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Erstveröffentlichung in / First published in:

European Conferences on Biomedical Optics. Munich, 2017. Bellingham: SPIE, Vol. 10416
{Zugriff am: 23.05.2019}.

DOI: <https://doi.org/10.1117/12.2286078>

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Julia Walther, Edmund Koch, "Lateral resonant Doppler flow measurement by spectral domain optical coherence tomography," Proc. SPIE 10416, Optical Coherence Imaging Techniques and Imaging in Scattering Media II, 1041602 (1 August 2017); doi: 10.1117/12.2286078

SPIE.

Event: European Conferences on Biomedical Optics, 2017, Munich, Germany

Lateral resonant Doppler flow measurement by spectral domain optical coherence tomography

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Abstract: In spectral domain optical coherence tomography (SD-OCT), any transverse motion component of a detected obliquely moving sample results in a nonlinear relationship between the Doppler phase shift and the axial sample velocity restricting phase-resolved Doppler OCT. To circumvent the limitation, we propose the lateral resonant Doppler flow quantification in spectral domain OCT, where the scanner movement velocity is matched to the transverse velocity component of the sample motion.

1. Introduction

Considering phase-resolved Doppler OCT [1] for the case of an oblique sample movement in spectral domain OCT (SD-OCT), the discrepancy to the assumed linear relationship between the Doppler phase shift and the axial velocity may be dramatic in the case of a highly transverse velocity component [2-4]. To overcome these limitations, the present approach proposes the matching of the 2D-scanner in the sample arm to the transverse velocity component of the sample motion. Consequently, the backscattering signals corresponding to the tracked oblique sample movement will be highly correlated whereas those of static sample structures and slowly moving scatterers will be less correlated and damped depending on the scanner velocity. By lateral resonant scanning, the impact of the transverse motion component on the Doppler phase shift can be reduced theoretically to an axial motion only. A simple geometric model is defined on the basis of Fig. 1, where a Gaussian sample beam and an oblique sample motion are considered in a simplified manner. There, an obliquely moving sample with arbitrary Doppler angle θ is assumed, where a group of scattering particles is supposed to be seen at the end of the detection intervals, $[T_1, T_1+T_{\text{Int}}]$ and $[T_2, T_2+T_{\text{Int}}]$, of two consecutive A-scans. The respective position of the particles detected at time T_1+T_{Int} and T_2+T_{Int} is shown by two blue distances and labeled with I and II in Fig. 2. As seen in (a), the limited width of the Gaussian sample beam alters the detected axial displacement Δz of the scattering particles between subsequent detection periods, for which reason a reduced axial displacement Δz_d and with this a reduced $\Delta\phi$ is measured especially for small Doppler angles and large transverse displacements [2,3]. Case (b) shows the lateral resonant scanning towards the sample movement, where the sample beam in gray represents the position at T_1+T_{Int} and the one drawn in green shows the position at T_2+T_{Int} . Since the scanner velocity is matched to the transverse velocity of the moving sample, the group of particles detected at time point T_1+T_{Int} are tracked over the entire A-scan time $T_{\text{A-scan}}$ until T_2+T_{Int} . For a temporally invariable sample, the movement detected by the OCT-system is purely axial, why the $\Delta\phi$ - v_z -relation will be linear.

Fig. 1. Schematic of the obliquely moving scattering sample relative to (a) a static Gaussian sample beam and (b) a lateral resonant scanning beam.

2. Scanning protocol of the LR-DOCT

The two galvanometer scanners integrated in the customized 3D-scanner are controlled by software based on LabVIEW®, with which arbitrary 2D-scanning patterns along the sample surface are realizable. The modified scan protocol for LR-DOCT is shown in Fig. 2a. The first of two B-scans at identical X- and Y-scanner position is an M-scan. For the lateral resonant scan, LR-scan, the Y-scanner is driven along the moving direction of the sample with stationary X-scanner. The resulting M- and lateral resonant B-mode image consisting each of 512 A-scans detected close to the capillary center with $f_{A\text{-scan}} = 12$ kHz and a detector dead time $\Delta T/T_{A\text{-scan}}$ of 0.05 are presented in Fig. 2b. For the LR-scan, the Y-scanner was driven lateral resonantly to the flowing oil particles of the 1% Intralipid emulsion at the capillary center.

Fig. 2. (a) Lateral resonant Doppler scanning protocol of the X- and Y-galvanometer scanners. (b) Resulting M-scan and LR-scan due to the modified scanning protocol for LR-DOCT.

