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# Volumetric vessel reconstruction method for absolute blood flow velocity measurement in Doppler OCT images

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## 1. INTRODUCTION

Recently, quantitative cerebral blood flow velocity (BFV) measurement has been investigated using DOCT [1] to reveal better functional information from brain imaging [2-5]. Given the laser central wavelength $\lambda$ and the refractive index $n$ of the scattering media, the absolute velocity of the moving particles can be described by

$$v=\frac{\lambda f}{4\pi n\Delta T\cos\theta} \tag{1}$$

where $f$ is the Doppler phase shift, $\Delta T$ is the time interval between two samplings, and $\theta$ is the Doppler angle. Eq. (1) indicates that the velocity measurement not only relates to the properties of the laser and the scattering particles, but it also relates to the geometry of both directions of the laser beam and the flow. To measure the absolute BFV, vessel connection [3], *en face* signal integration [4] and gradient vessel tracking methods [5] were proposed. These approaches provide methods for Doppler angle correction, but usually they can only detect the BFV at one or multiple manual labeled locations. Effective methods for measuring the fully distributed absolute BFV along a vessel, which may reveal the overall hemodynamics of that entire vessel, are still limited.

Focusing on the analysis of cerebral hemodynamics, this paper presents a method to quantify the total absolute blood flow velocity in middle cerebral artery (MCA) based on volumetric vessel reconstruction from pure DOCT images. Given a seed point position on the MCA, our approach could achieve automatic quantification of the fully distributed absolute BFV. Experiments on rodents demonstrated the feasibility of our approach.

## 2. METHOD

As shown in Fig. 1, taking the phase-resolved Doppler OCT images captured with different time intervals as the input, the whole process of our absolute BFV measurement method is as follows: first, due to the limited dynamic range of the Doppler method, the input images are averaged to produce high-contrast vessel profiles; second, a restricted region growing algorithm is adopted to locate the MCA branches; third, the segmented MCA structure is skeletonized and smoothed after which the Doppler angle is calculated according to the geometry of the vessel skeleton. Finally, incorporating the acquired Doppler angles, the absolute BFVs at each location are calculated from the mean vessel signals within the segmented lumen through Eq. (1).

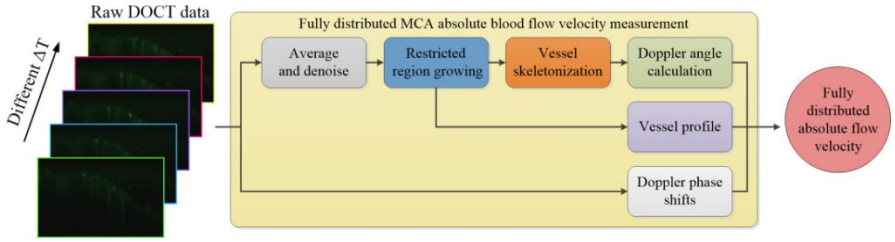


Fig. 1. The work flow of the proposed volumetric vessel reconstruction method for fully distributed absolute BFV measurement.

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The vessel signals in the DOCT images are affected by the Doppler angles and the flow pulses, resulting in discontinuities in boundary pixel intensities. To overcome these problems and effectively segment the MCA from stacked DOCT images, a restricted region growing algorithm is proposed. The algorithm is named "restricted" because the growing process is constrained simultaneously by the adaptive threshold and a circular shape prior.

1) The adaptive threshold $t$ is given by the compounding of the mean gray value $t_1$ of the boundary at the previous frame and a hard threshold $t_2$ derived from a Region-of-Interest (ROI) at a current frame: $t = (t_1+t_2)/\alpha$, where α is the compounding ratio. In this study, the ROI at a current frame is given by the neighboring region of the previous vessel center, and threshold $t_2$ is defined as a specific portion of the maximum gray value in this ROI. Using the adaptive threshold, the boundary pixel intensity fluctuation caused by changes in Doppler angle and blood flow pulse is overcome.

2) The circular shape prior is a circular boundary where the vessel region will stop growing when they encounter each other. The center $c$ of the circular boundary is given by the previous vessel center coordinates while its radius $r$ is derived from the mean vessel radius at the previous frame. In this way, the leaking problem during segmentation can be prevented.

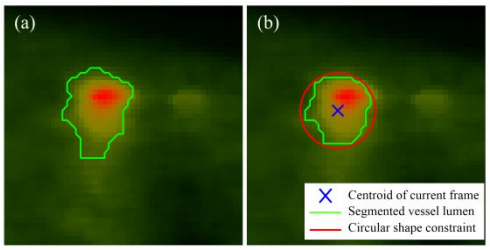


Fig. 2. (a) Ordinary region growing method leads to a diffuse vessel border; (b) the vessel lumen was successfully controlled by the two constraints using the proposed restricted region growing method.

The growing process starts with a seed point on a branch of the middle cerebral artery and grows at B-scan-wise. The stopping criteria are (1) no pixel satisfies the constraints, (2) the variance of the current ROI is smaller than a pre-defined value and (3) the displacement between the vessel centers of adjacent frames is larger than a threshold.

After the segmentation of the MCA, skeletonization is performed and then an averaged gradient method is used to calculate the flow direction. The gradient direction of a point is defined as $[dx_k, dy_k, dz_k]^T$, then the Doppler angle at point $P_k$ is given by:

$$\theta_k = \arccos\left(\frac{\eta dz_k}{\sqrt{dx_k^{\,2} + dy_k^{\,2} + dz_k^{\,2}}}\right) \tag{2}$$

where $\eta$=1 for forward flow and $\eta$ = -1 for reverse flow.

