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Adaptive-weighted bilateral filtering and other pre-processing techniques for optical coherence tomography☆

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ABSTRACT

This paper presents novel pre-processing image enhancement algorithms for retinal optical coherence tomography (OCT). These images contain a large amount of speckle causing them to be grainy and of very low contrast. To make these images valuable for clinical interpretation, we propose a novel method to remove speckle, while preserving useful information contained in each retinal layer. The process starts with multi-scale despeckling based on a dual-tree complex wavelet transform (DT-CWT). We further enhance the OCT image through a smoothing process that uses a novel adaptive-weighted bilateral filter (AWBF). This offers the desirable property of preserving texture within the OCT image layers. The enhanced OCT image is then segmented to extract inner retinal layers that contain useful information for eye research. Our layer segmentation technique is also performed in the DT-CWT domain. Finally we describe an OCT/fundus image registration algorithm which is helpful when two modalities are used together for diagnosis and for information fusion.

1. Introduction

Optical coherence tomography (OCT) has recently become a powerful tool in medicine, particularly in the diagnosis and monitoring of retinal damage in a range of diseases [1,2]. It provides high-resolution cross-sectional images of biological tissues using noninvasive imaging technology. While recent improvements in OCT technology offer higher scan speed and better signal sensitivity, the spatial-frequency bandwidth of the interference signals is still limited and causes a granular appearance, called '*speckle*' [3].

The assessment of retinal disease using OCT images has so far focused on the delineation of the retinal layers and emphasized the detection of cell loss and anatomical disruption of the retinal architecture. Indeed, in glaucoma for example, OCT images reveal the thinning occurring in the retinal nerve fibre layer (RNFL) and retinal ganglion cells (RGCs) [4]. However, this is characteristic of late disease. Recently, studies showing that many retinal conditions begin with a loss of neuronal connectivity and consequent damage in the RGC/IPL complex (the combined RGC and inner plexiform layers (IPL)) make identifying such changes by OCT an important goal [5,6]. Work in [7] showed that the light scattering properties of retinal layers affected by retinal neural atrophy can be detected by OCT. Therefore, we hypothesize that the texture of light reflections within the RGC/IPL complex can possibly be used for detecting neuronal changes such as those seen in early glaucoma. This paper presents a framework to prepare OCT data for feature extraction and other image analysis tasks that help diagnosis. For example, through texture analysis, ganglion cell degeneration in the retina could be automatically detected.

The proposed process is illustrated in Fig. 1. The first step involves image enhancements in which speckle noise, that appears as a grainy texture (as shown in Fig. 2) and degrades the quality of the OCT image, is removed. However, since OCT speckle results mostly from multiple forward scattering it may also contain diagnostically useful information. The extraction of this information, which we shall refer to as *texture* is challenging. The simplest and oldest way of removing speckle is median filtering [8]. Directional filters and anisotropic diffusion filters have also been employed to improve despeckling results and to preserve edges [9,10]. In recent

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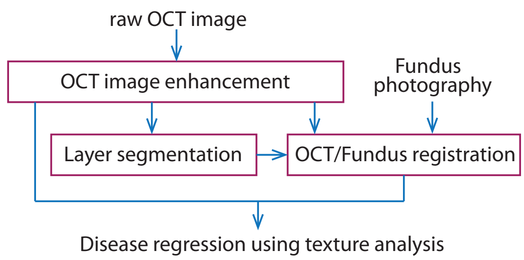

Fig. 1. Proposed methods preparing for decease analysis.

years, the wavelet transform has been widely used due to its effectiveness and simplicity [11]. As the speckle noise can be modelled as multiplicative noise, the logarithmic operation is used to transform speckle noise into the classical additive white noise, thereby allowing simple image noise removing algorithms to be employed. We implement our algorithms in the wavelet domain using a dual tree complex wavelet transform (DT-CWT), followed by the proposed texture-preserving smooth process which employs a novel adaptive-weighted bilateral filter (AWBF).

The next step is layer segmentation. This is aimed at delineating the retinal layers, such as the RGC/IPL complex, which will be used in the disease detection process and for measuring layer thickness [12]. This process is also performed in the DT-CWT domain. Finally an OCT/fundus photography image registration algorithm is proposed. This is necessary because precise and reproducible control of the OCT image position on the fundus is especially important for morphometry, such as measurement of NFL thickness in glaucoma diagnosis [13]. In addition, some defects are easier to capture in one image modality than the other, so working on both types of images increases the diagnostic confidence [14]. The OCT/fundus image registration is one of the most challenging problems as it tries to correlate the retinal features across the different imaging modalities, a process which involves feature detection, warping and similarity measurement. Moreover, our OCT images are affected by eye movement.

