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Using of Porous Portion to Simulate Pulmonary Resistance in the Computational Fluid Dynamic Models of Fontan Connection

Qi Sun, Jinlong Liu, Yi Qian, Haifa Hong and Jinfen Liu

Abstract—**In this study, we performed computational fluid dynamic (CFD) simulations in a patient-specific three-dimensional extracardiac conduit Fontan connection. The pulmonary resistance was incorporated in the CFD model by connecting porous portions in the left and right pulmonary arteries. The pressure in the common atrium was set as boundary conditions at the outlets of the pulmonary arteries. The flow rate in the innominate veins and the inferior vena cava (IVC) was set as inflow boundary conditions. Furthermore, the inflow rate of IVC was increased to 2 and 3 times of that measured to perform another two simulations and the resistance provided by the porous portions was compared among these three conditions. We found out that the pulmonary resistance set as porous portion in the CFD models remains relatively steady despite the change of the inflow rate. We concluded that, in the CFD simulations for the Fontan connections, porous portion could be used to represent pulmonary resistance steadily. The pulmonary resistance and pressure in the common atrium could be acquired directly by clinical examination. The employment of porous portion together with pressure in the common atrium in the CFD model could facilitate and accurate the set of outlet boundary conditions especially for those actual pulmonary flow splits was unpredictable such as virtual operative designs related CFD simulations.**

I. Introduction

Fontan-type procedures are now widely used in the treatment of patients suffered from congenital heart diseases which yielded to univentricular heart.[1-4] The superior vena cava (SVC) and IVC are anastomosed to the pulmonary arteries in this kind of procedures bypassing the right part of the heart. This vessel cross attracted the attention from the surgeons and the engineers because the flow features in it and control volume power loss changed dramatically as the geometric characteristics changed. The CFD research about this kind of surgical connection grew rapidly in the recent decades thanks to the computing capacity of the computer.[5-7] However set of the boundary conditions remains a big problem in the numerical simulations, especially the outlet boundary conditions in the pulmonary arteries. The inlet and outlet vessels were often extruded for an appropriate distance for computational purposes in the CFD simulations. Fixed pulmonary flow splits can be implemented on the CFD model to define the outflow boundary conditions in the simulation based on clinical data. However, in virtual operative designs, it is impossible to set either pulmonary flow rate or pressure at the end of extruded sections of the pulmonary arteries as outlet boundary conditions because neither of them could be acquired clinically or be predictable. Some researchers have used multi-scale modeling to achieve a more realistic inlet and outlet flow environment by coupling the 3-dimensional numerical domain with a reduced order lumped-parameter model. This methodology still suffers from limitations such as the absence of any feed-back control. The appropriate values of the parameters for the lumped model were still hard to be defined and the accuracy of the 3-dimensional flow features simulated in the model may be influenced due to the decrease of dimension. [8-9]

Some researchers have reported their results of CFD simulations for carotid bifurcation using the porous mediums as peripheral resistance of the vessels.[10] As we have known that the pulmonary resistance and pressure in the common atrium could be measured during the Fontan procedure or post-operative catheterization. We assumed that if pulmonary resistance could be simulated steadily by porous portions despite the change of the flow rate in the pulmonary artery, the pulmonary resistance as well as pressure in the common atrium could be set as outlet boundary conditions in the CFD simulations for Fontan connections, which reflected the clinical conditions more directly and realistically.

Pulmonary flow splits in the Fontan connection were determined by the anatomical structure of the vascular connection area and the pulmonary resistance simultaneously, so any CFD simulations for virtual operative designs without considering the actual left and right pulmonary resistance could not reflect real pulmonary flow splits at all. Balanced lung perfusion is acknowledged as a very important aspect to evaluate whether the Fontan connection performed well.[11] From this point of view, coupling the actual lung resistance in the CFD models is essential for the simulations of virtual operative designs related CFD simulations, which represent the newest tendency of CFD research in this field.

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II. METHODS

A. Clinical data

The present study was reviewed by the ethics committee of Shanghai Children's Medical Center. Written informed consent from the patient was acquired before this research.

