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Hemodynamic Characteristics in Aorta-Pulmonary Artery System

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Abstract. The child patients of hypoplastic left heart syndrome undergoes major operations such as the Norwood procedure, the Bidirectional Glenn procedure and the Fontan procedure. Patent Ductus Arteriosus (PDA) stenting, which is instead of these procedures, is recently performed to prevent closure of ductus arteriosus and to alleviate the burden for the patient. This study clarified that hemodynamics in aorta-pulmonary artery system and mechanism of thrombus formation using Computational Fluid Dynamics (CFD) analysis and Particle Imaging Velocimetry (PIV) measurement. As a result of CFD analysis, low wall shear stress was observed at neighborhood of PDA stent. From results of CFD analysis and PIV measurement, the main blood flow was formed toward from aorta to pulmonary artery and there is no blood stagnation region in PDA.

1. Introduction

Hypoplastic left heart syndrome is one of the congenital heart diseases. The disease is characterized by hypoplasia of left atrium, mitral valve and aortic arch. In such the patient, blood flow balance is kept by patent ductus arteriosus (PDA) during unborn child. After birth, ductus arteriosus is naturally closed and then blood flow to lungs increase. This blood flow balance change causes various symptoms like lungs hyperemia, polypnea, oliguria and shock state. In order to treat the child patient some operations are required; i.e., the Norwood procedure and the Bidirectional Glenn procedure and [1, 2]. The Fontan procedure is finally performed to improve cardiopulmonary function. PDA stenting is recently performed to prevent from ductus arteriosus closing instead of the Norwood procedure and the Bidirectional Glenn procedure [3]. This surgery makes less burden on the patients compared with the conventional procedures. However, some clinical reports have reported that PDA stenting causes thrombosis around ductus arteriosus [4-6]. The detail mechanism why thrombus is formed has not been clarified until now. It is necessary to unravel blood flow balance of aorta-pulmonary artery system in the state of PDA. The purpose of this study is to elucidate hemodynamics of aorta-pulmonary artery system and thrombus formation mechanism using particle image velocimetry (PIV) measurement and computational fluid dynamics (CFD) analysis.



2. Method

2.1. Numerical Simulation

In order to estimate the influence of PDA stent on blood flow characteristics around PDA, CFD analysis is performed using CFX ver.18 (ANSYS Co.). The Analysed PDA model is shown in Fig. 1. As for boundary condition of CFD analysis, inlet flow rates at the aorta and pulmonary artery were set at 4.89 (L/min) and 2.11 (L/min), respectively. Outlet boundary conditions were given pressure Neumann boundary condition. Furthermore, wall boundary was given no slip condition. Shear stress transport (SST) model was used as a turbulent flow model. This analysis assumed blood as Newtonian fluid of which kinetic viscosity was set at $4.43 \times 10^{-3} \text{ m}^2/\text{s}$.

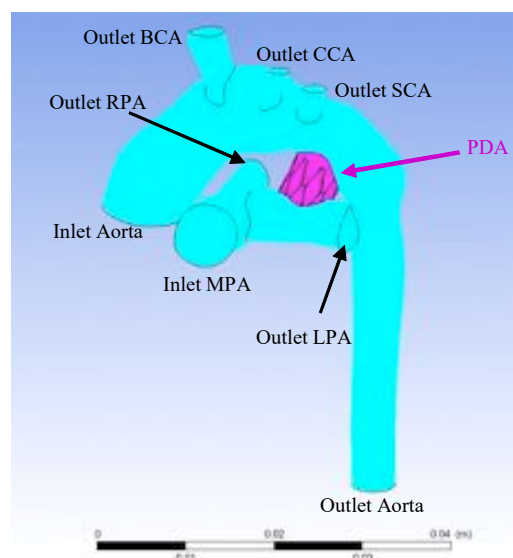


Figure 1. Analysis model of aorta-pulmonary artery system

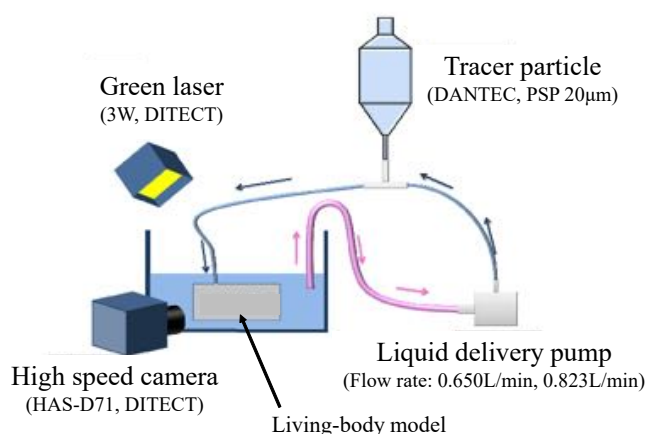


Figure 2. Experimental apparatus of PIV measurement.

