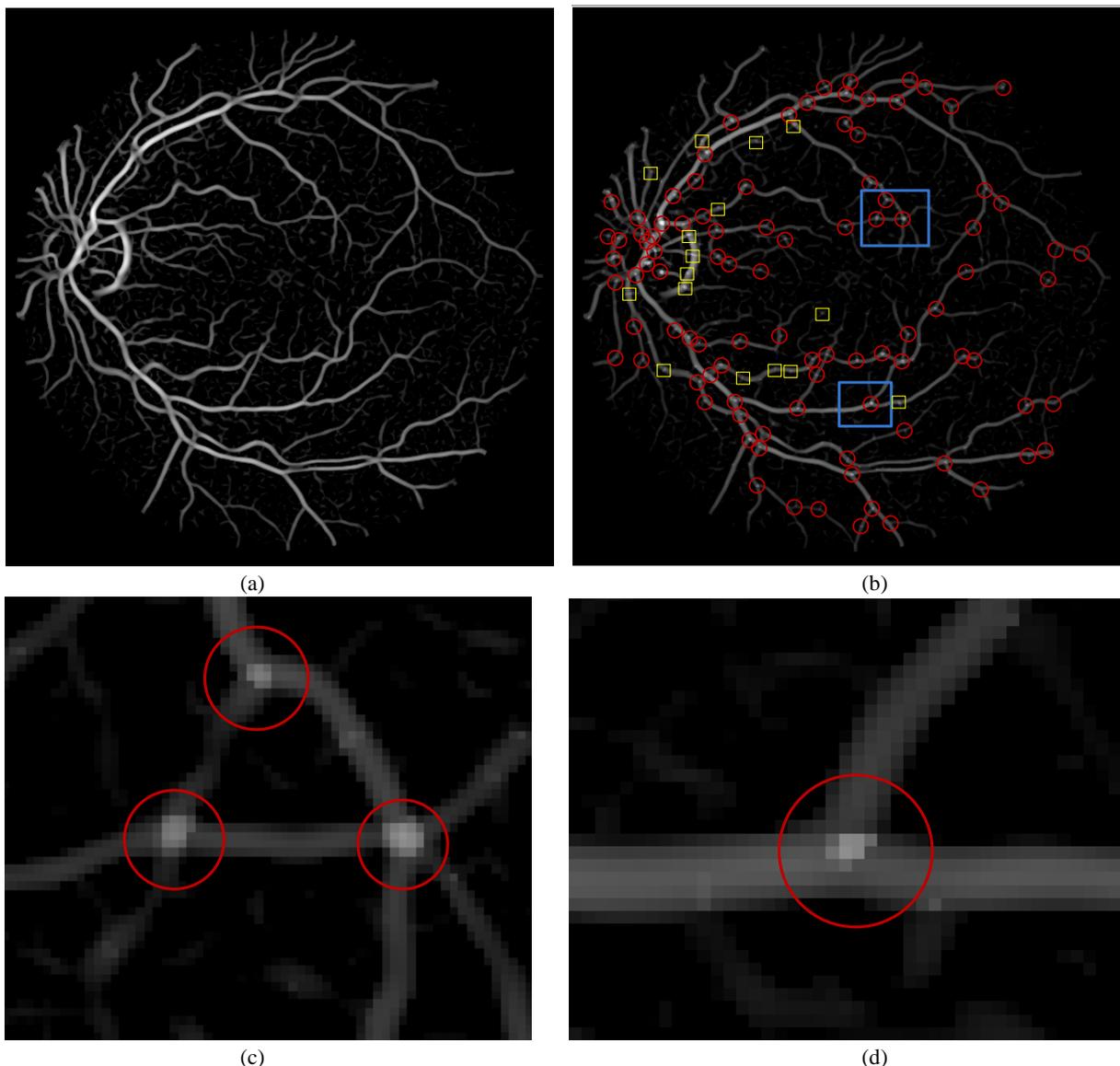


Fig. 4: (a) our method ($\eta=1$), (b) our method ($\eta=3$), (c) the enlarged crossovers, (d) the enlarged bifurcation.

4. CONCLUSIONS AND FUTURE WORK

In this study, a novel method is proposed to detect bifurcations and crossovers of the retinal vascular tree. The experimental results show that the central reflex of the vessel could be suppressed and the false candidate feature points could be reduced by preprocessing with the Gaussian filter. By using the isotropy and anisotropy of each pixel the new multi-scale vessel filter could even detect the bifurcations and crossovers of thin vessels or low contrast vessels. The tubular structures are enhanced by using a smaller η and the bifurcations and crossovers are enhanced by using a larger η .

Our future work will focus on two aspects. Firstly, we will focus on increasing the precision of the detection. Secondly, we will focus on using the bifurcations and crossovers of the retinal vascular tree to extract the retinal vessels combined with some vessel tracking method.

5. ACKNOWLEDGEMENT

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