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2016

Bo, E., & Liu, L. (2016). Spectral domain optical coherence tomography with extended depth-of-focus by aperture synthesis. Optics in Health Care and Biomedical Optics VII, 10024, 1002451-. doi:10.1117/12.2239997

<https://hdl.handle.net/10356/90171>

<https://doi.org/10.1117/12.2239997>

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Spectral Domain Optical Coherence Tomography with Extended Depth-of-focus by Aperture Synthesis

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ABSTRACT

We developed a spectral domain optical coherence tomography (SD-OCT) with an extended depth-of-focus (DOF) by synthesizing aperture. For a designated Gaussian-shape light source, the lateral resolution was determined by the numerical aperture (NA) of the objective lens and can be approximately maintained over the confocal parameter, which was defined as twice the Rayleigh range. However, the DOF was proportional to the square of the lateral resolution. Consequently, a trade-off existed between the DOF and lateral resolution, and researchers had to weigh and judge which was more important for their research reasonably. In this study, three distinct optical apertures were obtained by imbedding a circular phase spacer in the sample arm. Due to the optical path difference between three distinct apertures caused by the phase spacer, three images were aligned with equal spacing along z-axis vertically. By correcting the optical path difference (OPD) and defocus-induced wavefront curvature, three images with distinct depths were coherently summed together. This system digitally refocused the sample tissue and obtained a brand new image with higher lateral resolution over the confocal parameter when imaging the polystyrene calibration beads.

Keywords: optical coherence tomography, medical and biological imaging, medical optics instrumentation, aperture synthesis.

1. INTRODUCTION

Optical coherence tomography (OCT) is a three-dimensional interferometric imaging technique [1] that has been widely applied in ophthalmology [2] and cardiology [3] since it was firstly introduced for retinal imaging [1]. The DOF, defined as the confocal parameter in the classical theory of Fourier domain OCT (FD-OCT), is proportional to the square of the lateral resolution. Consequently, a trade-off exists between the DOF and the lateral resolution: a longer DOF results in a lower lateral resolution. To achieve a high lateral resolution over an extend DOF, various approaches have been presented and in-depth studied in the past decade. Generally these methods can be classified into three categories: Bessel beams with increased system complexity [4, 5], phase [6, 7] or amplitude [8, 9] apodization suffering from a signal loss of ~ 10 dB for both illumination and detection beams, and adaptive optics needing indispensable phase stabilizing setup [10, 11] or interferometric synthetic microscopy (ISAM) suffering from heavy computation cost and needing extra phase stabilization setups [12, 13]. Digital refocusing approach, such as multiple aperture synthesis [13-15] has drawn great research interest for the sake that it just requires minute hardware changes on conventional Fourier-domain OCT. Recently, a novel approach named depth-encoded synthetic aperture has been brought up to extend the DOF by synthesizing aperture and correct wavefront curvature due to defocus effect [13-15]. This approach can be of low computation cost, and with good compatibility with conventional FD-OCT, work without phase stabilization setups.

2. THEORY

Axial resolution and lateral resolution are two critical factors that determine the performance of OCT system. The axial resolution is determined by the light source with a central wavelength of λ_c and a spectral full-width-half-maximum (FWHM) of $\Delta\lambda$ respectively, as demonstrated by the equation $\Delta z = 2 \ln(2) \lambda_c^2 / \pi \Delta\lambda$. Hence the axial resolution remains constant over the full imaging depth. However, the lateral resolution Δx is approximately maintained only in the depth

of focus (DOF), for the sake that the lateral resolution is determined by three factors: λ (the wavelength of light source), f (the focal length of the objective lens) and d (the diameter of the beam passing the objective lens). Δx is regarded as the diffraction limited spot size of the focused beam, and defined as the beam waist diameter on the condition that a Gaussian input beam is assumed. Then the lateral resolution can be expressed as $\Delta x = 2\lambda/\pi NA$, where $NA = d/2f$ is the numerical aperture (NA) of the objective lens. With the same assumption, we define the DOF as the confocal parameter, which is the axial distance between the value of z (axial depth) where the beam size is two times larger than it is at the beam waist. When the Rayleigh range is defined as $z_R = \pi\Delta x^2/2\lambda$, $DOF = 2z_R = 4\lambda/\pi NA^2$ is denoted by twice the Rayleigh range. According to definitions stated above, the lateral resolution is inversely proportional to the NA of the objective lens, and DOF is proportional to the square of the lateral resolution. Consequently, a trade-off exists between the lateral resolution and the DOF: a higher lateral resolution results in a shorter DOF.

