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Segmentation of optic disk and optic cup from digital fundus images for the assessment of glaucoma

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ABSTRACT

Glaucoma is an eye disease that results in irreversible loss of vision. The manual examination of optic disk (OD) is a standard procedure used for detecting glaucoma. This paper presents a glaucoma expert system based on the segmentations of OD and optic cup attained from color fundus images. A novel implicit region based active contour model is proposed for OD segmentation which incorporates the image information at the point of interest from multiple image channels to have robustness against the variations found in and around the OD region. A novel optic cup segmentation method is also proposed based on the structural and gray level properties of cup. Based on the precise information about the contours of OD and cup different parameters are calculated for glaucoma assessment. The proposed system is evaluated on 59 retinal images comprising 17 normal and 42 glaucomatous images against the groundtruths given by an experienced ophthalmologist. The proposed OD segmentation method achieved an average *F*-score of 0.975, average boundary distance of 10.112 pixel and average correlation coefficient of 0.916. The cup segmentation method attained an average *F*-score of 0.89, average boundary distance of 18.927 pixel and average correlation coefficient of 0.835. The mean error and standard deviation of the error σ for all the parameters are much smaller in glaucomatous images compared to normal images. This indicates high sensitivity of the proposed method in glaucoma assessment.

1. Introduction

Glaucoma is a potentially blinding disease that affects approximately 80 million persons worldwide by 2020 [1]. It is the second leading cause of blindness. Glaucoma is a chronic and irreversible neurodegenerative ocular disorder in which the optic nerve head is progressively damaged, leading to deterioration in vision and quality of life [2]. Glaucoma is commonly asymptomatic. The patients are usually ignorant about it until a noticeable visual loss occurs at a later stage, giving rise to its nickname the ‘silent thief of sight’. Over a period of 5 years, the optic nerve fiber loss progression in glaucoma can range from 9% to 63% [3,4]. As the lost capabilities of the optic nerve cannot be recovered, early detection and treatment are essential for glaucoma patients to safeguard their vision.

A high intraocular pressure (IOP) damages the neuro retinal rim leading to functional failure of visual field which is the very first sign of glaucoma [5]. Even though visual field loss is correlated to the amount of neuro retinal rim loss and in turn to the level of IOP, assessment of abnormal visual field is not suitable either for early detection of glaucoma or to estimate the progression of glaucoma as it is a subjective test. However, early detection of glaucoma is made possible either by measuring IOP level [6] or by assessing the amount of neuro retinal rim damage [7,8]. Former is neither precise nor subtle enough. However, from the last few years 2D and/or 3D image processing techniques are employed for quantifying the amount of neuro retinal rim damage. The scope of 3D imaging modalities (OCT and HRT) used for optic disc (OD) damage assessment is limited as the high cost is involved [9]. The 2D color fundus image serves the pressing need for systematic and economic way of detecting early stage of glaucoma suitable for large scale screening programs and is widely used in recent years.

Diagnosis of glaucoma using 2D fundus images is motivated by the fact that the amount of optic nerve fiber loss has a direct effect on the neuro retinal rim configuration resulting in a quantifiable geometric parameters related to OD, optic cup and neuro retinal rim such as Cup-to-Disc ratio (CDR), ISNT distances and minimum rim width-to-disc diameter that is useful for the calculation of disc damage likelihood scale (DDLS) (Fig. 1).

As more and more optic nerve fibers die, the optic cup becomes larger with respect to the OD which corresponds to an increased

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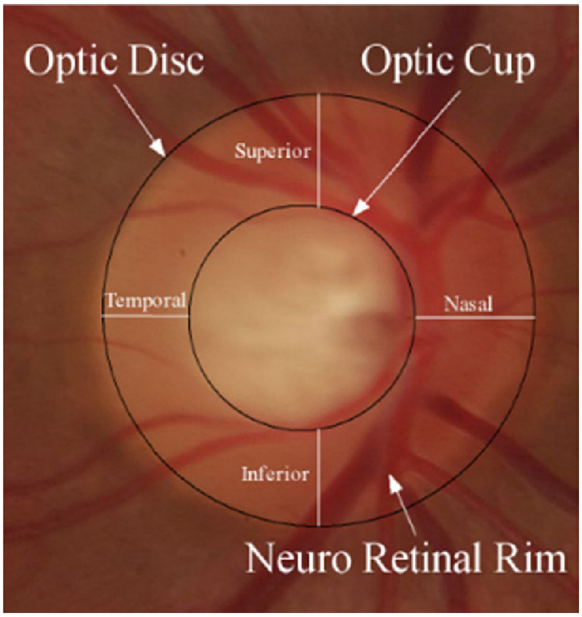

Fig. 1. A Sample OD centric color retinal image with annotated OD and other retinal structures for the calculation of CDR, verification of ISNT rule and DDLS. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

CDR value. However, CDR has been found to be inconsistent in explaining the amount of OD damage caused by glaucoma as CDR cannot interpret various configurations of optic cup, neuro retinal rim and focal notching [10]. The neuro retinal rim configuration is usually with decreasing order of thicknesses along the Inferior, Superior, Nasal and Temporal regions respectively for a healthy subject. Any violation from these ordered thicknesses is identified by the verification of ISNT rule and hence the presence of glaucoma is detected. As the detection of glaucoma is ensured either by CDR values or by ISNT rule verification, the severity of the disease is evaluated by DDLS which describes the amount of OD damage instigated by glaucoma. Although the aforementioned three parameters are apparently different from each other, the commonality among the three is that all of them require precise information of the boundaries of the OD and the optic cup alongside a rich description of the neuro retinal rim.

