Transverse flow-velocity quantification using optical coherence tomography with correlation

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Abstract: We describe a method that uses classic optical coherence tomography to measure the transverse fluid-flow velocity quantitatively without knowing the Doppler angle. An intensity based cross-correlation calculation is taken point-to-pointly between two close cross sections of the scattering fluid to estimate the time delay for scattering particles passing through the two sections which are scanned alternately at a high speed. The transverse velocity distribution of the scattering fluid-flow in the whole section is achieved finally. The experimental results agree well with the preset ones. This method is insensitive to the Doppler angle and provides a variable velocity detection range in different application conditions.

1. Introduction
Optical coherence tomography (OCT) [1] is a non-invasive imaging technique capable of providing internal structure information of objects with a micrometer-scale spatial resolution. Doppler optical coherence tomography (DOCT) permits determining location and flow velocity of moving particles in highly scattering media [2-4], which shows a good application prospect, such as in vivo imaging of microvasculature in medical diagnostics [5-6] and flow characteristics measurement in microfluidic devices design [7-8]. However, only the component of the velocity parallel to the incident beam can be measured by conventional DOCT [9]. It is therefore necessary that the angle between the incident beam and the flow vector (the Doppler angle) must be precisely known before an exact value of the fluid flow velocity can be calculated. But in many applications it is difficult to estimate the Doppler angle accurately, flow samples with complex geometry for example, and particularly when the flow is embedded in the highly scattering medium such as the situation of in vivo blood-flow monitoring.

Attempts have been made to reduce the reliance on the Doppler angle. Technique employed with multiple sample beams was developed in several forms [9-10] and often needed OCT systems with relative improvement. The Doppler shift on interference signal and
the Doppler spectrum broadening were used combinedly to estimate the values of Doppler angle and average fluid velocity by Proskurin et al [11]. However, like conventional DOCT, this method suffered from detection accuracy decreasing when the transverse velocity was small. Time varying speckle in OCT structural images was studied to carry about tissue structure and flow information [12-13]. Nevertheless, the speckle variance OCT has been used only in qualitative analysis of the fluid-flow velocity up to present.

In this paper, a method which is capable of measuring the transverse flow velocity precisely independent of the Doppler angle is presented. The technique takes a point-to-point cross-correlation calculation between two series of structural images to estimate the time delay for scattering particles passing through two close cross sections, and then achieves the transverse velocity distribution of the scattering fluid-flow in the whole section finally. In our experiments, a classic frequency domain OCT system was used to measure the preset flow velocity. The results agreed well with the preset ones even in the small-velocity condition.

2. Materials and Methods

2.1. Optical coherence tomography system

The spectral domain OCT system used in our experiments was shown in figure 1(a). The light source was a super luminescent diode with a center wavelength of 830 nm and a 3-dB bandwidth of 40 nm, corresponding to a coherence length of 7.6 μm in air. The low-coherence light illuminated the source arm of a fiber-based Michelson interferometer. Then the interference signal of the light beams reflected from the reference and sample arms was coupled in the detection arm, which consisted of an achromatic collimating lens (CM: f= 75 mm), a 1200-line/mm transmission grating, an achromatic focusing lens (FL: f= 200 mm), and a line-scan CCD camera (2048 pixels, each 14×14 μm in size). The integration time of the CCD camera was set to be 40 μs and the system was operated at an A-scan frequency of 20 kHz. The output power of the sample arm was 0.5 mW.

![Figure 1](image.jpg)  
**Figure 1.** (a) Schematic of our spectral domain OCT system: SLD, super luminescent diode; CM, collimator; DG, diffraction grating; FL, focusing lens; DAQ, data acquisition system; FC, flow channel. (b) Sample scanning manner in our experiments. A two-axis scanner with two galvo mirrors was used to scan two close sections (A and B) of the fluid sample alternately at a high speed. Distance L between section A and B can be set flexibly to meet the requirement of the measurement range.
2.2. Methods

As for this method, a two-axis scanner with two galvo mirrors was used to scan two cross sections (A and B) of the fluid-flow sample alternately at a high speed (illustrated in figure 1(b)). One scanning mirror was driven by a sawtooth waveform voltage signal while the other by a square waveform voltage signal. The distance L between section A and section B (along the axis of flow channel) was set to be very small, several ten to several hundred microns for example, so it can be considered that section A and B are parallel to each other. After a certain acquisition time t, we got a series of structural images at each cross section. Then pixel intensity with the same coordinate in the images of one series was extracted and formed an intensity array in the acquisition order, which recorded different scatterers passing through a certain position in the fluid section during the acquisition time. A cross-correlation calculation was taken between two intensity arrays extracted from the corresponding position of the two sections to estimate the time delay \( \tau \) for scatterers passing through section A and section B. The average flow velocity \( \nu \) of that position is decided by \( \nu = \frac{L}{\tau} \). By repeating the calculation in the whole fluid section, we achieved the transverse velocity distribution finally.

Exactly speaking, the transverse velocity measured with this method is the velocity along the axis of flow channel, not the general meaning which is in the direction perpendicular to the scanning plan. The velocity measurement range of this method can be calculated with the distance L, acquisition time t and the section-scan frequency f determined. The period of the section A and B scanning is marked as T, \( T=\frac{2}{f} \). Assuming that we obtain N frame structural image data at each section in the acquisition time \( t=NT \). Theoretically cross-correlation taken between two arrays whose data length are both N can provide a maximum time delay as \( \pm (N-1)T \) and a minimum time delay as \( \pm T \) (\( \pm \) denotes two opposite flow directions). So the velocity measurement range is \( \pm (\frac{L}{(N-1)T-\frac{L}{T}}) \). These parameters could be flexibly set to meet variable velocity measurement range.

