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Quantitative photoacoustic velocimetry technique using multi-angle observations

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Abstract: By changing the ultrasonic receiving angle in post-processing, we can obtain flow vectors from a photoacoustic experiment on a blood vessel phantom by solving the photoacoustic Doppler equation using a least-squares optimisation approach.

1. Introduction

Photoacoustic imaging (PAI) is a rising medical diagnostic modality in which the absorption of laser light generates high frequency pressure waves, which can be detected using clinical ultrasonic transducers and reconstructed to locate the position of optical absorbers [1, 2]. By recording a sequence of images, the Doppler shift corresponding to the motion of the absorbers can be observed to quantify the velocity of blood flow. [3].

Even though ultrasound methods are already used clinically to measure and map blood flow, the nature of measuring flow with PAI has the potential to be more powerful in many scenarios. PAI inherently offers a better SNR than ultrasound for determining blood flow as there is a high optical contrast between chromophore-rich red blood cells and the surrounding tissue while in ultrasound, acoustic waves are only weakly reflected by these cells. In low flow-rate scenarios, the signal reflected by blood flow can be overpowered by slow-moving respiratory or cardiac motion in ultrasound. However, in PAI this problem is less prominent as the photoacoustic waves are emitted primarily from blood flow and not tissue walls, resulting in less signal clutter. As a result, PAI is a promising technique to map the flow speeds in micro-vasculature.

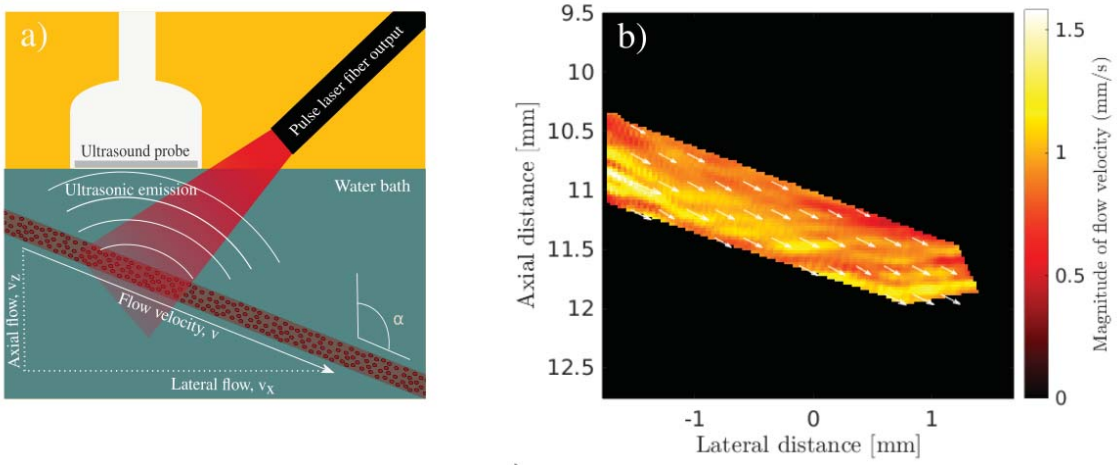

Fig. 1. **a)** Experimental PA velocimetry set-up used to measure the flow rate in a blood vessel phantom. A 680 nm pulsed laser illuminates a blood mimicking fluid which absorb this light and emit ultrasonic vibrations. The emitted ultrasonic PA waves are detected on the sample surface by a clinical ultrasound probe with 128 receiving elements. **b)** Experimental flow map obtained using a blood vessel phantom flowing at an average speed of ∼0.887 mm/s. White arrows represent the PAV calculation overlaid on each pixel's speed. A mask has been applied to remove noisy pixels which do not correspond to regions where the blood-mimicking fluid is flowing.

2. Methodology

Existing photoacoustic flow methods require the angle of flow to be known *a priori*, which is rarely the case, particularly in small, complex vasculature [1]. In this presentation, I will discuss the development of a new technique, termed photoacoustic velocimetry (PAV), which computes both the magnitude and direction of flow automatically.

