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Adaptive optimization of reference intensity for optical coherence imaging using galvanometric mirror tilting method

Ji-hyun Kim, Jae-Ho Han, Jichai Jeong*

Department of Brain and Cognitive Engineering, Korea University, 145 Anam-Ro, Seongbuk-ku, Seoul 136-701, Republic of Korea

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ABSTRACT

Integration time and reference intensity are important factors for achieving high signal-to-noise ratio (SNR) and sensitivity in optical coherence tomography (OCT). In this context, we present an adaptive optimization method of reference intensity for OCT setup. The reference intensity is automatically controlled by tilting a beam position using a Galvanometric scanning mirror system. Before sample scanning, the OCT system acquires two dimensional intensity map with normalized intensity and variables in color spaces using false-color mapping. Then, the system increases or decreases reference intensity following the map data for optimization with a given algorithm. In our experiments, the proposed method successfully corrected the reference intensity with maintaining spectral shape, enabled to change integration time without manual calibration of the reference intensity, and prevented image degradation due to over-saturation and insufficient reference intensity. Also, SNR and sensitivity could be improved by increasing integration time with automatic adjustment of the reference intensity. We believe that our findings can significantly aid in the optimization of SNR and sensitivity for optical coherence tomography systems.

1. Introduction

Optical coherence tomography (OCT) provides high-resolution cross sectional image by measuring interference between back-reflected light from sample layers and a reference mirror [1–3]. Spectral domain OCT (SD-OCT) uses a spectrum of an interferogram for obtaining depth information without a mechanical depth scanning apparatus used in time domain OCT (TD-OCT) [4]. In addition, SD-OCT has advantages over sensitivity, signal to noise ratio (SNR), and scanning speed than TD-OCT [5–7]. SNR and sensitivity of SD-OCT are the important criteria for evaluating image quality and system performance [8]. SNR is basically defined as a ratio between mean-square fringe amplitude from a mirror and variance of photon with detector noise. Sensitivity can be explained as the minimum input signal required for producing an output in a specified SNR. The SNR and sensitivity depends on various factors such as detector responsivity, the power returning from a sample, reference intensity, detection bandwidth, integration time (exposure time), and the number of pixels in a detector. Even though most of the factors are fixed by the hardware specification, the integration time and the reference intensity were easily controllable by users [9]. Theoretically, we can improve SNR and sensitivity by increasing integration time. However, it does not have great effects on them by increasing reference intensity in shot noise limited detection. High level of reference intensity in TD-OCT and SS-OCT possibly reduces SNR and sensitivity due to excess noise (relative intensity noise), however the excess noise is negligible as compared to receiver and shot noise for SD-OCT [6]. In addition, high level of reference intensity helps to reduce coherence noise from self-interference. Thus, it is better to maintain high level of reference intensity with relatively long integration time for improving image quality of SD-OCT.

Placing lens in a reference arm can maximize light intensity back reflected from a reference mirror, and minimize dispersion of a point spread function due to refractive index mismatch by applying the same lens in a sample arm. In some cases, focusing reference light causes over-saturation of a detector. Thus, fixed or variable neutral density (ND) optical filters are commonly used in a reference arm for reducing the intensity [10–12]. However, fixed ND filters are troublesome for choosing appropriate reduction rate, and variable ND filters are less stable and bulky than the fixed ND filters. Also, it is hard to change exposure time of a detector in the ND filter based OCT systems, because manual exchange of a filter with optimization requires preparatory time.

In this paper, we proposed an optimization method for reference intensity using a galvanometric mirror scanning system in a reference arm. By tilting beam direction to a reference mirror, we precisely controlled reference intensity without ND filters. The

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* Corresponding author.
E-mail address: jcj@korea.ac.kr (J. Jeong).

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tracking algorithm in our system searched proper reference intensity automatically to get desired intensity while maintaining spectral shape. As a result, the proposed method enabled to change exposure time without manual calibration of the reference intensity, and prevented image degradation due to over-saturation and insufficient reference intensity.

2. Instrumentation and measurement

2.1. Experimental system configuration

Fig. 1 shows the schematic diagram of the SD-OCT system. A broadband optical fiber coupler was introduced to construct Michelson interferometer. A light source had four superluminescence diodes (SLDs) for achieving a broadband full width half maximum bandwidth of 236 nm centered at 1367 nm. The spectrometer covered a spectral bandwidth of 220 nm within 1024 camera pixels. A high speed line scan camera attached in the spectrometer had the 92 kHz maximum scanning rate with a minimum integration time of 6.96 μs. A dual-axis scanning galvanometer system was placed in the sample arm for 2-D scanning of a sample. The scanning mirror system had a maximum scan angle of ± 12.5° with a full scale bandwidth of DC-to-250 Hz for sinusoidal wave. The same scanning mirror system was positioned in the reference arm, and a data acquisition board (DAQ) in a workstation controlled scanning motion. Therefore, we used four analog voltage output channels to control the galvanometer pairs separately. Sawtooth wave performed rasterized scanning of a sample with the 90% duty cycle and l0% mirror returning period. The same scan lenses designed for 1310 nm wavelength were used in the sample and the reference arms to minimize broadening of point spread function due to refractive index mismatch.

