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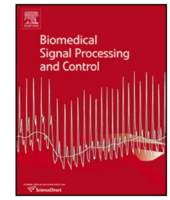

Layered vasculature segmentation of color conjunctival image based on wavelet transform

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ABSTRACT

The vasculature segmentation is one of the essential procedures in the conjunctival image analysis in medicine and biometrics. The vascular patterns segmented from the images are affected by the multi-scale, especially the multi-layer feature of the conjunctival vessel. Based on the Monte Carlo simulation and wavelet transform analysis, a layered vasculature segmentation approach for color conjunctival images were developed, so as to extract the conjunctival vessels by layers from image with fine details, which has great potential in biometrics and the gaze tracking.

1. Introduction

The conjunctiva is a membrane that lines the inside of the eyelids and extends over the front of the sclera, which contains a vascular network responsible for the anti-infection and the nutrition supply of the ocular surface [1]. Since the conjunctiva offers the physician a readily accessible site for the study of the peripheral vasculature, the assessment of the conjunctival vessels has received considerable attention throughout decades [2–4]. Because the visible rich vascular network of ocular conjunctiva could be easily recorded by digital camera, the method based on conjunctival image analysis (also called sclera image) has been generally thriving in areas of evaluation of ocular hemodynamics [5,6], eye redness estimation [7,8] and erythema diagnosis [9]. The conjunctival vasculature also serve as a an specific and identifiable pattern in biometrics [10] because of its high degree of randomness and stability throughout lifetime [11,12]. And recently, it also has been employed in gaze tracking [13].

The vessel segmentation is the essential procedure in the conjunctival image analysis. Most state-of-the-art conjunctival vessel extraction methods are derived from the retinal vessel recognition [14] and fluorescence image analysis [15]. But unlike the well-equipped hospital environment [16], the “easily-accessible” advantage of conjunctival image also means the researchers especially in biometric study have to confront the issues like large intensity variation, low contrast between vessels and the sclera background, low image resolution with respect to the vascular fineness of conjunctiva [17]. Among these methods, the global thresholding method is only adopted in high contract constrained area or when the computation speed is essential [13]. The adaptive histogram equalization is employed to accommodate the complex illumination condition [18,19]. The selective enhancement filter for the minutiae points extraction is used in order to improve sensitivity to vein detection and segmentation [17,20,21]. The Gabor filter is also introduced to mitigate the non-unified illumination to achieve an illumination-invariant process [22,23]. Since the veins of the conjunctiva image are different in width and thickness, the contourlet transform is used to extract edges and the smooth contour information with benefits of multi-resolution and multi-directionality [24,25].

With the continuous improvement of the vessel extraction methods, the multi-layer feature of conjunctival vasculature has brought more concerns in the conjunctival vessel segmentation [22,23]. Because the vascular patterns of conjunctival image are formed by several layers of vessels, which are contained respectively within the conjunctiva and the sclera, and shall deform along with eye rotation [1]. This nonlinear deformation makes it difficult to get more accurate result in conjunctival feature extraction and matching. Although some elaborately selected feature descriptors such as “Y shape branches” have been introduced to bypass the

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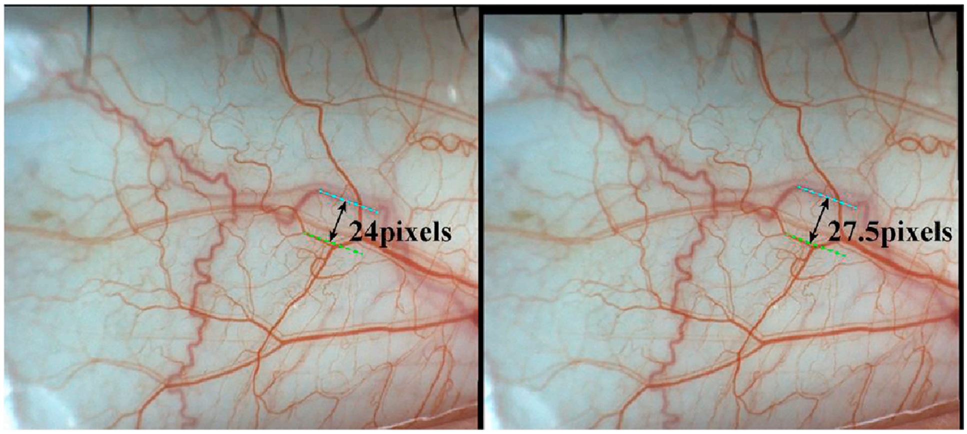

