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Retinal image analysis aimed at blood vessel tree segmentation and early detection of neural-layer deterioration

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ABSTRACT

An automatic method of segmenting the retinal vessel tree and estimating status of retinal neural fibre layer (NFL) from high resolution fundus camera images is presented. First, reliable blood vessel segmentation, using 2D directional matched filtering, enables to remove areas occluded by blood vessels thus leaving remaining retinal area available to the following NFL detection. The local existence of rather faint and hardly visible NFL is detected by combining several newly designed local textural features, sensitive to subtle NFL characteristics, into feature vectors submitted to a trained neural-network classifier. Obtained binary retinal maps of NFL distribution show a good agreement with both medical expert evaluations and quantitative results obtained by optical coherence tomography.

1. Introduction

One of the increasingly frequent causes of sight damage or even loss is deterioration of retinal neural fibre layer (NFL) that provides connection between the light sensing elements of the eye and the sight nerve bundle leaving the eye at its retinal terminal, so-called optical disc (OD). As it has been reported in medical literature e.g. [3], the incidence of the glaucomatous illness in population is on average 2.4% and reaches 4.7% for seniors over 75; it is expected to reach around 80 million cases worldwide in 2020 [45]. The degree of retinal NFL damage is an important indicator of the disease progression, which can be hindered or even stopped if discovered early; thus automatic screening methods applicable for generic use are highly desirable.

Quality of the NFL status estimation importantly influences the treatment and prognosis of a patient illness. Ophthalmologists mostly assess the NFL status visually either directly via ophthalmoscope or by evaluating standard retinal images (as in Fig. 1) obtained by optical wide-angle fundus cameras using flash illumination in dark environment [6]. The neural fibre layer shows up as a faint stripy structure, usually lighter than regions with defective or lacking NFL. The local brightness is the main feature used by medical experts in visual evaluation; however, this is an unreliable attribute due to spatially varying illumination of retina so that a great ophthalmologist's experience is required. These manual diagnoses show a large interpersonal variance among different experts and would also require enormous human effort when used for screening. Therefore, automatic approaches based on analysing the available image data are looked for [49]. Besides the generally available fundus camera imaging, new alternative methods for examining more exactly the NFL status exist [6]; among them, the most promising seems to be the optical coherence tomography (OCT), which can measure the NFL local thickness quantitatively; however, this approach is still expensive and not quite generally available [15]. The fundus camera thus remains a basic data source with expectably good potential for basic NFL screening, if the image quality is high and suitable analytic methods are provided.

Retinal image analysis is a vivid research forum, namely in both closely connected areas of blood vessel segmentation and NFL detection. As for the blood vessel segmentation phase, some approaches have used simple matched filters [2,5,16,18,54] and/or edge detection, e.g. [24] using Canny detector. Alternative methods are based on multiscale feature extraction and region growing approach [43], on tracing the vessels starting from a

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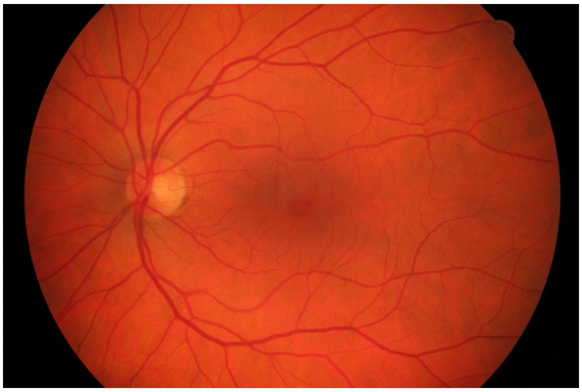

Fig. 1. Example of a colour fundus-camera image of retina (from the database of authors, converted into grey scale).

predetermined point [7,13,51] or on morphological operations [35,52,53], or may be using the wavelet transform [22,46]. The recent paper [48] utilises ridge-based algorithm and the papers [1,9,50] and recent [25] apply model-based methods. Other recent approaches, based on supervised machine-learning and divergence of vector fields, were proposed in [26,31,33]. A comparison of common methods for retinal vascular tree segmentation can be found in [38]. The NFL analysis in fundus camera images has been treated from different aspects, one of the first pilot studies being [30]. A subjective evaluation of NFL status in digitised fundus photographs is subject of [8]. From a wider perspective, most of papers aiming at automatic support of glaucoma diagnosis are differently oriented, analysing the size and shape of the optic disc in fundus-camera images where from they derive some geometric parameters indirectly indicating the possible glaucomatous damage, e.g. [19,37] and also a new paper [3], deriving s.c. glaucoma risk index based also on morphology of the optical disc. In [47], an expert system aimed at glaucoma screening is presented, using, besides other features like intraocular pressure and visual perimeter measurements, also the optic disc morphology derived from fundus camera images. Some publications aim at a direct local analysis of NFL damage considering only the relatively unreliable brightness information, e.g. [27]. Only few papers deal with direct NFL texture analysis in fundus photographs: [41] and [14] in rather low-resolution images; recently also fractal representation based paper [23]. The paper [40] presents a NFL analysis where the textural features are formed by parameters of a Markov random field [28] model, while still another approach (features derived by local binary patterns [34]) is subject of [39]. Very recent paper [36], dealing with NFL analysis in low-resolution images, extends the earlier work [14] particularly by extensive statistical evaluation of the results.

