Cardiol Young 2004; 14 (Suppl. 3): 53–56
© Cambridge University Press
ISSN 1047-9511

Original Article

The patterns of flow in the total extracardiac cavopulmonary connection

Antonio Amodeo,[1] Mauro Grigioni,[2] Giuseppe D'Avenio,[2] Carla Daniele,[2] Roberto M. Di Donato[1]

[1]*Department of Paediatric Cardiology and Cardiac Surgery of the Bambino Gesù Hospital;* [2]*Laboratory of Biomedical Engineering, Istituto Superiore di Sanità, Rome, Italy*

Keywords: Total cavopulmonary anastomosis; haemodynamics; computer model

MORE THAN 30 YEARS AGO, FONTAN AND Baudet[1] proposed bypass of a dysfunctional right ventricle by connecting the pulmonary arteries directly to the right atrium, the so-called atriopulmonary anastomosis. Since then, much experience has been accrued in the field of the functionally univentricular circulation. The proposed connections have been subjected to several modifications, aiming towards minimizing the losses of energy in the cavopulmonary system, and thereby improving the clinical outcomes.[2–4] A remarkable improvement[2] was achieved with the introduction of the concept of the total cavopulmonary connection, specifically the combination of a bi-directional Glenn anastomosis with a tubular intracardiac extension from the inferior caval venous to the pulmonary arteries. This design was shown to avoid the dissipation of energy associated with the swirling patterns seen in the traditional atrio-pulmonary anastomosis.[1]

In recent years, in vitro,[5–7] in vivo,[8–10] and computational[11] studies on the optimal geometry, from the standpoint of fluid dynamics, have shown that one potential problem associated with the total cavopulmonary connection is that of competition between the two venous flows. Finding the best configuration for the total cavopulmonary connection, therefore, remains an open question.

We have now, for some time, adopted the concept of the total extracardiac cavopulmonary connection in our clinical practice at the Bambino Gesù Hospital in Rome.[4,12] The present study is based on a 12-year experience with this procedure, and presents an in vitro quantitative and qualitative analysis of the flows relative to the two more frequent geometrical patterns used at our institution, one with the venous anastomose offset from each other, and the other with the two venous flows directly opposed. The total extracardiac cavopulmonary connection is a spatially complex system, and demands a highly accurate method for the analysis of flows. We have used an advanced technique, namely particle imaging velocimetry, that provides high spatial and temporal resolution.

Materials and methods

Data from angiographic and magnetic resonance imaging investigation of 110 patients undergoing a total extracardiac cavopulmonary connection were used to identify the two more frequently used geometric configurations of the total extracardiac cavopulmonary connection. Two glassblown phantoms were produced at the Istituto Superiore di Sanita. The first had the inferior caval venous conduit placed to the left of the Glenn anastomosis, with a 6-millimetre horizontal offset at the midpoint of the two. In the second, the inferior caval venous conduit was directly opposed to the Glenn anastomosis. In the former configuration, the inferior caval venous conduit formed a 112° angle with the left pulmonary artery. The diameter of the superior and inferior caval veins was set at 11.5 millimetres. The left and right pulmonary arteries both were configured with a diameter of 8.6 millimetres.

The two models were evaluated in steady-flow regime, on account of the limited role played by the residual pulsatility present in the venous return.[13]

Correspondence to: Antonio Amodeo MD, Dipartimento Medico Chirurgico di Cardiologia Pediatrica, Ospedale Bambino Gesù, Piazza S. Onofrio 4, 00165, Roma, Italy. Tel: +39 06 68592258; Fax: +39 06 68592257; E-mail: antonioamodeo@yahoo.it

Accepted for publication December 2003

The models were inserted in a steady-flow loop, in which the flow could be controlled in each branch of the connection by regulating the pressure of the corresponding outlet and inlet. The changes in pulmonary arterial resistance were achieved by narrowing the tubes connected to either pulmonary arterial branch.[7]

The measurements were performed with a water–glycerol solution as the circulating fluid, having a dynamical viscosity of 3.6 centipascal, this being the typical value for blood viscosity. Pressure measurements were performed with a catheter-mounted piezometer (Millar Instruments Inc., Houston, TX, USA). This was done for each point of a predefined set of measurements points inside the superior and inferior caval venous, and the right and left pulmonary arteries, at 20 millimetres from the center of each model. The measurements were performed at combined rates of flow of 1, 2, 3 and 4 litres per minute. The ratio of flow between the arteries was set at the values 30–70%, 50–50%, and 70–30%. The ratio of flows through the caval veins was fixed at 40–60% in favour of the inferior vein and 50–50%.