3. Experimental results of LR-DOCT

In order to validate LR-DOCT for moving volume scatterers, Doppler flow experiments are performed by means of a 1% Intralipid emulsion flowing through a glass capillary. The Doppler angle is measured to be 1.7° and the maximum flow velocity at the capillary center is estimated to be 69 mm/s. Fig. 3 presents the processed flow-relevant parts of the grayscale structural (a), the Doppler flow (b) and the phase noise images of the detected M-scan and the lateral resonant scan (LR-scan). There, the number of analyzed A-scans is chosen to be 512. As expected, highly correlated speckle appears at the capillary border for the M-Scan due to the small flow velocity at this area. For the LR-scan, the correlation at the border area gets lost, whereas a high correlation occurs at the capillary center identified by the elongate speckle pattern.

Fig. 3. (a) Grayscale structural SD-OCT images of the M-scan and the LR-scan of the 1% Intralipid flow through a $312\ \mu\text{m}$ glass capillary. (b) Corresponding phase-resolved Doppler flow images for the measured Doppler angle θ of 1.7° . (c) Standard deviation $\sigma_{\Delta\phi}$ of the mean Doppler phase shift of 512 single A-scans overlaid to the structural images.

Fig. 4. (a) Calculated and fitted mean flow profiles and corresponding Doppler phase noise of the flowing 1% Intralipid emulsion as a function of the radial position r inside the 312 μm capillary for the M-scan and the FLR-scan.

For quantitative analysis, the averaged phase shift of 512 single measurement points is presented in Fig. 4a. For the classic Doppler measurement, the determined $\Delta\phi$ of the M-scan shown by the blue points does not display a quadratic profile verified by the fitted power law with an exponent of 2.4. The result of the LR-scan presented by the red points conforms to a quadratic parabolic profile with the expected maximum velocity of 69 mm/s at the capillary center. In spite of the increased phase noise at the upper and lower capillary border, the Doppler phase shift of the tracked Intralipid particles is not limited and consequently truly measured by the linear relation between $\Delta\phi$ and v_z . The standard deviation $\sigma_{\Delta\phi}$ against the radial position r inside the capillary in Fig. 4b shows that the velocity of the Y-galvanometer scanner is matched very well to the oil particles for the LR-scan, since the behavior of the phase noise $\sigma_{\Delta\phi}$ of the M-scan (blue points) and the LR-scan (red points) is inverted.

In analogy to the Intralipid flow experiment, flow measurements are performed with the identical capillary model in combination with diluted fresh human blood. There, the fresh human blood of a young healthy volunteer was stabilized extracorporeally with anticoagulant citrate dextrose solution (ACD-A) and diluted with a solution of 6% dextrose and 0.9% sodium chloride in distilled water with a ratio of 1:2 resulting in a hematocrit of $\sim 15\%$. The measured Doppler angle θ amounts to 1.7° again. Since the flow rate is set to 8 ml/h, the measurement parameters concerning the tracked transverse velocities are similar to the Intralipid flow phantom. Obviously, the speckle pattern is different to the experiments with Intralipid flow, first due to the larger size of the highly scattering wheel-shaped erythrocytes in comparison to the small spherical oil particles of the Intralipid relative to the size of the sample beam at the focal plane, and second due to the inhomogeneous distribution of the erythrocytes of the diluted blood sample. Though, the velocity of the galvanometer scanner can be matched to the transverse flow velocity of the erythrocytes at the capillary center.

Fig. 5. Grayscale structural images (a), phase-resolved Doppler images (b) and phase noise images of the M-scan and the LR-scan of the diluted human blood within the 312 μm glass capillary.

4. Conclusion and Outlook

A new method for resonant Doppler measurement in spectral domain OCT (SD-OCT) is proposed for very small Doppler angles and high absolute sample velocities. Lateral resonant Doppler optical coherence tomography (LR-DOCT) is validated by means of two flow phantoms with a 1% Intralipid emulsion and diluted human blood, respectively. LR-DOCT is working excellent for volume scatterers consisting of many small particles (e.g. 1% Intralipid flow) relative to the wavelength λ_0 and the sample beam width w_0 at the focal plane, whereas the method

is limited for particles exceeding one or both (e.g. highly scattering erythrocytes of blood flow). On that condition, LR-DOCT overcomes the nonlinear relation between Doppler phase shift $\Delta\phi$ and axial sample or rather flow velocity and with this the limitation of PR-DOCT in SD-OCT for oblique sample motion with strong transverse velocity component. Consequently, LR-DOCT enables advantageously the simple correct and unlimited phase-resolved Doppler measurement of sample and flow velocities in SD-OCT.

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