A Custom-Designed Ultrasound Echo Particle Image Velocimetry System: Initial Experiments

Lingli Liu, Hairong Zheng, Logan Williams and Jean Hertzberg

Department of Mechanical Engineering, University of Colorado, Boulder, CO.

Craig Lanning and **Robin Shandas**

Department of Mechanical Engineering, University of Colorado, Boulder, CO; Department of Pediatrics, The Children's Hospital, Denver, CO.

Echo-PIV is a novel contrast-based ultrasonic technique for measuring multi-component velocity vectors in opaque flows. Ultrasound contrast microbubbles are used as flow tracers, and digitally acquired RF-data are converted into B-mode images. A pair of sequential images is cross-correlated to determine particle displacement, using algorithms derived from optical particle image velocimetry (PIV). The resulting data provides temporally and spatially resolved two-dimensional velocity fields of two velocity components. This technique has been successfully implemented using off-the-shelf clinical ultrasonic imaging systems, but such systems currently lack sufficient control and frame rates. A customized system is being developed with extended capabilities. To date, excellent temporal (<0.6 msec) and spatial resolution (<0.4mm) resolution has been achieved. Both phased-array and mechanically scanned systems are being developed. The system performance parameters and limitations are described. Examples of measurements of velocity fields from several flows including steady and transient vortexes are presented.

Keywords: PIV, particle image velocimetry, echo, B-mode, hemodynamics, vascular imaging,

1 INTRODUCTION

Non-invasive assessment of cardiovascular hemodynamics is an important part of the comprehensive clinical examination of both adult and pediatric patients. The ability to obtain multi-component blood flow velocity data non-invasively would have a number of immediate benefits. Vascular investigators would be able to compute various shear stress parameters to quantitatively examine factors related to intimal hyperplasia, restenosis after stenting, arteriosclerotic plaque development, venous and arterial thrombus formation, vascular aneurysms, and other disease conditions where shear stress (both within the fluid and along the wall) has been shown to play an important role in amplifying or attenuating a disease process. Cardiologists could more comprehensively characterize flow within the coronary arteries, evaluate shear stress parameters within the atrium and ventricle, quantify diastolic filling more accurately, and measure the multiple components of flow through prosthetic heart valves.

A variety of methods have been examined for measurement of multiple blood velocity components *in vivo*. Magnetic resonance imaging (MRI) velocimetry provides multiple components of velocity with good spatial resolution; however, the method is cumbersome to use since it requires breath-holds, collection of data over multiple cycles for ensemble averaging, and possesses relatively poor temporal resolution [i,ii] Ultrasound Doppler measurement of local velocity has also been examined [iii,iv]. Although this method provides greater temporal resolution, it is dependent on the angle between the ultrasound beam and the local velocity vector, only provides velocity along the ultrasound beam (1-D velocity), and has difficulty in measuring flow near the blood-wall interface.

The recent development of microbubbles to enhance ultrasound backscatter provides a potential ultrasound-based imaging solution for velocimetry of vascular and other opaque flows. This solution is based on the synthesis of two existing technologies: particle image velocimetry (PIV) and brightness-mode (B-mode) contrast ultrasound echo imaging. We have termed this Echo PIV. Figure 1 illustrates the schematic of the general Echo PIV technique. In the method, B-mode image frames are first obtained by sweeping a focused beam of ultrasound through the desired field of view. The ultrasound beam is scattered by contrast microbubbles, resulting in a clear image of the particle positions. Two sequential image frames are then subjected to PIV analysis: the images are divided into interrogation windows (sub-windows); a cross-correlation is performed on the sub-window images to provide the local displacement of the particles; extension of the cross-correlation to all sub-windows over the entire frame allows the velocity vector field to be determined since the time between images (_*t*) is known.

