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A new supervised retinal vessel segmentation method based on robust hybrid features

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ABSTRACT

In this paper, we propose a new supervised retinal blood vessel segmentation method that combines a set of very robust features from different algorithms into a hybrid feature vector for pixel characterization. This 17-D feature vector consists of 13 Gabor filter responses computed at different configurations, contrast enhanced intensity, morphological top-hat transformed intensity, vesselness measure, and B-COSFIRE filter response. A random forest classifier, known for its speed, simplicity, and information fusion capability, is trained with the hybrid feature vector. The chosen combination of the different types of individually strong features results in increased local information with better discrimination for vessel and non-vessel pixels in both healthy and pathological retinal images. The proposed method is evaluated in detail on two publicly available databases DRIVE and STARE. Average classification accuracies of 0.9513 and 0.9605 on the DRIVE and STARE datasets, respectively, are achieved. When the majority of the common performance metrics are considered, our method is superior to the state-of-the-art methods. Performance results show that our method also outperforms the state-of-the-art methods in both cross training and pathological cases.

1. Introduction

Study of retinal vasculature in fundus images is one of the most important tasks in medical image analysis because of two main reasons. Firstly, it is the only part of the blood circulation system that can be observed directly [1] and secondly, it is extremely important for diagnosis of several medical pathologies containing age-related macular degeneration and diabetic retinopathy. These two are the most common causes of blindness, as well as hypertension, arteriosclerosis and so on [2]. For example, changes in vessel diameter and development of neovascularization are some signs of diabetic retinopathy. Hypertension and arteriosclerosis cause a decrease in the ratio between the diameter of retinal arteries and veins, bringing an increased risk of stroke and myocardial infarction. Early detection of such vascular changes followed by early intervention can save the patients from important vision losses or vital risks.

Accurate segmentation of the retinal vessels from the background in fundus images is a critical and initial step for subsequent operations such as automatic assessment for blood vessel anomalies of optic fundus [3]. The presence of noise, the low contrast between vasculature and background, the variability of vessel width, brightness and shape, presence of lesions, exudates and other pathological effects in images make segmentation extremely difficult [4].

Both manual and automatic methods and algorithms are used for segmentation of retinal vessels. In the case that the retinal vessels are manually segmented by an expert, it should be envisaged that manual delineation is more accurate than automatic methods but it is still exhausting, monotonous, time consuming and impossible if a large volume of fundus image dataset are given. In contrast to the manual delineation, automatic algorithms are faster, and therefore, simplify and speed up the subsequent decisions by ophthalmologists, providing a source for other automatic phases in the early diagnosis of certain diseases. The disadvantage of automatic vessel segmentation methods is that the accuracy of segmentation is lower than manual segmentation cases due to the presence of different types of noises in image that was referred to in the previous paragraph. Therefore, for computer analysis of retinal fundus images, an appropriate processing should be performed in developing an automatic system for retinal vessel segmentation.

A literature search reveals that there are many automatic methods available for retinal vessels segmentation. These methods can be categorized into two main groups: unsupervised and supervised [5].

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Unsupervised methods are rule-based and find vessel locations by using presumed rules for vessels. There are five main subgroups for unsupervised methods including vessel tracking, matched filtering, morphological processing, model based algorithms and multi-scale analysis. Vessel tracking methods [6–9] in general speaking are based on local information of a single vessel in such a way that after detecting a set of seed points, the vessel center lines are pursued, and ultimately the blood vessel tree is extracted. Matched filtering techniques [5,10–13,38] are designed to simulate the profile of the cross-section of a blood vessel by using a two-dimensional kernel based on a Gaussian or its derivatives for vessel localization. Mathematical morphology operations are firstly used for enhancing the vessels and then by combination with curvature evaluation [14] and matched filtering for line detection [15,16] is deployed for retinal vessel segmentation [17]. Multi-scale approach techniques amongst the unsupervised methods make use of the scale space analysis. For instance, in Ref. [18], a multi-scale based method was proposed for measuring the width, and attaining the size and orientation information in order to extract blood vessels by utilizing a growing procedure. A vesselness measure is presented in Ref. [19] based on eigenvalue analysis of the Hessian matrix, by examining the multi-scale second-order local structure of an image. On the other hand, model based approaches that are also considered in the unsupervised category develop probabilistic models for the shapes and the variations of the vessel structures in images. Vessel profiles [20,21,39,42], active contour [22], and level sets [23,43] are some models used for segmenting retinal vessels.

