

Slow Axis Displacement Correction for Stripe Artefact Removal in Optical Coherence Angiography

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Abstract

The method for displacement correction along the slow axis of Optical Coherence Tomography (OCT) data volumes is presented. The method is based on the recursive replacement of the next displaced OCT measurements by the weighted summation of itself and the previous OCT measurement in the slow axis dimension already corrected for the displacement. The values of the appropriate weight multipliers were defined from the local correlation of the two measurements. The proposed method was used as a preprocessing step for Optical Coherence Angiography processing of the OCT data. Substantial reduction of the motion-induced stripe artifact was demonstrated.

Keywords: optical coherence tomography, optical coherence angiography, motion correction, signal processing

1. Introduction

In the past decades, several techniques were proposed which allow vessel visualization from Optical Coherence Tomography (OCT) data sets^{1,2}. Such techniques are known by the common name Optical Coherence Angiography (OCA). The majority of these techniques are based on the detection of the object motion between several consecutive OCT measurements (A-scans). For example, Doppler OCT³ evaluates phase difference between two adjacent A-scans; phase variance OCT⁴ methods evaluate the variance of the phase between several adjacent A-scans; speckle variance OCT^{5,6} evaluates variance of the signal amplitude. Mapping of the local correlation between two neighboring cross-sectional OCT images (B-scans)⁷ allows vessel visualization as the regions of the decreased correlation. Different frequency-discriminating methods are sometimes referenced as OMAG^{8,9}. The related high-frequency filtration methods

operate in both frequency¹⁰ and signal^{11,12} domains and allow real-time visualization of vessel cross-section images.

Since in aforementioned techniques discrimination of the vessels from the surrounding tissue is synonymous with the detection of the areas which experienced some motion during the OCT data acquisition, bulk tissue motions compensation is an essential preprocessing step for all of these methods. The modern bulk motion compensation techniques are able to compensate axial motions both uniform along with the full OCT imaging depth¹³⁻¹⁶ and nonuniform due to objects' nonuniform deformation¹¹. Lateral displacements along the fast scanning axis can also be compensated¹⁴. All of the motion compensation techniques use current B-scan as a reference and adjust the next B-scan in accordance with this reference. The application of these techniques allows vessel visualization from the OCT data even in case of relatively poor fixation of the object and use of the OCT device with a hand-held probe¹¹.

However, even after motion correction compensation, some characteristic stripe artifacts remain in the OCA images (see Figure 1a). These artifacts can be caused by the sample motion along the slow axis. Such motions are not addressed by the modern motion compensation approaches since it is not clear how to use the ‘adjusting to the reference B-scan’ approach used for the motion compensation in two other dimensions. In the present paper, an approach partially compensating non-uniform object displacements along the slow axis is presented and its performance is demonstrated on the experimental data.

2. Materials and methods

OCT setup

In this work spectral-domain OCT (SD OCT) setup at 1.3-micrometer central wavelength with axial resolution equals to 10 micrometer and lateral resolution equals to 15 micrometers in the air was used. The SD OCT system was equipped with a home-made spectrometer with a Linear Indium Gallium Arsenide Photodiode Array SU512-LD (512 Pixel) from SENSORS UNLIMITED. The A-scan rate was 20 kHz. Home-made a Data Acquisition board with USB2.0 interface was designed to send instructions, receive, and transmission data. In regards to data acquisition, home-written C++ software to control the line scan CCD camera to snap each line image in synchronization with the scanning system was utilized.

Angiography processing

The high-frequency filtration of the complex OCT data in the signal domain along the slow axis was used to extract vessel images:

$$V_{k,j,n} = \sum_{m=0}^{m=2 \cdot N} b_m B_{k,j-N+m,n} \quad (1).$$

Here k is a fast axis index, $j, j-N+m$ – slow axis index and n is an axial index, $B_{k,j,n}$ is the j th complex B-scan, absolute values of $V_{k,j,n}$ form the j th cross-section of the vasculature image (angiography B-scan), b_m are coefficients of the high-pass filter impulse response.

Using such filtration one angiography B-scan can be obtained from every $2N+1$ OCT B-scans and every following angiography B-scan can be re-evaluated during the following structural B-scan acquisition. In this study N equals 3 was used, thus OCT angiography can be calculated and visualized in real-time from every 7 consecutive B-scans.