The main contributions of this work are:

(i) An integrated system for OCT image preprocessing that serves the purpose of glaucoma detection.
(ii) In the enhancement component of our system, we propose an adaptive-weighted bilateral filtering (AWBF).
(iii) In the layer segmentation, we perform multiscale-based segmentation by taking advantage of improved directional selectivity.
(iv) In the OCT/fundus image registration component, we propose a technique for blood vessel extraction for OCT photograph and a new score for multi-modal registration to solve scaling problems.

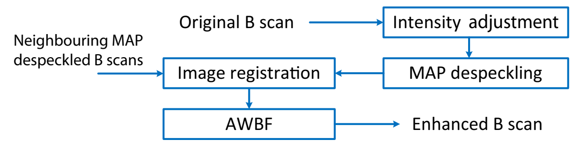

Fig. 3. Proposed image enhancement process.

The remaining part of this paper is organized as follows. The proposed image enhancement process, layer segmentation and OCT/fundus image registration are explained in Sections 2–4, respectively. The proposed system is evaluated with discussion in Section 5. Finally the conclusions of this work are stated in Section 6.

2. Image enhancement for OCT images

The proposed OCT image enhancement method is depicted in Fig. 3. The first step is intensity adjustment, where a linear intensity histogram stretching is employed. Subsequently, a two-step denoising process is employed. The speckle resulting from interference of the waveforms from multiple scatterers within the OCT focal volume is typically large (i.e. is spatially correlated), while some noise due to interference from multiply scattered photons is generally small, typically a single pixel wide [15]. Therefore, we exploit a two-step process in our OCT image enhancement to remove the speckle noise so that the OCT image retains the information rich structure, i.e. the *texture*. Firstly, the spatially correlated speckle is removed by a published wavelet-based denoising algorithm using a Cauchy distribution [16] after applying a logarithmic operation to the OCT image. Then, multiple neighbouring B scans are registered to the current B scan in order to improve structure of retinal layers. The speckle from scattered photons is subsequently removed using the proposed adaptive-weighted bilateral filtering (AWBF). The shape of spatial filter in our proposed method is varied according to local entropy. Generally, the entropy is used for measuring uncertainty of a group of data. For OCT images, higher entropy can imply a larger amount of speckle. Therefore, we apply a wider bell-shaped spatial filter to such areas. Boundaries of retinal layers are preserved through weighting using a similarity function.

OCT images are 3D stacks captured as a series of slices corresponding to a sequence of *xz* scans, called B-scans; however, our proposed image enhancement is applied on 2D slices. The main reason for this is that, during image acquisition, misalignment across slices can occur due to the natural and involuntary movement of the subject's eyes. This can be seen as rough surface in the *xy* planes and discontinuities in the *yz* planes in Fig. 4.

2.1. Despeckling with Cauchy model

The wavelet transform decomposes an image into multiscale and oriented subbands. Statistical modelling of the image

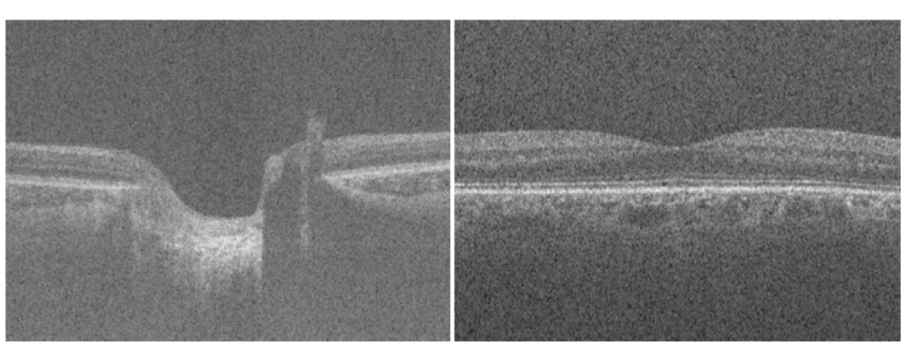

Fig. 2. Example slides (*xz* planes) of raw OCT images. Left: Optic nerve head. Right: Macula.