The NFL appearance in a fundus camera image is characterised by certain local characteristics, which can be revealed by texture analysis; however, this analysis would be heavily disturbed by the structure of retinal vessels, which are overlaid on the retinal images. This disturbance must be prevented by detecting and segmenting out the vessels, while preserving as much of the retinal background carrying the NFL information as possible. The presented compound method of fundus-camera image analysis is thus focused on two closely connected problems: first to segment out reliably the blood vessel tree without unnecessarily excluding useful areas of the image from the following NFL texture analysis, and second, to show an objective analytic approach, leading to local binary classification of the NFL as present or absent. A highly reliable segmentation of the blood vessel structure is therefore a crucially important first phase in the NFL analysis. The presented approach based on multiple directional 2D matched filtering has proved very efficient in detecting the complete blood vessel tree with vessels of very different thicknesses and directions. The second analytic phase – the NFL detection – evaluates several differently defined local textural features that were found characteristic for the NFL. As the NFL is barely visible in the images and the individual textural characteristics are thus individually of low reliability, multiple local features are combined into local feature vectors that proved to carry sufficient information enabling to achieve reasonably reliable NFL detection. The local feature vectors are then classified by a chosen learning algorithm; among tested neural networks (NN) and Bayesian classifiers, a simple NN has shown the best performance. The binary classification results then indicate regions of healthy or missing NFL on the retinal image.

The presented method suggested several partly novel approaches. The generic image processing methods as described, e.g. in [20] or [44] served often as starting points; however, the presented methodology and its implementation is novel in combining the individual known (often modified) partial methods as building blocks into working structures achieving the required goals. The resulting compound method formulates an integrative fully automated approach starting from an unprocessed fundus-camera image and yielding finally a 2D overlay map indicating locally the presence or absence of the NFL in the medically decisive area of the retinal image considered. The results obtained by the method using the available experimental set of data were originally compared with visual assessment of the images by experienced medical experts; a good degree of agreement was achieved considering the generic rather high uncertainty and large variety of the medical estimates. Recently, when the first couples of corresponding fundus-camera images and OCT measurements became available, comparisons of the detection results obtained by the presented method with the objective NFL thickness measurements were possible, giving a good agreement, as commented in Section 4. The present paper deepens the description of the method as preliminarily described in [21] and adds further methodological developments. The assessment of the detection method has been recently objectified by the initial comparisons with the OCT results [12]; partly extended test results are included.

Besides being the crucial first phase in the NFL analysis, the blood vessel tree segmentation approach provides the detailed retinal vessel structure map, indicating locally both the widths and directional orientations of blood vessel segments. This result has found yet another successful medical application – as a by-product – in assessing development of changes linked to diabetes mellitus [10].

The paper is organised in the standard way: experimental data description (Section 2), used methods of analysis (Section 3), discussion of obtained results (Section 4) and conclusions. The structure of the Section 3 forming the core of the paper is as follows: Section 3.1 describes the novel method of retinal vessel tree segmentation by the directional 2D matched filtering approach using the realistic blood vessel profiles, and also how the occlusion problem in the NFL analysis (substitution of retinal pixels hidden behind the vessels) is solved. Section 3.2 is devoted to the novel analysis of NFL by the textural methods, to fusion of the individual results and the final NFL classification. In both Sections 3.1 and 3.2, the initial paragraphs summarise the purpose of the respective method that is then detailed in the following sections. Section 4 presents and discusses the obtained experimental results; besides the comparison with medical estimates, there are also novel comparisons of the fundus-camera based detection results versus the quantitative NFL thickness measurements by the OCT method.

The paper concentrates on the used methodology, and the experimental results are so far based on only a relatively low number of available high-resolution retinal images, as the high quality images, particularly those accompanied by the corresponding OCT data, are still quite rare and difficult to provide; no public database of this kind exists so far. The presented results are thus verifying the