DIGITAL ULTRASOUND SPECKLE IMAGE VELOCIMETRY FOR QUANTITATIVE CARDIOVASCULAR FLOW VISUALIZATION

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ABSTRACT

For *in vivo* and optically inaccessible *in vitro* flows, accurate measurements of the velocity field and shear stresses are generally considered to be difficult to obtain. *In vivo* flow velocities are typically measured using Doppler ultrasound, but this technique has major limitations. We have developed Digital Ultrasound Speckle Image Velocimetry (DUSIV), an efficient speckle tracking method that is not subject to the limitations of Doppler ultrasonography. This method can also be applied to *in vitro* measurements without requiring optical accessibility. DUSIV accuracy was evaluated by comparing it to conventional optical Digital Particle Image Velocimetry (DPIV). A transparent flow phantom was constructed that allowed flows to be examined by both the DUSIV and DPIV techniques. The phantom was designed to produce a backward-facing step flow. DUSIV velocities and vorticities were very similar to the DPIV results for matching flow rates and step heights. This suggests that DUSIV may be very useful as a visualization tool for both *in vivo* flows and optically inaccessible *in vitro* flows. We are currently using this approach to study a variety of flows involving the cardiovascular system.

INTRODUCTION

Knowledge of detailed flow characteristics can be extremely valuable in a variety of scientific and clinical settings. Quantitative flow visualization is a very useful tool for obtaining such information. For *in vitro* studies, visualization and analysis are typically performed with transparent flow conduits. *In vivo* flow dynamics are most commonly examined using ultrasound. Specifically, Doppler ultrasonography is the predominant method used to determine blood flow velocities.

Doppler ultrasound techniques are subject to several significant limitations. These include aliasing (when scatterer velocities are too high) and the inability to detect flow perpendicular to the transmitted beam (making estimated velocities dependent upon the often ambiguous angle between the beam and the true flow direction). Such issues can make it difficult to obtain detailed and accurate results from ultrasound data.

Speckle tracking methods avoid these issues and are being investigated as alternatives to Doppler techniques for determining blood velocities from ultrasound measurements [1]. Speckle tracking involves dividing a two-dimensional B-mode image (or, if desired, radio frequency data image) into subregions and mapping frame-to-frame displacements of the corresponding speckle patterns. This can be done because the speckle patterns are relatively stable between frames. An effective technique is to find the displacement for each speckle pattern that gives the maximum normalized cross-correlation between consecutive images. Direct calculation of cross-correlation values, however, turns out to be quite demanding computationally. In order to facilitate real-time speckle tracking capabilities, a number of alternative correlation algorithms and scanning protocols have been suggested [1,2].

This study evaluated an approach using the fast Fourier transform (FFT) to simplify and speed up the cross-correlation process. With this method, calculations can be performed in the frequency domain rather than the spatial domain, leading to a significant reduction in computational requirements. This approach has been successfully applied to *in vitro* optical flows seeded with tracer particles [3,4]. We refer to that visualization technique as Digital Particle Image Velocimetry (DPIV). We term the implementation of FFT-based cross-correlation of ultrasound images as Digital Ultrasound Speckle Image Velocimetry (DUSIV) [5].

METHODS

An experimental setup was constructed allowing both DPIV and DUSIV measurements to be made on the same flow phantom. The system consisted of a transparent silicone tube (1” I.D.) mounted within a water-filled acrylic tank. A short acrylic tube (1” O.D.) was inserted into the upstream portion of the silicone tube to create a backward-facing step flow. The wall thickness of the acrylic tube was varied in order to examine various step heights (1/16”, 1/8” and 1/4”).

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A steady pump was used to circulate water seeded with fluorescent tracer particles (having a mean diameter of 50 μm) through the flow loop. Flow rates ranged from 0.3 L/min to 3 L/min.

Images for conventional DPIV analysis were obtained using laser sheet illumination of the fluorescent particles within an equatorial plane of the flow phantom. Velocity vectors and vorticity contours were calculated using a DPIV software package designed to perform cross-correlation operations using the FFT algorithm.

Images for DUSIV analysis were captured using a GE Vingmed System Five ultrasound system (at up to 242 frames/second using a submerged 10 MHz probe). In these tests, the fluorescent particles acted as ultrasound scatterers. B-mode ultrasound images were recorded in the same equatorial plane of the tube and were exported for use with the same analysis package that the laser sheet images were. Color Doppler flow maps were also obtained for comparison.