The patient investigated in this study was a 4-year-old boy, who was diagnosed as mirror image dextrocardia, pulmonary atresia, transposition of the great arteries, ventricular septum defect, complete common atrioventricular canal. Staged Fontan procedure was performed for him, I stage left bidirectional Glenn procedure was performed when he was one year and 7 months old, then extracardiac conduit Fontan procedure was performed when he was 4 years old.

Magnetic resonance imaging (MRI) was performed to determine the 3-dimensional geometry of the Fontan connection. A 1.5 Tesla Signa Hispeed scanner (GE Healthcare, USA) was used to acquire a series of continuous 5 mm-thick MRI images with a 256×192-pixel field of view. Magnetic resonance phase-contrast velocity measurements were performed to acquire the mean flow rate in the left innominate vein (LIV), right innominate vein (RIV) and IVC, which was 0.653 L/min, 0.554 L/min and 0.599 L/min respectively. Catheterization was performed to acquire the average left and right pulmonary resistance which is 5.45 wood units and 4.38 wood units respectively as well as the average pressure in the common atrium which is 10 mmHg.

B. Three-dimensional reconstruction

Patient-specific geometry reconstruction of the Fontan connection was performed in Mimics® 12.0 according to the MRI scans, as was shown in figure 1. The vessels were cut orthogonally to their axes near their distal ends. The LIV, RIV and IVC were extruded over a distance for computational purposes. The left and right pulmonary arteries were extruded for 30 times and 40 times of their diameters and then connected with porous portion respectively.

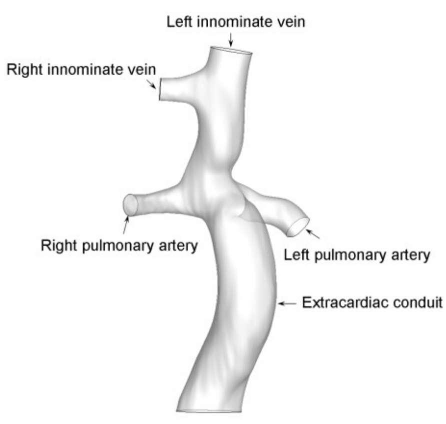


Figure 1. Three-dimensional reconstruction of the extracardiac conduit Fontan connection

C. Governing Equations

The blood flow performed by the computational analysis system of equations is the Navier-Stokes (N-S) equation and continuity equation (1) that describe the most general movement of fluid medium. These equations are defined below.

$$\begin{cases} \dfrac{\partial}{\partial t}(\rho u_i) + \dfrac{\partial}{\partial x_j}(\rho u_i u_j) = -\dfrac{\partial p}{\partial x_i} + \dfrac{\partial}{\partial x_j}\left[\mu\left(\dfrac{\partial u_i}{\partial x_j} + \dfrac{\partial u_j}{\partial x_i}\right)\right] + f_i \\ \dfrac{\partial \rho}{\partial t} + \dfrac{\partial}{\partial x_j}(\rho u_j) = 0 \end{cases} \quad (1)$$

where i, j=1,2,3, x_1, x_2, x_3 means coordinate axes, u_i, u_j and p are the velocity vector and the pressure in the point of the fluid domain, ρ and μ are blood density and viscosity, t is time. The term f_i expresses the action of body forces.

Due to the relative large size of the vessels compared to individual blood cells and typically great shear rates in arteries, the blood flows were assumed to be a Newtonian fluid, with constant density (ρ = 1060 kg/m^3) and viscosity (μ =4.0×10^{-3} Pa s). The body forces of blood were omitted. The maximum Reynolds number is lower than 1000. Therefore, the flow is able to be described as a laminar flow in the study.

The porous portion model was used to create a constant resistance for the physiological imitation of pulmonary resistance. The stability of the resistance generated by the model was carefully examined in laminar flow with different Reynolds numbers before we applied it on the patient-specific vascular geometry. The resistance can be calculated as follows:

$$R = \frac{\Delta P}{Q} \quad (2)$$

where R (unit: wood) is the resistance of the porous portion, ΔP (unit: mmHg) is the pressure differences between the inlet and the outlet of the porous portion, and Q (unit: L/min) is the flow rate.

D. Mesh generation

We use ANSYS-ICEM® 13.0 to perform mesh generation. Tetrahedral mesh was generated in the central connection area and three boundary-fitted prism layers were generated at the near-wall regions to improve the resolution of the relevant scales in fluid motion.