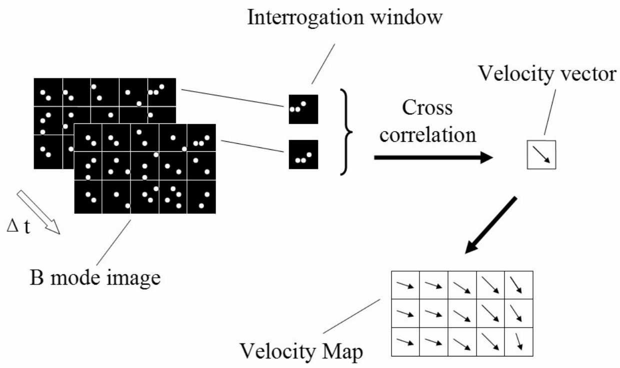

Figure 1: Schematic of the Echo PIV technique

The application of PIV analysis to echo images was first reported by Crapper et al. [v], who used a medical ultrasound scanner to image kaolin particles in a study of sediment-laden flows. PIV algorithms were applied to B-mode video images, and speeds of up to 6 *cm/s* were obtained. Others have used 2D ultrasound speckle velocimetry (USV), a combination of classical ultrasonic Doppler velocimetry and 2D elastography techniques, for flow imaging [vi,vii, viii]. The USV technique can provide velocity vectors by analyzing the acoustic speckle pattern of the flow field, which is seeded with a high concentration of scattering particles. However, this technique is limited by the requirement for extremely fast acquisition systems, heterogeneous signals caused by polydispersed particles, and high noise induced by high concentration of scattering particles. The inherent necessity of very high scatterer particle concentrations in particular, seriously limits the application of USV in hemodynamics measurement in living creatures [ii].

We first implemented Echo PIV algorithms on image data obtained from a commercial clinical ultrasound apparatus [ii]. The maximum achievable frame rate of the commercial system was 500 image frames per second (fps) at reduced imaging window size. Using such frame rates, we were able to raise the measurable maximum velocity 50 *cm/sec*, with axial resolution up to 1.2 *mm* and lateral resolution of 1.7 *mm*. Although these studies were useful in that they showed the potential for Echo PIV, both the velocity range and spatial resolution were insufficient to meet the full range of vascular blood flow imaging requirements.

2 NEXT GENERATION SYSTEM DESIGN

Accurate measurements of velocity fields using Echo PIV depend on a number of interdependent parameters, which must be optimized for each application. Our initial target for Echo PIV is peripheral vascular imaging, including blood velocity measurements in vessels such as the carotid, brachial, femoral, popliteal, illiac, aortic, and renal arteries, as well as central and peripheral veins. A rectangular field of view is used, which requires a linear array transducer (sector images can be used, but coordinate transformations result in a loss of resolution and accuracy). To measure velocity profiles and shear stress accurately, we estimate 20 vectors will need to be measured across the vessel lumen [ix]. Thus, for a 1.0 *cm* vessel, the minimum resolution perpendicular to the vessel would be 0.5 *mm*. This will then dictate transducer firing characteristics such as pulse length, bandwidth, etc.

Considering the key requirements for vascular velocimetry, a custom echo imaging system from the Tetrad Corp. was designed with a 128-element 1D linear ultrasound array transducer, novel control and receiver system, and signal processing. This was then combined with our Matlab-based Echo PIV processing and display software. The linear array transducer has a 7.8 *MHz* center frequency and a 73% fractional bandwidth (6 *dB*), so it can efficiently transmit and receive ultrasound pulses in a 5-10 *MHz* frequency range. The processing system allows flexible control of system parameters, such as the size of imaging widow, focal depth, imaging frequency, beam line density (BLD, detailed later), power level, etc. Besides allowing display of real-time B-mode images, the system also enables separate acquisition of the summed RF signal into a high-resolution (16 bit) data acquisition (DAQ) card (Gage Applied Technologies, Inc., Canada), so that B-mode images can be generated selectively for Echo PIV analysis.

