IN VIVO VALIDATION OF THE ECHO-PIV TECHNIQUE: ANIMAL AND CLINICAL STUDIES

Robin Shandas(1,2), Hyoung-Bum Kim (1), Jean Hertzberg(1), Curt G. DeGroff (2), Eric Monet (3), Lilliam Valdes-Cruz (2)

(1) Dept. of Mechanical Engineering
University of Colorado
Boulder, CO

(2) Department of Pediatric Cardiology
The Children's Hospital
Denver, CO

(3) Dept. of Small Animal Surgery
Veterinary Teaching Hospital
Colorado State University, Fort Collins, CO

INTRODUCTION

There currently exists no easy method to measure time-resolved multi-component blood flow data *in vivo*. Such information would be useful for a number of cardiac, vascular and neurological applications where improved flow information would be extremely helpful in understanding *in vivo* hemodynamics. While MRI phase velocity mapping does provide multiple components of blood velocity, it is a highly cumbersome method with long scan times and poor temporal resolution. Ultrasound Doppler, while attractive due to its simplicity and ease of use, does not provide multiple velocity components.

We have recently developed an ultrasound, non-Doppler, method to measure multi-component velocity information non-invasively [1,2]. This method is the in vivo equivalent of optical particle image velocimetry (PIV) techniques that have been used extensively in fluid dynamics diagnostics, and is termed echo-PIV.

We have previously validated echo-PIV in simple in vitro models. Its applicability in vivo, however, was not tested. This project presents initial results from animal and clinical studies of a complex flow field, namely left ventricular filling.

EXPERIMENTAL APPARATUS AND METHOD

Animal Studies

A canine model of diastolic dysfunction was used. Restrictive physiology was created using an aortic band with sufficient constriction to create an increase of approximately 50 mm Hg in left-side pressures. This model simulated hypertrophic cardiomyopathy. In addition, a dilated cardiomyopathy model was created through tachycardic pacing of the ventricles for 3 weeks. Echo-PIV measurements of left ventricular flow were obtained pre and post induction. Pressure-volume loops were also obtained.

Clinical Studies

Left ventricular inflow patterns were obtained in the catheterization laboratory on patients undergoing diagnostic or electrophysiology studies using an FDA-approved IND protocol. Echo-PIV studies were carried out to measure ventricular inflow velocity components.

Echo PIV Technique

The echo-PIV technique takes advantage of the non-linear backscatter characteristics of small (2 – 5 μ) gas-filled microbubbles (also known as echo-contrast) that are introduced into the blood flow stream. Analysis of the sub- and super-harmonic signals within the backscatter allows separation of signals from tissue and flow and facilitates precise particle detection. Once particles are detected within the flow field, particle image velocimetry and particle tracking velocimetry algorithms can be applied to determine the local velocity vector. This process is performed on the radio-frequency (RF) backscatter data from the entire echo image, to produce a 2D map of velocity vectors as a function of time. Since frame rates can be increased to 200 fps and above, temporal resolution is excellent.

RESULTS

Figure 1A-C shows results from the animal studies, displaying flow patterns during different stages of ventricular filling. The initial rush of blood into the ventricle through the mitral valve can be seen in 1A. Subsequent swirling and A-wave flow can be seen in images B-C. The left ventricular apex is located at the top left of each image with the mitral valve located at the bottom right (about 5 o'clock).

Figure 2 shows similar data obtained in the catheterization laboratory from a 14 y/o child. The propagation of the initial bolus of diastolic flow down toward the apex (located at the top of each image) can be seen, as well as the flow connected with atrial contraction (middle picture).

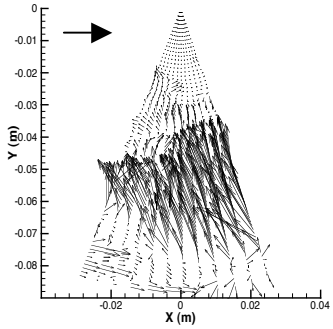

Figure 1A: Early mitral filling can be clearly seen in this echo-PIV image from the animal studies. The reference arrow corresponds to 50 cm/sec.

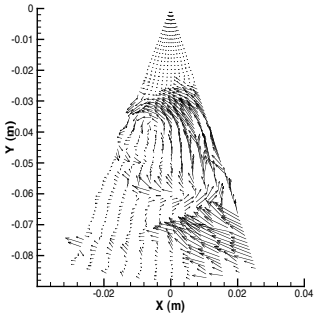

Figure 1B: Left ventricular flow during atrial contraction.

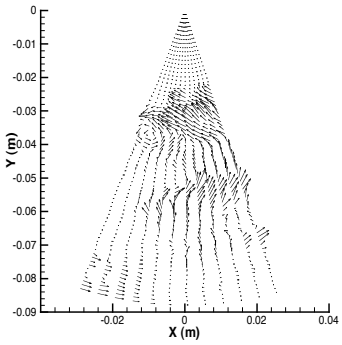

Figure 1C: LV inflow during end diastole.

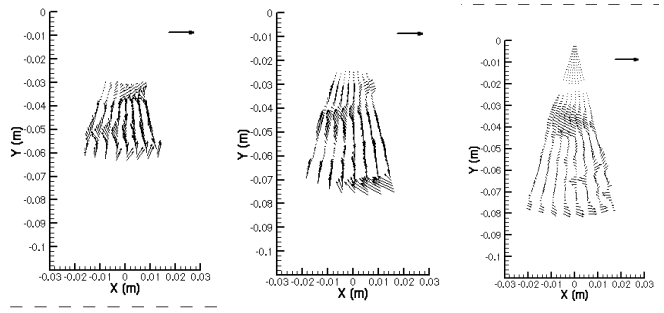

Figure 2: Preliminary clinical data from a 14 y/o child showing propagation of flow within the left ventricle at different points during diastole. The reference arrow corresponds to 40 cm/sec.

DISCUSSION

Echo-PIV appears to be a highly promising method for the non-invasive measurement of multiple velocity components in vivo. Applications for the method include dynamic quantitation of wall and fluid shear stresses, measurement of velocity profiles in complex flows such as prosthetic heart valves, ventricular filling, aortic outflow, etc., improved measurement of cardiac output and organ perfusion measurements, and increased accuracy for flow measurements in pediatric surgical connections such as the total cavopulmonary connection. A variety of contrast agents (ie., microbubbles) are approved for clinical use; moreover, echo-PIV requires only a fraction of the typical concentrations for optimal results. This method should also be useful in the assessment of hemodynamics in small animal imaging, especially knock-out models where flow-mediated effects on cellular expression at a local site need to be studied.

CONCLUSION AND FUTURE WORK

This study provides the first initial evidence regarding the utility of echo-PIV for in vivo flow measurements. Optimization of the method for a variety of clinical conditions through the development of mathematical models, improvements in signal and image processing techniques, and implementation into hardware is ongoing.

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ACKNOWLEDGEMENTS

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