Flow Visualizations and Laser Doppler Velocity Measurements in a Fontan Connection

Young H. Kim* and Ajit P. Yoganathan[1]
Institute of Biomedical Engineering, Seoul National University*
and Cardiovascular Fluid Mechanics Laboratory, Georgia Institute of Technology[1]

ABSTRACT

Three component velocity measurements with a refractive index-matching technique was used to investigate the flow characteristics in the atrio-pulmomnary (AP) Fontan connection under the steady flow condition. A strong swirl was observed in the extra-cardiac conduit and the main pulmonary artery (MPA). Maximum velocity magnitude in the MPA was about 0.8 m/s near the posterior wall at 6 liter/min. Swirling motion of the flow as well as geometric abnormalities of the connection are important factors in energy loss across Fontan connections.

INTRODUCTION

Approximately 7 out of 1000 babies born in the world have congenital heart defects [1]. Many of these defects interrupt or severely impair the pulmonary arterial flow pathway through which unoxygenated blood flows to the lungs. Since Fontan and Baudet [2] reported the first clinical successful procedure for total right heart bypass for treatment of tricuspid atresia in 1971, a number of modifications to Fontan's operation have been described that have simplified the operation and allowed its application to a variety of complex congenital heart defect [3-7]. Some of these connections require patches and/or extra-cardiac conduits.

Late results from clinical and autopsy studies show high incidence of conduit failure due to fibromuscular ingrowth, valvular degeneration and pseudo-intimal peel formation [8-10]. Many clinical studies [11-13] were conducted to investigate the outcome of Fontan procedures mainly using echocardiography with useful assessment of the flow velocity. Recently, magnetic resonance imaging techniques have been introduced to the post-operative studies on Fontan patients [14]. However, the accurate information of flow dynamics has not been easy to acquire, and the relationship between the optimal Fontan operation and its hemodynamic characteristics has remained unknown.

Success of the Fontan operation may lie on the consideration of energy loss due to the conduit. Studying complicated flow patterns in the Fontan connection shall provide surgeons with a more complete understanding of the optimal surgical path to take in the correction these congenital heart defects.

METHODS

Model

Computerized reconstructions of the images from the CT scanned casts from the lambs were performed on a Stardent 3000 Graphics mini-supercomputer. As shown in Figure 1, a Pyrex glass proximal AP model (whose conduit is connected proximal to the pulmonary sinus) was made based on the cast of three-month old lamb. The model consisted of the right atrium, a conduit (proximal) and the pulmonary trunk with left and right branches. Ventricular side of the MPA was occluded.

Flow Visualization

The schematic of the steady flow system is shown in Figure 2. Neutrally buoyant spherical particles (Amberlite particles) of size 100μm in diameter were used to illustrate the flow motion. Water-glycerin solutions were used as a working fluid to simulate the blood viscosity of 3.5 cP. Flow rates were varied from 4, 6 and 8 liters/min and the flow split ratio between the left pulmonary artery (LPA) and the RPA (right pulmonary artery) was 40% : 60%.

Laser Doppler Velocity Measurements

LDA measurements on the proximal AP model were conducted with a three-component Aerometric fiber-optic system interfaced to an FFT based Doppler signal analyzer.

The available LDA transmitting and receiving optics were mounted on a single three-dimensional traversing system capable of independent movement in each orthogonal plane with an accuracy of 0.0254 mm.

Refractive index matching techniques were employed to eliminate the optical access associated with the complex geometries of the in vitro models. The refractive index of the solution used for the study was 1.4775 at 25 C adequately matched the index of the Pyrex glass [15]. The fluid had a kinetic viscosity of 3.7 cP at 25 C. As shown in Figure 3, three measurement locations were employed for the AP connection model; at the mid-section of the conduit, 1 cm above the conduit junction in the MPA and downstream MPA (2.5 cm below the bifurcation).

RESULTS

Flow visualizations

Due to unbalanced incoming flows from both vena cava, a large unstable vortex was well developed in the right atrium changing its direction in a regular manner. This swirling motion was observed even at the entrance of the extra-cardiac conduit. Figure 4a and 4b show the flow patterns in the plane of the pulmonary bifurcation and its orthogonal plane, respectively. Since the conduit was curvily connected between the right atrium and the MPA, swirl was dominant in the conduit as well as in the MPA. A rebounding vortex was also observed at the bifurcation vertex in the posterior-anterior plane. Axial flow in the MPA was skewed toward the left wall. Stronger swirl was observed proximal to the sinus, and flow in the sinus was relatively disturbed.

