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A study on hemodynamics changes in aorta-pulmonary artery system caused by patent ductus arteriosus

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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 clarify that hemodynamics in aorta-pulmonary artery system and mechanism of thrombus formation using Computer 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.

Keywords: computational fluid dynamics, particle image velocimetry, patent ductus arteriosus

1. Introduction

Hypoplastic left heart syndrome is one of the congenital heart disease. 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 such as lungs hyperemia, polypnea, oliguria and shock state. In order to save the child patient some operations are required; the Norwood procedure and the Bidirectional Glenn procedure [1, 2]. Finally, the Fontan procedure is performed to improve cardiopulmonary function. PDA stenting is recently performed to prevent ductus arteriosus closing state instead of the Norwood procedure and the Bidirectional Glenn procedure [3]. This surgery is less burden to the patients compared with the conventional procedures. However, some clinical research has reported that PDA stenting causes thrombosis around ductus arteriosus. 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. Material and Method

2.1 Numerical Analysis

In order to estimate the influence of PDA stent on blood flow characteristics around PDA. CFD analysis is performed using CFX ver.15 (ANSYS.Co). The analysis model is shown in Fig. 1. The model was made from CT-data and it was provided from UTM. Size of the ductus arteriosus is approximately 6(mm). The number of elements are 10215715. 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 Neumman boundary condition. Furthermore wall boundary was given no slip condition. Shear stress transport (SST) model was used as a turbulent flow model.

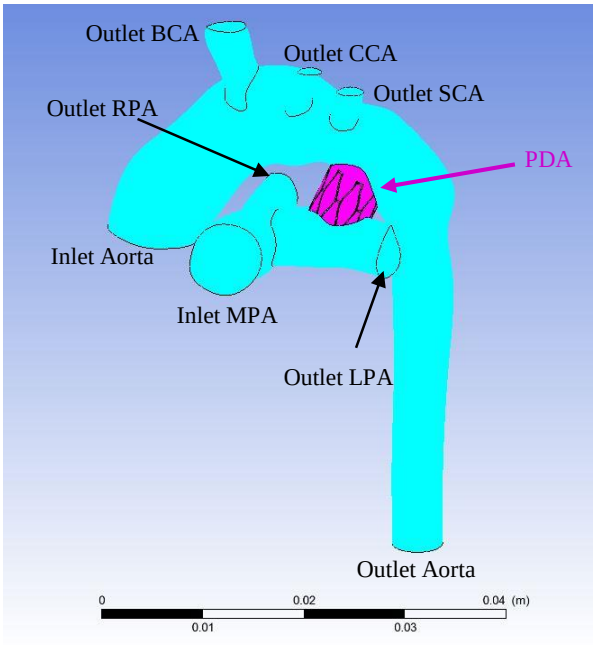

Fig.1 Analysis Model

2.2 Particle Image Velocimetry measurement

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PIV measurement has been developed as a calculation method for unsteady and instantenious 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 [4, 5]. The PIV apparatus in this study shows 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 20μm) and aqueous glycerin solution as working fluid. A living-body model of aorta-pulmonary artery system was made from a 3-d model shown in Fig. 3(a). It was made from silicon lubber and it's twice as large as the actual body scale (Fig. 3(b)). It has no stent. The red circle in Fig. 3(a) is imaging object region.

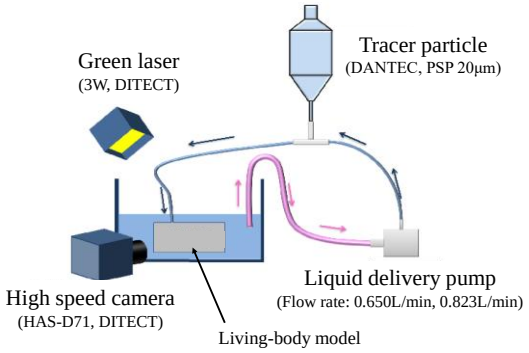
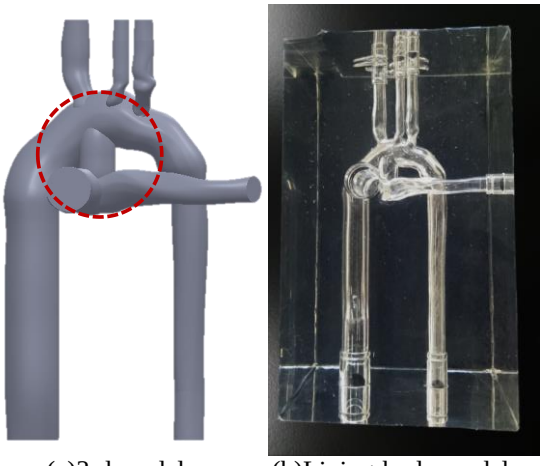