2.2. Particle Image Velocimetry

PIV measurement has been developed as a calculation method for unsteady and instantaneous flow characteristics using image analysis techniques. Fluid motion is visualized by tracer particle in fluid flow, and then is numerically evaluated using digital image processing [7, 8]. The PIV apparatus in this study is shown in Fig. 2, and composes of a high-speed camera (DITECT D71, 800fps), a laser light

source (DITECT 3W green laser), tracer particles (DANTEC PSP 20 μ m) and aqueous glycerine solution as working fluid. A living-body model of aorta-pulmonary artery system was made from silicon rubber and it is twice as large as the actual body scale (Fig. 3). Centrifugal pumps connected with both aorta and pulmonary artery inlets of the model. These flow rates are 0.650 L/min and 0.823 L/min, respectively.

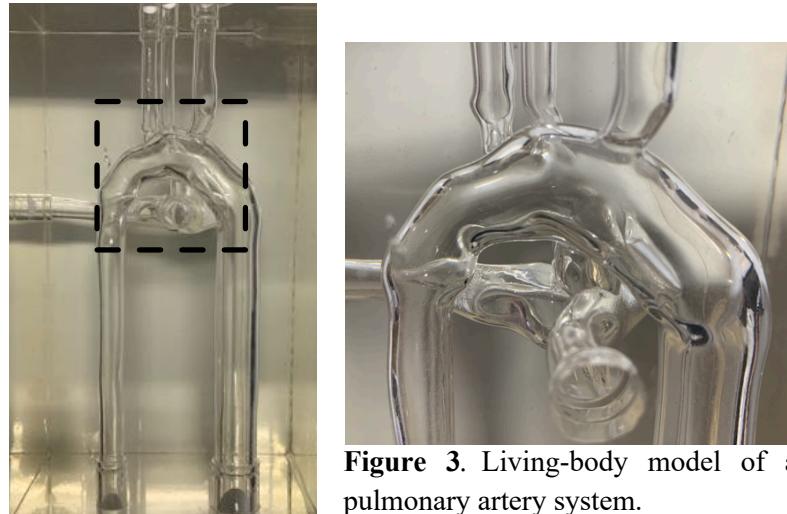


Figure 3. Living-body model of aorta-pulmonary artery system.

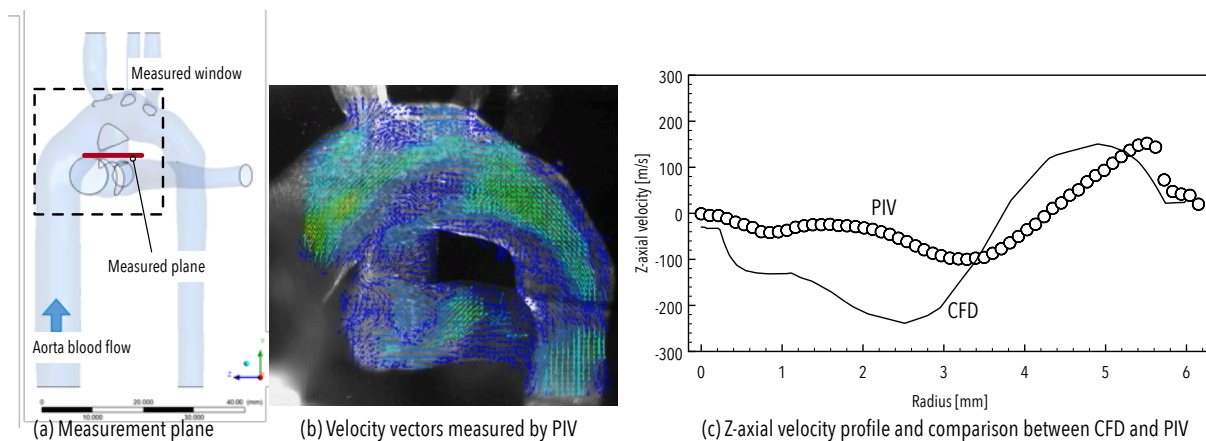


Figure 4. Measurement results of PIV experiment; velocity vectors and Z-axial velocity profile

3. Result and Discussion

Figure 4(a) and 4(b) show a 3-D data of original form of living-body model and velocity vector on a vertical section of PDA. As the result of the velocity vector, the main blood flow was formed toward from aorta to pulmonary artery. Figure 4(c) shows the measured Z-axial mean-square velocity profiles on a red line of Fig. 6(a), comparing with the result of CFD analysis. The results of CFD analysis and PIV measurement have not correspond quantitatively. However, the tendencies of the results show good agreement between them. This study assumed such the differences does not affect in following discussions significantly, using the results of PIV measurement and CFD analysis. Furtherer investigation and discussion are needed for the differences between PIV and CFD.