To date, several methods have been developed for the segmentation of the OD and cup regions from 2D color fundus images, with more methods on OD [11–23], but with fewer on cup [24–28] due to the cup's interweavement with blood vessels and surrounding tissues. A multiresolution sliding band filter (SBF) is applied for OD segmentation [11]. A low resolution SBF and a high resolution SBF are used to obtain a set of pixels associated with the maximum responses giving a coarse estimation of the OD boundary. This estimation is regularized using a smoothing algorithm. Principal component analysis (PCA) and mathematical morphology based method is used to extract OD contour [13]. This method employed different techniques such as generalized distance function, stochastic watershed, and geodesic transformation for segmenting OD. The contour of OD can be estimated as a circle or an ellipse as the shape of OD is round or vertically slightly oval [14]. A template-based methodology is used for detecting OD contour [14–17]. Morphological and edge detection methods followed by Circular Hough Transform can be applied to get a circular OD boundary estimation. A location methodology based on a voting-type algorithm is used to find the location of OD [14]. OD contour was estimated by the Hausdorff based template matching between the detected edges and the template of circle with different sizes [15]. This shape-based modeling of the OD region fails to illustrate shape irregularity which typically arises due to some pathological changes. Level sets were applied to detect the exact contour of OD [18–20]. The major advantage of level sets is their ability to bridge discontinuities in the image feature being located. However, these algorithms were sensitive to the preprocessing. The main difficulty to apply these methods for contour detection of OD is how to remove the influence of blood vessels. A modified active shape model was proposed to detect the shape of OD [18]. The OD center is found by applying the Circular Hough Transformation, and subsequently the disc boundary detection is done through active shape model (ASM) by defining 72 points around the disc. The gradient vector flow (GVF) is used to detect the boundary of OD [12,21]. A two-step methodology is used in [22]; first, the color morphology in *Lab* space is used to have homogeneous OD region, then the boundary of the OD is estimated by using level sets with variational formulation. These methods show promise in capturing a range of shape and image variations. However the accuracy in the segmentation is sensitive to the contour initialization and also in cases where the object to be segmented cannot be easily distinguished in terms of global statistics and may lead to erroneous segmentations. Also, these methods failed in the cases in which there is a smooth region transition at the OD boundary and the occurrence of peripapillary atrophy as these methods employ local intensity based statistics. To address these challenges, this work presents a novel OD segmentation algorithm by integrating local image information at each point of interest consisting of features like intensity, color and texture from multiple image channels.

Very few methods have been proposed for cup segmentation from color fundus image. 3D depth information is used to detect cup boundary [24]. In this method, a manually selected point is used to derive a set of probable pixels which belongs to cup. Then to detect the cup boundary an ellipse is fitted to this set of pixels. Thresholding is used to get the set of potential pixels which corresponds to the cup boundary and an ellipse is fitted based on these pixels [25,26]. But the thresholding used in [26] is not suitable to handle large inter-image intensity variations that arise due to complex imaging and physiological difference across patients. Vessel kinks (bends) are used to detect the cup boundary [27,28]. Localized patches are first generated from a preliminary cup boundary obtained using level set evolution. A statistical approach that uses features generated from edge detection and wavelet transform was employed to detect probable vessel edges. Based on the angular changes of these vessel edges, kinks are obtained. Subsequently, these kinks are used to obtain the cup boundary. Patches are extracted within the OD, from which segment based wavelet, edge and color features are generated for vessel candidates [27]. A shifting multi-scale window interval and SVM classifier are used to detect and localize kinking. The obtained kinks are combined with pallor-based information to determine the optic cup. A reliable subset called r-bends is derived using a multi-stage strategy and a local spline fitting is used to obtain the desired cup boundary [28]. These three approaches are highly dependent on the preliminary cup boundary obtained. Furthermore, the statistical rules used for selecting vessel pixels are very sensitive to the inter-image variations. Also, in regions where the vessel kinks are absent, these methods failed to have reasonable accuracy (unable to match the boundary marked by the experts). To meet these issues, a new optic cup segmentation method is proposed that use both structural and gray level properties of the OD region.

The foremost objective of this work is to derive a rich description of OD and cup that is suitable for aforesaid different glaucoma assessment methodologies. The main contributions of the work are: