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ORIGINAL PAPER

Compensation of motion artifacts in intracoronary optical frequency domain imaging and optical coherence tomography

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Abstract Intracoronary optical coherence tomography and optical frequency domain imaging (OFDI) have been utilized for two-dimensional and three-dimensional imaging of vascular microanatomy. Image quality and the spatial accuracy of multidimensional reconstructions, however, can be degraded due to artifacts resulting from relative motion between the intracoronary catheter and the vessel wall. To track the relative motion of a catheter with regard to the vessel, a motion tracking system was incorporated with a standard OFDI system by using wavelength division multiplexing techniques. Motion of the vessel was acquired by a frequency shift of the backscattered light caused by the Doppler effect. A single monochromatic beam was utilized for tracking the relative longitudinal displacements of a catheter-based fiber probe with regard to the vessel. Although two tracking beams are, in general, required to correct for longitudinal motion artifacts, the accurate reconstruction in a longitudinal view was achieved by the Doppler frequency information of a single beam. Our results demonstrate that the single beam based motion tracking scheme is a cost-effective, practical approach to compensating for longitudinal distortions due to cardiac dynamics, thus leading to accurate quantitative analysis of 3D intracoronary OFDI.

Keywords Motion artifacts · Image compensation · OCT · OFDI

Abbreviations

OCT	Optical coherence tomography
OFDI	Optical frequency domain imaging

Introduction

Optical coherence tomography (OCT) [1] is a high-resolution cross-sectional imaging modality that was first applied for human intracoronary imaging in 2001 [2]. Although OCT has been used extensively, its slow image acquisition speed renders it sensitive to image artifacts that can arise from motions of the catheter within the coronary artery during the cardiac cycle. The recent advent of optical frequency domain imaging (OFDI) [3, 4] has increased image acquisition speeds to greater than 100 frames per second, thereby diminishing motion artifacts within individual images. However, the significance of OFDI is that it enables volumetric imaging of entire coronary arteries. For this application, the reconstruction of three-dimensional vessel structure can be confounded by relative motion between the catheter and vessel wall. In intracoronary

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OFDI [5], a chirped imaging beam penetrates the vessel wall to a depth of about 2 mm, and scatters off structures at different depths from the lumen. The backscattered light interferes with a reference beam to produce a spectral fringe pattern, which mimics the axial profile of the vessel wall. The OFDI catheter consists of a single-mode optical fiber and an imaging core within a transparent outer sheath through which a flexible guide wire is threaded. The axial resolution, which is about 7 µm in tissue, depends on the wavelength sweep range of the imaging beam, while the transverse resolution is determined by the diffraction limited spot size. As most probes incorporate small lenses for focusing the imaging beam, the transverse resolution is on the order of tens of microns.

To create two-or three-dimensional images of vessels, a rotary junction motor spins the fiber probe in its outer transparent sheath, while a linear motor pulls it back within the sheath, causing the imaging beam to trace a helix along the inside of the vessel wall [6]. Typically, rotational speeds are approximately 100 revolutions per second and pullback speeds are in the 10–30 mm/s range [7, 8]. Although precise motor velocity control is possible for both rotation and pullback, the sheath itself can move significantly within the coronary artery during the cardiac cycle. In this case, the imaging data points are perturbed from a purely helical track that has equal data intervals as shown in Fig. 1. As a result, the two-and three-dimensional image representations of the data exhibit characteristic artifacts and spatial distortions. Although radial distortions arising from displacements of the sheath perpendicular to its axis can be minimized through lumen surface-aligning algorithms [5, 6], accurate compensation for longitudinal displacements based on image characteristics is more challenging (Fig. 2). As a solution to this problem, we have previously demonstrated that Doppler-based optical measurements provided by nearly perpendicular tracking beams can be used to monitor relative motion between an imaging probe and a sample [9]. Although this initial approach was not compatible with an intracoronary catheter, it demonstrated sufficient spatial accuracy to eliminate spatial distortions in image reconstruction. Three-dimensional reconstruction of vessels allows for a better understanding of vessel and plaque pathology. The quantitative analysis of unstable plaque elements such as the fibrous cap, lipid pool, and calcification could be improved. In addition, evaluating three-dimensional neointimal coverage at follow-up after stent implantation is of particular importance. The present quantitative analysis is performed by calculating number of uncovered and malapposed stent struts as well as neointimal obstruction. Thus, the reconstruction of longitudinal visualization of vessels could provide a more accurate quantitative analysis. In the present work, we demonstrate an innovative approach that is based on a single tracking beam, which can easily be delivered through a conventional OFDI optical catheter and that can be used to correct for longitudinal motion artifacts. To evaluate the feasibility of the tracking scheme, imaging of a cadaver coronary artery with a stent was performed ex vivo.

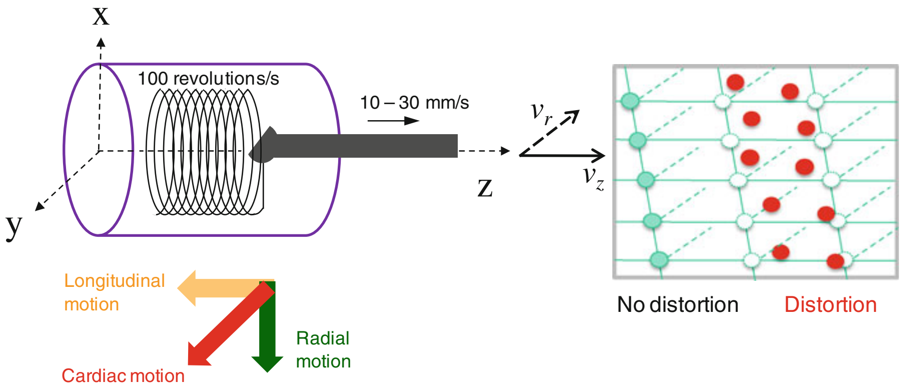

Fig. 1 Intracoronary OFDI method and image data displacement due to vessel motion

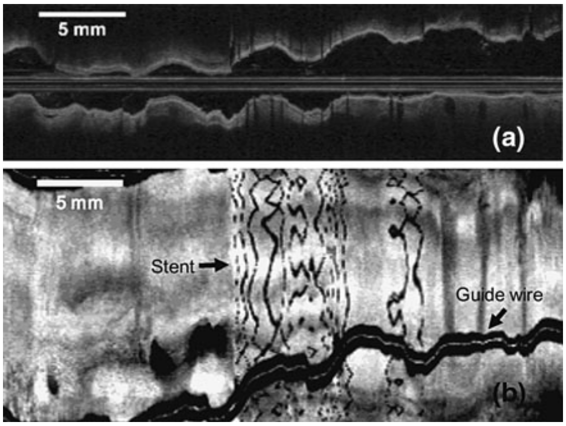

Fig. 2 **a** Longitudinal cutaway image and **b** unwrapped surface image of a 3D intracoronary OFDI dataset obtained from a swine coronary artery with an 8 mm stent in vivo. Stent structure is significantly distorted by motion artifacts caused by cardiac motion

Methods

Single beam based Doppler tracking

Figure 3 schematically illustrates the configuration of the distal end of the OFDI catheter probe. The single tracking beam is reflected from the facet of a polished ball lens along with the OFDI image beam, and illuminates the vessel wall at a tilted incidence angle. The instantaneous probe motion relative to the vessel wall can then be measured by the magnitude of the Doppler shift (f_D), which depends on the relative radial ($\vec{v_r}$) and longitudinal ($\vec{v_z}$) velocities, the incidence angle, θ, and the single tracking beam wavelength, λ:

$$f_{\mathrm{D}} = f_r + f_z = \frac{2}{\lambda}\left(-\vec{v_r}\cos\theta + \vec{v_z}\sin\theta\right) \tag{1}$$

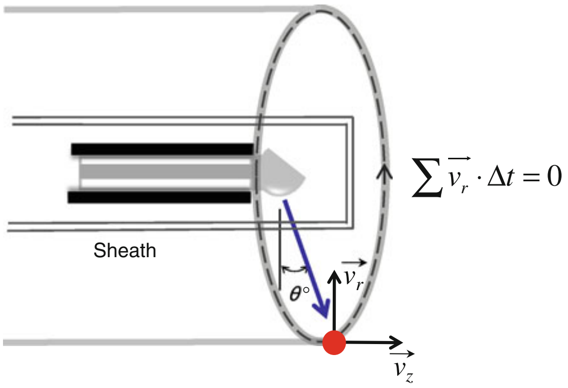

Fig. 3 Doppler tracking using a single tracking beam

The conventional approach to solving for the two unknown velocities requires the use of a second tracking beam at a different incidence angle, resulting in two equations and two unknown variables. This approach however requires significant modifications to the optical components of the catheter. Alternatively, the radial velocities may be acquired by comparing center displacements of the artery lumen based on image characteristics, and the longitudinal displacement, D_z, can then calculated through Eq. 2 by summing radial velocities and Doppler frequency shifts of the tracking beam over the time interval.

$$\begin{aligned} D_z &= \sum \vec{v_z} \cdot \Delta t \\ &= \frac{\cos\theta}{\sin\theta}\sum \vec{v_r} \cdot \Delta t + \frac{\lambda}{2\sin\theta}\sum f_{\mathrm{D}} \cdot \Delta t \end{aligned} \tag{2}$$

Conventional ways for obtaining the longitudinal motion displacements need information of the radial motions. However, the proposed method only requires the Doppler shifts of a single tracking beam since the summation of radial velocities over the single frame acquisition time is zero. Here, it should be noted that the direction and amplitude of relative radial motions of a fiber probe with regard to the vessel wall are constant during the single frame acquisition. Therefore, the longitudinal displacement, which is the frame-to-frame displacement, can be measured in terms of the Doppler frequency shifts and the known incidence angle.

