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Original Research Article

Fast, accurate and robust retinal vessel segmentation system

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A R T I C L E I N F O

Article history:
Received 13 December 2016
Accepted 9 April 2017
Available online xxx

Keywords:
Retinal images
Vessel segmentation
Morphological processing
DoOG filter
Automated analysis
Thresholding

A B S T R A C T

The accurate segmentation of the retinal vessel tree has become the prerequisite step for automatic ophthalmological and cardiovascular diagnosis systems. Aside from accuracy, robustness and processing speed are also considered crucial for medical purposes. In order to meet those requirements, this work presents a novel approach to extract blood vessels from the retinal fundus, by using morphology-based global thresholding to draw the retinal venule structure and centerline detection method for capillaries. The proposed system is tested on DRIVE and STARE databases and has an average accuracy of 95.88% for single-database test and 95.27% for the cross-database test. Meanwhile, the system is designed to minimize the computing complexity and processes multiple independent procedures in parallel, thus having an execution time of 1.677 s per image on CPU platform.

1. Introduction

The retinal vasculature has been acknowledged as an indispensable element in both ophthalmological and cardiovascular disease diagnosis such as glaucoma and diabetic retinopathy. The attributes of retinal blood vessels including length, width, tortuosity, branching pattern and angles will contribute to the diagnostic result. However, manual segmentation of retinal blood vessels, although possible, is a time consuming and repetitive work, and it also requires professional skills. To assist ophthalmologists with this complex and tedious work, the demand for the fast automated analysis of the retinal vessel images arises.

However, to fully automate the analysis and make it work for real-life diagnosis is a harsh task. First, because even the thinnest vessel may contribute to the differential diagnosis list, in order to avoid medical accidents, the extraction of blood vessels is required to be extremely accurate so as to help the diagnosis. Second, for many diseases such as diabetes and hypertension, patients are required to take regular ocular screening in order to detect retinopathy in early stages. However, patients who are inconvenient to move or live distantly from the city will be less approachable for the location-specific treatment. In this case, the automated solution is expected to be handy and portable in the future. Besides, almost every retinal vasculature extraction system is facing the trade-off between accuracy and computing

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http://dx.doi.org/10.1016/j.bbe.2017.04.001
0208-5216/

complexity. What's more, even though some algorithms have achieved a decent accuracy within a certain database, but they do not necessarily provide or maintain the similar performance over the cross-database test.

In an attempt to provide a fast, accurate and robust automatic segmentation, this paper proposes an innovative segmentation system that tries to solve the above problems. In recent researches, the most popular approaches for automated vessel segmentation are supervised methods, matched filtering, and morphological processing, while the proposed system combines both matched filtering and morphological processing together not just to achieve higher accuracy and better robustness, but also to decrease the computing complexity and shorten the execution time.

The organization of the paper is as follows. Section 2 will describe related works and introduce three basic approaches that have been applied to the proposed system and their contributions to this work. Section 3 will demonstrate the complete design of the proposed system including its workflow and function of every block. Section 4 will present the performance measurement on three aspects and compare with other works. Section 5 will conclude the paper and point out the future research direction.

2. Background

The proposed system is enlightened by numerous previous works and consists of several classic methods. This section will briefly cover the existing retinal vessel segmentation approaches and then introduce the principle and strength of the proposed system.

2.1. *Related works*

According to Fraz's survey [1], the existing retinal segmentation techniques on 2-D retinal images can be summarized into six categories; (i) pattern recognition, (ii) mathematical morphology, (iii) matched filtering, (iv) vessel tracking, (v) model based approaches and (vi) parallel/hardware approach, among which pattern recognition contributes to most of the accurate and robust works, while parallel/hardware methods accelerate the execution speed with a relatively lower accuracy [2,3]. (ii), (iii), (iv) and (v) contain the basic techniques that cooperate with each other or apply to (i) and (vi) to form an automated vessel segmentation system.

Pattern recognition based algorithms, dealing with the automated detection or classification of the retinal blood vessel and non-vessel features, are divided into supervised methods such as Refs. [4–8] and unsupervised approaches such as Ref. [9]. In supervised methods, the rule for vessel extraction is trained by the algorithm on the basis of manually segmented images by ophthalmologists. As supervised methods are developed with the reference of the gold standard dataset, their performance is usually better than that of the unsupervised ones. However, because such classified ground truth data will not be available in real life applications, a supervised algorithm thus shall be trained and tested over different databases to assess its robustness. The unsupervised classification methods intend to find inherent patterns of retinal vessels within images for deciding whether a particular pixel is part of the vessel or not.

Mathematical morphology containing a set of image processing techniques is one of the most famous approaches for image segmentation. It extracts image components that are useful while smoothing the rest area. The morphological operation has the advantage of speed and noise resistance in identifying specific shapes such as features, boundaries, skeletons and convex hulls, by applying structuring elements (SE) to greyscale or binary images [10–13].

Matched filtering techniques usually convolve a 2-D kernel (or structural element) for blood vessel cross-profile identification (typically a Gaussian or Gaussian-derivative profile). The kernel is rotated into many different directions to model a feature in the image at some unknown position and orientation, and the matched filter response (MFR) indicates the presence of this feature. Such techniques are very effective to detect vessel centerlines [10,14,12].

In most cases, vessel tracking algorithms are more effectively used in conjunction with matched filters of the morphological operators, such as Refs. [14] and [15]. Tracking a vessel means to follow the vessel centerline guided by local information and try to find the path which best matches a vessel profile model, through which not only the centerline but also the widths of each individual vessel will be accurately extracted.

Model-based approaches such as vessel profile models in Ref. [16], extracting retinal vessels by using explicit vessel models, are designed to handle both normal and pathological retinas with bright and dark lesions simultaneously. Some other methods using deformable models such as parametric models and geometric models are not as effective as the former one.

2.2. *Methodology*

In this work, mathematical morphology and matched filtering are applied to the proposed vessel segmentation system. During the processes, the retinal images shall firstly be transformed into greyscale and then go through the top-hat transform, intensity thresholding and centerline highlighting, which will be briefly discussed in this subsection.

2.2.1. *Morphology processing*

Two operations belonging to the mathematical morphology (MM) theory will be applied to the proposed system, which is top-hat transform and morphology erosion. The top-hat method is utilized to redistribute the greyscale intensity from a preprocessed greyscale retinal image, in order to generate a characteristic feature for vessel/non-vessel classification, while the erosion operation helps to de-noise the image and smooth the vessel edges in the final post-processing stage.

The principle of morphology processing is to simplify the image data through retaining their essential characteristics from a shape and removing other extraneous elements. The basic operations in MM processing are erosion, dilation, opening, and closing, which deduce the top-hat transform — one of the most efficient way to do feature extraction, background equalization, and image enhancement. The