Visualization of flow was performed by means of a sheet of Argon continuous-wave laser light and a Kodak Ektapro high-speed videographic system, set to record 100 frames at 50, 125 and 250 frames per second.

The velocimetric assessment was done with particle imaging velocimetry, employing a Dantec 2D particle imaging velocimetry system together with a Quantel Twins Nd:YAG Q-switched laser. The Visiflow program (AEA, UK) was used for the particle imaging velocimetry analysis.

The total power dissipation across each connection was calculated as:

$$W_{\text{loss}} = W_{\text{static}} + W_{\text{dyn}} \qquad (1)$$

where

$$W_{\text{static}} = P_I Q_I + P_S Q_S - P_R Q_R - P_L \cdot Q_L$$

is the dissipated power due to the static pressures, and

$$W_{\text{dyn}} = \frac{\rho}{2} V_I^2 Q_I + \frac{\rho}{2} V_S^2 Q_S - \frac{\rho}{2} V_R^2 Q_R - \frac{\rho}{2} V_L^2 Q_L$$

is the contribution due to the dynamic pressures. The subscripts I, S, L and R denote quantities relative to the inferior caval vein, superior caval vein, left pulmonary artery and right pulmonary artery, respectively. V, Q and P stand for average velocity, flow rate, and pressure, respectively.

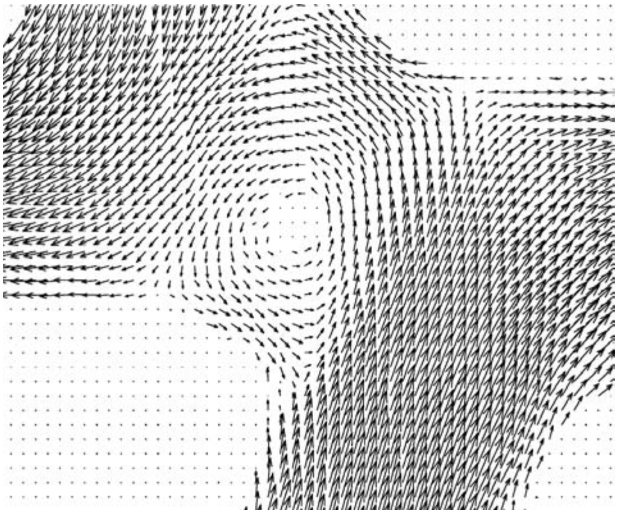

Figure 1.
Detail of the central zone of the velocity field as revealed by particle imaging velocimetric analysis. Note the presence of a large structure, which redistributes smoothly the incoming flows from the inferior and superior caval veins, set to favour the inferior vein in the ratio 60 to 40.

Results

In the first model of the total extracardiac cavopulmonary connection, the ratio of flows of 40 to 60 in favour of the inferior caval vein is associated with balanced pulmonary flows. There is a prevailing contribution of flow from the inferior caval vein to the left pulmonary artery, whereas the flow from the superior caval vein runs principally to the right pulmonary artery. In Figure 1, the particle imaging velocimetric analysis of the flow field shows an evident rotation at the center of the cross. The vortex appears to separate the venous flows away from each other, avoiding a significant collision, with favorable energetic consequences. At the same time, this permits an adequate mixing of blood from the lower body, with a portion of the inferior caval venous flow perfusing also the right lung. Equalising the ratio of flows did not reveal significant morphological variations with respect to the initial situation. In the case with equal flows, however, the left pulmonary artery carries the highest proportion of the flow (57.5%), with the center of the vortex shifted towards the left pulmonary artery.

In the case of unbalanced pulmonary flows, as for example in presence of a stenosis, the flow field is drastically altered. When the flows favour the left pulmonary artery in proportions of 30 to 70, the central flow structure disappears (Fig. 2), due to the hindrance caused by the stenotic pulmonary artery, and the consequent redirection of both venous flows towards the non-stenotic pulmonary artery.

