Quantitative Visualization of Blood with Diffraction/Interference-based Enhancement

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1. Introduction

Several experimental techniques commonly used in straight fluid mechanics researches have been employed to investigate flow characteristics of blood in a single channel, a stenosis-shape duct, and a branched duct. Most of them, however, have been unsatisfactory due to difficulty encountered in visualizing the opaque blood. Because RBCs charge about 45% (39%) of human blood for male (female) in volume, it is difficult to visualize blood flow with direct seeding of dye or tracer particles. Therefore, most hemodynamic researches have mainly been carried out using transparent substitutes of plasma and blood cells. For the cases of the conventional medical instruments such as MRI (Magnetic Resonance Imaging), ultra-sonography, CT (Computed Tomography) angiography or X-ray angiography, it is also difficult to get fluid-mechanic information of blood, despite of their permeability, due to their low contrast sensitivity and poor spatial resolution for real blood cells.

In this research, a highly coherent synchrotron x-ray source was used to visualize real blood using the phase-contrast radiology. The phase-contrast imaging mechanism is quite similar to the spatial variations of refractive index under visible light. At an edge between two objects having different refractive indices, the different deviations of light beams from the two sides create typical white-dark fringes, from enhancing the edge visibility.[1] Real blood flow, however, is not visualized with simple phase-contrast mechanism of synchrotron x-ray source as medical instruments aren't. This is mainly attributed to small difference of refractive index between blood cells and plasma. In this research, the fringe pattern of blood is induced by using other phase-contrast mechanism of Fresnel diffraction and interference-based enhancement of coherent synchrotron x-ray beam. In order to get a recognizable blood pattern, we optimized the experimental condition for the diffraction/interference-based image enhancement.

2. Experimental method

2.1 Experimental setup

The experiments were performed using (unmonochromatic) beam at the 1B2 beam line of the Pohang Accelerator Laboratory (PAL). A schematic diagram of the experimental setup for the synchrotron x-ray imaging method is shown in Fig. 1. The x-ray beam is converted into visible waves by passing $CdWO_4$ scintillator crystal. The blood patterns were recorded by a cooled CCD camera of 1280×1024 pixels resolution. The lateral resolution (Δx) is better than 5 μm when the CCD camera is coupled with a 10× magnification lens. Because the x-ray used is continuous beam, we installed a mechanical shutter to exposure x-ray beam on a test sample only when we capture images for short time interval (10 ms). A delay generator was used to synchronize the mechanical shutter and the CCD camera.

2.2 Pattern enhancement

To verify the effect of the diffraction and interference-based enhancement method on blood imaging, we captured 36 x-ray images of blood with varying the sample-to-detector distance (d=10, 20, 30, 40, 50 and 60 cm) for diffraction enhancement and the sample thickness (t=1, 2, 3, 4, 5 and 10 mm) for interference enhancement. In previous study, we found that the interference-based pattern enhancement becomes effective when the thickness of blood sample is larger than 1mm. In this study, we measured the pattern of blood of 1~10 mm thick. This size corresponds to the inner diameter of artery (~4 mm), considering coronary arteriosclerosis, carotid artery stenosis, etc.

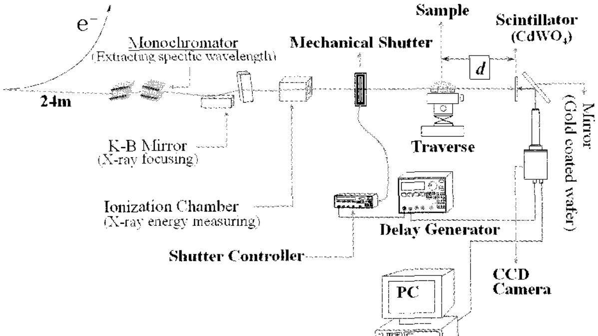

Fig. 1 Schematic diagram of experimental setup for synchrotron x-ray imaging

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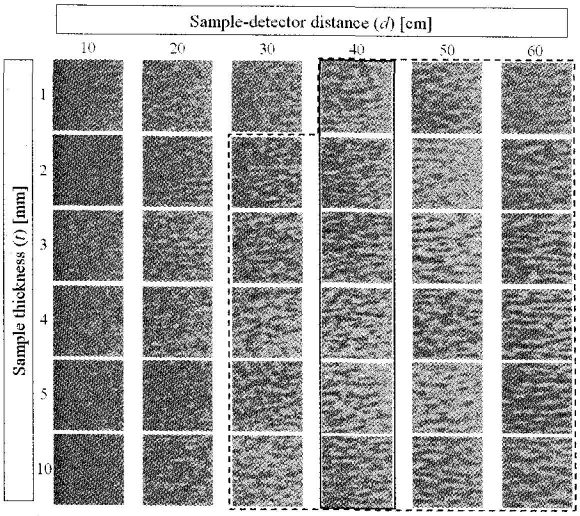

