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Two-dimensional Flow Study in a Stenotic Artery Phantom using Ultrasonic Particle Image Velocimetry

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Abstract—**Blood flow dynamics has an important role in atherosclerosis initiation, progression, plaque rupture and thrombosis, and it is important to investigate the flow characteristics in the context of a mild stenotic artery. In this paper, tissue-equivalent ultrasound phantoms of artery stenosis were fabricated, and ultrasonic particle image velocimetry (EchoPIV) method was applied for two-dimensional flow study. A flow circuit was established and steady flow was provided by the gear pump. Flow at the inlet and the stenosis region were researched with EchoPIV method and ultrasound Doppler technique. The detailed 2D two-component velocity vectors were determined with EchoPIV method, and the measuring accuracy outweighs that of Ultrasound Doppler by comparing to the theoretical values of Poiseuille flow.**

I. INTRODUCTION

STENOSIS happens in carotid artery, renal artery, coronary artery, cerebral artery, and peripheral arteries because of the development of plaques and formation of thrombosis. Accurate measurement of velocity profiles, multiple velocity vectors, and shear stress in arteries is important, because fluid shear stress is correlated to the developments of plaques and the formation of thrombosis [1]. For example, atheroma, plaques, and intimal hyperplasia are prone to happen in regions of flow separation, low mean wall shear, and oscillating wall shear stress [2, 3]. Molecular and cellular level studies also found that hemodynamic shear gradient stimulates the endothelial cell proliferation and favors the developments of plaques and atherosclerosis [4-6].

For accurate measurement of velocity vectors and shear stress, magnetic resonance imaging (MRI), ultrasound Doppler technique, and ultrasound speckle velocimetry have been investigated. However, all have limitations [7-9]. MRI is an attractive technique for blood velocity measurements since it provides multiple components of blood flow and has high spatial resolution. However, MRI possesses several limitations such as its cumbersome nature, expense in time and costs, and poor temporal resolution [7]. Conventional Doppler has the problem of angulations error, which limits the measurement to only the component of velocity along the ultrasound beam, thus requiring parallel alignment of the ultrasound beam to the flow direction. Also, due to limited spatial resolution, the velocity distribution near artery wall could hardly be obtained [8]. Ultrasound speckle velocimetry is to obtain the fluid velocity distribution indirectly by processing speckle patterns generated by scattering particles in fluid. When red blood cells are used as scatters, the signal to noise ratio is relatively low. When ultrasound contrast agents are used as scatters, high dosage is required, and there is potential harm to human body [9]. Thus, a non-invasive technique with good temporal and spatial resolution that can measure multiple-component velocity vectors (and thereby local shear stress) in real time would be an important additional tool to vascular and cardiac investigators.

For multi-component velocity imaging, Ultrasonic particle image velocimetry (Echo PIV) has been developed and become a potentially powerful technique for measuring instantaneous velocity fields in a plane or 3D space. The conventional Echo PIV algorithm consists of identifying and tracking a flow tracer (ultrasound contrast microbubbles) within a flow field, and computing local velocity vectors using a cross-correlation algorithm [10-12]. Echo PIV provides an effective means of quantitatively yet non-invasively characterizing the velocity distribution both in vitro and in vivo experiments.

The accuracy of measuring carotid stenosis is of utmost importance. Current methods include digital subtraction angiography (DSA), Doppler ultrasonography (DUS) and magnetic resonance angiography (MRA) [13]. In this paper, we fabricated tissue-equivalent ultrasound phantoms of artery stenosis, and determined detailed flow velocity distribution of the artery stenosis with ultrasonic particle image velocimetry (EchoPIV). Ultrasound contrast agents were used as flow tracers, and B-mode images were acquired and processed to obtained detailed two-dimensional (2D) flow velocity vectors and magnitude gradient. The accuracy of EchoPIV technique was proven by comparing with the theoretical values and the measuring results of ultrasound Doppler.

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II. MATERIALS AND METHODS

A. Stenosis Model

In order to fabricate the ultrasound phantom of artery stenosis, we first designed a pair of stenosis models. The rods of 8-mm diameter were fabricated on a rapid prototyping system using a material of plastic. Both the male and female rods had progressively tighter cosine-shaped stenosis geometries, as shown in Fig.1.