Fig. 4(b) and 4(c) reveal detail blood flow characteristics inside PDA; main blood flow was globally formed toward from aorta to pulmonary artery, at the same time, reverse direction flow was partially formed toward from pulmonary artery to aorta. In other words, aorta-pulmonary artery system is maintained blood flow balance by bilateral flow between aorta and pulmonary artery.

Figure 5 shows the streamlines in the aorta-pulmonary artery system calculated by means of CFD analysis. This result involves the influence of PDA stent installation. The laminar flow was observed in aorta and pulmonary artery, and complex and turbulence flows were observed around PDA. The main blood flow was formed toward from aorta to pulmonary artery as shown in the result of PIV measurement. Figure 6 shows wall shear stress (WSS) distribution in PDA. The areas alongside PDA stent showed partially lower WSS than other areas. This tendency implies that stagnation flow region is formed caused by the stent installation. The prior studies have reported that thrombus is easy to be formed at low WSS region [9-11]. In this study, CFD analysis has clarified that low WSS region is observed on the areas alongside the stent. These results in this study indicate that there is possibility of promoting thrombus formation due to PDA stent.

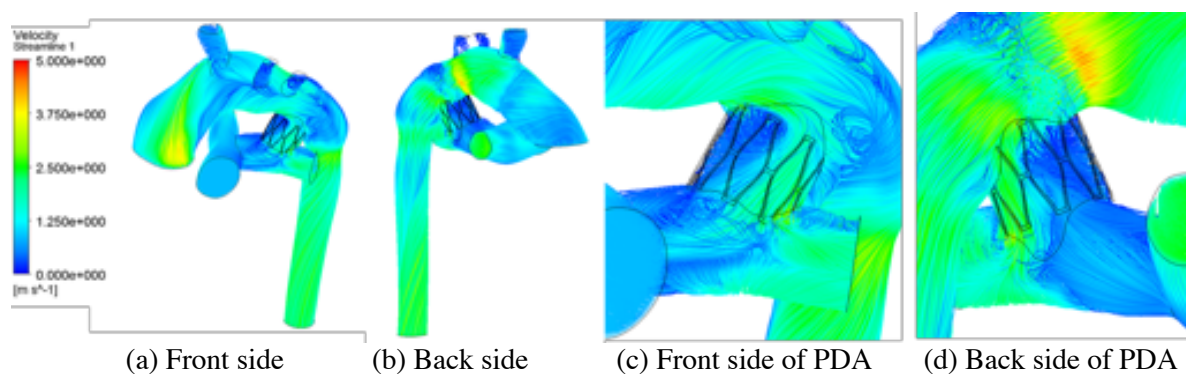


Figure 5. Streamline of blood flow in PDA

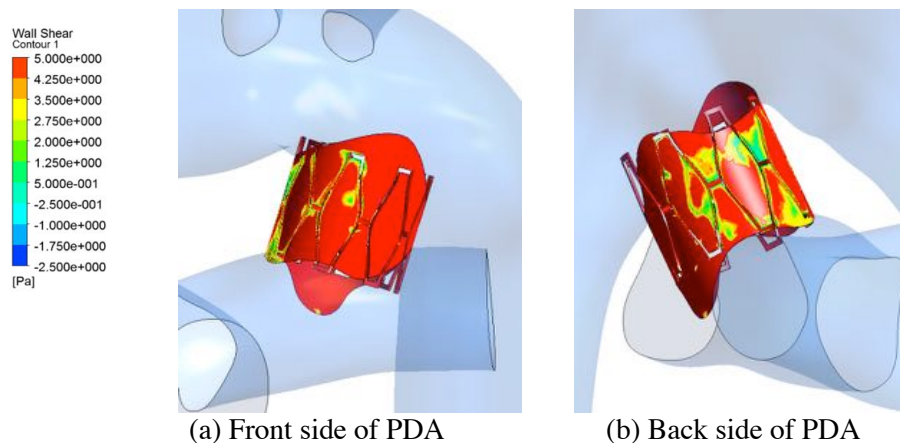


Figure 6. Wall Shear Stress on PDA wall

4. Conclusion

This study conducted both CFD analysis and PIV measurement for blood flow characteristics in aorta-pulmonary artery system. As the results, this study found that (1) main blood flow was observed toward from aorta to pulmonary artery, at the same time, reverse direction flow was also observed toward from pulmonary artery to aorta, (2) low WSS were found in the area alongside PDA stent, meaning that low velocity (stagnation flow) region was formed there, and consequently (3) these results indicate that there is possibility of promoting thrombus formation due to PDA stent.

The results of CFD analysis and PIV measurements show agreement qualitatively and discrepancy quantitatively. Furtherer investigation and discussion is needed for the differences. In addition, this study simplified blood flow as continuous steady flow. In the next study, the author is

going to elucidate pulsate flow characteristics in aorta-pulmonary artery system using Large Eddy Simulation (LES) model and stereo-PIV measurement system[] .

Acknowledgments

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