Figure 2 shows the signal collecting and processing procedures for the customized Echo PIV system. First the linear array transducer scans through the field of view by transmitting and receiving ultrasound pulses sequentially. Backscattered ultrasound is then received by transducer elements and turned into voltage signals which undergo amplification, time gain compensation (TGC) and digitization (analog-to-digital conversion). Then the echo voltages (RF data) pass through digital delay lines to accomplish the focusing functions and be summed together to produce the resulting scan line. The data acquisition (DAQ) card saves selected summed RF data, which are then used to generate B-mode images for PIV analysis.

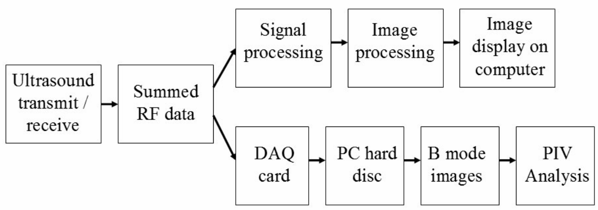

Figure 2: Data path schematic.

Based on the transducer characteristics, the lateral resolution ranges approximately from 0.5 *mm* to 1 *mm*, and the axial resolution is about 0.23 *mm* when the transducer operates at its center frequency.

The total field of view (FOV) required will be based on how much of the vessel geometry needs to be included within the Echo PIV imaging window. However, the larger the FOV, the longer the image takes to acquire, which then reduces not only the overall time resolution, but significantly impacts the dynamic range (i.e. the range of measurable velocities) as follows. In order to get a successful cross correlation between interrogation windows, the same particles must be in view in both windows. For simple PIV processing algorithms, this requires that the particles move across no more than _ of the interrogation window [x] in the interval between images. Thus, _t dictates the maximum measurable velocity. To avoid this stringent limitation, current optical PIV systems employ window offsetting techniques to move the second window to capture the particle motion, which dramatically extends the dynamic range. However, the results presented here do not employ such techniques, and thus represent a conservative estimate of the system performance.

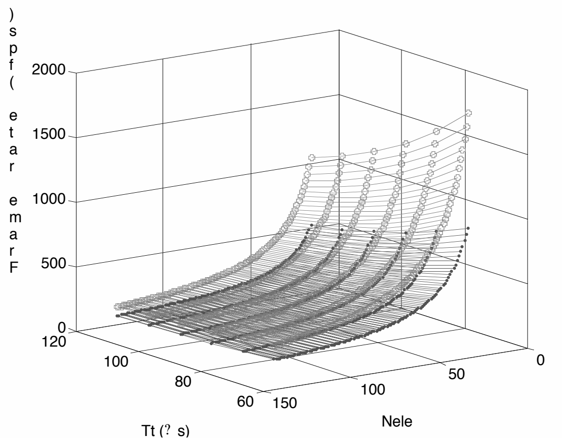

Figure 3: Frame rate as a function of FOV for BLD = 0.5 (red) and 1 (blue).

The maximum frame rate (which is 1/_t) is estimated as follows. *BLD* is the number of scan lines generated within one transducer element width (W_{ele}) in the B-mode image; options for the custom Echo PIV system are 0.5, 1, 2 and 4. The hardware response time T_h is the time period between receipt of the most distant echo and transmission of the next beam, and is set by system hardware to be 3 _s, which is small compared to the typical ultrasound round-trip time for each beam. The width (W_{FOV}) of the FOV is determined by W_{ele} and the number of activated transducer elements (N_{ele}), which ranges from 16 to 128. The length of the FOV is determined by the imaging depth (D) required, which ranges from 30 *cm* to 90 *cm*. Total frame rate FR is thus $FR = \dfrac{1}{T_f} = \dfrac{1}{BLD \times T_t \times N_{ele}}$, where T_t is the total time per beam and c is the speed of sound; $T_t = 2cD + T_h$. Calculated values of FR are shown as a function of FOV in Figure 3.