Fig.2 Experimental apparatus of PIV measurement



(a)3-d model (b)Living-body model

Fig.3 experimental model

Liquid delivery pumps connected with both aorta and pulmonary artery inlets of the model. These flow rate are 0.650 (L/min) and 0.823 (L/min), respectively.

3. Result and Discussion

3.1 Morphological Findings

Figure 4 shows the streamline of velocity. The laminar flow was observed in aorta and pulmonary artery, and the turbulent flow was observed around PDA. The main blood flow was formed toward from aorta to pulmonary artery. There was no blood stagnation region around PDA.

3.2 Wall Shear Stress Findings

Figure 5 shows the result of WSS in PDA. As the result, neighborhood of PDA stent had lower WSS than other region.

3.3 PIV Measurement Findings

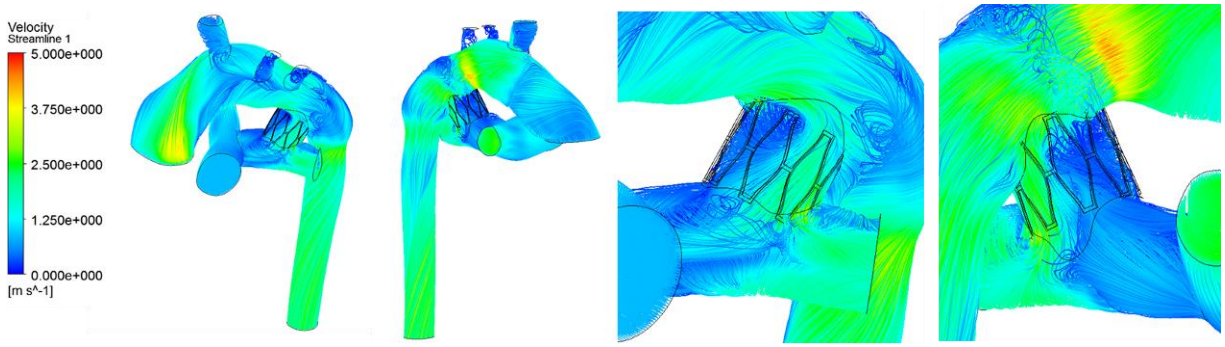
Figure 6(a) shows the result of velocity vector in red circle region of Fig. 3(a) which was obtained by PIV. The main blood flow was formed toward from aorta to pulmonary artery. Figure 6(b) shows the velocity profile on white line of Fig. 6(a). The velocity in the left side of PDA was higher than the right of PDA. Its characteristics seem like Hagen-Poiseuille flow.

3.4 Discussion

The thrombus is easy to be formed at low WSS region. In this study, CFD analysis has clarified that low WSS region is observed in the neighborhood of the stent. This result implies that there is possibility of promoting thrombus formation. It is necessary to obtain more detail data analyzing others case.

Features of the flow in the ductus arteriosus from the results of the experiment and analysis are similar however condition of CFD and PIV are different. It is necessary to investigate whether Reynold's number is related to forming the main blood flow.

In PIV measurement, the results were obtained at only one of the cross section. The others region may have blood stagnation. To obtain more detail need that measuring at some others vertical section using laser light sheet or conducting stereo-PIV [6].



