CONCENTRATED HIGH WALL SHEAR STRESS DUE TO THE TORSION OF THE AORTIC ARCH AND DEVELOPMENT OF THE AORTIC ANEURYSM

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INTRODUCTION

Aneurysm is a disease in which an area of arterial wall is expanded as the result of the decreased resistance of the wall structure against the internal pressure. In most cases the wall is fatally ruptured. Aneurysm is one of the serious diseases of circulatory system, and the thoracic aorta is known to be a site where aneurysms frequently develop.

The thoracic aorta consists of the ascending aorta (which extends from the left ventricle), the aortic arch (where the aorta curves about 180°), and the descending aorta. Of these three regions, the aortic arch has a characteristic configuration. One of its characteristics is that the centerline of the arch does not lie in a plane (non-planer). Yoshii et al. found a risk factor of the structure at the aortic arch with respect to the development of thoracic aneurysms by observing realistic three-dimesionally reconstructed images of the aortic arch using computed tomographical slices [1]. They introduced two characteristic angles, namely X, and Y defined as the angles between the ascending aorta and the ascending arch leg, and between the ascending and descending arch legs, respectively. These angles are quantitative measures of the distortion of the arch. They plotted these angles for 15 normal, and 10 aneurysm cases, as shown in Fig. 1. As clearly seen, it was suggested that the lower the X and Y angles were, the more frequently an aneurysm developed.

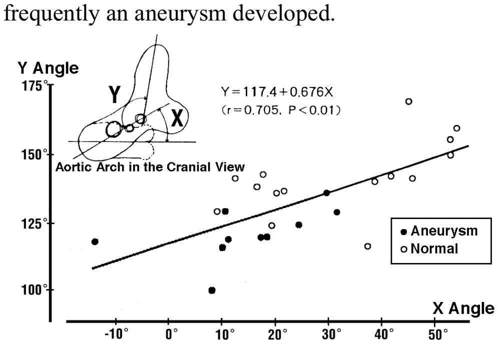

Figure 1. Relationship between X and Y angles [1]

However, their suggestion was not based on hemodynamic examinations. The correlation between the localization of various diseases, particularly atherosclerosis, and the distribution of fluid dynamical quantities [2,3] was not fully investigated in their study. Thus, in this study, our aim was to analyze the flow in various aortic arch models using computational fluid dynamics simulation in order to investigate the correlation between the aneurysms of the thoracic aorta, and the distortion of the arch from a fluid dynamical point of view.

METHOD

Computational Models

The computational models were constructed by using the Yoshii's X, and Y angles aforementioned as parameters which determine the shape of the vessel. A series of the centerlines of the aorta was parametrically defined based on the X, and Y angles, as shown in Fig. 2, and fitted to a cubic spline curve. Finally, the computational grids were generated on the normal planes along those space curves. Using this method, 15 models of the normal cases, and 10 models of the aneurysm cases were built. A radius of the arch, R shown in Fig. 2, was set to be 3.0 cm, and the diameter of vessel was

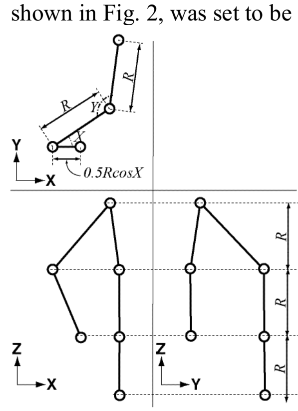

Figure 2. Definition of the aortic centerline

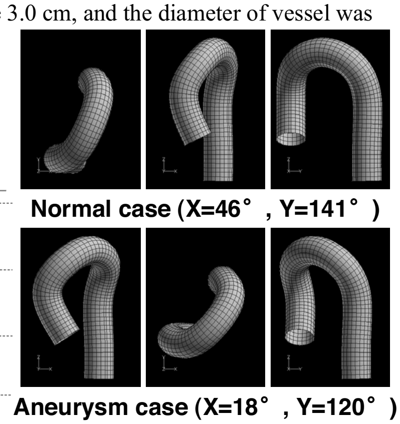

Figure 3. Representative computational models

assumed to be 2.0 cm. Figure 3 shows a representative model of the normal cases in which (X, Y) = (46°, 141°) (left), and a model of the aneurysm cases in which (X, Y) = (18°, 120°) (right). In the models of normal cases, the ascending aorta, the aortic arch, and the descending aorta tended to lie in a same plane, that is, they are planer as compared to the models of aneurysm cases.

Analysis

A commercial CFD program, SCRYU version 1.4, manufactured by Software Cradle, Osaka, Japan, was used for the computations. The following 3-D unsteady Navier-Stokes equations were solved:

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \mu \nabla^2 \mathbf{u}, \quad (1)$$

$$(\nabla \cdot \mathbf{u}) = 0, \quad (2)$$

where ρ is the density of the fluid, $\mathbf{u}$ is the velocity, p is the pressure, and μ is the viscosity. The solution was advanced in time using a finite volume method of discretization. The following boundary conditions were used: no-slip at the wall, zero pressure and zero velocity gradient at the outlet, and steady uniform velocity perpendicular to the cross section at the inlet. The Reynolds number defined by the velocity and the diameter at the inlet was 1,600.

