Optical Coherence Tomography Technology and Quality Improvement Methods for Optical Coherence Tomography Images of Skin: A Short Review

Biomedical Engineering and Computational Biology
Volume 8: 1–5

DOI: 10.1177/1179597217713475
SAGE

Saba Adabi[1,2], Zahra Turani[3], Emad Fatemizadeh[3], Anne Clayton[1] and Mohammadreza Nasiriavanaki[1]

[1]Department of Biomedical Engineering, College of Engineering and School of Medicine, Wayne State University, Detroit, MI, USA. [2]Department of Applied Electronics, Engineering Faculty, Roma Tre University, Roma, Italy. [3]Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran.

ABSTRACT: Optical coherence tomography (OCT) delivers 3-dimensional images of tissue microstructures. Although OCT imaging offers a promising high-resolution method, OCT images experience some artifacts that lead to misapprehension of tissue structures. Speckle, intensity decay, and blurring are 3 major artifacts in OCT images. Speckle is due to the low coherent light source used in the configuration of OCT. Intensity decay is a deterioration of light with respect to depth, and blurring is the consequence of deficiencies of optical components. In this short review, we summarize some of the image enhancement algorithms for OCT images which address the abovementioned artifacts.

KEYWORDS: Optical coherence tomography (OCT), Image enhancement, Speckle reduction, attenuation compensation, Deblurring

RECEIVED: February 23, 2017. **ACCEPTED:** May 3, 2017.

PEER REVIEW: Four peer reviewers contributed to the peer review report. Reviewers' reports totaled 597 words, excluding any confidential comments to the academic editor.

TYPE: Short Review

FUNDING: The author(s) received no financial support for the research, authorship, and/or publication of this article.

DECLARATION OF CONFLICTING INTERESTS: The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

CORRESPONDING AUTHOR: Mohammadreza Nasiriavanaki, 818 West Hancock Street, Detroit, 48201 MI, USA. Email: mrn.avanaki@wayne.edu

Optical coherence tomography (OCT) is a noninvasive, nonionizing optical imaging modality based on low coherence interferometry.[1] Michelson, Mach-Zehnder, and common path interferometers have been used in the configuration of the OCT system.[1–4] To form an OCT image, the magnitude and time delay of backscattered infrared light returned from a biological sample are measured transversally.[5,6] Optical coherence tomography is similar to the ultrasound imaging, except that it uses light instead of sound.[7] Providing high-resolution images and a moderate penetration depth, ie, 1 to 3 mm, OCT is currently used in several medical and biomedical applications including dermatology,[8–12] dentistry,[13] oncology,[3] gastrointestinal endoscopy,[14] intravascular imaging,[15,16] cardiology,[17] and neurology in addition to its initial successes in ophthalmology.[18]

An OCT system is characterized by several parameters such as imaging speed, lateral and axial resolutions, and penetration depth.[19] Although imaging depths are not as deep as ultrasound, the resolution of OCT is more than 10 to 100 times finer than standard clinical ultrasound.[7] There are 2 main types of OCT: time domain and spectral domain.[5] Spectral domain OCT is a newer technology in which the scan rate is much faster than that in time domain, in addition to have a better penetration depth and signal-to-noise ratio. These characteristics are further improved in swept-source OCT, the most favorite OCT device in the market. The high scan rate diminishes the likelihood of motion artifacts and consequently enhances the image contrast and reduces the chance of missing pathology.[20,21]

Optical coherence tomography images visualize the morphological details of tissue microstructures, ie, stratum corneum, epidermis, dermis, hair follicles, eccrine sweat ducts, and sebaceous gland.[8,22] Figure 1 illustrates some of the skin structures visible in OCT images.

Since the invention of OCT, several hardware and signal processing advancements have been implemented; for instance, ultrahigh-speed OCT with the ability of generating several 3-dimensional images per second and sub-micron resolution OCT; both of which have benefitted from novel laser light sources and graphical processing units.[23–25] Polarization-sensitive OCT uses the depth-resolved polarization states' information (birefringence property of tissues) of recorded interference to provide high-resolution images.[26] Endoscopic OCT is a newer modality with a miniaturized probe to image internal organs such as gastrointestinal, pulmonary, and urinary tracts as well as arteries and veins.[3] Functional/molecular OCT has also been implemented and used in clinical applications such as brain tumor surgery.[27] More recently, OCT has been used as an optical biopsy method for differentiating between healthy and tumorous tissues.[28–30]

Quantitative analysis of OCT images through optical properties' extraction using extended Huygens-Fresnel principle[31–34] has made OCT an even more powerful modality.[35–38] Some of the optical properties that can be extracted from OCT images include scattering coefficient, absorption coefficient, refractive index, and anisotropy factor.[39]

Optical coherence tomography is a powerful high-resolution imaging method for medical and biomedical applications.