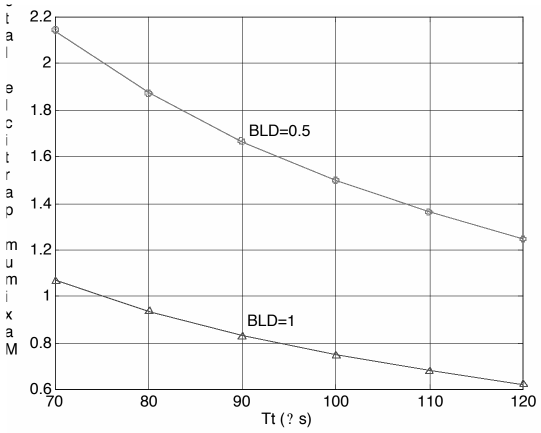

Figure 4: Maximum lateral velocity as a function of image depth.

The maximum frame rate can then be translated into an estimated maximum measurable lateral particle velocity V_{lmax} by assuming that the entire field of view is used for a single interrogation window, and that particles may convect no farther than _ of the window during _t. This case may be useful when a local wall shear stress is of primary interest. Since both the window width and the frame rate are proportional to the number of elements, V_{lmax} is actually independent of N_{ele}, and depends only on image depth, W_{ele} and *BLD:*

$$V_{l\max} = \frac{W_{FOV}/4}{T_f} = \frac{W_{ele}}{4 \times BLD \times T_t}.$$

Figure 4 illustrates this dependence. However, when multiple adjacent subwindows are used across the width of the image, V_{lmax} will be reduced by a factor equal to the number of windows.

3 INITIAL MEASUREMENTS

Initial measurements using the custom Echo PIV system were made on a steady rotating flow and a transient jet flow. The rotating flow was generated in a thin plastic 55 *mm* diameter beaker using a

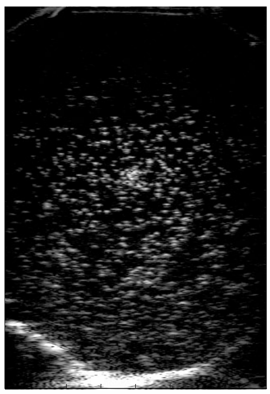

Figure 5: Echo PIV (B-mode) image of dilute contrast agent in a rotating flow.

magnetic stirrer. A 0.012 *ml* volume of commercially available ultrasound contrast microbubbles, Optison® (Amersham, UK), was injected in the beaker for each measurement. Figure 5 shows one B-mode frame of the microbubbles with a 46 *mm* focal depth. Figure 6 shows the resultant Echo PIV velocity vector map using an interrogation window size of 3 *mm* _ 3 *mm* with a 60% overlap of windows.

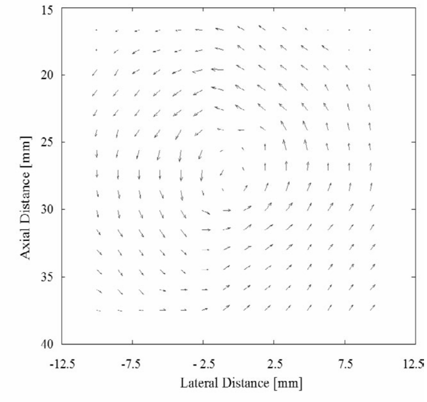

Figure 6: Velocity vectors resulting from Echo PIV processing of the image in Fig. 5.

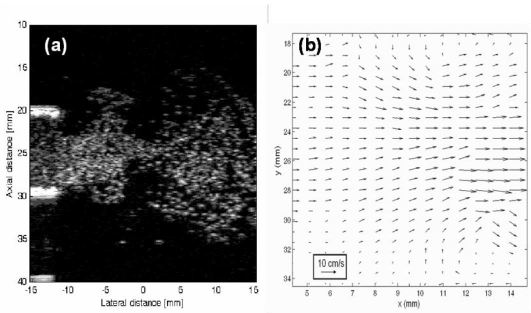

Figure 7: Jet flow measurement using Echo PIV: (a) B-mode particle imaging of the whole flow field; (b) Velocity field of the vortex ring at the head of the jet.

