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An empirical study on optic disc segmentation using an active contour model

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ABSTRACT

The accurate segmentation of the optic disc (OD) offers an important cue to extract other retinal features in an automated diagnostic system, which in turn will assist ophthalmologists to track many retinopathy conditions such as *glaucoma*. Research contributions regarding the OD segmentation is on the rise, since the design of a robust automated system would help prevent blindness, for instance, by diagnosing glaucoma at an early stage and a condition known as *ocular hypertension*. Among the evaluated OD segmentation schemes, the active contour models (ACMs) have often been preferred by researchers, because ACMs are endowed with several attractive properties. To this end, we designed an OD segmentation scheme to infer how the performance of the well-known *gradient vector flow* (GVF) model compares with nine popular/recent ACM algorithms by supplying them with the initial OD contour derived from the *circular Hough transform*. The findings would hopefully equip a diagnostic system designer with an empirical support to ratify the choice of a specific model as we are bereft of such a comparative study. A dataset comprising 169 diverse retinal images was tested, and the segmentation results were assessed by a gold standard derived from the annotations of five domain experts. The segmented ODs from the GVF-based ACM coincide to a greater degree with those of the experts in 94% of the cases as predicted by the least overall *Hausdorff distance* value (33.49 ± 18.21). Additionally, the decrease in the segmentation error due to the suggested ACM has been confirmed to be statistically significant in view of the *p* values ($\leq$1.49e−09) from the *Wilcoxon signed-rank test*. The mean computational time taken by the investigated approaches has also been reported.

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1. Introduction

Detection of retinal anatomical features is crucial to clinically assess the health of the retina. To facilitate this task, automated diagnostic systems critically rely on an accurate optic disc (OD) detection procedure, in the sense that other anatomical features such as retinal blood vessels, macula, optic cup, and lesions can in turn be detected with reference to the OD location [1]. In particular, the OD detection is extremely useful in diagnosing a retinopathy condition called *glaucoma*, which is the leading cause of blindness next to *cataract* [2]. According to Nayak et al. [3], glaucoma affects one in two hundred individuals around the age of 50, and one in ten above 80 years. Moreover, the detrimental effects of glaucoma surface only at a later stage, and hence it is commonly known as the "sneak thief of sight". Interestingly though, the detection of this disease at an early stage will help to retard its progression thanks to medical advancements [4]. In other words, the structural change in the OD provides vital clues concerning the prognosis of glaucoma. Fueled by the diagnostic and prognostic significance, automatic OD detection schemes have been attempted by many and their design still remains as a vibrant research area [5].

An accurate OD segmentation with computer-aided techniques faces several challenges due to factors that are common to other

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medical images, for instance, boundary insufficiencies—missing edges and/or inadequate texture contrast between regions of interest (ROIs) and the background. On the other hand, manually segmenting the OD is not deemed admissible, since it is subject to impediments such as limited perception of the human eye, fatigue, and the availability of voluminous fundus image data. Therefore, developing algorithms that can reliably detect accurate OD boundaries with less computational overheads is an imperative research goal.

To provide an overview of the research efforts along this direction, a brief survey on the state-of-the-art OD segmentation schemes is in order. Lalonde et al. [6] reported a technique for the OD localization in color fundus images by combining a Hausdorff-distance-based template matching on edge maps and a pyramidal decomposition. Li and Chutatape [7] applied the principal component analysis on a color retinal photography to locate the OD and an active shape model to segment the same. Foracchia et al. [8] described the common directional pattern of retinal vessels with a geometrical parametric model, and identified the coordinates of the OD center with a simulated annealing technique. Niemeijer et al. [9] formulated the OD detection task as an optimization problem that fits a single point distribution model to a color fundus photograph. Youssif et al. [10] adopted a filter to match the expected directional pattern of retinal blood vessels in the vicinity of the OD, and segmented the vessels with a 2-D Gaussian matched filter to estimate the OD center. Lu and Lim [11] designed a line operator, which evaluates the intensity variation along multiple line segments with specific orientations and traversing through retinal image pixels. Lu [12] employed a circular transformation, wherein every retinal image pixel corresponding to the maximum image variation along multiple evenly-oriented radial line segments of fixed length constitutes the OD boundary.