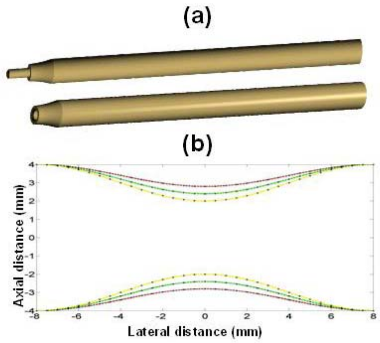

Fig. 1. The male and female rods (a) The 3-D model of the rods; (b) the cosine plots of the stenosis geometries of different stenosis (30%, 40%, 50%)

The rods were constructed in two sections, with the throat of the stenosis forming the join between the halves. The rods were manufactured out of a plastic material with a pin in the stenosis throat to reinforce the junction between each half. The models had a cosine-based geometry, which was defined by equation (1),

$$r(x) = 4\left[1 - \frac{k}{2}\left\{1 + \cos\left(\frac{x\pi}{D}\right)\right\}\right] \qquad (1)$$

where $r(x)$ is the radius as a function of axial distance x (with the origin at the stenosis throat), D is the inlet diameter (8 mm) and k was the degree of stenosis expressed in the range 0–1; for example, for a 50% stenosis by diameter, $k = 0.5$. Here, we fabricated three pair of rods, with different stenosis (30%, 40%, and 50%).

B. A Stenotic Artery Phantom

Tissue-equivalent ultrasound phantoms of artery stenosis were fabricated using agar (3g), silicon carbide particles (3g), glycerol (4g) and distilled water (90g). The chemicals were put into a beaker, stirred and heated until the temperature reaches 90 degrees centigrade to insure the chemicals are totally dissolved. The solution was put in room temperature to cool down to 60 degrees centigrade, and was then poured into a mold of a Perspex box and two joined rods, as in Fig.2(a).. Put the Perspex box at room temperature for about 3h, withdrawn the rods from both sides of the mold, and formed an artery stenosis phantom, as in Fig.2(c). The phantom had a speed value of 1540m/s for ultrasound at 24.5 degrees centigrade.

C. Flow Circuit and Ultrasound System

The flow circuit consisted of the artery phantom connected to a gear pump at one side and a reservoir at the other side. The inlet length was bigger than one meter to ensure fully developed flow at the insonation site. The working fluid was a suspension of microbubbles in de-ionized water. The gear pump provided steady flow. The flow rate through the circuit was measured with a graduated cylinder and a stopwatch. Artery phantoms with stenosis (30%, 40%, and 50%) were under test.

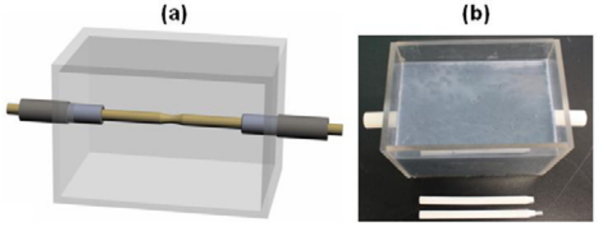

Fig. 2. (a) The descriptive of the mold for forming artery stenosis phantom, the solution at 60 degrees centigrade was poured into the mold; (b) Photograph of the manufactured stenosis model, the male and female rods were withdrawn from both sides to form the ultrasound phantom of artery stenosis.

D. Flow measurement with EchoPIV and Doppler Ultrasound

Doppler Ultrasound and EchoPIV measurement were performed on an ultrasound system (Sonix RP, Ultrasonix Medical Corporation, Canada) with a linear array probe (L14-5W/60). The transmitted frequency was 10.0MHz. For each artery stenosis phantom, Doppler signals were first acquired at a beam-vessel angle of 30 degrees, as a validation for the EchoPIV measuring results. Then, microbubbles were added as flow tracers, and a sequence of B-mode images was recorded at a rate of 100 frames per second, with the transducer vertical to the vessel. An optimized PIV algorithm

