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A two-step iteration mechanism for speckle reduction in optical coherence tomography

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ABSTRACT

Optical coherence tomography (OCT) is an imaging tool that has been widely utilized for various disease diagnoses for its noninvasive and high-resolution properties. Due to the dual role of speckles in the imaging process, however, OCT images suffer from the unavoidable speckle noise, which is usually regarded to be multiplicative in nature and reduces image contrast and resolution. In this study, we propose to categorize OCT speckle noise into additive portion and multiplicative portion, and present a simple two-step iteration (TSI) mechanism to suppress such noises separately. With the augmented Lagrange minimization (ALM) method adopted to recover a low-rank image, the first step of TSI is to remove the additive Gaussian noise, while the second step of TSI is to suppress the multiplicative noise by employing a split Bregman method (SBM) to solve the total-variation (TV) de-noising problem. Extensive experiments with OCT images of the swine eye, human and rabbit retina are conducted to verify the effectiveness of the proposed method. Results show that the proposed TSI method outperforms the existing methods in different cases. Specifically, TSI helps improve the peak signal-to-noise ratio (PSNR) and structure similarity (SSIM) of the swine eye images from 17.19 dB to 33 dB and 0.12 to 0.92, respectively, with the important structural details well preserved. The clearer boundaries and higher image contrast obtained with the TSI method would largely facilitate image analyses and interpretations for the clinical applications of OCT systems.

1. Introduction

Optical coherence tomography (OCT) is a low-coherence interferometry based imaging tool capable of providing high-resolution cross-sectional images of tissue microstructures [1]. Due to its noninvasive and high-resolution properties, OCT has received extensive research interests since its invention and been utilized in various areas. In recent years, with the advents of ultrahigh resolution OCT (UHR-OCT) and swept-source OCT (SS-OCT), the application areas of OCT have been further broadened for the improved system resolutions and scanning speed [2,44]. Currently, OCT has not only been utilized for eye disease diagnoses in clinical practice [3], but also been utilized in some other research areas, such as for airway function evaluations [4,45], cardiology and gastroenterology system imaging [5,6], and individual identifications in forensic science [7], etc..

As an interferometric imaging technique, however, OCT suffers from speckle noise like some other similar technologies, such as the synthetic aperture radar (SAR), remote sensing, ultrasound and sonar, etc. [8]. Speckle is an inherent characteristic of OCT images, which typically arises from the random interference between reflected wave signals that are mutually coherent. Among all those factors impacting on spatial coherence of the detection waves, the multiple backscattering of the incident beam inside and outside volumetric specimen as well as multiple forward scattering caused detection wave random delays are the two main ones. Both factors could change wave front shapes of the returning waves, which thus generates speckles due to the constructive and destructive interference effects. In OCT images, speckle plays a dual role as both source of speckle noise components and carrier of information about tissue

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microstructures [9]. Such a dual role makes speckle noise unavoidable in OCT images, which thus reduces the image contrast and resolution, making the tissue boundaries difficult to be resolved. To meet the rapid development and wide applications of OCT in different areas, especially for high-scattering tissues imaging, speckle noise reduction techniques are highly desired for resolving the tissue microstructures in clinical practice.

Extensive efforts devoted either to the hardware-side system design or to the software-side image post-processing mechanisms for OCT image speckle reduction have been made in literature. By acquiring multiple images with uncorrelated speckle patterns, the hardware design methods typically try to average the acquired images to reduce speckle noises. Angular compounding [10–12], frequency compounding [13], and spatial diversity based design [14–16] are representative hardware-side methods. In practice, however, such methods usually impose extensive changes upon the OCT systems, which thus makes the system bulky and complex. In addition, the denoising effects of such methods are also limited. On the contrary, those software-side methods are post-processing techniques, and mainly include the digital filtering and sparse coding mechanisms. Various image processing algorithms using either a single frame or multiple frames have been proposed thus far [17–24]. Based on wavelet-filter design and parametric optimization, the proposed digital filtering mechanisms have achieved encouraging results [17–20]. While with the volumetric intra-frame redundancy or inter-frame redundancy or both taken into consideration, the sparse coding mechanism has gained much research interests in recent years [21–24]. However, although such software-side methods achieve improved signal to noise ratio (SNR) without introducing any artifacts, they are still computational extensive and time-consuming. For example, the multi-frame methods [18,20,21,23–25] requires the acquisitions of multiple frames for noise reduction processing, which thus slows down the scanning speed and limit their practical applications in clinical practice, while the single-frame methods, including image-domain methods [26–29], and wavelet methods [19,30,31], either suffer from the high-computational cost or the wavelet domain processing artifacts. Those drawbacks largely limit the practical applications of those methods, especially for in vivo imaging. Furthermore, it is also worth noting that all previous studies assumed that the OCT speckle noise consists mainly of multiplicative noise, and the additive noise, which consists mainly of the inherent shot noise, light intensity noise and electronic noise, is relatively small and could be negligible as compared to the multiplicative noise [19,22,24,28,32,33]. However, although such multiplicative noise model is relatively reasonable, and both simulation and experimental results agree well with predicted Gamma distribution [32], there still exists certain difference between the simulation and experimental results, and OCT images still suffer from the inherent additive noises in OCT systems [19]. The SNR improvements with those proposed methods are also limited, especially for tissues with high speckle noise contamination. So far, no previous studies have ever evaluated the influences of additive noise to OCT images, to the best of our knowledge. Specifically, all such existing algorithms regard the speckle noise to be multiplicative in nature, and thus the SNR improvements with those methods are limited, especially for tissues with high speckle noise contamination.