In the second model, with facing cavopulmonary anastomoses, the venous flows are both directed to the center of the cross, so that a region of disordered flow can be found in the zone of competition, with circular swirling patterns and secondary flows

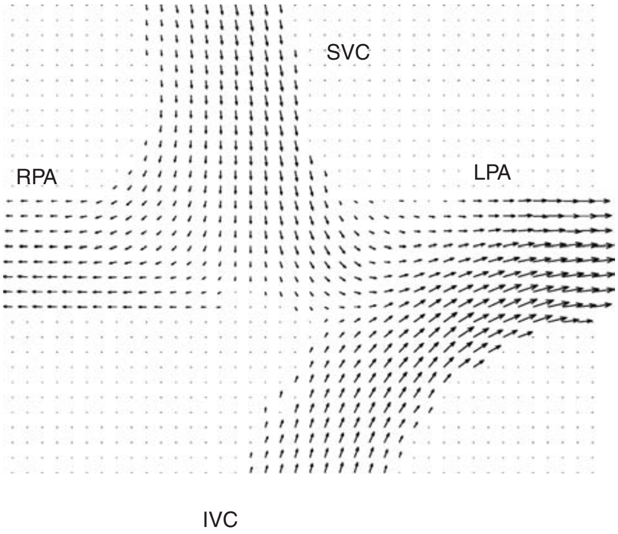

Figure 2.
The particle imaging velocimetric velocity fiel as seen in the setting of a stenosed right pulmonary artery, and with the flows set to favour the right pulmonary artery (RPA over the /left (LPA) in the ratio of 70 to 30). IVC: inferior caval vein; SVC: superior caval vein.

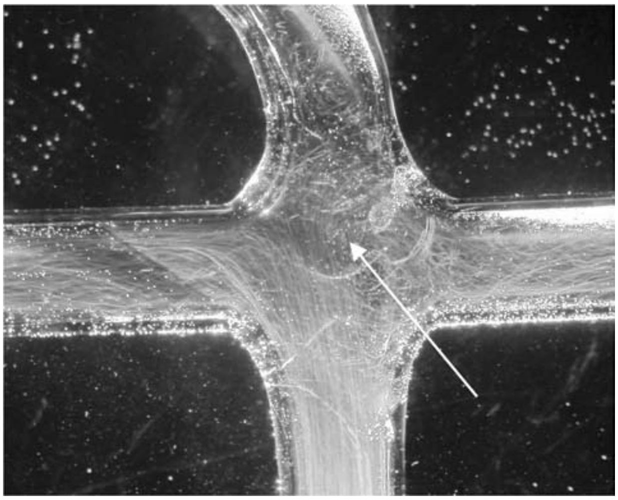

Figure 3.
Flow visualization of the second model of the total extracardiac cavopulmonary connection, with directly opposed caval venous flows. The disordered nature of the flow in the central zone (arrow) is evident.

(Fig. 3). The comparison with Figure 1 shows that the flow is less smoothly distributed than in the first model, as the flows exiting the caval veins are not directed preferentially towards one or other pulmonary artery.

Table 1 summarises the results of the power dissipation study. The performance of the total extracardiac cavopulmonary connection with offset is clearly superior to that of the other design.

Table 1. Power dissipation in the two models of the total extracardiac cavopulmonary connection.

Cardiac output (l/min)	TECPC model 1 (mW)	TECPC model 2 (mW)
1	1.4	2.5
2	3.9	7.5
3	6.4	13.2
4	11.8	20.1

Abbreviation: TECPC: total extracardiac cavopulmonary connection

Discussion

Since the introduction of the total cavopulmonary connection,[2] starting from an in vitro study that demonstrated the superiority of this connection with respect to the atrio-pulmonary anastomosis, there has been evidence of satisfactory early and mid-term results both with intra[14] and total extracardiac cavopulmonary connections.[13] It is still to be determined, however, which is the best configuration for such artificial circulatory pathways, considering the need to make best use of the low pressure in the venous return. The optimal total geometry of the extracardiac cavopulmonary connection, therefore, should be identified in terms of both favorable characteristics of dissipation and safe clinical applicability.

We have used the total extracardiac cavopulmonary connection since 1989 as our principal technique for completion of Fontan operation. From this experience, we can state that, when the inferior caval venous inflow is placed on the right of the bi-directional Glenn anastomosis, the inferior conduit may fall too close to the right pulmonary artery, and this may cause kinking of the artery itself, with impairment of perfusion of the right lung. Moreover, placing the inferior caval venous connection close to a bifurcation is not haemodynamically advantageous. On the contrary, it is preferable to connect the inferior caval venous conduit at some distance from the distal branching of the pulmonary arteries to prevent potential impairments in pulmonary perfusion. Moreover, as for the hydrodynamics, the comparison between the two models herein studied shows that there is an evident energetic advantage in the first model. In fact, in the second model, competition between the flows engenders losses of kinetic energy, which should be avoided. Instead, the model with the inferior caval vein offset to the left pulmonary artery shows a fluid dynamic efficiency due to the regulatory role of the central region of flow.