Heterodyne Doppler beating

Doppler frequency shifts were measured using a heterodyne interferometer where backscattered light from the vessel wall was mixed with light from a local oscillator (LO) or heterodyne reference. The resulting beam was then directed to a detector. The detected signal associated with interference was approximately given by:

$$I(t) \approx I_{\mathrm{LO}} + \sqrt{I_{\mathrm{LO}} I_{\mathrm{S}}}\cos[2\pi(f_{\mathrm{LO}} - f_{\mathrm{D}})t] \tag{3}$$

where I_{LO} is the heterodyne reference intensity, f_{LO} is the local oscillator frequency, and I_{S} is the intensity of the returned tracking beam. The Doppler frequency shift, f_{D}, changes as the vessel moves. The frequency information of the LO is utilized to discern the direction of vessel motion and to determine the corresponding relative velocity. The beat frequency of the Doppler interference signal was recorded during the entire image data acquisition. Analyzing the time series Doppler data using a short time–frequency transform yielded the instantaneous Doppler frequency shift, which, in turn, was proportional to the velocity. Converting the frequency to velocity and multiplying the result by the time interval gave an estimate of the actual displacement between data samples. Finally, the image compensation procedure was performed with the Doppler frequency information and intensity based image reconstruction [9].

Results

Experimental configuration

Figure 4 shows the experimental setup for demonstrating the Doppler motion tracking using a single beam. The tracking system was combined with a standard OFDI system by a wavelength division multiplexing (WDM) filter. The wavelength-swept laser using a semiconductor optical amplifier and a polygon scanning filter was operated at a repetition rate of 51.4 kHz with a wavelength sweeping range of 120 nm. The OFDI system provided an axial resolution of ~7 μm and a transverse resolution of ~30 μm with a ranging depth of 6.3 mm. An inexpensive coarse wavelength division multiplexing (CWDM) distributed feedback (DFB) laser operating at a wavelength of 1,550 nm was used to generate the longitudinal tracking beam. Roughly 1% of the WDM coupled light was directed to acousto-optic modulators (AOMs), while the remaining light was directed to the sample arm. In order to determine the direction of motion, a heterodyne reference signal at a frequency of 1.2 MHz was generated by using two cascaded AOMs at driving frequencies of 25 MHz and 23.8 MHz (Brimrose, Inc.) respectively.

Generation of vessel motion

In order to demonstrate the effects of motion artifacts in a longitudinal view, a ~2.5 mm diameter cadaver coronary artery with a stent was used. The artery on the stage was moved back and forth by a galvanometer driven by 2 Hz sine waves, which achieved velocities up to 60 mm/s. Images of the vessels were acquired while the catheter was rotated at 100 revolutions per second and translated longitudinally with a pullback velocity of 5 mm/s. At the distal end of the probe, a single tracking beam of 8 dBm at a wavelength of 1,550 nm along with the OFDI imaging beam operating at a center wavelength of 1,310 nm illuminated

