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Segmentation of optic disc and blood vessels in retinal images using wavelets, mathematical morphology and Hessian-based multi-scale filtering

Luiz Carlos Rodrigues*, Maurício Marengoni

Department of Electrical Engineering, Universidade Presbiteriana Mackenzie, São Paulo, Brazil

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ABSTRACT

The high importance of the accurate and early diagnostic has motivated the development of computer vision techniques of image processing and segmentation required for an completely automated assessment system for the retinal conditions. In this study we present a new algorithm built on wavelets transforms and mathematical morphology for detecting the optic disc and we explore the tubular characteristic of the blood vessels to segment the retinal veins and arteries. Both, optic disc and vascular structure, are landmarks for image registration and are essential for the retinal image analysis. Instead of a manual try and error method to choose the best parameters for detecting vessels as accurately as possible, we used a genetic algorithm and its sequence of generations and crossovers. However the technique of exploring the tubular characteristic of the vessels reaches its limits when the vessels are represented by, sometimes not continuous, winding lines of 1 pixel. To overcome this limitation we adopted a graph based approach using Dijkstra's shortest path algorithm to track the segments and a statistic method of Student *t* distribution to assess whether or not the identified segment is part of the vascular structure. The proposed method was developed and tested on the Digital Retinal Images for Vessel Extraction (DRIVE) freely available database, which contains 40 annotated color eye fundus image.

1. Introduction

Over the last decade, large population-based studies have demonstrated that retinal calibers are associated with a wide range of subclinical diseases, such as atherosclerosis, hypercholesterolemia, inflammation and endothelial dysfunction, as well as clinical cardiovascular diseases, such as arterial hypertension [28], diabetes mellitus, stroke, kidney and heart diseases [22]. The increasing development of retinal image techniques and the more recent understanding of the clinical significance of retinal changes prompts the development of retinal vascular caliber measurement as a biomarker for vascular diseases [20].

During the recent years, automated retinal image analysis has become a large field of research due to advances in computer vision techniques, and image acquisition has opened exciting possibilities to study the pathogenesis of a number of diseases. This growing interest is due, but not exclusively, to several factors outlined below [36]:

1. The eye fundus is the unique region of the human body where one can visualize *in vivo* the blood vessels in a natural and non-invasive way.
2. Retinal images are inexpensive to produce, distribute and process.
3. Changes in the diameter and tortuosity of veins and arteries of the retina are strong and trustable indicators of pathologies such as diabetes, arterial hypertension and high levels of cholesterol.

Additionally, automated methods of retinal image analysis may have a social and economic impact because they enable exams to be performed very quickly in a large number of images, making the exams cheaper, saving time and human resources and still offering more quantitative metrics than techniques that involve human observation exclusively.

The high importance of accurate and early diagnosis of retinal images has motivated the development of computer vision techniques on the segmentation of vessels and the optic disc on ocular fundus images, which are required for a completely automated

* Corresponding author.
E-mail addresses: lcfrod@hotmail.com (L.C. Rodrigues), mauricio.marengoni@mackenzie.br (M. Marengoni).

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assessment system for retinal conditions. Both the optic disc and vascular structure are landmarks for image registration and are essential for any retinal image analysis. We present in this study a new algorithm built on wavelet transforms and mathematical morphology for detecting the optic disc. We also explore the tubular characteristic of the blood vessels to segment the retinal veins and arteries [19]. To segment the retinal vessels we used the filter described by Frangi et al. When applied on these scale spaces, the method requires five parameters: an initial standard deviation (σ), a value to increment σ, the number of scales and two thresholds for the filter sensitivity. These parameters control the response filter, therefore we should select suitable parameters to obtain the highest accuracy possible. Instead of a manual trial and error method to choose the best parameters for detecting vessels as accurately as possible, we applied a genetic algorithm (GA) and its sequence of generations and crossovers to find the optimal algorithm parameters.

However, the technique of exploring the tubular characteristic of the vessels reaches its limits when the vessels are represented by non continuous, winding lines that are of 1 pixel in width. To overcome this limitation we adopted the algorithm proposed by Steger to segment 2D curvilinear structures [40], which are represented by curves that are 1 pixel wide and not segmented by the Frangi et al. vessel detector [13]. This curvilinear detector will detect the winding lines that will be attached to the main vessels using Dijkstra's shortest path algorithm, which integrates the segmentation of thick and thin vessels.

The performance and robustness of the proposed method has been tested on two publicly available retinal images databases.