In this study, we propose a two-step iteration (TSI) mechanism for speckle reduction for OCT systems. Specifically, we propose to categorize OCT speckle noise into multiplicative portion and additive portion as compared with the existing methods, and adopt an augmented Lagrangian minimization (ALM) method together with a split-Bregman method (SBM) to suppress such noises separately. Extensive experiments with images of the swine eye, human and rabbit retina are conducted to verify the effectiveness of the proposed TSI method. Results show that the TSI method largely outperforms the existing methods in achieving higher peak SNR (PSNR) and structure similarity (SSIM) in different cases.

2. TSI Method

2.1. OCT image noise modeling

Speckle noise in OCT images is usually considered to be multiplicative in nature due to the multiple backscattering effects [34]. However, since an OCT system also includes both laser source and electronics components, e.g., charge coupled devices (CCD) in spectrometer, OCT images also suffer from the inherent laser intensity noise, photonics shot noises as well as thermal noise from electronics. Both intensity noise and photonics shot noise are distributed with random-rate Poisson distribution and could be indistinguishable from true Gaussian noise with high laser power, while thermal noise itself is white Gaussian noise [15,32,35], therefore, we reasonably assume that an OCT image contains both multiplicative noise and additive noise with the latter one being Gaussian white noise in this study. Furthermore, due to the different tissue scattering capabilities at different tissue positions, the signal intensities collected from the tissue are different, and therefore, both multiplicative noise and additive noise are dependent with the imaging position. Since the system inherent additive noise is independent of the interference signals, and it is also smaller as compared with the multiplicative noise, both additive and multiplicative noise could be processed independently from each other.

Denote a random position in an imaging area of the tissue to be x. Let $L(x)$ be a noise free B-scan frame of the tissue containing x, $N(x)$ be the speckle noise, and $E(x)$ be the Gaussian white noise, we adopt the same expression in [19] to express an obtained B-scan frame M(x) as follows,

$$M(x) = L(x) \times N(x) + E(x) \tag{1}$$

where the symbols $M(x)$, $L(x)$, $N(x)$ and $E(x)$ are two-dimensional (2D) matrices $\in R^{m\times n}$, and would be used interchangeably with M, L, N and E throughout this paper.

Through utilizing such a noise model, it is expected that the multiplicative noise and the additive white noise could be differentiated and processed separately, and therefore, the overall image noise could be suppressed. The TSI method described below is proposed for such purpose.

2.2. The TSI method

Fig. 1 presents the main flow diagram of the TSI method. As can be seen, the TSI method includes a pre-processing step, namely image registration, together with two iteration steps, which are for the additive noise reduction and multiplicative noise suppression, respectively. Below we give a detailed description of each step.

2.2.1. Pre-processing for image registration

Although the typical scanning speed of OCT systems is high, misalignment of the same imaging point among different OCT images still exists due to the motions of both OCT scanners and the imaging object, especially for in vivo imaging, which thus could introduce motion artifacts to OCT images. To alleviate the influences of those motion artifacts while obtain the full information of a certain imaging point, image registration has to be performed to align the related images [36]. Specifically, a single frame has to be chosen as the standard reference first, and then a number of consecutive frames are selected, and then they are either rotated or translated to a certain degree to align with this reference frame accordingly, such that the image difference between these frames are minimized. Such a process is called the image registration process, and once