The in vitro investigation confirmed that the positioning of the extracardiac conduit to the left side of the superior caval venous anastomosis, which is the modality currently preferred at our hospital, leads to a better performance than the other geometry. As also shown with a numerical study,[15] the central vortex in the total extracardiac cavopulmonary connection constructed with an offset is more a zone of circulation than a vortex, yielding a limited pressure drop between the inlet and outlet.

From the surgical point of view, the left-sided position of the conduit offers more freedom to impart a flaring to the anastomosed vessel, and allows avoiding the potential impingement of the conduit itself on the right pulmonary veins.

In conclusion, we believe that constructing the total extracardiac cavopulmonary connection with an offset is surgically feasible, as well as offering positive haemodynamic features.

References

1. Fontan F, Baudet E. Surgical repair of tricuspid atresia. Thorax 1971; 26: 240–248.
2. de Leval MR, Kilner P, Gewilling M, Bull C, Mc Goon DC. Total cavopulmonary connection: a logical alternative for complex Fontan operation. J Thorac Cardiovasc Surg 1988; 96: 682–695.
3. Puga FG, Chiavarelli M, Hagler DJ. Modifications of the Fontan operation applicable to patients with left atrioventricular valve atresia or single atrioventricular valve. Circulation 1987; 76: III-53–III-60.
4. Marcelletti C, Corno A, Giannico S, Marino B. Inferior vena cava–pulmonary artery extracardiac conduit: a new form of extracardiac bypass. J Thorac Cardiovasc Surg 1990; 100(2): 228–232.
5. Kim Young H, Walker PG, Fontaine AA, Enseley AE, Oshinski J, Sharma S, Ha B, Lucas CL, Yoganathan PA. Hemodynamics of the Fontan connection: an in vitro study. J Biomech Eng 1995; 117: 423–428.
6. Sharma S, Goudy S, Walker P, Panchal S, Enseley A, Kanter K, Tam V, Fyfe D, Yoganathan A. In vitro flow experiments for determination of optimal geometry of total cavopulmonary connection for surgical repair of children with functional single ventricle. J Am Coll Cardiol 1996; 27: 1264–1269.
7. Grigioni M, Amodeo A, Daniele C, D'Avenio G, Formigari R, Di Donato RM. Particle image velocimetry analysis of the flow field in the total cavopulmonary connection. Artif Organs 2000; 24(12): 946–952.
8. Sharma S, Enseley AE, Hopkins K, Chatzimavroudis GP, Healy M, Tam VKH, Kanter KR, Yoganathan AP. In vivo flow dynamics of the total cavopulmonary connection from three dimensional multislice magnetic resonance imaging. Ann Thorac Surg 2001; 71: 889–898.
9. Lardo AC, Webber SA, Friehs I, del Nido PJ, Cape GE. Fluid dynamic comparison of intra-atrial and extracardiac total cavopulmonary connections. J Thorac Cardiovasc Surg 1996; 117: 697–704.
10. Fogel MA, Weinberg PM, Rychik J, Hubbard A, Jacobs M, Spray TL, Haselgrove J. Caval contribution to flow in the branch pulmonary arteries of Fontan patients with a novel application of magnetic resonance presaturation pulse. Circulation 1999; 99: 1215–1221.
11. De Leval MR, Dubini G, Migliavacca F, Jalali H, Camporini G, Redington A, Pietrabissa R. Use of computational fluid dynamics in the design of surgical procedures: application to the study of competitive flows in cavopulmonary connections. J Thorac Cardiovasc Surg 1996; 111: 505–513.
12. Amodeo A, Galletti L, Marianeschi M, Picardo S, Giannico S, Di Rienzi P, Marcelletti C. Extracardiac Fontan operation for complex cardiac anomalies: seven year's experience. J Thorac Cardiovasc Surg 1997; 114: 1020–1030.
13. Senzaki H, Isoda T, Ishizawa A, Hishi T. Congenital heart disease: reconsideration of criteria for the Fontan operation: influence of pulmonary artery size on postoperative hemodynamics of the Fontan operation. Circulation 1994; 89(3): 1196–1202.
14. Stamm C, Friesh I, Mayer JE, Zurakoswki D, Triedman JK, Moran AP, Lock RA, Del Nido PJ. Long-term results of the lateral tunnel Fontan operation. J Thorac Cardiovasc Surg 2001; 12(1): 28–41.
15. Amodeo A, Grigioni M, Oppido G, Daniele C, D'Avenio G, Pedrizzetti G, Giannico S, Filippelli S, Di Donato RM. The beneficial vortex and best spatial arrangement in total extracardiac cavopulmonary connection. J Thorac Cardiovasc Surg 2002; 124(3): 471–478.