The Digital Retinal Images for Vessel Extraction (DRIVE), is a freely available image database that contains 40 annotated color eye fundus images, equally divided into training and test subsets [39]. A manual segmentation of the vascular structure is available for each image of the training set, while for the test set two segmentations made by two observers are available: the first segmentation should be used as the gold standard and the second can be used to benchmark proposed algorithms, comparing them with those annotated by an independent human observer. For each image a ROI mask with diameter of 650 pixels is provided.

The High-Resolution Fundus Image Database (HRF-DB) is a freely available image database that contains 45 retinal images [32]. For each image, a manual segmentation is available and a ROI mask with diameter with approximately 1015 pixels is provided. The images are equally grouped in healthy, diabetic retinopathy and glaucomatic images.

Retinal photography requires the utilization of an optical system called a fundus camera, a low power light with an attached camera capable of simultaneously illuminating and capturing the fundus of the ocular globe, the retina. The results presented in this paper shows impressive performance, very close to state-of-art methods recently published. Compared to other studies, our model has several advantages, such as reduced complexity and the lack of a requirement for preprocessing or enhancement image models.

2. Related works

2.1. Optic disc segmentation

Among the most important structures in a retinal image, the optic disc (OD) has a fundamental role in the assessment of health conditions of the human eye.

The morphological characteristics of the OD constitutes an important structural reference for assessing the presence and stage of retinal pathologies such as diabetic retinopathy, arterial hypertension, glaucoma, hemorrhages, vein occlusion and neovascularization [37].

The segmentation of the OD is usually one of the first modules for most of the computational applications that measure the indexes related to vascular caliber alteration, such as the arteriolar-to-venular-ratio (AVR) whose decreased value commonly is established as a marker of stroke, cerebral atrophy and other cardiocirculatory events in adults [1]. The estimation of these indexes frequently requires the segmentation of the OD and the delimitation of a circular region of interest around it. Due to the importance of OD segmentation, several studies have been dedicated to the automatic location and segmentation of it borders. Most of these studies can be classified into four categories [8]:

1. Template-based method: In the first category fall those studies using template-based methods, for example, Giachetti et al assume that the OD has an elliptic shape and use a radial symmetry prior derived to locate the OD and initialize the segmentation [16]. The authors submit the image for preprocessing, resizing the image using bicubic interpolation and then performing a rough vessel segmentation on the green channel by subtracting the top-hat filtered version from the original image and thresholding the result by applying the Otsu algorithm. The obtained vessel mask is processed with morphological operations, such as dilation and the removal of small areas. The grayscale image without the vessels is then extracted by taking the grayscale version of the original image and inpainting the mask pixels.
2. Deformable model: Adopting the deformable model approach [21] enhanced a region-based active contour model and improved the Chan-Vese model by using the local red channel intensities and two texture feature spaces in the neighborhood of the pixels under analysis. The method proposed by Yu et al. is based on template matching and a directional matched filter to locate the OD [45]. For OD segmentation, the authors divided the task into two steps. The first step consists of the use of morphological operations in association with filtering to eliminate the blood vessels and the brighter regions from the image. On the second step, the authors proposed segmentation through a level set method processed with optimized parameters to identify and segment the OD borders.
3. Morphological-based approach: In the category of studies using mathematical morphology techniques for OD localization and segmentation, Welfer et al. uses an adaptive mathematical morphology approach developed in two stages [42]. First, a preliminary segmentation of OD borders is processed and in the second stage, the achieved results are enhanced using dilation with a fixed radius disk as the structuring element. The method proposed by Morales et al. is also composed of two stages [30]. First, it uses principal component analysis (PCA) to obtain an enhanced delineation of the OD on the gray image. The pixels corresponding to the blood vessels are then removed and a modified method of the watershed technique is applied. In the second stage, the authors apply a geodesic transformation to characterize the watershed regions as either OD or non-OD regions.

   Implemented with a graphics processing units (GPU) using parallel software and based on Hough algorithm, Díaz-Pernil et al. proposed a method for the localization of the OD in retinal fundus color images. The image edges were extracted using a gradient operator, named AGP-color segmentator. The resulting image is binarized with Hamadani's technique and, at the end of the process, the Hough circle cloud algorithm and an improved Hall & Guo algorithm for a parallel thinning are applied for the detection of the OD [10].
4. Pixel-based classification methods: Based on the values of the pixels, Cheng et al. proposes optic disc and optic cup