In order to visualize 3D vessels distribution in-plane, conventionally used Maximum Intensity Projection (MIP) was utilized:

$$MIP_{k,j} = \max_n |V_{k,j,n}| \quad (2)$$

Motion correction preprocessing

The displacement compensation method from¹¹ was used to compensate displacements between two neighboring B-scans. The compensation was achieved by multiplying the next B-scan by the correction phase distribution which can be found as:

$$\varphi_{k_0,n_0} = \arg \left(\sum_{n,k} B_{k,j,n} \cdot B_{k,j+1,n}^* \cdot \text{rect}_M(n-n_0, k-k_0) \right) \quad (3),$$

where $\arg()$ is the argument of the complex number, $\text{rect}_M(n-n_0, k-k_0)$ – is the rectangular window of size M , centered at the location (k_0, n_0) . The effect of such correction can be seen in Figures 1a,b. One should note that such correction does not compensate for lateral motions along the slow scanning axis.

Slow axis displacement correction

The OCA signal increases as the local correlation between two neighboring B-scans decreases. In the case of uncompensated bulk tissue motion, this leads to the high OCA signal in the whole cross-sectional OCA image which in turn leads to the stripe artifact in the MIP vessel image. The correction algorithm should make the next OCT B-scan more correlated with the previous B-scan in case if such correlation before preprocessing is low and do nothing to the next B-scan if such correlation is high since in this case vessels are visible in MIP images without an artifact. Thus, the proposed slow axis displacement correction works as follows:

$$\begin{aligned} B_{k,j+1,n}^{\text{corrected}} &= \alpha(C_{j,j+1}) \cdot B_{k,j,n}^{\text{corrected}} + (1 - \alpha(C_{j,j+1})) \cdot B_{k,j+1,n} \\ \alpha(C_{j,j+1}) &= A \cdot \exp \left[(C_{j,j+1} - 1)^2 \right] \\ C_{j,j+1} &= \frac{2 \cdot \sum_{n,k} B_{k,j,n}^{\text{corrected}} \cdot B_{k,j+1,n}^* \cdot \text{rect}_M(n-n_0, k-k_0)}{C_{j,j} + C_{j+1,j+1}} \\ C_{j,j} &= \sum_{n,k} B_{k,j,n}^{\text{corrected}} \cdot B_{k,j,n}^* \cdot \text{rect}_M(n-n_0, k-k_0) \\ C_{j+1,j+1} &= \sum_{n,k} B_{k,j+1,n} \cdot B_{k,j+1,n}^* \cdot \text{rect}_M(n-n_0, k-k_0) \end{aligned} \quad (4),$$

where A is the maximum weight of the previous corrected B-scan in case of the absence of the correlation between the two consecutive B-scans. In experiments A was set to be equal to 0.1. The maximum weight for the previous corrected B-scan has to be set to the value not greater than 0.5 to prevent algorithm stacking at this value in case of the zero local correlation between the two B-scans. Preprocessing

according to eq.(4) is applied after the correction according to eq. (3).

3. Results and discussion

In Figure 1 OCA images obtained from the same dataset using high-frequency filtration of the complex OCT signal according to eq. (1) are presented. MIP OCA image in Figure 1a is obtained after the application of the motion correction preprocessing according to the eq. (3) was applied to the OCT data, while the MIP OCA image in Figure 1b is obtained after the correction according to eq. (3) followed by the correction according to the eq. (4). One can see a significant reduction of the stripe artifact, caused by the bulk tissue motions undercompensated using eq. (3). The proposed preprocessing is applied to the B-scans recursively and can be used for the on-line visualization of the vessel images, which is important in the clinical application of the technique. The reduction of the stripe artifact not only increases the visibility of the vessel network for the human user but also facilitates quantification of the network, the approach which gains popularity among the OCT researchers^{17,18}.

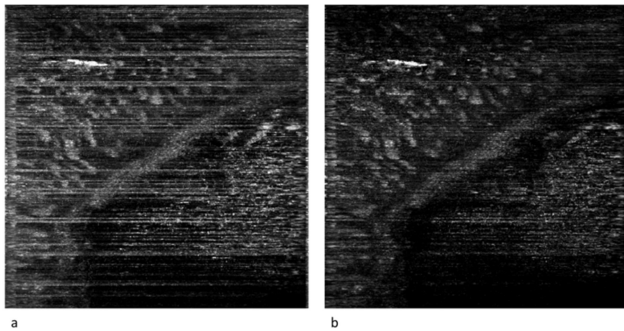


Figure 1 **a** image of the gingival vasculature of a volunteer obtained after the motion correction preprocessing according to eq. (3) **b** image of the gingival vasculature of a volunteer obtained after the motion correction preprocessing according to eq. (3) followed by preprocessing according to eq. (4). One should note that without any preprocessing vasculature is totally obfuscated by the motion-induced artifacts.

5. Conclusions

In this work, slow axis displacement correction preprocessing for Optical Coherence Angiography was proposed. It was shown that the proposed preprocessing combined with the preprocessing compensating for the displacement along the remaining two axes can drastically reduce the stripe artifact characteristic for the OCA.

Acknowledgements

The study was supported by the Russian Science Foundation project no. 17-72-20249.

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