RESULTS

Secondary Flow Pattern

Figure 4 shows the streamlines at certain cross sections along the arch. The upper and lower rows illustrate the flow in the normal model, and the aneurysm model, respectively. The global flow pattern was observed not to be significantly different among all of them, regardless they were from healthy and disease cases. The flow was composed of a large right-handed rotational flow at the top of the arch (left column), and a large left-handed rotational flow at the downstream end of the arch (right column).

Wall Shear Distribution

Figure 5 illustrates the wall shear stress (WSS) distributions of same models shown in Fig. 4. It was shown that the localized patterns of the high and low WSS were not again strongly different between the normal and the aneurysm models, similar to the secondary flow patterns. Relatively high WSS region were observed around the upstream end of the arch, and the downstream end of the arch where the centerline of the vessel breaks away from the plane formed by the centerline of the arch, as shown by circles in Fig. 5.

Figure 6 shows the relationship between the X and Y angles, and the peak WSS values at the region of the downstream end of the arch where Yoshii et al. [1] pointed out that aneurysm preferentially develops. The size of circle is proportional to the magnitude of the WSS value, and the numeral within the circle shows the value itself with a unit of 10^{-2} [Pa]. It is noted that the WSS tends to increase with decreasing of both the X, and Y angles. In case of models with large X, and Y angles, that is, normal cases, the WSS was observed to be remarkably low compared with the aneurysm cases.

DISCUSSION AND CONCLUSION

In this study, it was observed that the global feature of the secondary flow pattern, and the WSS distribution was not depend on the X, and Y angles measured by Yoshii et al. from qualitative view. However, the quantitative value of the WSS was demonstrated to be apparently affected by the angles. This result suggest that the distortion of the aortic arch strongly influences the wall shear stress distribution in the site where the aneurysm preferentially develops.

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REFERENCES

1. Yoshii, S., Kamiya, K., Matsukawa, T., and Ueno, A., 1988, "3D Analysis of the Aortic Arch Aneurysm: Importance of the Transverse Arch Curve from the Horizontal View," J. Jpn. Surg. Soc., (in Japanese), 89, p. 972.
2. Caro, C. G., Fitz-Gerald, J. M., and Schroter, R. C., 1971, "Atheroma and Arterial Wall Shear: Observation, Correlation and Proposal of a Shear Dependent Mass Transfer Mechanism of Atherogenesis," Proc. R. Soc. Lond., B 177, pp. 109-159.
3. Fly, D. L., 1972, "Localizing Factors in Arteriosclerosis," In atherosclerosis and Coronary heart disease, W. Likoff et al., eds., Grune and Stratton, pp. 85-104.

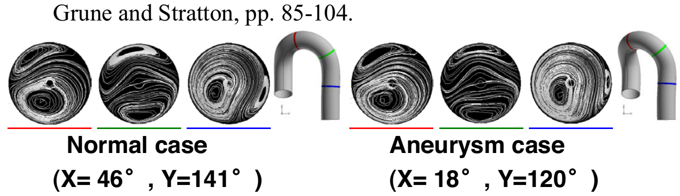

Figure 4. Secondary flow pattern at certain cross sections along the arch

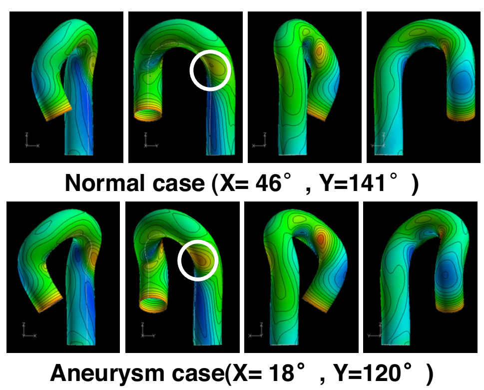

Figure 5. WSS distribution from different directions

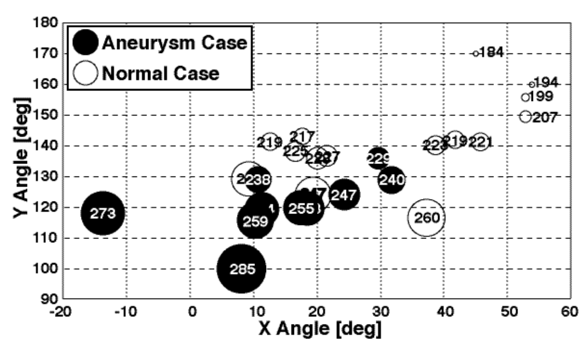

Figure 6. Relationship between X and Y angles and WSS value at the region of the downstream end of the arch