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Three-Dimensional Speckle Suppression in Optical Coherence Tomography Based on the Curvelet Transform

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Abstract

Optical coherence tomography is an emerging non-invasive technology that provides high resolution, cross-sectional tomographic images of internal structures of specimens. It holds great potentials for a wide variety of applications, especially in the field of biomedical imaging. OCT images, however, are usually degraded by significant speckle noise. Here we report a 3D approach to attenuating speckle noise in OCT images. This approach is based on the 3D curvelet transform, and is conveniently controlled by a single parameter that determines the threshold in the curvelet domain. Unlike 2D approaches which only consider information in individual images, 3D processing, by analyzing all images in a volume simultaneously, has the advantage of also taking the information between images into account. This, coupled with the curvelet transform's nearly optimal sparse representation of curved edges that are common in OCT images, provides a simple yet powerful platform for speckle attenuation. We show the approach suppresses a significant amount of speckle noise, and in the mean time preserves and thus reveals many subtle features that could get attenuated in other approaches.

Key words: Optical Coherence Tomography, Speckle Imaging, Image Enhancement

Introduction

Optical coherence tomography (OCT) has been undergoing rapid development since its introduction in the early 1990s. [1] It provides high resolution, cross-sectional tomographic images of internal structures of specimens, and therefore gains a wide variety of application in the field of biomedical imaging. Compared with other medical imaging modalities, 3D OCT has advantages in that it is non-invasive and it can acquire and display volume information in real time. However, due to its coherent detection nature, 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.

Various methods have been developed to minimize the effect of speckle noise. Those methods can generally be classified into two categories: the first one performs noise attenuation by acquiring extra data, such as using spatial compounding and frequency compounding. [2, 3] While effective, this method generally requires extra effort to acquire data and cannot process images from standard OCT systems, and is therefore less preferred than the second category, which uses digital signal processing techniques to process images acquired with standard OCT systems. Different digital signal processing algorithms have been proposed, including for example enhanced Lee filter [4], median filter [4], symmetric nearest neighbor filter [4], adaptive Wiener filter [4], I-divergence regularization [5], as well as filtering in a transform domain such as the wavelet [4, 6-9]. Recently we described a speckle suppression algorithm in a transform domain called curvelets.[10] There we showed the curvelet representation of OCT images is very efficient, and with that,

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we significantly improved qualities of OCT images in the respects of signal to noise ratio, contrast to noise ratio, and so on.

In almost all those algorithms, however, speckle reduction is performed on each image in a volume individually, and then all despeckled images are put together to form a volume. This process treats images as if they are independent from each other and therefore no relationship among different images is utilized, which is a waste of information provided by 3D OCT data. As many biological structures have layered structures not just in 2D, but also in 3D, and speckle noise is still random in 3D, we would expect that a despeckling algorithm based on 3D processing will be more powerful in attenuating noise and preserving features, especially those fine features across different images.

There are a number of ways to do 3D processing, such as extending those two-dimensional filters mentioned above to three dimensional, or performing a 3D transform followed by processing in the transformed domain. The 3D transform can be, for example, the 3D wavelet transform, the 3D curvelet transform, or a hybrid one, such as a 2D curvelet transform of individual images followed by a one-dimensional wavelet transform along the perpendicular direction. Given the many superior properties of the curvelet transform, here we extend our earlier work of 2D curvelets to 3D, by performing the speckle attenuation in the 3D curvelet domain.

Method

The curvelet transform is a recently developed multiscale mathematical transform with strong directional characters.[11-13] It is designed to efficiently represent edges and other singularities along curves. The transform decomposes signals using a linear and weighted combination of basis functions called curvelets, in a similar way as the wavelet transform decomposes signals as a summation of wavelets. Briefly, the curvelet transform is a higher-dimensional extension of the wavelet transform. The wavelet transform provides structured and sparse representations of signals containing singularities that satisfy a variety of local smoothness constraints, including for example piecewise smoothness. This structure and sparsity enable many simple yet powerful signal processing capabilities. However, while wavelets are particularly apt for representing singularity-rich one-dimensional signals, they are unable to capitalize in a similar effective fashion on signals of two and more dimensions. The curvelet transform is developed to have a nearly optimal sparse representation of curved edges. The curvelet transform can measure information of an object at specified scales and locations but only along specified orientations. Curvelets partition the frequency plane into dyadic coronae and (unlike wavelets) further subpartition the coronae into angular wedges.[11] Curvelets have time-frequency localization properties of wavelets, yet (unlike wavelets) also show a high degree of directionality and anisotropy. The curvelet transform is particularly suitable for noise attenuation, as it maps signals and noise into different areas in the curvelet domain, the signal's energy is concentrated in a limited number of curvelet coefficients, and the reconstruction error decays rapidly as a function of the largest curvelet coefficients.