By harnessing advancements from ultrasonic vector flow imaging [4], our PAV technique solves the Doppler equation (Equation 1):

$$\frac{f_d c}{f_0} = \frac{\omega c}{2\pi f_0} = v_x \cos\phi + v_z \sin\phi, \tag{1}$$

to find the axial (v_z) and lateral (v_x) flow components for each pixel in the imaging grid. Here, f_d is the Doppler frequency generated by moving PA emitters, f_0 is the detected center frequency of PA waves, and ϕ is the angle between the ultrasound probe and the pixel of interest. ω is the angular frequency of a pixel, obtained using the lag-one auto-correlation method that is prolific in ultrasound colour flow imaging [3].

By selecting which receiving elements in the ultrasound probe are used for each pixel's reconstruction, the receiving angle, ϕ, can be varied in post-processing. If three of more Doppler shift frequencies(f_d) are obtained for each pixel by varying the receiving angle, an over-determined linear equation (Equation 2) can be constructed and solved to determine the axial and lateral flow components [4].

$$\begin{bmatrix} \cos\phi_1 & \sin\phi_1 \\ \vdots & \vdots \\ \cos\phi_n & \sin\phi_n \end{bmatrix} \begin{bmatrix} v_x \\ v_z \end{bmatrix} = \frac{c}{2\pi f_0} \begin{bmatrix} \overline{\omega}_1 \\ \vdots \\ \overline{\omega}_n \end{bmatrix}. \tag{2}$$

3. Results

This PAV methodology has been demonstrated in bench-top experiments that replicate a blood vessel surrounded by soft tissue. For improved repeatability, a blood-mimicking fluid is used, comprised of glassy carbon spheres (15 %, 2-12 μm diameter) in a sodium polytungstate solution. Using a 128 element ultrasound probe (L22-14xv LF) with a center frequency ∼16 MHz, flow speeds on the order of 1 mm/s can be accurately obtained, as shown in Figures 1b and 2.

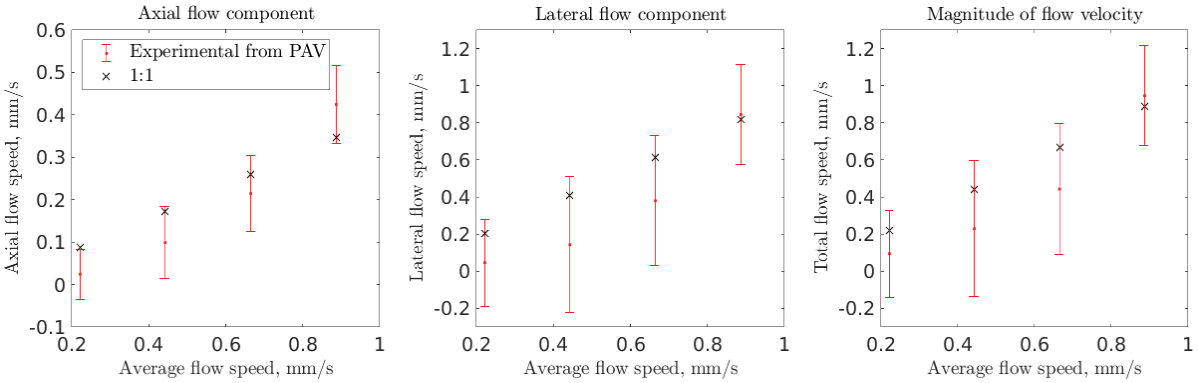

Fig. 2. Axial, lateral and magnitude of flow velocity calculated using PAV for four different flow speeds in a blood vessel phantom. The black crosses indicate the average flow speed in the tubing, while the errors bars are equal to one standard deviation.

References

1. Paul Beard. Biomedical photoacoustic imaging. *Interface Focus*, 1(4):602–631, 2011.
2. Thore M Bücking, Pim J Van Den Berg, Stavroula Balabani, Wiendelt Steenbergen, Paul C Beard, and Joanna Brunker. Processing methods for photoacoustic Doppler flowmetry with a clinical ultrasound scanner. *Journal of Biomedical Optics*, 23(2):026009, 2018.
3. David H Evans, Jørgen Arendt Jensen, and Michael Bachmann Nielsen. Ultrasonic colour Doppler imaging. *Interface Focus*, 1(4):490–502, 2011.
4. Billy YS Yiu and CH Alfred. Least-squares multi-angle Doppler estimators for plane-wave vector flow imaging. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 63(11):1733–1744, 2016.