Fig. 1. The 300th frame(left) and the 350th frame(right) of a stabilized conjunctiva monitoring video were compared to illustrate the multi-layer feature of the conjunctival image. During the corresponding moment, the distance between the superficial vessel (green dotted line) and the deep-seated vessel (blue dotted line) were enlarged from 24 pixels to 27.5 pixels, according to the subtle eye moment of measured subject. (Notice: for purpose of monitoring conjunctiva, the conjunctival vascular pattern was stabilized based on the features extracted by our method, so the scleral vessels moved relatively in this video). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

multi-layer problem [23], it is still highly valuable to separate the conjunctival vasculature from the ones within sclera during the segmentation.

In this paper, we propose a layered conjunctival vessel segment method based on wavelet transform to address the multi-layer problems in the conjunctival image analysis.

- We used the Isotropic Undecimated Wavelet Transform (IUWT) to segment the vessels from the conjunctival color image by the parameter thresholding. (Section 2.1) With the advantage of multi-resolution and stability, our method could preserve the fine vessel details under the non-unified illumination. (Section 3)
- Based on the Monte Carlo simulation, we found the intensity difference between the blue and green channel of the conjunctival color image was the essential parameter to separate the conjunctival vessel from the ones within sclera. Through comparing of the conjunctival vessels (superficial) and the scleral vessels (deep-seated) in the color image, we carried out the separation parameter of our method. (Section 2.2)
- Combining the wavelet transform and the proposed separation parameter, we developed a segmentation scheme to extract the vessels from the conjunctival color images by two layers, then conducted an experiment to test its effectiveness in practice. (Section 3)

2. Materials and methods

In our research, we mainly focused on the close-range recorded conjunctival images, as illustrated in Fig. 1, which had higher resolution and were well illuminated. For the general purpose of the conjunctival vascular analysis, the recognizable vessels in the conjunctiva image are mainly composed of two layers [26]: the major superficial vascular network is confined to the stromal layer of the conjunctiva [27], and the coarse veins are buried deeper in the episclera [28]. So in general, the thickness of conjunctiva or episclera above the vessels made them different in appearance. Because of small scattering coefficient and absorption coefficient, conjunctiva is nearly transparent. So the superficial vessels in the conjunctiva preserved fine recognizable details, which required the multi-resolution property of the potential segmentation method. On the contrary, with relatively large scattering coefficient and anisotropy coefficient, only the coarse main veins within the sclera could be observed in visible light. Due to the coefficient difference in the blue and green light, the deep-seated scleral vessel appears more blueish.

Because the elasticity of conjunctiva, the vessels within it could be stretched with the moment of eye, which would cause a relative movement with respect to the scleral vessels. This nonlinear formation of the conjunctival vascular pattern was noticeable in the higher resolution image, even with the subtle subconscious eye movement, as illustrated in Video S1.

2.1. *Vessel segmentation by Isotropic Undecimated Wavelet Transform(IUWT)*

The two dimensional wavelet transformation has good spatial resolution in the high frequencies, which made it remarkable for preserving the finest details, while maintaining good connectivity of the main vessels. The Isotropic Undecimated Wavelet Transform (IUWT) we adopted is a powerful, redundant wavelet transform that has been applied in astronomy [29] and biology [30,31]. It affords an implementation: at each iteration j, scaling coefficients c_j is computed by lowpass filtering, and wavelet coefficients w_j by subtraction [32]. The scaling coefficients preserve the mean of the original signal, whereas wavelet coefficients have a zero mean and encode information corresponding to different spatial scales present within the signal. Applied to a signal c_0, subsequent scaling coefficients are calculated by convoluting with a filter h^j.

$$c_{j+1} = c_j * h^j \tag{1}$$

where $h = [1,4,6,4,1]/16$ is derived from the cubic B-spline, and h^j is the upsampled filter obtained by inserting $2^j - 1$ zeros between each pair of adjacent coefficients of h_0. If the original signal f is multidimensional, the filtering can be applied along all dimensions. Wavelet coefficients are then simply the difference between two adjacent sets of scaling coefficients, i.e.

$$w_{j+1} = c_j - c_{j+1} \tag{2}$$

Reconstruction of the original signal is straightforward by adding all wavelet coefficients and the final set of scaling coefficients,

$$c_0 = c_n + \sum_{j=1}^{n} w_j \tag{3}$$

The set of wavelet coefficients generated at each iteration is referred to as a wavelet level. Thanks to the multi-resolution