To find the best mesh for hemodynamic simulation, we performed grid-independent verification by increasing grid number step-by-step at the central connection calculated with actual flow rate of the branches as boundary conditions. Energy loss (EL) served as an indicator to estimate grid number for the calculation. We found when the grid number is over 0.4 million, EL was close to a plateau. This suggested that grid numbers around 0.4 million would make the most efficient mesh. Therefore, we used 877,650 grids and 377,917 nodes in the present study. Figure 2 shows details of the mesh and the position of porous portion.

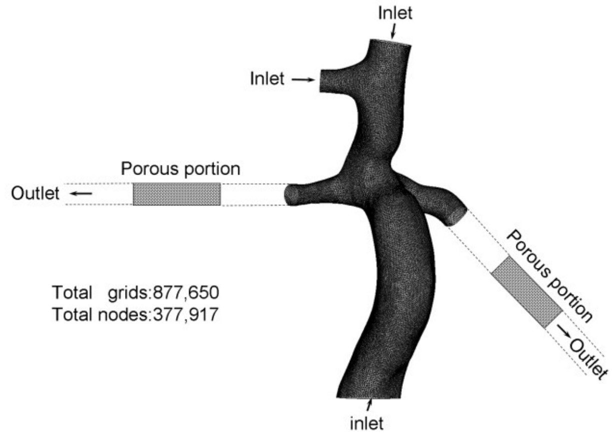


Figure 2. Illustration of the grid in the central connection area and incorporation of porous portion on the pulmonary arteries

E. CFD simulations and analysis

We applied the finite volume solver package ANSYS® -CFX 13.0 to calculate the laminar flow inside the connection area. The mass flow rate in the LIV, RIV and IVC was set as inflow as measured at the extend boundaries. The outlet pressure was set as the pressure of the common atrium (10mmHg) both in the left and right pulmonary arteries. Then the flow rate of the IVC was increased to 2 and 3 times of that measured to simulate moderate and severe exercise conditions.

The porous portion model was used. The parameters of linear and quadratic resistance coefficients were selected in the computation to be satisfied with clinical measurements. The resistance provided by the porous portions was calculated after the simulations to confirm the stability of the model in the analysis of the patient-specific vascular geometry.

For convergence criteria, the relative variation of the quantities between two successive iterations was smaller than the pre-assigned maximum, 10^{-4}. We chose a second-order upwind scheme for discretization of the equations and all calculations were converged to 10^{-5}.

III. RESULTS

The resistance provided by the porous portion in measured inflow level and two enlarged IVC inflow levels was calculated respectively and compared. The flow rate in the left and right pulmonary arteries and also the pulmonary flow ratio were investigated. The total pressure in the central connection area in these three conditions was demonstrated by contour plots.

A. Pulmonary resistance

The resistance provided by the porous portion was showed in Table 1.

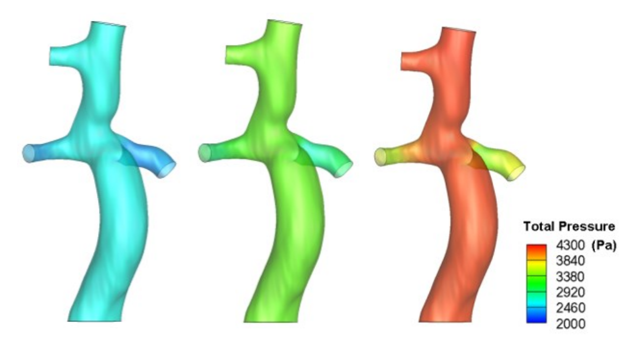
TABLE I Pulmonary Resistance Provided by Porous Portion

Pulmonary Resistance(Wood units)	×1 IVC	×2 IVC	×3 IVC
Left	5.47	5.41	5.49
Right	4.37	4.35	4.41

B. Pulmonary flow rate

	×1 IVC	×2 IVC	×3 IVC
Left Pulmonary Flow Rate(L/min)	0.73	0.99	1.25
Right Pulmonary Flow Rate(L/min)	1.06	1.41	1.74
Flow ratio(Left/Right)	0.69	0.70	0.72

C. Contour plots in three IVC inflow conditions



(a) (b) (c)
Figure 3. The distribution of total pressure with the IVC flow increase (a) ×1 IVC; (b) ×2 IVC; (c) ×3 IVC

IV. DISCUSSION

Set of the boundary conditions especially outlet boundary conditions is really a big challenge we had to face in the CFD simulations for Fontan connection or other numerical simulations aimed to investigate hemodynamic features in the vessels.