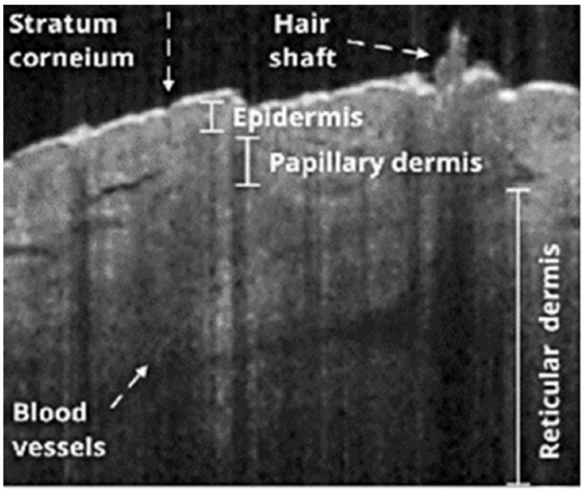

Figure 1. Optical coherence tomography image of skin of sole.

Many modifications have already been applied to OCT hardware and software; however, OCT images still have artifacts.[19] Five major artifacts found in OCT images are speckle noise, intensity decay, sample or device motion, refractive index change, and blurring and dispersion. In this review article, we briefly present the nature of the artifacts as well as a summary of the solutions to overcome them.

Similar to other low coherent imaging modalities, OCT images are contaminated with a grainy pattern of speckle which degrades the quality of images and conceals diagnostically relevant features.[40] In fact, speckles make the images vague and tissue microstructures may become indistinct. There are 2 main speckle reduction methods: software based and hardware based.[41–49] The most common hardware-based speckle reduction method is compounding. In compounding methods, the sample is imaged several times by the OCT system. There are 4 types of compounding: angular compounding, sample imaged from different angles; frequency compounding, sample imaged with different wavelengths; polarization compounding, sample imaged with different polarizations; and finally, spatial compounding, sample imaged from different positions.[1,44,49–51] Then, the acquired images are averaged and a speckle-reduced image is obtained. Software-based speckle reduction methods rely on digital filtering based on a mathematical model of speckle and do not need several images to work. There are 3 main classes of digital filters: sliding window, adaptive statistical-based, and edge-preserved patch or pixel correlation–based. *Sliding window filters*, a class of filter including mean, median, and symmetric nearest neighbor,[52] are highly efficient and can be used in real-time speckle reduction applications such as video-rate OCT imaging.[52] Although they effectively reduce speckle noise in the OCT image, they smooth edges in the image and create blurriness.[53,54] *Adaptive statistical-based filters*, a class of despeckling filter, include Kuwahara filter[55] and homomorphic Wiener filter and use statistical features, eg, mean and variance, extracted from the image or a part of the image.[56,57] *Patch or pixel correlation–based filters*, a class of despeckling filters, including nonlocal mean filter,[58] total variation,[59] and block matching and 3D filtering,[60] are based on high inter- or intracorrelations among nearby pixels or patch of pixels.[59,61–64] Wavelet-based algorithms are also considered as effective speckle reduction methods in which speckles are separated in higher level of decomposition.[47,60,65,66] In addition to these 3 main categories, there are artificial neural network–based denoising methods that are considered as effective speckle reduction approaches.[67–72]

Intensity decay is due to decline in the incident and backscattered light amplitudes when it passes through a biological sample.[1] The decay follows the Beer-Lambert law in the simplest model of skin—a single scattering model. When the light is attenuated, far less energy is deposited in deeper structures. By finding attenuation coefficients of skin layers and using the inverse Beer-Lambert law and some numerical methods, attenuation can be compensated.[73,74] Optical coherence tomography images are considered logarithmic and because of that their exponential nature is changed to linear. Hence, by finding the slope of A-scan profiles in a homogeneous area, the attenuation coefficient is found and the intensity decay can be compensated.