A strong swirl in the MPA still existed just below the pulmonary bifurcation. Fluid in pulmonary branches become skewed toward the inner walls due to the centrifugal force. Flow in the LPA seemed to be less swirling, while the swirl was still dominant in the RPA. The RPA had stronger secondary motion compared to the LPA. Flow separation was relatively limited due to this strong swirl in the MPA and pulmonary branches. The center of the swirl near the occlusion moved toward the right wall. There was no significant differences in the flow field with different flow rates except the stronger swirl with higher flow rates.

Laser Doppler Velocity Measurements

Three-dimensional LDA measurements on the proximal AP connection model verified the large strong swirl in the conduit as well as in the MPA. Fig 5a, 5b and 5c show three-dimensional velocity distributions at the mid-section of the conduit, 1 cm above the conduit in the MPA and 2.5 cm below the bifurcation in the MPA at 6 liter/min. An M-shaped velocity profile was skewed toward the posterior wall with maximum velocity magnitude of 0.75 m/sec. On the other hand, the tangential component of the velocity suggested high swirl in the conduit with maximum magnitude of 0.5 m/s. This implies that a swirl already exists in the conduit due to the flow mixing in the right atrium and due to the centrifugal force. At 1 cm above the conduit in the MPA, very strong swirl was observed. In fact, the swirl became the major velocity component at this location. Due to the curvature of the conduit, the axial velocity profile was also skewed toward the posterior wall with maximum magnitude of 0.27 m/sec. At further downstream in the MPA, about the same size of the swirl still existed with a weakened skewness of the axial velocity profile.

DISCUSSIONS

De Leval et al [16] emphasized the importance of the streamlining in Fontan connections. They reported flow dynamic disadvantages of the AP connections due to the flow disturbances at the inlet and outlet of the atrial cavity and head losses at the bifurcation at the level of the AP anastomosis. Flow visualization studies showed highly swirling flow pattern in the right atrium for the AP connection. Swirl in the pulmonary arteries might cause significant energy loss in the low-pressure right heart system. Three-dimensional LDA measurements verified this strong swirl in the conduit as well as in the MPA. Smoothly curved end-to-end anastomoses between the transected vena cava and the transected RPA could reduce the localized flow disturbance such as swirl.

The change of the swirl direction in the right atrium was a very interesting phenomenon in the gravity-driven steady flow system. A strong swirl in the right atrium appeared to be very unstable. The reason for this phenomenon might be the effect of swirl in the curved extra-cardiac conduit: In the beginning, unbalanced venous flows meet in the right atrium. Due to asymmetric location of the conduit to the pulmonary artery, a swirl occurs in the right atrium. In addition, as the flow entered the conduit with a coherent swirling potential, flow velocity increases. This asymmetric swirl located at the tip of the conduit affects the unstable swirl in the right atrium. The swirl or the change in flow direction consumes much energy and should be avoided in order to minimize the energy loss in the Fontan flow system.

CONCLUSIONS

An unstable swirl was the dominant flow pattern in the right atrial cavity for AP extra-cardiac Fontan connection. This swirl propagated toward the conduit with larger energy losses. LDA measurements verified this strong swirl in the Fontan connections.

This study convinced us that the geometry of the conduit plays an important role in the flow dynamics of Fontan connections. Swirling motion of the flow as well as geometric irregularities of the connection must be important factors in energy losses across the Fontan connections. Further in vitro studies will assist cardiologists and surgeons in selecting the optimal geometry with detailed information of fluid dynamics on Fontan type operations.