RESULTS

Velocity fields and vorticity contours were obtained for all geometries and flow rates. At higher flow rates, vortex eddies were visible in the shear layer. Both instantaneous and time-averaged velocities and vorticities were calculated. Examples of time-averaged velocity fields obtained by DPIV and DUSIV for identical configurations are shown in Figure 1. Velocity profiles for similar positions downstream of the step are shown in Figure 2. Velocities and vorticities obtained by the two methods showed very good agreement.

DISCUSSION

FFT cross-correlation is widely accepted as an accurate means of determining velocities from images of optical tracer particles. We utilize this technique in all of our DPIV analyses [3,4]. In this study, we evaluated FFT cross-correlation of ultrasound speckle patterns. The resulting velocities were quite similar to those obtained from DPIV for identical flows.

The DUSIV approach does not require optical accessibility of the flow field. It also provides more detailed information than is available from conventional echocardiographic imaging. Hence, we believe DUSIV has great potential as both an experimental research tool and an advanced technique for noninvasive examination of cardiovascular function. We are currently using this method to study *in vitro* flow in a compliant model of the aorta, as well as the *in vivo* flow dynamics of the porcine heart.

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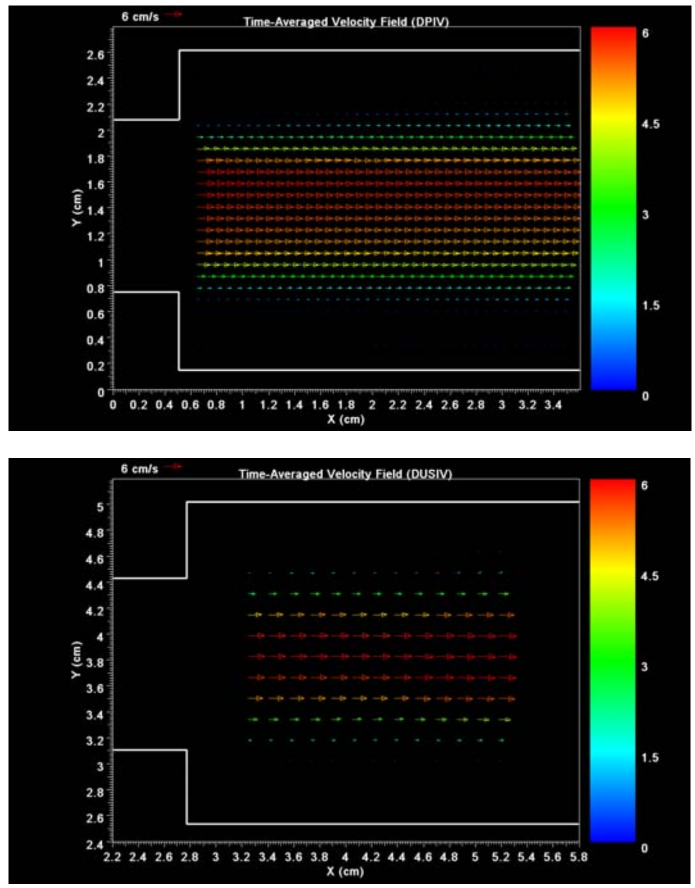

Figure 1. Comparison of time-averaged velocity fields for 1/4" step at 0.3 L/min

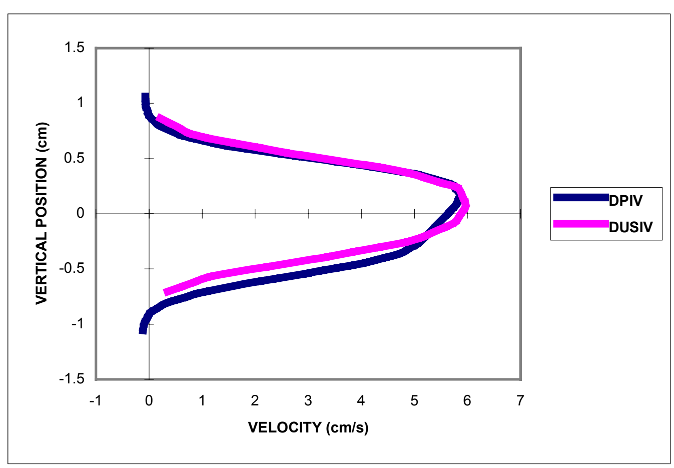

Figure 2. Comparison of velocity profiles (1.5 cm downstream of step)