Motion artifact in OCT is a result of sample or device motion.[75,76] It is clear that longer acquisition times lead to greater motion artifacts. Optical coherence tomography systems with higher speed conserve experience with far fewer motion artifacts. To overcome the motion artifact, both hardware (using markers) and software (registration) solutions should be used.[76]

Being a noncontact method, the OCT image is distorted as a result of diffraction phenomenon that occur at the air/tissue interface. Therefore, algorithms are introduced to correct this distortion in OCT.[77]

Blurring is as a result of aberration which is due to imperfections in optical devices used in the configuration of the OCT.[78] Blurring deteriorates the lateral resolution of OCT images. Adaptive optics (AO) and deconvolution are 2 methods to reduce aberration and blurring.[79,80] The main components in an AO system are tilt mirrors, digital mirror devices, spatial light modulators, and deformable mirrors.[78,81] As the OCT signal is a convolution of the sample response with the coherence function of the light source, deconvolution methods are used to solve the depth resolution degradation caused by the depth point spread function envelope.[1,80,82–86] Lucy-Richardson and Weiner deconvolution algorithms are 2 popular methods in this area.[80,82,86] An OCT image on which some of the abovementioned processing, ie, speckle reduction, deblurring, and attenuation compensation, have been applied is shown in Figure 2.

Dispersion also degrades depth resolution. Therefore, equalizing dispersion between the reference and sample arms is essential to obtain a higher depth resolution. There are Fourier transform–based numerical dispersion compensation methods as well as pre-imaging optical techniques to compensate for OCT dispersion.[89] The common pre-imaging method to solve distortion is to use dispersive materials (such as prisms) in the reference arm of the interferometer.[90–92]

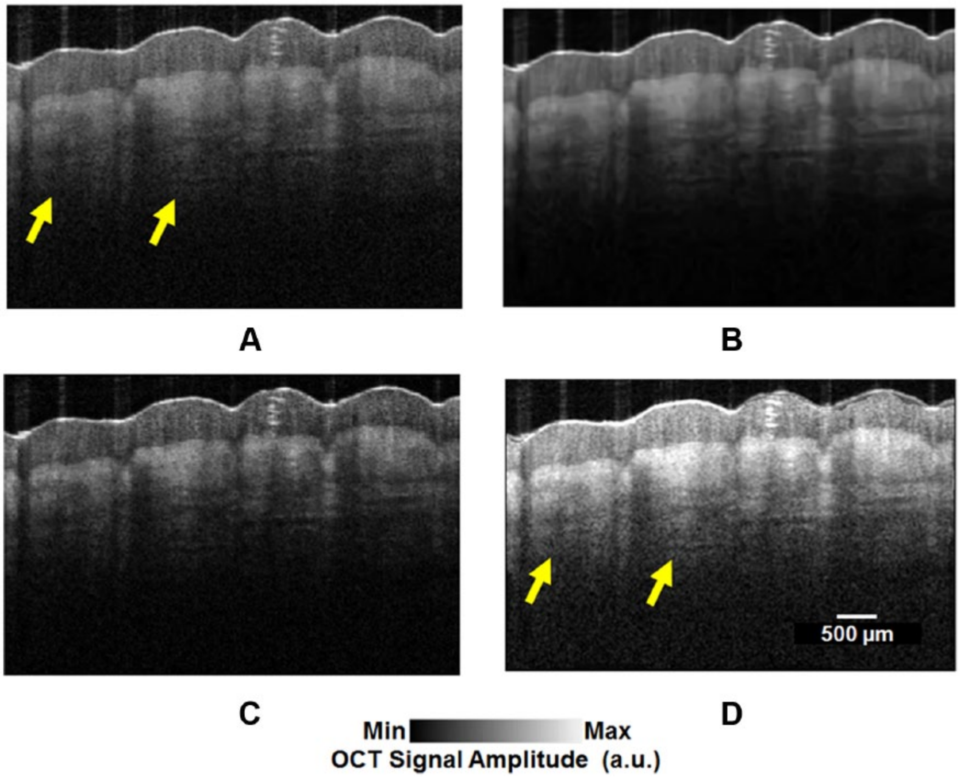

Figure 2. Optical coherence tomography images of a 24-year-old male's thumb pad. (A) Original image, (B) despeckled image,[51,57,64,66,67,72,87] (C) deconvolved image,[80,86] and (D) attenuation-compensated image.[88] Yellow arrows refer to the clearer structures at deeper depths before and after attenuation compensation.

Due to intermediate resolution and penetration depth, OCT has been a favorable device in many medical and biomedical applications. To make the diagnostically relevant features in OCT images more salient, and assist the specialists in making better diagnostic decisions using OCT images, quality improvement algorithms have been used. Required image quality and resolution is dependent on the application of OCT. Most of the causes of OCT image artifacts discussed in this short review could be resolved by some changes in the hardware of the OCT before imaging.[93] Further image quality improvement could be accomplished by software during postprocessing of OCT images. Many novel hardware modifications and technology advancements undergo test and evaluation to make the OCT system a more useful and versatile device. There have been other high-resolution imaging modalities added to OCT to improve some of its limitations, eg, penetration depth.[94,95]

Author Contributions

MA designed the research. SA, ZT, EF and MA wrote the manuscript and all authors participated in paper revisions.

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