REFERENCES

1. Hoffman JIE: Pediatric Cardiology, Vol 1. London: Churchill Livingstone, 1987, pp.4.
2. Fontan F, Baudet E: Thorax 26:240-248, 1971.
3. Kreutzer G et al.: J Thorac Cardiovasc Surg 66:613-621, 1973.
4. Bull C et al.: J Thorac Cardiovasc Surg 85:21-31, 1983.
5. Douville EC et al.: Ann Thorac Surg 51:893-900, 1991.
6. Lins RFA et al.: J Thorac Cardiovasc Surg 84:633-635, 1982.
7. Gale AW et al.: J Thorac Cardiovasc Surg 78:831-838, 1979.
8. Dobell AR et al.: Ann Thorac Surg 42:664-667, 1986.
9 Shannon FL et al.: Pediatr Cardiol 7:209-212, 1986.
10. Fyfe DA et al.: J Am Coll Cardiol 18:1733-1737, 1991.
11. Hagler DJ et al.: J Am Coll Cardiol 65:819-821, 1990.
12. Muster AJ et al.: Circ 105:112-119, 1993.
13. Penny DJ, Redington AN: Br Heart J 66:372-374, 1991.
14. Rebergen SA et al.: J Am Coll Cardiol 21:123-131, 1993.
15. Kim YH et al.: J Biomech (in press).
16. De Leval MR et al.: J Thorac Cardiovasc Surg 96:682-695, 1988.

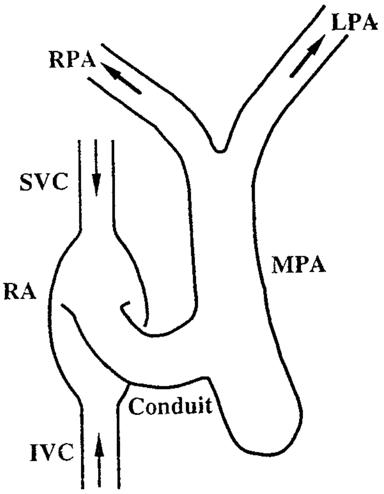

Figure 1. Proximal atrio-pulmonary Fontan model.

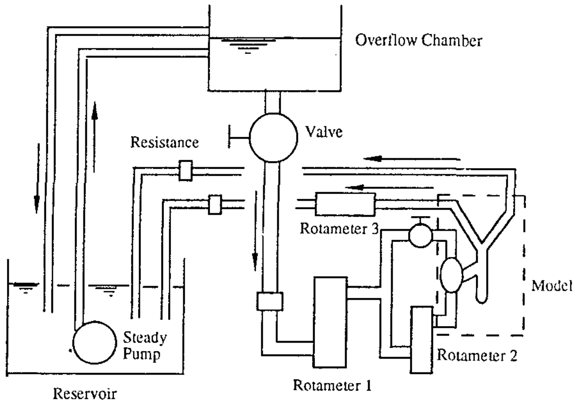

Figure 2. Schematic of the flow system.

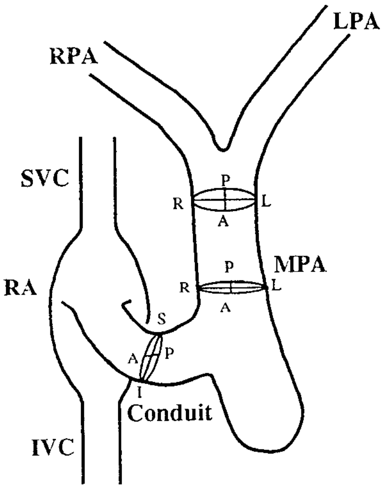

Figure 3. LDA meaurement locations.

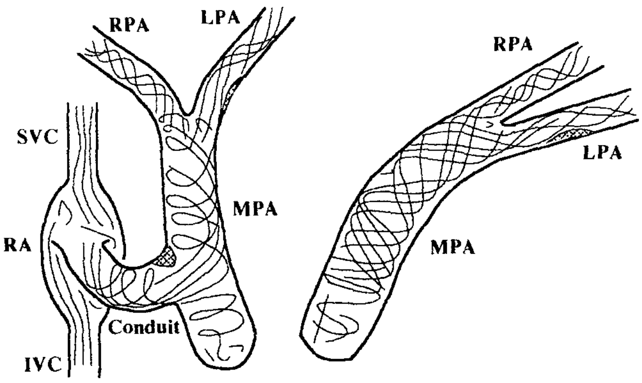

Figure 4. Flow patterns in the plane of pulmonary bifurcation and its orthogonal plane.

