Supplementary material

Modified Phase-II numerical phase stabilization

In this study, we employed a custom-made HP-OCA system. Most of the details have been described in Ref. 32, except for an updated algorithm for Doppler tomography reconstruction. HP-OCA relies on software based phase stabilization algorithms, called phase-1 and phase-2 phase stabilizations. The phase-1 stabilization cancels the phase error of OCT that occurred because of system instability. The phase-2 stabilization is for fine cancelation of system-induced phase error and also for cancelation of the offset Doppler shift that occurred with bulk motion of the eye. The HP-OCA system employed in this study uses an updated version of the phase-2 stabilization algorithm.

The details of the original version of the phase-2 stabilization algorithm is described in Section 2.3 of Ref. 32. The core process of this algorithm is iterative weighted regression of the measured depth-resolved Doppler shift signal. In the original algorithm, the weight was updated according to the following equations for each iteration (Eqs. (11) and (12) of Ref. 34).

$$W_m(\zeta) = \begin{cases} \sqrt{I(\zeta)} & : \ I(\zeta) > \varepsilon^2 \\ 0 & : \ \text{otherwise} \end{cases} \quad \text{for } m = 0 \tag{1}$$

$$W_m(\zeta) = \begin{cases} 0 & : \ \left|\Delta\varphi(\zeta) - (a_{m-1}\zeta + b_{m-1})\right| > \pi/(2m) \\ W_{m-1}(\zeta) & : \ \text{otherwise} \end{cases} \quad \text{for } m \geq 1 \tag{2}$$

where $m = 0, 1, \cdots, M$ is the index of iteration with M of the maximum iteration index, $W_m(\zeta)$ is fitting weight of *m*-th iteration with ζ as the Fourier pair of wavenumber. $I(\zeta)$ is signal intensity of OCT, ε^2 is the noise level of the OCT. $\Delta\varphi(\zeta)$ is the measured Doppler phase signal corrected by phase-1 stabilization algorithm and $a_{m-1}\zeta + b_{m-1}$ is a linear fitting of the phase at (*m*-1)-th iteration.

In the updated algorithm, the Eq. (2) was revised to be

$$W_m(\zeta) = \begin{cases} 0 & : \ \left|\Delta\varphi(\zeta) - (a_{m-1}\zeta + b_{m-1})\right| \geq T(m; p, M) \\ W_0(\zeta) & : \ \text{otherwise} \end{cases} \tag{3}$$

where

$$T(m;\, p, M) = \frac{\pi}{p}\left\{1 + \frac{p-1}{1 + \exp(m - M/2)}\right\}. \tag{4}$$

where p is a constant determined by the phase stability obtained after the phase-1 phase stabilization. Note that Eq. (4) is a monotonically decreasing sigmoid function with the maximum limit of π and the minimum limit of π/p, and we set p to make π/p to be the phase noise level. In our particular case, $p = 12$. M is the total iteration number of iteration, and in our particular case, $M = 7$. Note that Eq. (4) is a sigmoid function. And hence, In this condition, $T(m;\, p, M)$ keeps large for the first iterations, rapidly decreases at around the middle of the iteration, and becomes relatively constant for the late steps of the iterations. Hence this algorithm estimates the phase error caused by the system instability and the bulk eye motion more accurately than our previous algorithm, and improves the image quality of Doppler tomography and OCA.

After applying the phase-2 stabilization, we applied a 3-D Kasai auto-correlation filter[33,34] to the Doppler signal to further improve the Doppler sensitivity as described in Section 2.3 of Ref. 32. In this particular study, we have further optimized the kernel size of this filter in comparison to that of Ref. 32. The kernel sizes utilized in this study were 4 pixels (depth) × 4 pixels (horizontal) × 1 pixel (vertical) for the bi-directional scanning mode, and 4 pixels (depth) × 1 pixel (horizontal) × 4 pixels (vertical) for the high-sensitive scanning mode. This kernel sizes correspond to the physical size 19.0 μm (depth) × 38.8 μm (horizontal) × 30.0 μm (vertical) for the bi-directional mode and 19.0μm (depth) × 30.0 μm (horizontal) × 38.8 μm (vertical) for the high-sensitive mode.

References

32. Hong Y-J, Makita S, Jaillon F, et al. High-penetration swept source Doppler optical coherence angiography by fully numerical phase stabilization. Opt Express 2012;20:2740–2760.

33. Kasai C, Namekawa K, Koyano A, Omoto R. Real-Time Two-Dimensional Blood Flow Imaging Using an Autocorrelation Technique. Sonics and Ultrasonics, IEEE Transactions on 1985;32:458 – 464.

34. Yang VXD, Gordon ML, Mok A, et al. Improved phase-resolved optical Doppler tomography using the Kasai velocity estimator and histogram segmentation. Opt Commun 2002;208:209– 214.