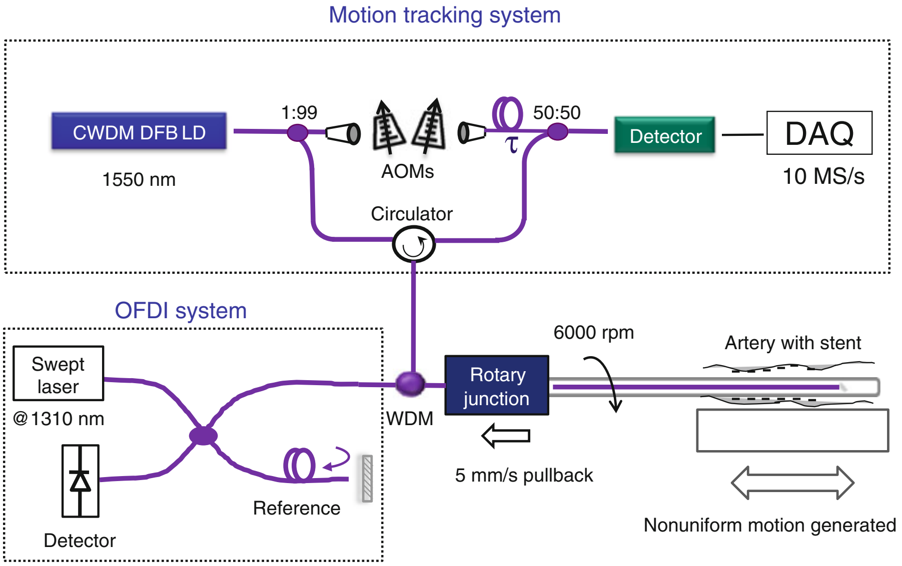

Fig. 4 Proof-of-principle experimental demonstration of a combined tracking system with an OFDI system for ex vivo imaging of a cadaver coronary artery with a stent. *LD* laser diode, *WDM* wavelength division multiplexer

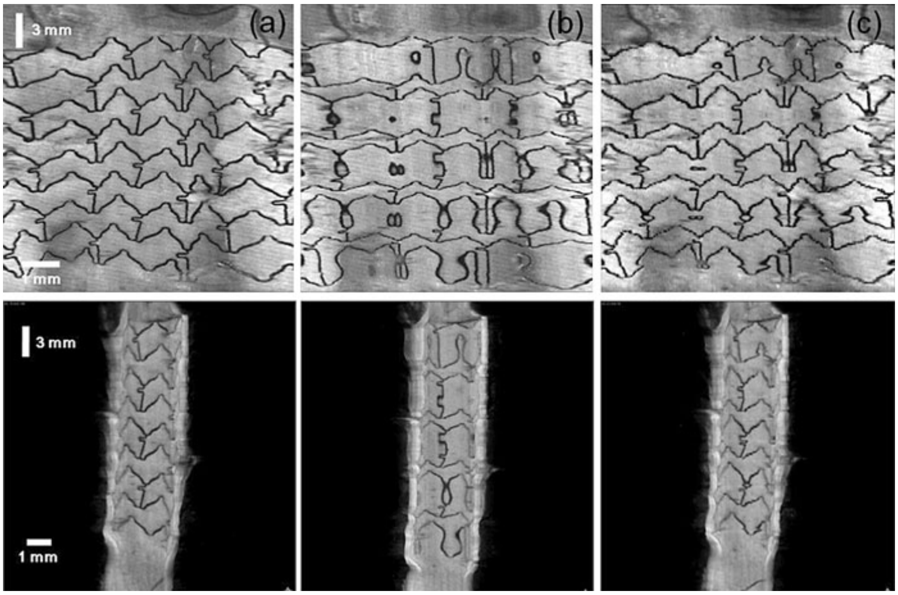

Fig. 5 Longitudinal surface views and volumetric longitudinal cutaway images of the cadaver coronary artery with a stent **a** without motion artifacts and **b** before and **c** after distortion compensation

at an incidence angle of 33° to achieve a large measurement sensitivity of the longitudinal motion.

Compensation of image distortion

The OFDI system used in this experiment provided 100 frames per second with a total of 512 radial scans per frame. Thus, the OFDI image data consisted of $1{,}024 \times 512 \times N$ ($N =$ number of frames) pixel data sets, which were processed using Image J to display the surface of the unwrapped artery. The surface image was created with the projection of vertically averaged pixel intensity. The corresponding volumetric artery images were generated with a 3D volume rendering program (OsiriX 2.75, The OsiriX Foundation, Geneva, Switzerland). Imaging was first performed with uniform scanning to simulate the case devoid of motion artifacts (Fig. 5a). Subsequently, uncontrolled artery motion was simulated by using the galvanometer. This resulted in the structure of the stent within the artery lumen to appear distorted and indistinguishable as shown in Fig. 5b. To compensate the distortion in the image, the Doppler tracking signals and OFDI image data were simultaneously acquired at DAQ acquisition rates of 10 and 85 MS/s, respectively, and the re-registration of scans was performed with the Doppler frequency information. Although the galvanometer moved the coronary artery back and forth to generate longitudinal motion, the small rotational motion was also generated, which caused the additional struts in the image of the stent structure in Fig. 5c. However, our results demonstrated that this simple compensation technique significantly improved the longitudinal view of the artery.

Conclusions

We have developed a single beam motion-tracking scheme to reconstruct a longitudinal map of a coronary artery. In contrast to conventional methods that require two beams to identify one of two motions in Doppler tracking, tracking relative longitudinal velocities of a catheter using a single beam can be accomplished for compensating distortions in catheter-based imaging. Therefore, we believe that this technical approach to solving spatial motion displacements due to cardiac dynamics opens opportunities for advances in the accurate volumetric longitudinal visualization of coronary arteries.

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Conflict of interest The authors of this manuscript are inventors on patents owned by MGH and licensed to Terumo Corporation and therefore may share in licensing income.

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