Visualization of flow structures inside the patient specific aneurysm model

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Abstract Cerebral aneurysm is a cardiovascular disorder which causes serious conditions such as subarachnoid hemorrhage. Recently, a number of hemodynamic analyses have been conducted to reveal the correlation between the hemodynamics and aneurysmal rupture. Especially, measurement of three-dimensional velocity and wall shear stress (WSS) distributions inside patient-specific elastic-vessel-wall models under pulsation is highly in demand to extract the hemodynamic parameters for the rupture prediction. This study aims to develop an experimental system to visualize the three-dimensional flow fields and the WSS distributions inside the cerebral aneurysm models whose wall position repeatedly changes due to the flow pulsation. An elastic patient specific aneurysm model was fabricated using a transparent silicone rubber so that the model reproduced the periodic deformation under pulsation which imitated the average flow rate waveform of healthy men. The velocity distribution inside the aneurysm was measured by the scanning stereoscopic particle image velocimetry (SSPIV). For the three-dimensional velocity measurement, the model was dipped in an index-matching-liquid bath to eliminate optical distortions. Because the index matching also conceals the model wall, the wall position, which is necessary to calculate the WSS, was estimated by superimposing the particle images and applying the marching cubes method. The WSS was calculated from the reconstructed wall and the near-wall velocity information acquired by the SSPIV. The three-dimensional rotational flows inside the aneurysm model were successfully visualized at all three different pulsation phases we measured. Furthermore, we also successfully reconstructed the three-dimensional wall geometry of the model and observed the periodical changes of the elastic model wall and corresponding WSS distribution in the aneurysm.
Keywords: Cerebral aneurysm, Scanning stereoscopic-PIV, Wall shear stress, Wall estimation

1 Introduction

Cerebral aneurysm is a cardiovascular disorder whose balloon-like shape is formed by expanding the cerebral artery. Although the prediction of aneurysmal rupture is essential for the precaution of serious conditions such as subarachnoid hemorrhage (of which 30% patients die immediately), there is no reliable prediction method because the underlying mechanism of the growth and rupture of aneurysm still remains unclear. Therefore, a variety of hemodynamic analyses are conducted in order to understand the mechanism both numerically and experimentally. Many numerical studies suggest that it is essential to obtain the three-dimensional velocity distributions inside patient-specific elastic vessel-wall models under pulsatile flow conditions for the reliable evaluation and extraction of the hemodynamic parameters to predict the rupture risk [1, 2]. However, in experimental studies, measurement of three-dimensional flow inside moving wall is challenging. The aim of this study is to develop an experimental system that can measure three-dimensional velocity fields and the wall position of deformable aneurysm models and to measure the flow inside the patient-specific aneurysm models in which velocity and the wall repeatedly change due to the pulsation.

2 Experimental method

A patient specific aneurysm model was fabricated from transparent silicone rubber based on the digital subtraction angiography (DSA) data of a patient. The thickness of the model wall was adjusted to approximately 0.6 mm so that the model exhibits the mechanical properties of the original aneurysm. The velocity distribution inside the aneurysm model is measured by the scanning stereoscopic particle image velocimetry (SSPIV) under the pulsatile flow condition which imitates the average blood flow rate waveform of healthy men [3]. The model was dipped in a liquid bath which was filled with liquid having the same refractive index to the silicone to eliminate the optical distortion (index matching). For the wall shear stress (WSS) determination, the wall position (which was invisible due to the index matching) was estimated from superimposed particle images and three-dimensional geometry was reconstructed using the marching cubes method. The WSS was calculated from the reconstructed wall and the near-wall velocity information acquired by the SSPIV. Here, the flow field and the WSS distribution were obtained at the timing of maximum, average, and minimum flow rate (denoted as Phases 1-3, respectively).

3 Results and discussion

Measurement results of flow fields and WSS distributions in the model is shown in Fig. 1. Stagnation regions in the bleb part (top portion of the aneurysm) and a rotational flow were observed in all Phases. The visualization shows that the flow enters into the aneurysm at the edge of the neck (opening section) and a large part of the flow direction at the neck cross-section is toward the outlet branches at low velocity. In addition, owing to the pulsation, the shape of the elastic model indicates the periodic change. The surface area of the aneurysm was increased by 6.9% from the minimum to the maximum flow rate (from Phase 3 to Phase 1) whereas the flow rate was increased by 55%. The WSS distribution also changed due to the pulsation. Moreover, the WSS was gradually decreased as the distance from the parent vessel increased. Especially at the timing of minimum flow rate (Phase 2), the WSS was extremely low at the bleb.

4 Conclusion

In conclusion, we successfully observed the instantaneous deformation of the model as well as the velocity and the WSS field synchronized with the pulsation of the flow. The result suggests that the WSS measurement with elastic walls under the pulsatile flow condition will provide valuable information to understand the growth and the rupture mechanisms.

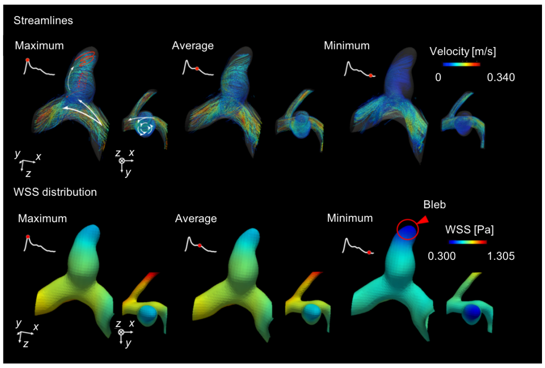

Fig. 1 Streamlines and WSS distributions in the patient-specific model in Phases 1-3.

References

[1] Torii R, Ohshima M, Kobayashi T, Takagi K, Tezduyar T E (2006) Fluid-structure interaction modeling of aneurysm with high and normal blood. *Computational Mechanics,* vol. 38, pp 482-490. doi: 10.1007/s00466-006-0065-6

[2] Bazilevs Y, Hsu M C, Zhang Y, Wang W, Liang X, Kvamsdal T, Brekken R, Isaksen J G (2010) A fully-coupled fluid-structure interaction simulation of cerebral aneurysms. *Computational Mechanics,* vol. 46, pp 3-16. doi: 10.1007/s00466-009-0421-4

[3] Ford M D, Alperin N, Lee S H, Holdswoth D W, Steinman D A, (2005) Characterization of volumetric flow rate waveforms in the normal internal carotid and vertebral arteries. *Physiological Measurement,* vol. 26(4), pp 477-488. doi: 10.1088/0967-3334/26/4/013