FLUID DYNAMIC ANALYSIS AND POWER LOSS ASSESSMENT FOR TOTAL CAVOPULMONARY CONNECTION USING DIFFERENT MESHING METHODS

Yutong Liu(1), Kee Suk Ryu(2), David Frakes(1), Ajit P. Yoganathan(1)

(1) Georgia Tech/Emory University, Department of Biomedical Engineering, Atlanta, GA 30332

(2) University of Illinois- Urbana-Champaign, Department of Mechanical Engineering, Champaign, IL 61820

INTRODUCTION

The total cavopulmonary connection (TCPC) is a modification of the Fontan procedure introduced by de Leval et al [1]. It has been widely used for the palliation of single-ventricle congenital heart defects. In this procedure, the superior vena cava (SVC) is directly connected to the right pulmonary artery (RPA), and the inferior vena cava (IVC) is connected to RPA by construction of a lateral tunnel through the right atrium or an external shunt in order to divert blood flow around the right atrium. This procedure places an increased workload on the single ventricle, thus the energy losses generated by this procedure are critical for long-term success following TCPC operations. Both in vitro experiments [2] and computational fluid dynamic studies [3, 4] have been performed to investigate the flow fields and energy loss of the TCPC for different geometric configurations and boundary conditions. However, most of the models used in previous investigations employed simplified geometries. Moreover, comparisons have not been made between results associated with the different meshing methods employed in the computational fluid dynamics aspect of the TCPC analysis. In this study, a model with a more anatomically realistic geometry was studied. The flow fields and energy loss were calculated for different flow split conditions. The effects of different meshing methods on these results were assessed. Also, the energy loss calculations in different models and the effects of flow split conditions on the energy losses were further investigated.

NUMERICAL METHOD

Geometry of the TCPC model

Figure 1a and b show the meshes of the TCPC model with physiological IVC diameter, SVC diameter, and curved pulmonary artery. The inner diameter of pulmonary arteries is 13.34 mm. The inner diameters for the SVC and IVC are 8 and 15 mm, respectively, based on MRI data from an eight-year-old patient. The angle between the RPA and left pulmonary artery (LPA) at the connection is 120^o based on the same MRI data. The site of caval anastomosis is offset by one diameter of the pulmonary artery. The geometries of the anastomoses of the SVC and IVC with the RPA are modeled as 4 and 7.5 mm constant radius fillets, respectively. The structured model consists of about 118,000 hexahedral cells, and the unstructured model consists of similar number of tetrahedral cells. With the exception of using different meshing methods, calculation conditions were the same for these two models.

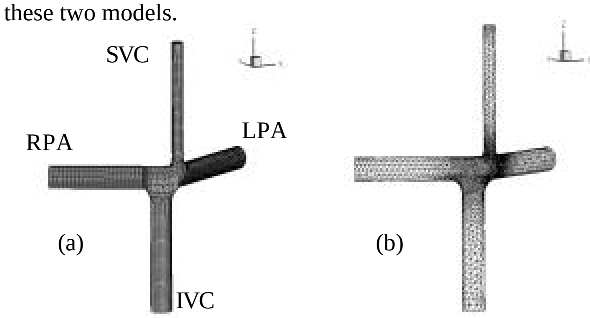

Figure 1. TCPC model with physiological IVC diameter, SVC diameter and curved PA with (a) structured mesh, and (b) unstructured mesh

Computational Simulations

CFD-ACE (Version 2002, CFD Research Corporation, Huntsville, AL) general purpose fluid dynamics software was used to solve the computational model. The total cardiac output was assumed to be 4 liters/min. It was assumed that 40% of the total cardiac output entered the TCPC through SVC with the remaining 60% entering through IVC. The pressure values at the two pulmonary outlets were set to have the LPA flow splits ranging from 30 to 70 percent of the total inflow to the TCPC model. Several assumptions were employed in the computational simulations and boundary condition settings:

1) Blood was assumed incompressible and Newtonian (density ?=1060kg/m^3, viscosity $\mu=3.5\times10^{-3}$ kg/m·s).
2) Blood flow was assumed steady and laminar.
3) Vessel wall was assumed rigid and impermeable; no-slip boundary condition was applied at the wall.
4) Inlet velocities were assumed to be uniform

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5) Outlet pressures were assumed constant across the vessels; outlet velocity profiles were obtained by assuming zero streamwise diffusion at the boundary.

Energy Loss Calculations

Energy losses were calculated using the control volume method:

$$\dot{E}_{loss} = -\int_{cs}\left[p+\frac{1}{2}ru_j u_j\right]u_i n_i dS \quad ,$$

where CS is the control surface, p is the static pressure, u_i defines the components of the velocity vector, n_i represents the components of the outward surface normal vector of the control surface, and dS is the area of the differential control surface.