2.3. Flow phantom

In the experiment shown in figure 1(b), a glass capillary with an inner and outer diameter of 0.3 mm and 1.0 mm was placed on a goniometer stage, and polystyrene microsphere aqueous suspension (mean diameter: 10 \( \mu \)m, volume concentration: 1.5%) was used as working fluid driven by a syringe pump. Then the pump was controlled to generate an average flow rate of 6.29 mm/s in the capillary. And the capillary was tilted by an angle of 85\(^\circ\) with respect to the incident beam. The distance L between the two sections was adjusted to 0.3 mm. 400 frame structural image data of the two sections were acquired alternately in \( t=2 \) seconds, giving section-scan frequency \( f=200 \) Hz. Each frame contained 100 A-Scan. These parameter settings provided a measurement range of \( \pm (0.151 \sim 30 \) mm/s).

3. Results and Discussions

Figure 2(a) shows the OCT intensity image of the capillary filled with microsphere solution. A two-dimensional cross-correlation between two images acquired at section A and section B (figure 1(b)) was calculated to provide a coordinate deviation in order to correct the pixel corresponding relation. Then the transverse velocity distribution of the scattering fluid-flow in the whole section was calculated, filtered and shown in figure 2(b). The velocity profiles before and after smooth filtering along the white line in figure 2(b) were illustrated in figure 2(c). The flow showed a parabolic profile with an average velocity calculated to be 6.27 mm/s,
which showed a good agreement with the preset one (6.29 mm/s). A three-dimensional representation of the transverse velocity distribution after smoothed was presented in figure 2(d).

![Figure 2](image.png)

**Figure 2.** (a) Intensity tomogram of the perfused capillary. (b) Transverse velocity distribution of the fluid sample in the whole section. (c) Velocity profiles along the white line in figure 2(b). Dash-dot line: before smooth filtering. Solid line: after smooth filtering. (d) Three-dimensional flow front profile within the capillary.

The principle of this method is based on structural image cross-correlation, and the measurement is performed without the need of knowing the angle between the incident light and the flow velocity field. To examine the influence of the angle of incidence on the velocity measurement, for the second experiment we changed the Doppler angle in steps of 5°, and measured 20 times at the same angle. The averaged results agreed well with three different preset velocities with the angle varied in ±15°, as shown in figure 3. The experiments performed showed that the velocity determined by our method was independent of the orientation of the velocity vector in a large range.

The capability of measuring slow flow is of great importance. However, experimental results of velocity below 0.2 mm/s were seldom reported though some techniques were proved theoretically to have a high velocity sensitivity of the order of 10 μm/s [5,14]. Both DOCT and speckle flow techniques have an inherent tradeoff in flow sensitivity with acquisition time [5,14-15], and the phase-sensitive demodulation based techniques are vulnerable to the background noise or phase instability in slow flow detection mode, especially at high frame rates [14]. To further validate our method in the low-velocity condition, we changed the experiment parameters to L = 0.048 mm, t = 2 seconds and f = 200 Hz, corresponding to a measurement range of 0.024 ~ 4.8 mm/s. We performed a series of measurements at 15 different preset velocities with the same Doppler angle of 85°. Every preset flow was measured 20 times and the averaged results were plotted as a function of preset velocity in figure 4. The average deviation from the set velocity for flows from 0.06 to 0.2 mm/s was 1%. And the correlation coefficient for the data set was calculated to be 0.9999.
The results indicated a high correlation between preset and calculated velocities. This method eliminates the need for phase-sensitive detection or spatial frequency analysis, and is robust to factors confounding both Doppler and speckle analysis techniques, such as non-linear motion of the reference arm mirror and movement of the sample.

Figure 3. Measured velocity for three different preset velocities in different incident angle condition. The incident angle at 0 degree represents normal incidence. Dash lines: preset velocities.

Figure 4. Estimation of different preset velocities in slow flow condition. Solid line: line fit. Dot line: unity slope.

In the practical application we found that measurable velocity range by means of this technique was smaller than the theoretical calculation. This could be due to the quasi-synchronous manner of the image acquisition at section A and section B as scatterers recorded at section A may not be totally detected at section B, which also led to measurement error. Increasing the section-scan frequency \( f \) and the acquisition time \( t \) could enlarge the velocity measurement range and reduce measuring error effectively. Obviously, this method does not work when a flow velocity is parallel to measured cross sections, but it still shows a considerable potential in absolute flow velocity measurement if combined with other techniques, three-dimensional OCT imaging for example. Velocity measurement technique suitable for complex applications will be studied in future research.

4. Conclusion

We presented a method to measure the scattering fluid-flow velocity quantitatively using classic OCT system without knowing the Doppler angle. It was demonstrated that one can obtain the transverse velocity distribution of the fluid flow with high accuracy using cross-correlation calculation with intensity from OCT images. This method provides an adaptable measurement in different flow conditions. The good performance in low-velocity detection also indicates a considerable value of this technique in real application.

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