Optik 127 (2016) 7809–7821

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Speckle reduction and cartoon-texture decomposition of ophthalmic optical coherence tomography images by variational image decomposition

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ARTICLE INFO

Article history:
Received 10 September 2015
Accepted 26 May 2016

Keywords:
Optical coherence tomography
Variational image decomposition
Speckle reduction
Cartoon
Texture

ABSTRACT

Optical coherence tomography (OCT) provides high resolution, cross-sectional tomographic images of internal structures of specimens, with wide application in ophthalmology. OCT images, however, are usually degraded by significant speckle noise. Development of successful speckle noise reduction algorithms while preserving fine details of image for ophthalmic OCT is particularly challenging, because of the difficulty in separating the noise and the information parts of a speckle pattern. In this paper we presented a new speckle reduction and cartoon-texture decomposition method of ophthalmic OCT images by using variational image decomposition. Experimental results show that the proposed method could decompose the ophthalmic OCT images into cartoon part, texture part and speckle noise part. Further it is also shown the advantage of variational image decomposition in the speckle reduction of ophthalmic OCT images.

1. Introduction

Optical coherence tomography (OCT) has been a well-established modality which allows for noninvasive cross-sectional imaging of weakly scattering, semitransparent samples with high sensitivity [1]. It gains a wide variety of application in the field of biomedical imaging. By now, OCT has been a powerful method for imaging the internal structure of biological systems and is becoming an essential tool in ophthalmology to obtain high-resolution images of the retina and the anterior segment of the eye [2–4]. Further quantitative image analysis such as retinal layer segmentation facilitates the quantification of retinal layers from the nerve fiber layer to the pigment epithelium layer. Retinal layer thickness derived from such image analysis methods may improve the clinical diagnosis during glaucoma progression and age-related macular degeneration. Therefore, the processing of ophthalmic OCT images is of great importance to the diagnosis of glaucoma progression and age-related macular degeneration and so on. However, as any imaging technique that is based on detection of coherent waves, ophthalmic OCT images are accompanied with a significant amount of speckle noise, which not only limits the contrast and signal-to-noise ratio of images, but also obscures fine image features. Development of successful speckle noise reduction algorithms while preserving fine details of image for OCT is particularly challenging, because of the difficulty in separating the speckle noise and the image features.

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http://dx.doi.org/10.1016/j.ijleo.2016.05.088

There have been considerable researches devoted to speckle reduction of OCT images. Various methods have been developed to minimize the effect of speckle noise in OCT images. Those methods can generally be classified into two categories: the first one performs speckle noise reduction in spatial domain, and another performs speckle noise reduction in transform domain. The spatial domain based methods such as adaptive filters [5], rotating kernel transformation [6], I-divergence regularization approach [7], adaptive complex diffusion method [8–10], and general Bayesian estimation method [11] and have been developed or adapted for the improvement of image quality of OCT images. The transform based methods include wavelet transform method [12], dual tree complex wavelet transformation method [13], multiframe based wavelet transform method [14], curvelet transformation method [15,16] and contourlet transform method [17] and so on.

The methods which perform speckle noise reduction in spatial domain such as adaptive filters are designed to suppress speckle noise while keep the details of ophthalmic OCT images as much as possible. However, when the ophthalmic OCT images contain fine details such texture information, these models are not well able to preserve these texture part of images in the process of speckle reduction. In other words, the texture information of ophthalmic OCT images is usually degraded to some large extent. In fact, ophthalmic OCT images involve abundant texture parts especially for the measurement of retinal layer in ophthalmic OCT such as the layer structure that is composed by inner limiting membrane, nerve fiber layer inner plexiform layer, inner nuclear layer, outer plexiform layer and so on. Therefore, it is a great challenge for the spatial domain based methods such as adaptive complex diffusion method to preserve the texture information in the process of speckle reduction of ophthalmic OCT images.

The basic principle of transform domain filtering is to shrink transformed coefficients according to some threshold values. Wavelet shrinkage techniques have been employed successfully in speckle noise reduction for ophthalmic OCT images. By transforming the ophthalmic OCT image into the wavelet domain, speckle noise is usually coded by small wavelet coefficients while signals are coded by large ones. By keeping large coefficients and suppressing small ones, speckle noise can be effectively attenuated. However, the wavelet representation is not very effective in dealing multidimensional signals containing distributed discontinuities such as edges. Usually edges discontinuities are common in ophthalmic OCT images. To overcome this limitation, one has to use basis elements with much higher directional sensitivity and of various shapes, to be able to capture the intrinsic geometrical features of multidimensional phenomena. The curvelet transform is a well developed multiscale mathematical transform with strong directional characters [18]. The curvelet transform can measure in formation of an object at specified scales and locations and only along specified orientations. Curvelet representation of ophthalmic OCT images is very efficient, and with that, significantly improved qualities of OCT images in the respects of signal to noise ratio, contrast to noise ratio, and so on [15,16].

As mentioned above, the ophthalmic OCT images contain cartoon part, texture part as well as speckle noise part. Each part has its own characteristic and should be described by a suitable model. It is expected to describe the three parts by different models separately to attain the goal of perfect denoising results. By now, the spatial domain based methods are able to describe the two parts that are cartoon part and noise part, but are not able to describe texture part. It is urgent to introduce a new way to describe the three parts simultaneously, to preserve the texture of OCT images as large as possible. Recently, varitional image decomposition method has becoming a popular method to describe an image with different parts [19,20]. It seeks a decomposition of an image into various parts representing different information in an image. For instance, it can split an image into cartoon part u, texture part v and noise part w in the form of $f = u + v + w$.

In this study, we mainly aim to propose varational image decomposition to decompose an ophthalmic OCT image into cartoon part, texture part and speckle noise part. The contributions of our paper are mainly as follows: Firstly, ophthalmic OCT images are modeled by using variational image decomposition. In detail, the cartoon part of ophthalmic OCT images is described by total variation spaces, and the texture part is described by G space and adaptive Hilbert space, and the speckle noise part is described by curvelet space. Based the mentioned function spaces, we propose two new variational image decomposition models, TV-G-Curvelet and TV-Hilbert-Curvelet for ophthalmic OCT images. Secondly, the proposed method combines the advantages of total variation and curvelet method, while the existing speckle reduction method only use one kind of them, as mentioned above. Lastly, since varational image decomposition can give the three parts of ophthalmic OCT image that are cartoon part, texture part and noise part, it does not only give the speckle reduction result, but also gives the cartoon-texture decomposition results. The decomposition results are great of significance for the future processing of ophthalmic OCT images such as edge detection, segmentation and layer thickness evaluation.

2. Variational image decomposition for ophthalmic OCT images speckle reduction and cartoon-texture decomposition

2.1. Variational image decomposition and function spaces

The goal of variational image decomposition is to decompose a given image f into two parts u and v in the form $f = u + v$ or three parts u, v, and w in the form of $f = u + v + w$. Usually an image contains two parts or three parts in the above forms, where u is considered as cartoon part, v is texture part and w is noise part. In this paper, we focus on the three parts