Results

Figure 1 shows a Fourier domain OCT image of fovea, before (a) and after (b) curvelet denoising. Details of the OCT instrument and image acquisition have been previously described [14]. The low-coherence light source has a center wavelength of 890nm and an FWHM bandwidth of 150nm. A broadband optical isolator was used to prevent optical feedback before light enters a 2 by 2 broadband fiber- coupler-based interferometer. Light at the reference arm was focused onto a reference mirror. The sample arm was modified from the patient module of a Zeiss Stratus OCT instrument. The detection arm was connected to a high performance spectrometer, which makes the system bench-top sensitivity of 100 dB with 650 μw light out of the sample-arm fiber and 50 μs CCD integration time. A 9 dB of SNR roll-off from 0 mm imaging depth to 2 mm depth was observed. The system speed was set to be 16.7 K A-lines/s, with its CCD A-line integration time being 50 μs and the line period being 60 μs. With the system, we acquired a 3D volume of human retina, with a lateral resolution of 7.8 μm and axial resolution of 4 μm. Much of the speckle in the original image has been reduced, making some image features hidden in the original image more obvious, To better appreciate the performance of the algorithm, Fig. 1(c) shows a cross section of the images at the indicated dotted line in Fig. 1(a) and (b). The denoised signal is much cleaner than the original one, with all the noise at the beginning of the original signals being attenuated to zero. The image features and the edge sharpness of the original signal are both well maintained, demonstrating the ability of the algorithm to preserve signal while attenuating noise.

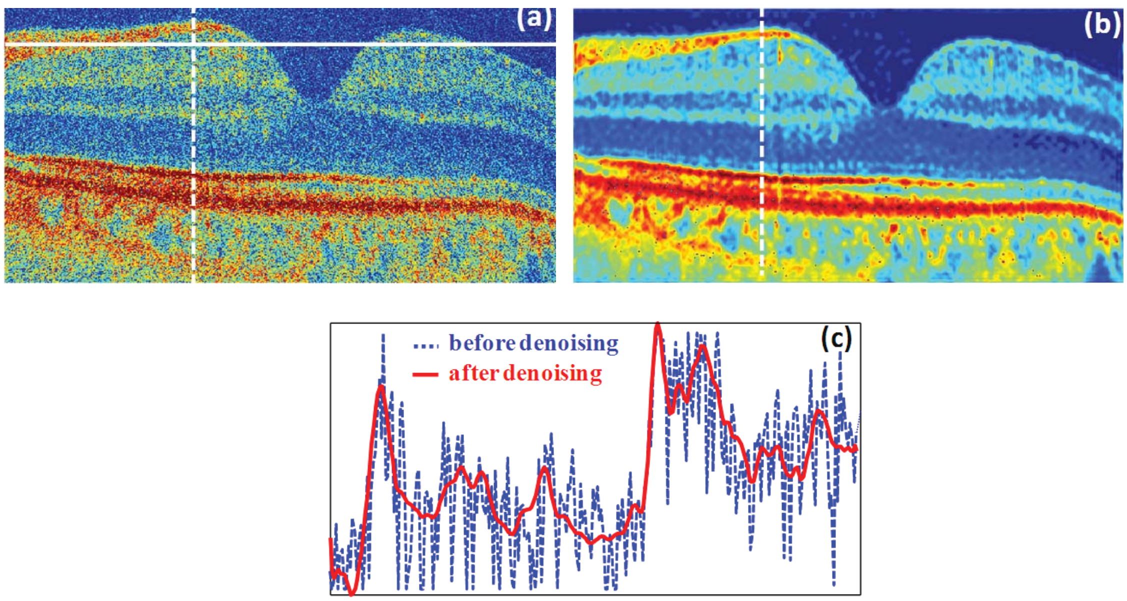

Figure 1 A cross-section retina image in the x-y plane (B-scan plane) of a volume, before (a) and after (b) curvelet despeckling. (c) is the cross section signal along the white dot lines in (a) and (b), and it shows the edge sharpness of the original image is well preserved in the denoising process. The denoising process also makes clearer the layered structure of the retina, as indicated by the more distinct peaks in the denoised signal.