In view of the inherent advantages of active contour models (ACMs), there is an emerging trend to make use of ACMs in OD segmentation tasks. In general, ACMs have been proven successful in image segmentation applications [13,14]. They are based on profound mathematical properties and efficient level-set-based numerical schemes. It is possible to achieve a sub-pixel accuracy of object boundaries with the ACMs [15]. They lend themselves to incorporate a prior knowledge, e.g., shape and intensity distribution [16]. Furthermore, they can be implemented to exploit several properties, e.g., edges, statistics, and texture, which are normally considered by other segmentation procedures. Besides producing quite regular contours, the segmented regions possess continuous boundaries. In addition, the level set theory offers a lot of flexibility in their implementation.

In that vein, a few interesting contributions involving an ACM to segment the OD are listed below. Lowell et al. [17] presented an algorithm, which localizes the OD using a specialized template matching, and then segments it with a deformable contour model. Unlike other edge detection methods, this model reliably segmented the ODs from images of diseased retinae including strong distractors. Chrástek et al. [18] presented an automated algorithm for the OD segmentation in scanning-laser-tomography images. This method is based on morphological operations, the Hough transform, and an anchored ACM derived from the works of Cohen and Cohen [19] and Kucera [20]. Xu et al. tackled the problem of vessel occlusion that interferes with the OD segmentation in [21] by incorporating a knowledge-based clustering of contour points and a smoothing update into the original *snake* by Kass et al. [22]. Joshi et al. [24] enhanced the robustness of the ACM by Chan and Vese [23] against variations in the vicinity of the OD region by integrating the local image information around each point of interest in a multidimensional feature space; the segmentation results were shown to be consistent with respect to geometric and photometric variations in retinal images. Yu et al. developed a fast and fully automatic OD segmentation algorithm in [25], which applies an initial OD contour identified with the template matching to a hybrid level set model proposed by Zhang et al. [26]. The robustness and accuracy of segmented OD boundaries are attributed to the fact that the model in [25] combines the region and local gradient information in the retinal images.

Notwithstanding a dedicated research effort in the design of ACM-based image segmentation tools, as far as we know, a rigorous comparison of a wide range of ACM techniques has not yet been reported in the context of the OD segmentation. In fact, empirical results from an exhaustive study involving popular ACM methods on a large collection of retinal images would be suggestive of the kind of ACM scheme to be advocated in the design of a fully automated OD segmentation system for clinical screening purposes. Within this framework, we methodically compared the OD segmentation results from ten theoretically well-established ACM techniques supplied with 169 diverse retinal fundus images annotated by domain experts. To be fair in our comparison, the ACM algorithms were initialized with a contour obtained by a morphological process and the *circular Hough transform* (CHT). Unless the resultant contour warrants further tuning, the default parameters were kept unaltered for the ACM models.

2. Materials and methods

2.1. Test database

The open retinal image database for optic nerve evaluation (RIM-ONE) is an online dataset of 169 retinal fundus images annotated by five experts in ophthalmology [27]. The retinal photograph is captured (with non-mydriatic fundus camera) while the pupil is not dilated with flash intensities that avoid saturation. The images are stored in the red-green-blue (RGB) color bitmap (i.e., BMP) format with intensities ranging from 0 to 255 in each channel. The domain experts have classified the images in the dataset into the following categories: 118 normal eye (non-glaucomatous), 12 early glaucoma, 14 moderate glaucoma, 14 deep glaucoma, and 11 *ocular hypertension* (OHT). A gold standard has been provided for each image from the contours demarcated by five experts.

2.2. Overview of the proposed approach

A schematic diagram of the proposed methodology to enhance the segmentation accuracy of the OD is presented in Fig. 1. The retinal images under investigation are preprocessed using the *adaptive histogram equalization* in the red channel, which facilitates an accurate OD identification due to the image contrast improvement. Subsequently, the morphological processing is performed using a line operator to remove any blood vessel present in the image. Following the preprocessing, the CHT is applied to estimate the contour that roughly encloses the circular-shaped OD. Based on the empirical study involving ten well-known ACM algorithms, which is deferred to Section 6, the *gradient vector flow* (GVF) model is recommended in our work. Note that the GVF model is acclaimed to be a fast and hybrid level set method, which fine-tunes the contour initialized with the CHT until it accurately fits the boundary of the OD.

3. Preprocessing

Retinal images usually contain noise due to interference of various phenomena. Nonuniform illumination is one such problem because of the complexity of the image acquisition system. The noise and artifacts thus introduced complicate the retinal image analysis. For instance, they may cause only minor differences

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