Many researchers have tried their own method to settle this problem. Multi-scale modeling by coupling the 3-dimensional numerical domain with a reduced order lumped-parameter model using an electric analogy was now relatively widely used in the simulations for Fontan connections to achieve a more realistic inlet and outlet flow environment. The absence of any feed-back control and difficulty to define appropriate values of the parameters for the lumped model limited the accuracy of the 3-dimensional flow features simulated in this kind of model. Artificially different pulmonary flow splits to the pulmonary arteries attempting to contain all of the possible pulmonary flow ratios can not represent the actual pulmonary flow ratio in the patient at all because the left and right pulmonary resistance is specific in a patient, which can only result in a specific pulmonary flow ratio. Furthermore, the pressure calculated in the connection area can not represent the actual value of the patient because the absence of the real pulmonary resistance and pressure at the outlet.

The pathophysiology of Fontan connection is special. Venous blood from the SVC and IVC flows directly into the pulmonary arteries bypassing the right part of the heart. And then the venous blood flow into the common atrium through the left and right lungs respectively. The blood stream from the venae cavae to the common atrium is a continuous process. If we can find a numerical method suitable for the simulation of pulmonary resistance, we can set outlet boundary conditions as pressure in the common atrium. We performed simulations in different levels of inflow conditions and found that pulmonary resistance simulated by porous portion had no prominent relationship with the magnitude of the pulmonary flow rate and kept relatively steady. This phenomenon hinted that we could use it to represent real pulmonary resistance of the specific patient despite the change of the pulmonary flow rate.

The pressure in the connection area and the common atrium can be easily acquired because the catheter in the SVC and the common atrium were routinely placed during the Fontan procedure for the intensive care and therapy during the perioperative period. The flow rate in the inlet and outlet vessels of Fontan connection can be acquired by bedside ultrasound. So the left and right pulmonary resistance can be calculated respectively. These data can also be acquired by catheterization in the follow up of the patients.

Pulmonary flow splits in the Fontan connection were determined by the anatomical features of the connection area and the pulmonary resistance at the same time. The anatomical features of the central connection area changed after the virtual operation, which led to change of the pulmonary splits inevitably. However, it is impossible to know the actual pulmonary flow splits after the virtual operations without considering the actual left and right pulmonary resistance. The change of the geometry in the vascular connection area will also cause unpredictable change of the pressure in both pulmonary arteries. So it is impossible to set the outlet boundary conditions either by pulmonary flow rate or by pressure in the pulmonary arteries. However the pulmonary resistance and the pressure in the common atrium would not change prominently because the pulmonary resistance was determined by the structure of the pulmonary artery tree which was not influenced by virtual operations directly and the common atrium was downstream the pulmonary artery tree and far from the vascular connection area. Whether the lung perfusion was balanced or not is important to evaluate a Fontan connection. Only coupling the actual left and right lung resistance in the CFD models for the simulations of virtual operative designs related CFD simulations can we obtain the actual pulmonary flow splits. The employment of the porous portion as steady pulmonary resistance presenter solved this problem and made the set of outlet boundary conditions more reasonably and realistically.

We plan to testify the stability of the porous portion in pulsatile simulations in our future research and give our results in the future. The porous portion were connected to the extrusion of the left and right pulmonary artery without considering the main branches of the pulmonary arteries, this may decrease the accuracy of regional flow features in the connection area. Other studies maintaining the main branches of the pulmonary arteries and connected the porous portion in each branches were still needed.

V. Conclusion

Porous portion can be used to simulate specific pulmonary resistance steadily despite change of the flow rate in the pulmonary arteries. With the employment of porous portion in the CFD model of Fontan connection, we could set realistic pulmonary resistance and pressure in the common atrium as outlet boundary conditions in the simulations which were more reasonably and realistically.

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