In summary, we present a three-dimensional despeckling algorithm based on the curvelet transform. We demonstrate that the algorithm can significantly suppress speckle noise, while at the same time can preserve image features well. We show the 3D processing takes use of inter-information among images, and preserves weak features across images. These encouraging results highlight the power of the curvelet processing in biophotonic and biomedical image processing. Of course, those benefits come at a cost. The 3D curvelet transform requires more memory and is computation more demanding, when comparing to other 2D methods such as 2D curvelet and wavelet transforms. This limits the size of data volume that can be processed. However, we believe this problem can be mitigated, such as by parallel computation of multiple processors when necessary.

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Reference

1. D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. A. Puliafito, and J. G. Fujimoto, "Optical Coherence Tomography," Science **254**, 1178 (1991).

2. J. M. Schmitt, "Array detection for speckle reduction in optical coherence microscopy," Phys. Med. Biol. **42**, 1427 (1997).

3. J. M. Schmitt, S. H. Xiang, and K. M. Yung, "Speckle in Optical Coherence Tomography," J. Biomed. Opt. **4**, 95 (1999).

4. A. Ozcan, A. Bilenca, A. E. Desjardins, B. E. Bouma, and G. J. Tearney, "Speckle reduction in optical coherence tomography images using digital filtering," J. Opt. Soc. Am. A **24**, 1901 (2007).

5. D. L. Marks, T. S. Ralston, and S. A. Boppart, "Speckle reduction by I-divergence regularization in optical coherence tomography," J. Opt. Soc. Am. A **22**, 2366 (2005).

6. D. C. Adler, T. H. Ko, and J. G. Fujimoto, "Speckle reduction in optical coherence tomography images by use of a spatially adaptive wavelet filter," Opt. Lett. **29**, 2878 (2004).

7. M. Gargesha, M. W. Jenkins, A. M. Rollins, and D. L. Wilson, "Denoising and 4D visualization of OCT images," Opt. Express **16**, 12313 (2008).

8. P. Puvanathasan, and K. Bizheva, "Speckle noise reduction algorithm for optical coherence tomography based on interval type II fuzzy set," Opt. Express **15**, 15747 (2007).

9. S. H. Xiang, L. Zhou, and J. M. Schmitt, "Speckle Noise Reduction for Optical Coherence Tomography," Proc. SPIE **3196**, 79 (1997).

10. Z. Jian, Z. Yu, L. Yu, B. Rao, Z. Chen, and B. J. Tromberg, "Speckle Attenuation by Curvelet Shrinkage in Optical Coherence Tomography," Optics Letters **34**, 1516 (2009).

11. E. J. Candès, L. Demanet, D. L. Donoho, and L. Ying, "Fast Discrete Curvelet Transforms," SIAM Multiscale Model. Simul. **5**, 861 (2006).

12. E. J. Candès, and D. L. Donoho, "Curvelets -- a surprisingly effective nonadaptive representation for objects with edges," in *Curves and Surface Fitting*, C. Rabut, A. Cohen, and L. L. Schumaker, eds. (Vanderbilt University Press, Nashville, TN., 2000).

13. E. J. Candès, and D. L. Donoho, "New tight frames of curvelets and optimal representations of objects with piecewise C^2 singularities," Communications on Pure and Applied Mathematics **57**, 219 (2003).

14. Zhongping Jian, Zhaoxia Yu, Lingfeng Yu, Bin Rao, Zhongping Chen, and Bruce J. Tromberg, "Speckle attenuation in optical coherence tomography by curvelet shrinkage," Opt. Lett. **34**, 1516-1518 (2009).