In order to obtain a high lateral resolution over an extended DOF, we develop a synthetic aperture OCT to extend the DOF, which is analogous to synthetic aperture radar (SAR). Fig. 1 demonstrates the principle of aperture synthesis. The synthetic aperture element includes a glass spacer and a glass window, which is termed as SW. Due to the existence of the glass spacer, the full beam is separated into two distinct parts: the central area and ring area. SW has been added into the sample arm of a general FD-OCT, as shown in Fig. 1. There will be three distinct paths when light undergoes a double pass through the SW. In the first path, as Fig. 1(a) shows, both the illumination and detection get through the ring area. In the second path, as fig. 1(b) shows, the illumination gets through the ring area to the tissue, and the detection gets through the central area. Or the illumination gets through the central area to the tissue, and the detection gets through the ring area. In the third path, as fig. 1(c) shows, both the illumination and detection get through the central area. The wavefront of the central area is delayed with respect to that of the ring area due to additional optical path length through the glass spacer, which is denoted by $z_d = \Delta z(n-1)$, where Δz and n are the thickness and refractive index of the glass spacer respectively. Moreover, additional optical length z_c exists due to the defocus-induced wavefront curvature if the sample tissue is not placed at the focus of the objective lens. Three images captured through three paths are encoded in three distinct depths in B-scan. When the OPD in three distinct depths are corrected and the wavefront is reconstructed, three images with distinct depths will be coherently summed together. This system refocuses the sample tissue and obtain a brand new image with nearly the same lateral resolution at the focus over an extended DOF by synthesizing the aperture.

Fig. 1. Three paths of aperture synthesis to extend the DOF of OCT. SMF, single mode fiber; L1, collimation lens; L2, objective lens; SW, spacer and window.

In classical theory of FD-OCT, the detected interference signal $I(k)$ in k -space, including direct-current (DC) term, cross-correlation (CC) term, and auto-correlation (AC) term, can be denoted as the following simplified formulation.

$$I_D(k) = S(k)[DC + 2 \int_{-\infty}^{\infty} \sqrt{I_r(k)} \sqrt{I_s(k)} \cos(2kz) dz + AC] \quad (1)$$

where $S(k)$ is the spectral distribution of the light source. $I_r(k)$ and $I_s(k)$ are the electric field reflectivity from the reference arm and the sample arm at the depth of z . DC term is a pathlength-independent bias, and its amplitude is proportional to the sum of the power from reference and sample arms. AC term are mainly composed of the interference signals between different sample tissue depths, and served as artifacts in OCT images. For the sake that only the CC term encodes depth-resolved information for OCT imaging, so $S(k)$, DC term and AC term are elided for simplification. Besides, the additional OPD caused by the glass window in the SA will be counterbalanced by the other identical glass window in the reference arm, so only the delayed OPD z_d with respect to the glass spacer and z_c with respect to the wavefront curvature will be taken into consideration in the following derivation. Then for one single point in the sample tissue, the CC term with the SA inserted in the sample arm is given by

$$I_{original}(k) = 2\sqrt{I_r(k)I_s(k)} \{ [\exp(i2kz) + \exp(i2kz + ik(z_d + z_c)) + \exp(i2kz + ik2(z_d + z_c))] + C.C. \} \quad (2)$$

where $C.C.$ is the abbreviation for the complex conjugate. $C.C.$ will be omitted in the following derivation. To correct OPD and wavefront curvature, and coherently sum three images with distinct depths into one single image, we set $k = k_0 + \Delta k$, $\phi = \Delta k z_d$ and $\varphi = k_0(z_d + z_c)$ to simplify the calculation.

$$I_{original}(k) = 2\sqrt{I_r(k)I_s(k)} \exp(i2kz) [1 + \exp(i\phi)\exp(i\varphi) + \exp(i2\phi)\exp(i2\varphi)] \quad (3)$$

Compared to the first term without phase spacer, the second and third terms are attached with ϕ induced by the phase spacer and constant φ induced by wavefront curvature.