After the determination of the Doppler angle, the images taken at the appropriate delay, which results in minimum phase wrapping within the vessel lumen, are selected for the calculation of the absolute BFV. The BFV in one B-scan image is considered uniform, and thus the BFV is measured as the average intensity within the vessel lumen at this frame. The absolute BFV is obtained by dividing this averaged intensity by the cosine value of the Doppler angle at the same location.

## 3. RESULTS

A 295–400g male Sprague Dawley rats was used in the in vivo experiment. The animal was injected intraperitoneally with a Nembutal bolus [55 mg/kg body weight (b.w.)] for anesthetization. After resection of soft tissue, a 6.5×8mm imaging area of the skull over the left primary somatosensory cortex was thinned to ~150 μm. Three-dimensional OCT data were acquired after carefully tilting the output laser beam to avoid the phase wrapping of the blood flow. The DOCT images were then fed into our algorithm to verify the algorithm's applicability.

Vessel reconstruction was carried out first. For better reference of the vessel distribution, the intensity-based Doppler variance (IBDV) [6, 7] was used to visualize vessel densities during the experiment. Fig. 3(a) shows the *en face* maximum intensity projections of the IBDV images. The white arrows indicate the branches of the MCA. After vessel segmentation, MCA structures were reconstructed (fig. 3(b)) and further smoothed by averaging neighboring pixel coordinates to produce the refined vessel lumen structures (fig. 3(c)). The MCA skeletons were obtained afterward as displayed in fig. 3(d) with artery branches coded in different colors. The reconstructed vessel structures coincide with the

*en face* image and reveal the necessary vessel geometry for absolute BFV measurement, and the overlapping of different vessels and the MCAs was successfully avoided.

Doppler angles on the entire reconstructed MCA skeletons were calculated using the proposed averaged gradient method. Fig. 3(e) shows the angle measurement result with the cosine value of the Doppler angle at each position coded in red and black. It can be seen that the cosine value was in good accordance with the vessel geometry. Figs. 3(f) and 3(g) show the enlarged details of the dashed-line-frames in Fig. 3(e) with arrows showing the flow direction at each discrete point, which represent the vessel center at each B-scan image.

Finally, the absolute BFV along all the MCA was found. In the corrected BFV distributions (fig. 3(i)), Non-uniformity was clearly seen at the corrected absolute BFV distribution (indicated by the changing color of the vessels). This velocity fluctuation was believed to be caused by the natural cardiac cycle of the animal. Fig. 3(j) shows the mean BFVs of different brunches, among all the artery branches we measured, the overall mean absolute BFVs of 15.27 mm/s was found, and the overall ratio between corrected and uncorrected BFV was 1.7249-fold.

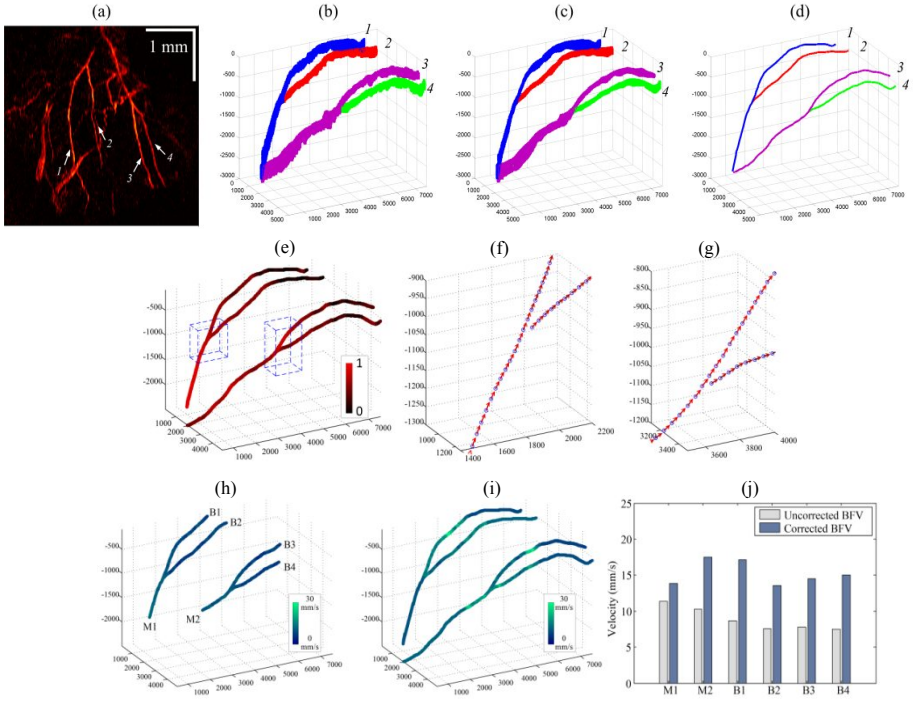


Fig. 3. Fully distributed absolute BFV measurement: (a) IBDV *en face* images; (b): reconstructed vessels before lumen refinement; (c): vessel structures after lumen refinement; (d): extracted vessel skeleton; (e): Doppler angle calculation results (cosine value); (f) and (g): details of the flow direction in (e); (h): color coded BFV measured without Doppler angle correction. (i): the reconstructed absolute BFV distributed along the entire vessel; (j): comparison between corrected and uncorrected flow measurement results of different main branches and side branches.

## 4. CONCLUSION

We demonstrated the fully distributed measurement of absolute blood flow velocity for the middle cerebral artery by reconstructing the vessel geometry using pure DOCT stack images. The algorithm automatically localizes the vessel lumens, calculates the Doppler angle, and then quantifies the absolute BFV on each position of the whole MCA. Our approach is verified by quantifying the hemodynamics of cerebral arteries of resting state rodents with custom-built, swept-source optical coherence tomography

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