To convert interference signal from the wavelength space to the wavenumber domain, we applied the cubic spline interpolation before inverse fast Fourier transform (IFFT), and it prevented depth dependent broadening of point spread function. In addition, fixed pattern was reduced by the periodic reference spectrum subtraction method [13] that periodically measured and subtracted reference spectrum for each B-scan. We programmed hardware control routine such as beam scanning, triggering, data storing, and camera control with LabVIEW. Core OCT signal processing including IFFT, cubic spline interpolation, and fixed pattern noise reduction was executed on graphic processing unit by loading functions from dynamic link library written in C^{++} with compute unified device architecture (CUDA) [14–17]. CUDA enabled real-time image reconstruction with handling the full speed measurement of our SD-OCT system [18].

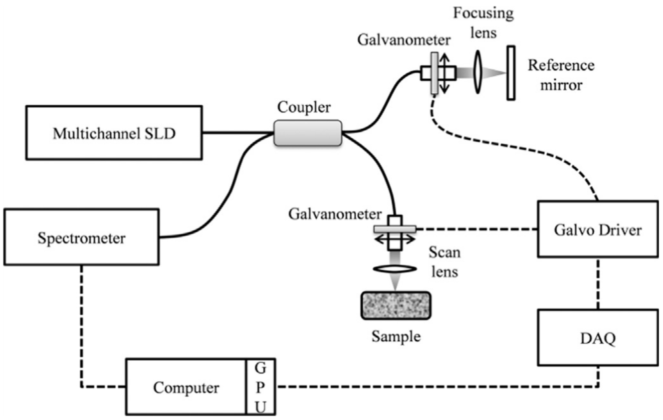

Fig. 1. Proposed fiber based SD-OCT setup for adaptively optimizing reference intensity. A dual-axis scanning galvanometer system was placed in the sample and the reference arms, respectively. Solid lines indicate optical fibers while dashed lines are electrical wires.

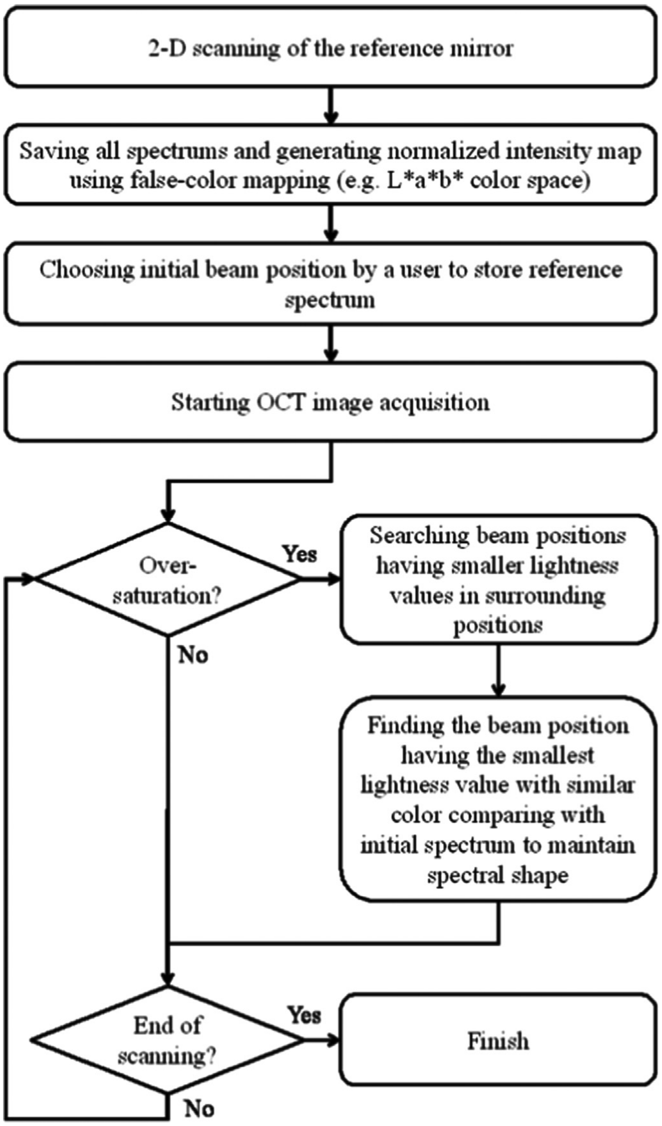

Fig. 2. Basic schematic diagram for reference intensity optimization.

2.2. Adaptive reference intensity optimization

Fig. 2 shows the basic schematic diagram of the algorithm for reference intensity optimization. At first, when the OCT system is started, the scanning mirror in the reference arm scans the reference mirror for generating 2-D intensity map. Acquired spectra are normalized in intensity values or mapped into color spaces for tracking intensity. Fig. 3 indicates the 2-D intensity map from the reference mirror that contains normalized intensity of the back reflected light. Axes of the intensity map indicate spatial beam position to the reference mirror, and bright region represents high reference intensity. In the reference intensity map, there existed non-reflecting points (black dots in Fig. 3) due to defection of the mirror surface; the non-reflecting positions should be rejected for accurate intensity control. After obtaining intensity map, the OCT system stores an initial beam position to use the spectrum on the point as reference data for intensity tracking. The initial intensity should not be over-saturated because the saturation significantly distorts original spectrum for intensity tracking.