The refocusing process by synthesizing aperture is composed of two main steps to correct ϕ and φ in sequence. Firstly, we correct the depth offset of the middle and bottom images and shift them to the original depth position by multiplying the second and third terms with $\exp(-i\phi)$ and $\exp(-i2\phi)$ respectively. Set three terms in Eq. (4) as $I_t(k)$, $I_m(k)$, and $I_b(k)$ for three images from top to bottom.

$$I_{shift}(k) = I_t(k) + I_m(k)\exp(-i\phi) + I_b(k)\exp(-i2\phi) \quad (4)$$

Secondly, the constant φ induced by defocusing wavefront curvature can be eliminated by multiplying a constant phase coefficient with the Fourier spectrum of the second and third terms in of Eq. (4). Set three terms in Eq. (4) as $I_{t-shift}(k)$, $I_{m-shift}(k)$, and $I_{b-shift}(k)$, the refocused single image is given by

$$I_{refocused}(k) = I_t(k) + I_{m-shift}(k)\exp(-i\varphi) + I_{b-shift}(k)\exp(-i2\varphi) \quad (5)$$

This refocusing process achieves constructive in the center and edge part of the focus spot, and enables OCT system with a higher lateral resolution over the extended DOF.

3. SYSTEM CONFIGURATION

Figure 2. Schematic of the experimental setup. OC, fiber optic coupler; PC, polarization controller; L1-L5, lens; SA, synthetic aperture unit, composed of a circular glass spacer and a circular glass window; GS, galvo scanner; NDF, neutral density filter; RM, reference mirror; G, grating; CL, camera link cable; IMAQ, image acquisition; WS, workstation; AO, analog output.

The schematic of SD-OCT system with synthetic aperture for extended focal depth was depicted in Fig. 2. A super luminescent diode (SLD) array (Superlum Broadlighters T-850-HP) provided a broadband spectrum with a full-width-half-maximum (FWHM) bandwidth of 165 nm centered at 850 nm. The light source, whose total output power was 18.0 mW, was split into the sample arm and the reference arm by a 2×2 wavelength-flattened fiber-optic coupler (750-950 nm, Gould Fiber Optics) with a splitting ratio of 50:50. The light beam in the reference arm was collimated by a lens L3 (AC050-010-B-ML, Thorlabs Inc.) and focused by a lens L4 (AC127-030-B-ML, Thorlabs Inc.) onto the reference mirror RM (PF10-03-P01, Thorlabs Inc.). L4 and RM could move together so as to match path length in the sample and reference arms. The neutral density filter (NDL-10C-4, Thorlabs Inc.) was used to counterbalance the optical path length caused by the glass window in the synthetic aperture unit (SA). The light beam in the sample arm was collimated by a lens L1 (AC050-010-B-ML, Thorlabs Inc.), projected onto the galvo scanner, and then focused by an objective lens L2 (AC127-030-B-ML, Thorlabs Inc.). The NA of the objective lens was 0.043, resulting in FWHM transverse resolution of $12.58 \mu\text{m}$ [16, 17] and confocal parameter of $292.46 \mu\text{m}$. To extend the focal depth, a SA composed of a circular glass spacer (GT-SP-100-0010-NC, GRIN Tech.) and a circular glass window (NT49-643, Edmund Optics), was placed between L1 and L2. The circular glass spacer was stuck onto the center of the circular glass window with an adhesive (Norland Optical Adhesive 65) cured when exposed to reproducible high-intensity (27 W/cm^2) light at 365 nm of a UV gun (CS2010, Thorlabs Inc.). Three images captured through three paths shown in Fig. 1 are encoded in three distinct depths in B-scan. These enabled this system to synthesize apertures and extend the depth of focus. The light backscattered from the sample arm and reflected from the reference arm was guided into the spectrometer, after collimated by an achromatic lens L5 (AC050-010-B-ML, Thorlabs Inc.). The spectrometer consists of a 1765 lines/mm diffraction grating (PING-Sample-020, Ibsen Photonics Inc.), a camera lens (Nikon, 85mm, f/1.8D), and a single-line CCD camera (AViiVA EM4, e2V Inc.). The spectrometer efficiency including grating diffraction efficiency, camera lens efficiency and CCD quantum efficiency was measured to be 0.45. Among 4096 pixels in a single line, 3500 pixels were occupied to detect a total spectral range of 165 nm and each CCD sensor pixel corresponded to a spectrum band of $\sim 0.047 \text{ nm}$. The A-line rate and exposure time of the CCD camera were adjusted to be 10240 lines per second and $97.66 \mu\text{s}$, respectively. The detected spectrum was digitized at 12-bit resolution and transferred to the workstation via an image acquisition board (KBN-PCE-CL4-F, Bitflow) and two camera link cables. Two-directional transverse scanning was implemented by two galvanometer-mounted mirrors drove with a saw-tooth pulse, which was generated by a 16-bit analog voltage driver including a data acquisition (DAQ) board (PCI-6221, National Instrument) and a shielded connector block (BNC-2110, National Instrument). The timing to trigger spectrum acquisition is generated by the