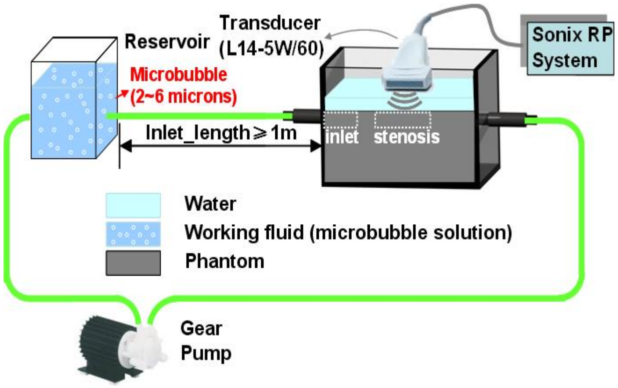

Fig. 3. Flow circuit and ultrasound system for Doppler and EchoPIV experiments, the steady flow was pumped through the stenotic artery phantom, and the flow was studies with ultrasound system.

was developed to process two sequential B-mode images to obtain 2D velocity fields. The detailed description about this algorithm is available in our recent new paper [14]. Here, the optimized algorithm is only briefly described. A cross-correlation method was first applied with a large interrogation window to estimate the displacement, and a multiple iterative algorithm was then adopted to enhance the spatial resolution of the velocity measurement. Twice implementation of the iteration algorithm would result in a final spatial resolution that is four times that of the first pass in each direction for velocity measurement. Then, the sub-pixel method, filter and interpolation method, and removal of spurious vectors were applied to improve the accuracy of velocity measurement. Gaussian peak fitting was used for sub-pixel analysis. The nearest-neighbor interpolation method was used to distinguish the displacement peaks when the displacements of two particles approach zero. Global and local filter was used to eliminate spurious vectors.

III. RESULTS

A. Ultrasound Data Acquisition

Individual frames were taken from the stenosis models using ultrasound system and were shown in Fig. 4. The models are smooth at the point of minimum lumen. The inner diameter at the stenosis point is in good agreement with the rods. In Fig 4(a), the artery boundary is clear in the existence of contrast microbubbles.

The inlet and the stenosis region were under test. The mean inlet velocity (cm/s) and the corresponding Reynolds number values were 1.2 (100), 2.5 (200), and 5.0 (400). Peak velocity at the inlet were calculated theoretically from the flow rate, and measured experimentally from the Doppler, and EchoPIV.

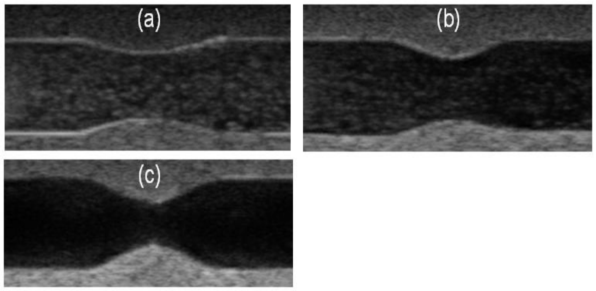

Fig. 4. B-mode images of stenosis artery model of different stenosis. (a)30% stenosis; (b) 40% stenosis; (c) 50% stenosis.

B. Velocity Estimation

The measuring results of the inlet flow were shown in Fig.5. The contrast image of the inlet flow was in Fig.5 (a). By processing two consecutive B-mode images, a 2-D map of velocity vectors at multiple points was obtained (Fig.5 (b)). Also, the velocity magnitude was denoted in colors. For validation, the theoretical value of peak velocity was calculated from the reading number of the flow rate, based on the Poiseuille flow theory. Measured results from Doppler and EchoPIV were compared with the theoretical value, respectively, as shown in Fig.5(c). While Doppler overestimates about 20%, the EchoPIV data were very close to the theoretical values.