(a) Front side (b) Back side (c) Front side of PDA (d) Back side of PDA

Fig.4 Streamline of velocity

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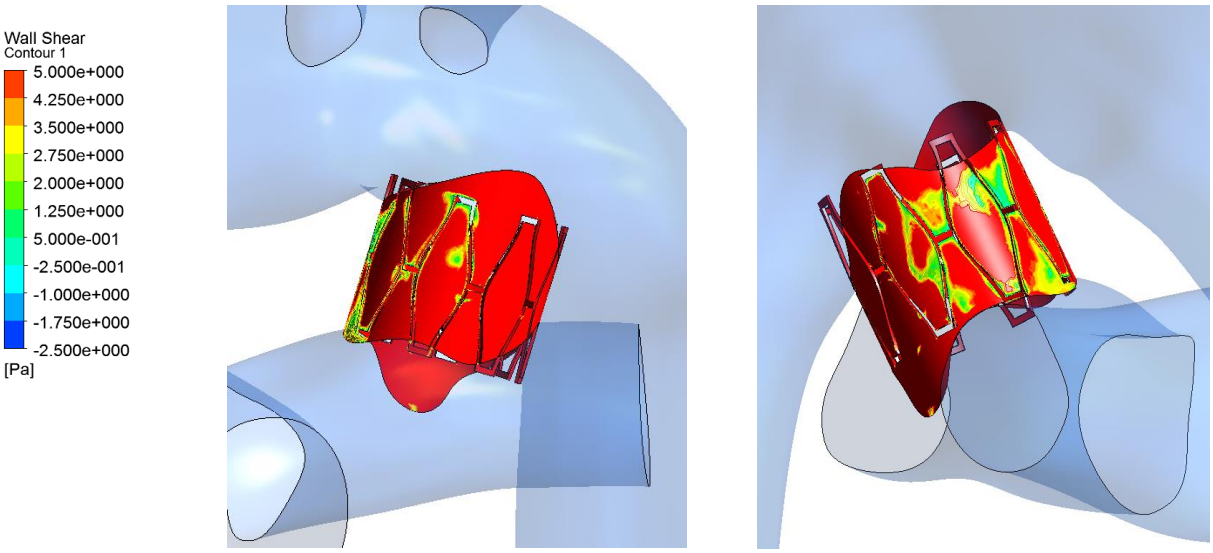
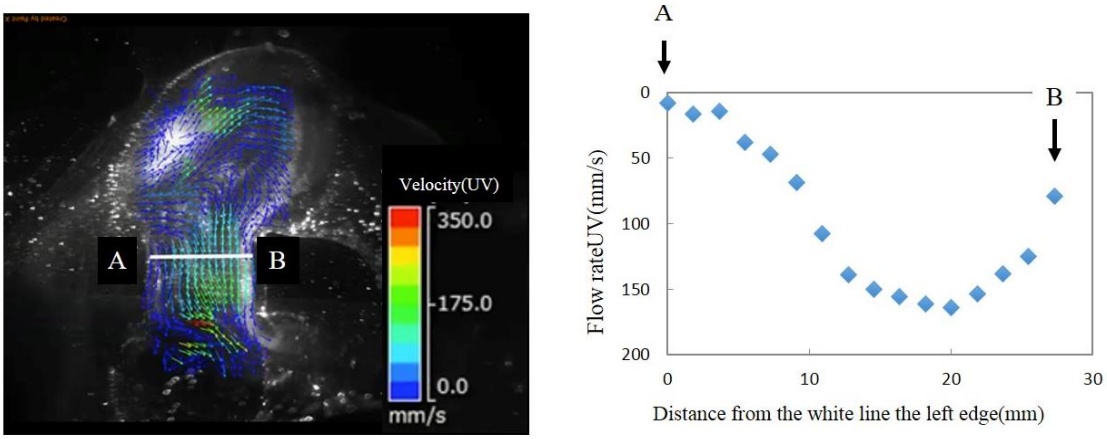


(a) Front side of PDA (b) Back side of PDA

Fig .5 Wall Shear Stress on PDA



(a) velocity vector (b) velocity profile on white line

Fig.6 Results of PIV measurement

5. Conclusion

This study conducted both CFD analysis and PIV measurement for blood flow characteristics in aorta-PDA-pulmonary artery. As the results, this study found that (1) low velocity region was observed in PDA, and (2) low WSS region was observed in PDA, on the other hand (3) there is no blood stagnation region inside PDA. These blood flow characteristics means thrombus formation will easily occur in PDA compared with in aorta and pulmonary artery.

6. References

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