workstation, and used to synchronize the camera for image capture and the glove scanner (GVSM002/M, Thorlabs Inc.) for two-directional transverse scanning. Finally, a discrete Fourier transform was performed on each frame of 512 A-lines obtained by the CCD to produce an axial depth profile of the sample.

4. EXPERIMENTS

Figure 3. Aperture synthesis process. (a)-(c) three cross-sectional images of a single B-scan of the polystyrene calibration beads sample at different depths; (d) cross-sectional image after the first step of aperture synthesis process; (e) cross-sectional image after the second step of aperture synthesis process.

In order to verify the performance of aperture synthesis, polystyrene calibration beads imaging experiment was conducted. Fig. 3 shows an experimental OCT image of the scattering phantom with the annular phase plate and the result of the refocusing process. The upper three images Figs. 3(a)-(c) were depth-encoded cross-sectional images corresponding to three different apertures. The corresponding lateral profiles of beads were also presented on the right side. According to Eqs. (4) and (5) in Section 2, the digital refocusing process was composed of two main steps.

Firstly, we corrected the depth offset of the middle and bottom images and shifted them to the original depth position by multiplying the second and third terms with $\exp(-i\phi)$ and $\exp(-i2\phi)$ in Eq. (4) respectively. Then we obtained a narrower lateral profile of the assigned beads as shown in Fig. 3(d). Secondly, we corrected the defocus-induced wavefront curvature. The constant ϕ induced by defocusing wavefront curvature was eliminated by multiplying a constant phase coefficient with the Fourier spectrum of the second and third terms in Eq. (5). The final results were shown as Fig. 3(e).

This refocusing process achieved constructive in the center and edge part of the focus spot, and enables OCT system with a higher lateral resolution at certain depth over the confocal parameter when imaging the polystyrene calibration beads. The lateral profiles of the same bead circled in colour in every single cross-sectional image in Fig. 3 providing detailed insight into the reconstruction process and how the focus was improved.

5. CONCLUSION

In conclusion, we developed a spectral domain optical coherence tomography (SD-OCT) with an extended depth-of-focus (DOF) by synthesizing aperture. Three distinct optical apertures were achieved by imbedding a circular phase spacer in the sample arm. Due to the optical path difference between three distinct apertures caused by the phase spacer, three images were aligned with equal spacing along z-axis vertically. By correcting the OPD and defocus-induced wavefront curvature, three images with distinct depths were coherently summed together. The feasibility and efficacy of this SD-OCT system was verified by imaging the polystyrene calibration beads and achieving a higher lateral resolution at certain depth over the confocal parameter.

We sincerely appreciate funding support from National Research Foundation Singapore (NRF-CRP13-2014-05), Ministry of Education Singapore (MOE2013-T2-2-107), National Medical Research Council Singapore (NMRC/CBRG/0036/2013) and NTU-AIT-MUV program in advanced biomedical imaging (NAM/15005).

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