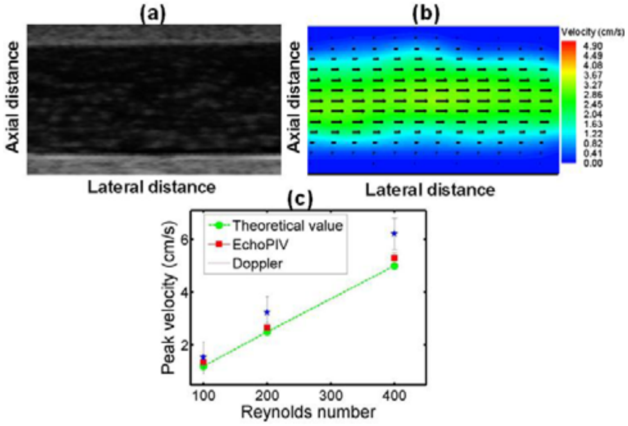

Fig. 5. (a) a B-mode image of the inlet flow; (b) the velocity vector map imposed on the velocity magnitude map, obtained by EchoPIV; (c) the comparison of peak velocity between theoretically-derived values, Doppler-measured values, and EchoPIV-measured values.

Fig. 6(a) shows the contrast image of 40% stenosis. Fig. 6(b) shows the result from EchoPIV method when the Reynolds number was 100. The velocity magnitude was denoted in color. The vectors at multi-points were imposed on the gradient pattern. The velocity maximizes (5 cm/s) at about 8mm downstream from the stenosis, not at the stenosis (4 cm/s). It is supposed that the flow was gradually restricted from the inlet to the stenosis and then jet. Thus, the velocity maximizes at the downstream. The maximum velocities were also measured with the Doppler Ultrasound technique. Similarly, the Doppler-measure velocity values were about 20% above the EchoPIV measured values. The experiments on 30% and 50% stenosis phantom presented similar results. It is regretted that no recirculation was observed in the post-stenosis area. Maybe the stenosis is not severe enough.

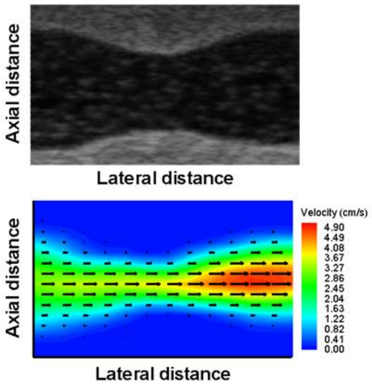

Fig. 6. (a) Contrast image of the 40% stenosis; (b) at Reynolds number of 100, 2-D velocity distribution and magnitude gradient denoted in color

IV. DISCUSSION

It is of great significance to measure the velocity distribution in the context of the artery stenosis accurately. Ultrasound techniques are used widely in the diagnosis of arterial disease and determination of blood flow patterns. However, the general tool, Ultrasound Doppler technique, can only obtain one-dimensional velocity information. Our former research results showed that EchoPIV technique is a promising tool for determining the 2D and multi-component velocity vectors of complex flows. In this paper, we fabricated a tissue-equivalent artery phantom with geometries of cosine-shaped stenosis, and applied EchoPIV technique to measure the flow velocity distribution in the context of artery stenosis. Detailed flow information including the map of velocity vectors and the magnitude map the values of the velocities were obtained. The accuracy of EchoPIV was proven to be better than Doppler.

For phantom studies, the conventional practice is to use components (tissue mimic, vessel mimic, blood mimic) whose acoustic properties are matched to those of human tissues. In the current study we used a wall-less tissue-equivalent artery phantom. The phantom has similar mechanical and acoustic properties as to human tissue and arteries. De-ionized water, not blood mimic, was used as working fluids in experiments. This may cause some discrepancies to the real human blood flow condition. Also, we only research steady flow condition, which is not same as the pulsatile human blood flow. Thus, more experiments should be conducted based on a new pulsatile flow circuit. Furthermore, the phantoms we fabricated here contained only 30%, 40%, 50% stenosis. Phantoms resemble severe artery stenosis (such as 70%, 80% or 90% stenosis) may contribute some interesting results to our research studies.

V. CONCLUSION

In this paper, tissue-equivalent ultrasound phantoms were fabricated, a flow circuit was established, and steady flow was provided by the gear pump to flow through the artery phantom to simulate blood flow in stenotic artery. Ultrasonic particle image velocimetry (EchoPIV) method was applied for detailed 2D two-component flow velocity measurements. The comparison of the measured results of EchoPIV, ultrasound spectral Doppler technique, and the analytical results has demonstrated that EchoPIV can provide a 2D and accurate flow velocity vectors and color-coded velocity magnitude map, and outweigh the ability of traditional 1D Doppler technique.