RESULTS

Blood Flow Fields

Flow fields at the connection region of the TCPC model with 30% of the total cardiac output directed towards the LPA are shown in Figure 2b and c. The streamtrace was drawn at the center plane of the SVC and IVC as indicated in Figure 2a. Due to the curved feature, only the pulmonary artery at the connection section was drawn, and the streamtrace in the pulmonary artery is slightly removed from the center plane. Nevertheless, it is evident that the flow fields are very similar in the structured and unstructured models. Fluid entering the connection from the IVC flowed dominantly towards the RPA. A recirculation zone occurred at the center of the connection. At the flow split condition of LPA 70%: RPA 30% (Figure 3), an approximately equal amount of the IVC inflow was directed towards each PA. However, in the structured model (Figure 3a), a tiny recirculation zone occurred distal to the IVC-to-LPA flare, which is absent from the unstructured model (Figure 3b).

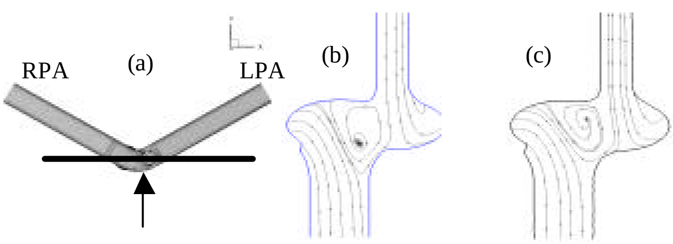

Figure 2. Comparison of flow fields in structured and unstructured models at the flow split condition of LPA 30%: RPA 70%

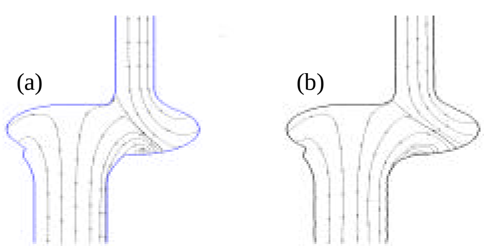

Figure 3. Comparison of flow fields in structured and unstructured models at the flow split condition of LPA 70%: RPA 30%

Energy Losses

Figure 4 shows the energy losses in both structured and unstructured models as a function of LPA flow percentage. These two different meshing methods gave very similar results. The largest difference occurred at the 30% LPA flow split, which is 4.5%. These results were also compared with those from previous study in our group using different models. The trends of all these models present similar patterns, all showing the maximum energy loss at the flow split of LPA 30%: RPA 70%, lesser energy losses near the equal flow splits, and increasing energy loss as the LPA flow increases or decreases to the extreme. The energy loss in the current model is higher than that in the models with constant IVC, SVC diameters, regardless of the planarity. The planar model with physiological IVC and SVC diameters has displayed the highest energy loss.

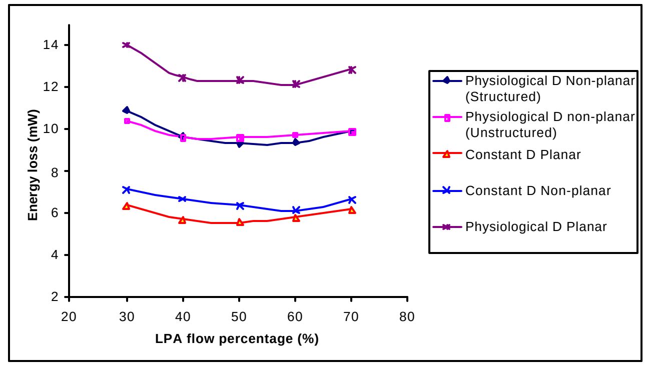

Figure 4. Energy loss assessment in different models plotted against the different LPA flow split conditions

DISCUSSION AND CONCLUSIONS

There are some small differences in the results from the two different meshing methods. These differences may result from the different shapes of the finite volumes, the different numbers of finite volumes, or the different numerical methods for handling the finite volumes. However, the two different meshing methods yielded very similar flow fields and energy loss results. Considering that the creation of an unstructured mesh is less time-consuming, especially for complex geometries, the unstructured-mesh methodology may be a superior choice for further numerical study for the TCPC

The results showed that this model displays the same trends in energy loss pattern as previously studied models [4]. When compared to previous results, it seems that assuming constant IVC and SVC diameters underestimates the energy loss, while using a planar model for the simulation overestimates TCPC energy loss.

ACKNOWLEDGEMENTS:

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REFERENCES

1. de Leval, M. R., Kilner, P., Gewillig, M., and Bull, C., 1988, “Total cavopulmonary connection: A logical alternative to atriopulmonary connection for complex Fontan operations. Experimental studies and early clinical experience,” J. Thorac. Cardiovasc. Surg., Vol. 96, pp. 682-695
2. Ensley, A., Lynch, P., Chatzimavroudis, G., Lucas,. C., Sharma, S. Pettigrew, R., and Yoganathan, A., 1999, “Toward designing the optimal total cavopulmonary connection: An in vitro study,” Ann. Thorac. Surg., Vol. 68, pp. 1384-1390
3. Dubini, G., de Leval, M., Pietrabissa, R., Montevecchi, F., and Fumero, R., 1996, “A numerical fluid mechanical study of repaired congenital heart defects: Application to the total cavapulmonary connection,” J. Biomech., Vol. 29, pp. 111-121
4. Ryu, K., Healy, T. M., Ensley, A. E., Sharma, S., Lucas, C, and Yoganathan, A. P., 2001, “Importance of accurate geometry in the study of the total cavopulmonary connection: computational simulations and in vitro experiments,” Ann. Biomed. Eng., Vol. 29, pp. 844-853