Pattern Recognition 44 (2011) 2314–2324

Contents lists available at ScienceDirect

Pattern Recognition

journal homepage: www.elsevier.com/locate/pr

Segmentation of retinal blood vessels using the radial projection and semi-supervised approach

Xinge You [a], Qinmu Peng [a], Yuan Yuan [b,*], Yiu-ming Cheung [c], Jiajia Lei [a]

[a] Department of Electronics and Information Engineering, Huazhong University of Science and Technology, Wuhan, China
[b] Center for OPTical IMagery Analysis and Learning (OPTIMAL), State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, Shaanxi, P. R. China
[c] Department of Computer Science, Hong Kong Baptist University, Hong Kong

ARTICLE INFO

Available online 20 January 2011

Keywords:
Radial projection
Retinal images
Steerable complex wavelet

ABSTRACT

Automatic segmentation of retinal blood vessels has become a necessary diagnostic procedure in ophthalmology. The blood vessels consist of two types of vessels, i.e., thin vessels and wide vessels. Therefore, a segmentation method may require two different processes to treat different vessels. However, traditional segmentation algorithms hardly draw a distinction between thin and wide vessels, but deal with them together. The major problems of these methods are as follows: (1) If more emphasis is placed on the extraction of thin vessels, the wide vessels tend to be over detected; and more artificial vessels are generated, too. (2) If more attention is paid on the wide vessels, the thin and low contrast vessels are likely to be missing. To overcome these problems, a novel scheme of extracting the retinal vessels based on the radial projection and semi-supervised method is presented in this paper. The radial projection method is used to locate the vessel centerlines which include the low-contrast and narrow vessels. Further, we modify the steerable complex wavelet to provide better capability of enhancing vessels under different scales, and construct the vector feature to represent the vessel pixel by line strength. Then, semi-supervised self-training is used for extraction of the major structures of vessels. The final segmentation is obtained by the union of the two types of vessels. Our approach is tested on two publicly available databases. Experiment results show that the method can achieve improved detection of thin vessels and decrease false detection of vessels in pathological regions compared to rival solutions.

1. Introduction

The retina is a complex, layered structure with several layers of neurons interconnected by synapses. It usually can be acquired as a retinal image by the fundus camera. Retinal images provide considerable information on pathological changes caused by local ocular disease which reveals diabetes, hypertension, arteriosclerosis, cardiovascular disease and stroke [1,2]. These disease often results in changes on reflectivity, bifurcations, tortuosity as well as other patterns of blood vessels. Hence, analyzing vessel features gives new insights to diagnose the corresponding disease early. For example, vessel tortuosity characterizes hypertension retinopathy [3] and diabetic retinopathy usually leads to neovascularization. The latter is one of the most common causes of vision defects or even blindness worldwide. If abnormal signs of diabetic retinopathy could be detected early, effective treatment before their initial onset can be performed. However, with a large number of patients undergoing regular screenings, huge volume of retinal images are also acquired, strictly manual delineation of the vessels becomes tiresome or even impossible.

Computer-aided analysis of retinal image should play a central role in diagnostic procedures, and extensive research efforts have been devoted to automating this process. Nevertheless, reliable vessel extraction encounters several challenges: (1) The blood vessels have a wide range of widths and diffident tortuosity. (2) Various structures appear in retinal image, including the optic disc, fovea, exudates and pigment epithelium changes, which severely disrupt the automatic vessel extraction. (3) The narrow vessels with various local surroundings may appear as some elongated and disjoint spots, which are usually lost. Considerable previous works have endeavored to address these issues. So far, vessel segmentation from retinal images is still a difficult problem that has been widely studied in the literature. These studies can be broadly grouped as pixel processing-based approaches [4–12], tracking-based approaches [13–15] and model-based approaches [16–22], respectively.

Pixel processing-based approaches consist of two steps. The first step is an enhancement procedure, which is usually done by

* Corresponding author.
E-mail address: yuany@opt.ac.cn (Y. Yuan).