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REFERENCES

[1] A. M. Shaaban and A. J. Duerinckx, “Wall shear stress and early atherosclerosis: A review,” American Journal of Roentgenology, vol. 174, pp. 1657-1665, 2000

[2] A. M. Malek, J. Zhang, J. W. Jiang, S. L. Alper, and S. Izumo, “Endothelin-1 gene suppression by shear stress: Pharmacological evaluation of the role of tyrosine kinase, intracellular calcium, cytoskeleton, and mechanosensitive channels,” Journal of Molecular and Cellular Cardiology, vol. 31, pp. 387-399, 1999.

[3] Y. N. Jiang, K. Kohara, and K. Hiwada, “Association between risk factors for atherosclerosis and mechanical forces in carotid artery,” Stroke, vol. 31, pp. 2319-2324, 2000

[4] C. M. Gibson, L. Diaz, K. Kandarpa, F. M. Sacks, R. C. Pasternak, T. Sandor, C. Feldman, and P. H. Stone, “Relation of Vessel Wall Shear-Stress to Atherosclerosis Progression in Human Coronary-Arteries,” Arteriosclerosis and Thrombosis, vol.13, pp. 310-315, 1993.

[5] S. Oyre, S. Ringgaard, S. Kozerke, W. P. Paaske, M. Erlandsen, P. Boesiger, and E. M. Pedersen, “Accurate noninvasive quantitation of blood flow, cross-sectional lumen vessel area and wall shear stress by three-dimensional paraboloid modeling of magnetic resonance imaging velocity data,” Journal of the American College of Cardiology, vol.32, pp.128-134, 1998.

[6] Y. N. Jiang, K. Kohara, and K. Hiwada, “Association between risk factors for atherosclerosis and mechanical forces in carotid artery,” Stroke, vol.31, pp.2319-2324, 2000.

[7] J. N. Oshinski, D. N. Ku, S. Mukundan et al, “Determination of wall shear stress in the aorta with the use of MR phase velocity mapping.” Journal of Magnetic Resonance Imaging, vol.5, pp.640-647, 1995

[8] A. Benetos, A. Simon, J. Levenson et al. “Pulsed Doppler: an evaluation of diameter, blood velocity and blood flow of the common carotid artery in patients with isolated unilateral stenosis of the internal carotid artery”. Stroke, vol.16, pp.969-972,1985

[9] L. Sandrin, S. Manneville, M. Fink, “Ultrafast two-dimensional ultrasonic speckle velocimetry: A tool in flow imaging,” Applied Physics Letters, vol.78, pp.1155-1157, 2001

[10] H.R. Zheng, L.L. Liu, L. Williams, J.R. Hertzberg, C. Lanning, R. Shandas, “Real time multicomponent echo particle image velocimetry technique for opaque flow imaging” Applied Physics Letters, vol. 88, 261915, 2006

[11] L.L. Niu, M. Qian, K. Wan, W.T. Yu, Jin QF, T. Ling, S. Gao, H.R. Zheng, “Ultrasonic particle image velocimetry for improved flow gradient imaging: algorithms, methodology and validation,” Physics in Medicine and Biology, vol.55, pp. 2103-2120, 2010

[12] M. Qian, L.L. Niu, Y.P. Wang, B. Jiang, Q.F. Jin, C.X. Jiang, H.R. Zheng, “Measurement of flow velocity fields in small vessel-mimic phantoms and vessels of small animals using micro ultrasonic particle image velocimetry (micro-EPIV),” Physics in Medicine and Biology, vol.55, pp. 6069-6088, 2010

[13] D. Netuka, S.Ostry, T. Belsan, et al, “Magnetic resonance angiography, digital subtraction angiography and Doppler ultrasonography in detection of carotid artery stenosis: a comparison with findings from histological specimens,” Acta Neurochirurgica, vol.152, pp.1215-1221, 2010

[14] L.L. Niu, M. Qian, K. Wan, W.T. Yu, Q.F. Jin, S.Gao, and H.R. Zheng, “Ultrasonic particle image velocimetry for improved flow gradient imaging: algorithms, methodology and validation,” Physics in Medicine and Biology, vol.55, pp. 2103-2120, 2010