Supervised methods, also called pixel feature classification methods, are machine learning techniques that assign labels, vessel or non-vessel, to each pixel. A pixel feature classification method by using ground truth data usually consists of two stages: feature extraction and classification. In the first stage, feature extraction, some features of each pixel and its neighborhood such as Gabor wavelets [24], line strengths [3], and vesselness [19], are extracted for further processing. In the next stage, classification stage, by using a classifier (or multi-classifiers) such as multilayer neural network [26], support vector machine (SVM) [3], random forest (RF) [4], bagging and boosting [25], and Bayesian [24], each pixel is classified as a vessel or non-vessel pixel. Classification stage itself consists of two distinct parts: training (or learning), and testing. The algorithm is statistically learnt to correctly classify pixels from some known classifications (ground truth) in the training stage. Then in the next stage, testing, the algorithm classifies previously unseen pixels. For proper assessment of a supervised classification method, training data and performance testing data sets must be completely disjointed [2]. In the literature, a variety of supervised methods exist. Soares et al. [24] utilized a supervised classification method for detecting the blood vessels in retinal fundus images by applying different scales of two-dimensional complex Gabor wavelet in the feature extraction stage and then by using a Bayesian classifier in the classification stage. Ricci and Perfetti [3] proposed a computationally simple but effective supervised method by using two modified line operators which take into account the properties of blood vessel structures for computing the feature vectors. They used a linear SVM as a classifier. Nguyen et al. [44] linearly combined the responses of Ricci's line operator [3] at varying lengths in an unsupervised multiscale approach. Marin et al. [30] computed a 7-D feature vector of moment invariant and grey level features and used a neural network classifier. In Ref. [41], a feature vector is constructed from the responses of line operator on images enhanced by multiscale complex wavelet transform and a linear SVM is utilized as a classifier for semisupervised classification. Fraz et al. [25] performed a multi-feature analysis by combining the features of gradient orientation analysis, morphological transformation with linear structuring element, line strength measures and Gabor wavelet responses. Their feature vector is shown to have good ability of encoding information by accurately segmenting both normal and pathological retinal images with both bright and dark lesions. They used a multi-classifier of boosted and bagged decision trees. Lupascu et al. [28] also performed multi-feature analysis using a feature vector containing 41 features extracted at different scales to train an AdaBoost classifier. Staal et al. [29] proposed a method based on locating image ridges which overlap roughly with vessel centerlines and then computing features in their neighborhoods. For classification, they used a *k*-nearest-neighbor (KNN) classifier. Cheng et al. [4] used a supervised method for the segmentation of the blood vessels by extracting a large set of hybrid features within a local context region whose orientation was also estimated. As a result of their feature extraction scheme, more than 200 features were extracted and then fed to a random forest classifier to take advantage of its strong discriminative power and its flexibility of fusing heterogeneous features in the classification stage.

Supervised blood vessel segmentation methods are usually more time consuming and computationally expensive than unsupervised methods due to extraction of different kinds of features and training of complex classifiers with a huge amount of data. But, on the other hand, the results of supervised blood vessel segmentation methods, in most cases, are more accurate than unsupervised methods. Nonetheless, automatic segmentation of blood vessels still remains as a challenging task due to the presence of numerous problems such as the variation in vessel appearance, shape and orientations, low and uneven contrast between vasculature and background, presence of noise and abnormal regions including lesions and other pathologies [3]. For instance, the low contrast area in retinal images and variation in vessel shape and orientation can mislead the matched filters [12]. Therefore, it is hard to use a single feature or a few features to address all of these problems. It has been shown by the recent studies that multi-feature analysis yielding hybrid feature vectors [4,25,28] plays an important role in increasing the accuracy of supervised blood vessel segmentation methods. A post-processing step following the segmentation by supervised methods is another common strategy for obtaining better results in this kind of challenges [30].

This paper presents a supervised method that is based on a multi-feature analysis of retinal images and uses an ensemble RF classifier [31] for blood vessel segmentation. The key point to our approach is to have an adequate collection of robust features including contrast enhanced intensity, morphological top-hat transformed intensity, vesselness measure, multi-scale response of Gabor filter and response of B-COSFIRE (bar-selective combination of shifted filter responses) filter. These features are combined into a hybrid feature vector that characterizes every pixel in an image for pixelwise classification. After the feature vector is constructed, an ensemble classifier based on the RF decision trees is employed as a classifier to segment the blood vessels in retinal images. RF classifiers are widely utilized in many application areas of image analysis due to its strong discriminative power and flexibility of fusing information from different types of features. The proposed method outperforms all the state-of-the-art methods according to the most of the performance measures computed for evaluation, and yields the best average accuracy in both cross training and pathological cases.

The rest of the paper is organized as follows. In Section 2, we describe the datasets used for the evaluation of the proposed method, and then explain the method including the feature extraction algorithms and the classifier used. The implementation details of our method and its performance comparison to the state-of-the-art methods are presented in Section 3. Eventually, the discussion and conclusion are given in Section 4.