0031-3203/$ - see front matter © 2011 Published by Elsevier Ltd.
doi:10.1016/j.patcog.2011.01.007

applying a convolution operator; the second step may use adaptive threshold, morphological operations as well as classification method to select the vessel pixels. The concept of matched filter detection was proposed by Chaudhuri et al. [4]. The image was convolved with a set of 2-D Gaussian kernels (fixed size and 12 diffident orientations), retaining the maximum response with respect to the angle. Hoover et al. [5] further developed this approach. The authors exploited local vessel attributes with region-based attributes, using a novel threshold probing technique to test whether the local piece is vessel or not. A general framework of adaptive local thresholding based on the use of a multithreshold scheme, combined with a classification procedure to verify each resulting binary object, was presented by Jiang et al. [6]. In [7], a multiscale matched filter was applied for vessels, using an appropriate normalizing multiplier to allow the combination of response across scales. Zana et al. [8] combined morphological filters with cross-curvature evaluation to segment vessel-like patterns in retinal images. Niemeijer et al. [9] presented a vessel segmentation algorithm based on pixel classification using a simple feature vector. In [10], a multiscale analysis was performed on the image using the Gabor wavelet transform. Further, Bayesian classifier was adopted to yield a fast classification. Staal et al. [11] applied a supervised classification step using feature vector in the neighborhoods of the nominal vessel center lines. In [12], a modified line operator was applied to construct the feature vector, used to train a supervised classifier. Then, the classifier distinguishes the vessel pixels from non-vessel pixels.

Tracking-based approaches are inherently appealing and can always provide a satisfactory description of the vessel network, but it is time-consuming and insufficient to provide complete extraction in the presence of the branching points and low contrast. Tolias and Panas [13] developed a fuzzy C-means clustering algorithm starting from the optic disc, the tracking method was driven by a fuzzy model of a 1-D vessel profile and finally judged each candidate vessel. However, the approach tends to terminate at branch points and thus yields premature detection results. The algorithm in [14] was based on recursively tracking the vessels starting from initial seed-points associated with directional templates, aiming at detecting vessel boundaries. These templates were also recursively used for estimating the position and orientation of the next vessel point. In [15], the proposed algorithm based on consecutive scanline could obtain accurate vessel directions which were used to guide tracking. Further, combined with a prior knowledge, termination criteria for tracking and look ahead detection were introduced to prevent any premature tracking failures due to noise. Compared to other tracking methods, this approach could automatically extract the majority of vascular network and highlight accurate local vessel geometry.

Model-based approaches apply explicit vessel models to extract the vasculature. Although they usually give new angle to characterize the vessels, we may face some difficulty in description and selection parameter for the model. Kozerke et al. [16] applied a modified definition of the active contour models in their technique to automatically segment vessels in cine phase contrast flow measurements. To estimate the local orientation of the evolving front, a level-set-based geometric regularization method was used in [17]. FLUX was developed by Vasilevskiy et al. [18] to segment narrow elongated vessels. A more efficient implementation was proposed by Max et al. for spherical flux computation, which was applied to vascular segmentation in [19]. Kayikcioglu et al. [20] used a parametric model with elliptical cross-sections to reconstruct coronary arterial trees from biplane angiograms. Sato et al. [21] proposed a semi-automated method based on Hessian-based technique to determine the position, orientation, and diameter of stenoses in coronary angiograms. Also, Wang [22] used multiresolution Hermite model to analyze the retinal vasculature.

In summary, the existing methods have made great progress in the vessel segmentation. However, the following aspects are needed to be improved for the segmentation algorithm.

1. The produced vessels should be linked and have good visual appearance. Such vessels are helpful to recognize the underlying shape.
2. False detection occurs in abnormal images for the border of tissues, hemorrhages, and other types of pathologies that present strong contrast. The algorithm should be concerned with the influence and decrease the errors.
3. The narrow vessels with low contrast are often lost. To detect valid small vessels is a much more difficult task, but they are very important in the fine analysis of medical images.

In this paper, we present a novel approach for the automatic segmentation of the retinal image. We first introduce the radial projection which is able to detect the low-contrast and narrow vessels. It is developed to locate vessel centerlines. When the vessels are very thin, the centerlines are the thin vessels themselves, because the width of these vessels is small. So the vessel centerlines contain the thin vessels and the centerlines of the major vessels, which are used as guidelines for the subsequent union of vessels. Further, a modified steerable complex wavelet is applied to adaptively enhance the retinal image, and vector feature is constructed to train a classifier, yielding the segmentation of major structures of vessels. The final segmentation is obtained by the union of the vessel centerlines and the major structures of vessels.

The rest of the paper is organized as follows. In Section 2, the concept of the proposed method is presented, and we show the implementation details for each step. In Section 3, we perform tests on the images of the DRIVE and STARE databases, and compare results with other retinal vessel segmentation methods. Finally, Section 4 is devoted to discussions and conclusions of this work.

2. Methods for vessel segmentation

We work on the inverted green channel of image, because it normally exhibits a higher vessel/background contrast while the red channel could be saturated and the blue channel is usually very dark and noisy. An example is shown in Fig. 1. The preprocessing algorithm includes two stages: the first stage is to

Fig. 1. Inverted green channel of retinal image.