Fig. 2 Blood pattern images captured by the diffraction and interference-based enhancement

3. Results and discussion

Due to diffraction enhancement, as we can see from Fig. 2, the blood image becomes to show detectable pattern with increasing the sample to detector distance d. When the distance d is larger than 30 cm, the blood pattern is recognizable except the case of t=1 mm. When the distance d is over 50 cm, however, the blood patterns begin to be slightly blurry due to excessive diffraction enhancement. Nevertheless the blood pattern is still reasonable for recognizing blood (dot-line box). In this research, the patterns in the solid-line box of Fig. 2 are clearly suitable for applying PIV algorithm for velocity field measurements.

In the point of view of interference enhancement, the blood patterns are recognizable for the sample thickness of t=1~10 mm. Especially, the blood sample of 10 mm thickness show good permeability of x-ray beams even though the sample thickness of 10 mm is too tough (or thick) to visualize the diffraction or interference pattern using the synchrotron x-ray source. It is interesting to notice that the x-ray images at the distance d=40 cm show excellent enhancement for PIV analysis irrespective of sample thickness. This range of experimental condition is marked by a solid-line box. From these results, we can see that our diagnosis will be available for thicker blood sample such as blood flow in aorta or heart.

In addition, we captured 15 x-ray images of blood patterns with changing the volume concentration of blood cells (c=0.0, 2.4, 6.5, 9.1, 10.0, 13.0, 14.3, 16.7, 20.0, 25.0, 33.3, 45.0, 50.0, 66.7 and 100 %) and the results are shown in Fig. 3. The concentration c=0.0 % consists of only plasma and the concentration c=100 % denotes pure blood cells (condensed blood). The concentration c=45 % represents the whole blood. All images were captured under the condition of diffraction and interference enhancement with d=40 cm and t=3 mm to verify the effect of blood cells existence in the image enhancement. For the cases of c=0~6.5 %, as the concentration of blood cells increases, the blood pattern becomes to appear slightly. The blood pattern is dramatically recognizable at the concentration of c=9.1 %. This indicates that the blood pattern is formed due to presence of a amount of blood cells. The blood patterns for the concentration of 9.1~50.0 % (dot-line boxes) are clearly visible. The blood patterns disappear when the concentration c is over 50.0 %, and the pattern of the condensed blood (c=100 %) is almost unrecognizable. This particular phenomenon can be explained as follows; a certain amount of plasma having different refractive index from blood cells is required to form the fringe pattern of blood cells. The blood sample with higher concentration blood cells without the minimum space of plasma might be considered as a sample of a single refraction index. Therefore, the sample cannot induce any diffraction, interference or refraction from the difference of refractive indices between blood cells and plasma.

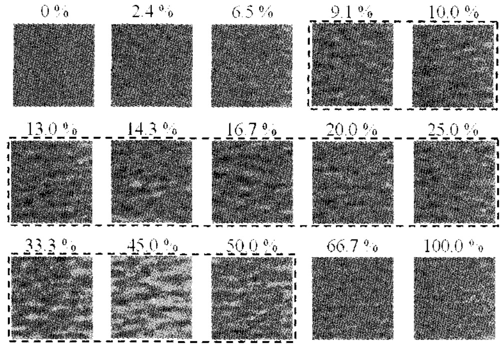

Fig. 3 Blood pattern images with respect to blood cells concentration (volume fraction)

4. Conclusion

In this study, we found the optimum condition (sample to detector distance, sample thickness and blood cells concentration) for acquiring suitable x-ray images of blood pattern which can be used for PIV velocity field measurements. As the sample-detector distance increases, the RBC flow pattern becomes detectable with the induced diffraction-based enhancement. The optimum distance was about 40 cm. The x-ray imaging technique also can be applied to blood samples thicker than 1 mm, corresponding to blood flow in artery, aorta and heart comportments. For the blood cells concentration of 9.1~50.0 %, the x-ray blood pattern is clearly visible. These results can be used for visualizing and analyzing blood flow of real blood quantitatively without any seeding particles.

Acknowledgments

This work was supported by grant No.R01-2004-020-10500-0 from Korea Science and Engineering Foundation.

References

(1) Hwu, Y., *et. al.*, 2004, "Synchrotron microangiography with no contrast agent", Phys. In Medicine and Biology, vol. 49, pp. 501~508.