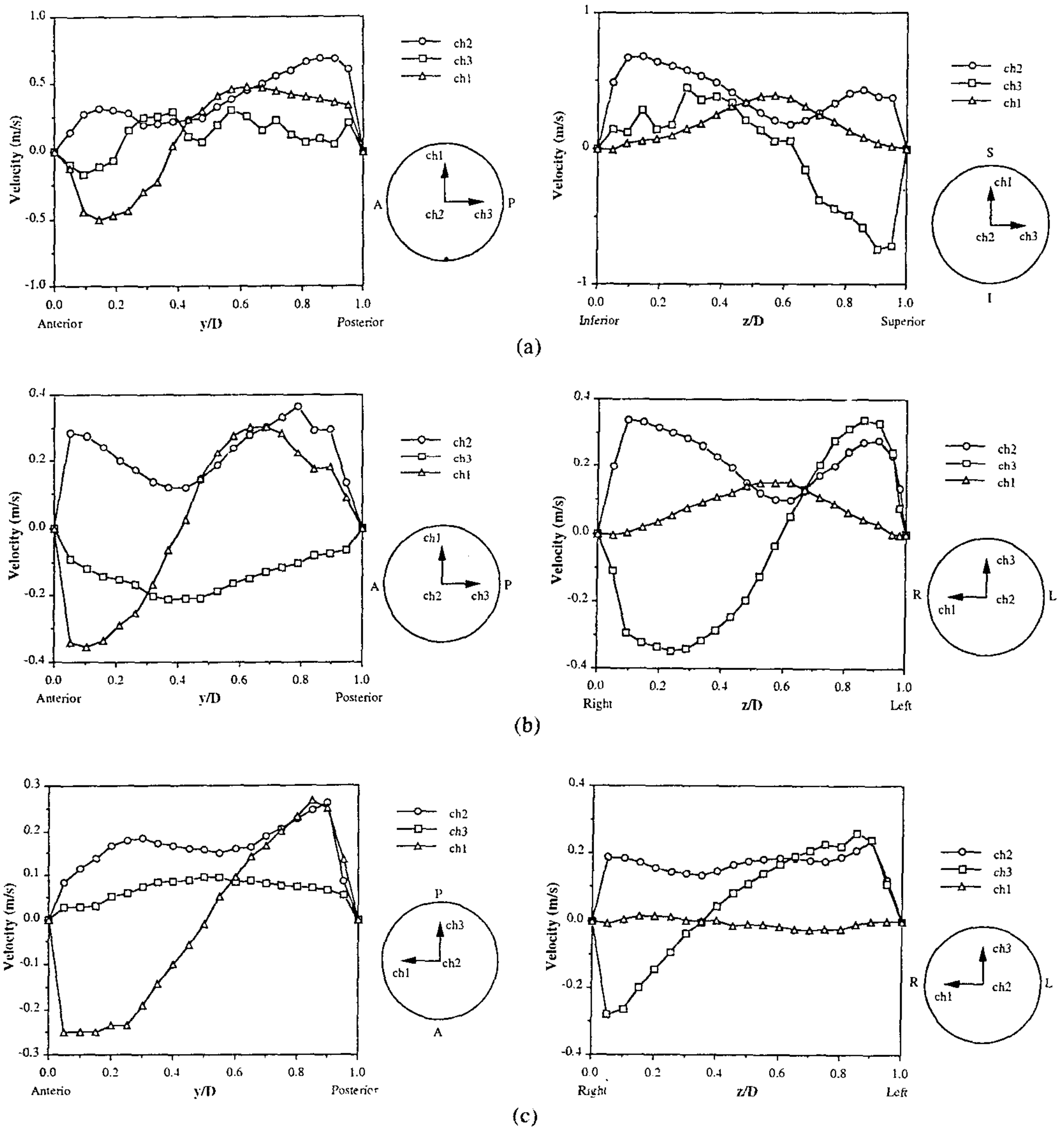

Figure 5. Three-dimensional velocities at 6 liters/min.
(a) at the mid-section of the conduit.
(b) at 1 cm above the conduit in the MPA.
(c) at 2.5 cm below the bifurcation on the MPA.