A transient, suddenly started jet, which mimics ventricular filling, was also imaged by Echo PIV (Fig 7). Such a flow is typically difficult to capture using ultrasound Doppler or MRI velocimetry due to the inherently transient nature of the flow, the existence of multi-component velocity vectors and high velocity gradients. Data were obtained at a frame rate of 90 fps using 104 ultrasound beams with focal depth of 24 mm and FOV of 40mm. The sub-window size was 20x20 pixels. Echo PIV provided clear delineation of the velocities in the two vortex rings.

The optimum microbubble concentration was determined by quantitatively evaluating data quality using the cross-correlation index (CCI), which is produced by the cross-correlation function and indicates the effectiveness of the pattern-matching between the two sub-windows. Optimal local bubble concentration was found at 1~2_10^3/ml. This concentration is about 100 times lower than suggested clinical upper limits for conventional contrast imaging. The CCI can also be used as a real time indicator of optimal bubble concentration during *in vivo* imaging.

4 CONCLUSION

Echo PIV is a promising new non-invasive technique for vascular flow imaging. Estimates spatial resolution and dynamic velocity range were derived based on transducer specifications and controllable system parameters. Successful initial measurements were made in rotating and transient flows.

REFERENCES

[i] Zananiri FV, Jackson PC, Halliwell M, Harris, RA, Hayward JK, Davies ER, Wells PNT (1993): A comparative-study of velocity-measurements in major blood-vessels using magnetic-resonance-imaging and doppler ultrasound, *Brit. J. Radiology*, **66**, pp. 1128-1133.

[ii] Kim HB, Hertzberg JR, Shandas R. (2004): Development and validation of echo PIV', *Exp. Fluids*, **36**, pp. 455-462.

[iii] Samijo SK, Willigers JM, Barkhuysen R, Kitslaar, PJEHM, Reneman RS, Brands PJ, Hoeks APG (1998): Wall shear stress in the human common carotid artery as function of age and gender, *Cardio. Res.* **39**, pp. 515-522.

[iv] Forsberg F, Morvay Z, Rawool NM, Deane CR, Needleman L (2000): Shear rate estimation using a clinical ultrasound scanner, *J. Ultrasound Med.* **19**, pp. 323-327.

[v] Crapper M, Bruce T, Gouble C (2000): Flow field visualization of sediment-laden flow using ultrasonic imaging, *Dyn. Atm. and Oceans*, **31**, pp. 233-245.

[vi] Manneville S, Sandrin L, Fink M (2001): Investigating a stretched vortex with ultrafast two-dimensional ultrasonic speckle velocimetry, *Phys. Fluids*, **13**, pp. 1683-1690.

[vii] Sandrin L, Manneville S, Fink M (2001): Ultrafast two-dimensional ultrasonic speckle velocimetry: A tool in flow imaging, *Appl. Phys. Lttrs*, **78**, pp. 1155-1157.

[viii] Gharib M, Beizaie M. (2003):Correlation between negative near-wall shear stress in human aorta and various stages of congestive heart failure, *Annals Biomed. Engr.*, **31**, pp. 678-685

[ix] Kim HB, Hertzberg JR, Lanning C, Shandas R. (2004): Noninvasive measurement of steady and pulsating velocity profiles and shear rates in arteries using echo PIV: In Vitro validation studies. *Annals Biomed. Engr.*, v 32, n 8, August, 2004, p 1067-1076

[x] Keane RD, Adrian, RJ (1990): Optimization of Particle Image Velocimeters .1. Double Pulsed Systems, *Meas. Sci. & Tech.*, **1**, pp. 1202-1215