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# Addition of a Small Curvature Reduces Power Losses Across Total Cavopulmonary Connections

Anja Gerdes, MD, Jörg Kunze, MSc, Gerd Pfister, PhD, and Hans-Hinrich Sievers, MD, PhD

Department of Cardiac Surgery, Medical University of Lübeck, Lübeck, and the Institute of Applied Physics, Christian-Albrechts-University of Kiel, Kiel, Germany

**Background.** In the Fontan circulation the vis a tergo for lung perfusion is limited. The hypothesis of this in vitro study was that energy dissipation at the common cavopulmonary connection can be reduced by the addition of caval curvature.

**Methods.** Two Perspex models were analyzed, the commonly used crosslike cavopulmonary connection (model 1) and a modified curved configuration (model 2). Pressures and flows across the connections were measured simultaneously at various caval and pulmonary artery flow splits and resistances. Mixing of inferior and superior caval fluid was evaluated.

**Results.** Caval pressure oscillations occurred in model

1 only. Curvature reduced power losses in all settings significantly ( $\alpha = 0.05$ ), most successfully at adult caval flow ratios and at high flow rates. At equal pulmonary resistances pulmonary flow was balanced in both models. The inferior caval fluid is preferably directed to the right lung in model 2 predominantly for caval flow conditions in younger patients.

**Conclusions.** Our data show that the modified curved cavopulmonary connection is hydrodynamically advantageous but might impair caval fluid mixing in younger children.

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Since 1971 when Fontan and Baudet [1] described a surgical technique for repair of tricuspid atresia, different methods to bypass the right heart in patients with single ventricle physiology have been developed [1–8]. A commonly used modification of the Fontan procedure is the total cavopulmonary connection reported by de Leval and associates in 1988 [9, 10]. This connection consists of an anastomosis of the superior and inferior vena cava directly opposite each other on the right pulmonary artery. Because the vis a tergo for lung perfusion via the cavopulmonary connection is limited and increased central venous pressures impair the clinical outcome [11], every effort should be made to evaluate optimized, surgically practicable cavopulmonary connections. In this context several modifications of cavopulmonary connections have been studied. Based on computational fluid studies, the common cavopulmonary connection is reported to be improved by enlarging and offsetting only the inferior vena cava at the right pulmonary artery anastomosis [12] or by asymmetric caval inflow into the right pulmonary artery [13]. Sharma and associates [14] in 1996 described a minimal energy loss by a caval offset of one caval diameter, and suggested that relatively large curving in addition to offset might reduce power losses even more but not at adverse pulmonary artery flow splits. None of these studies includes evaluation of pulmonary distribution of inferior caval blood

containing hepatic venous return that is reported to be essential for prevention of pulmonary arteriovenous malformations [15].

The aim of this in vitro study was to evaluate the power losses, flow patterns, and venous mixing of a cavopulmonary connection with a small caval curvature in comparison to the conventional cross configuration in relation to varying caval and pulmonary flow ratios. Flow distribution to each lung at equal lung resistances was also evaluated.

## Material and Methods

### Determination of Models

Two Perspex models were milled and polished. The inner diameters of 12 mm in the caval veins and the pulmonary arteries represent the anatomic situation in 4-year-old children [17, 18]. The first model, which simulated the commonly used total cavopulmonary connection, was shaped like a simple cross (Fig 1). To create a caval curvature at the total cavopulmonary anastomosis with potential surgical practicability, geometric conditions, including the smallest radius of curvature to prevent acute angles but totally separate caval inflow, were chosen as follows: The cranial segment of the superior vena cava (SVC) was curved toward the left pulmonary artery (LPA), and the cardiac segment of the superior vena cava (IVC) was curved toward the right pulmonary artery (RPA). The radius of curvature at both the caval inflows was two duct diameters, and the anastomotic offset was half a diameter of each caval vein resulting in an anas-

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Address reprint requests to Dr Sievers, Klinik für Herzchirurgie, Medizinische Universität zu Lübeck, Ratzeburger Allee 160, D-23538 Lübeck, Germany.

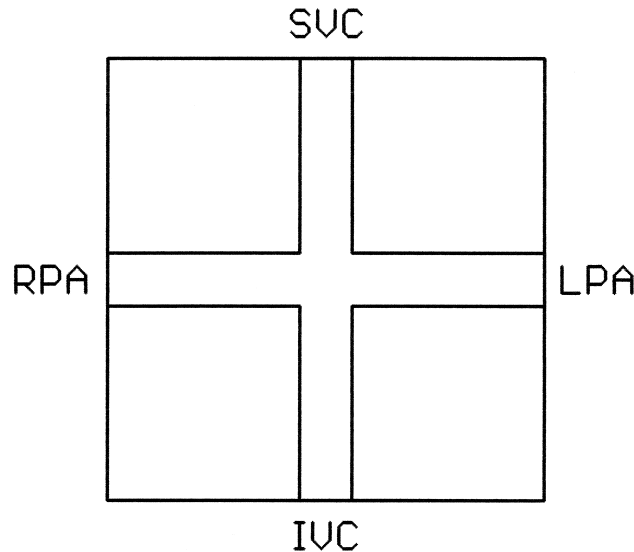


Fig 1. Scheme of the commonly used crosslike cavopulmonary connection. (SVC = superior vena cava; IVC = inferior vena cava; RPA = right pulmonary artery; LPA = left pulmonary artery.)

tomotic offset of one caval diameter. At the upstream end of the curvature the caval offset was zero (Fig 2).

#### Test Circuit and Experimental Conditions

Both models were integrated by silicone tubing in the nonpulsatile test circuit. The four flow rates were measured simultaneously by flow meters (working with suspended bodies) calibrated with the test fluid. The two flow rates in the caval veins were kept constant by two regulated pumps (Whale Supersub 881/12VDC, Munster

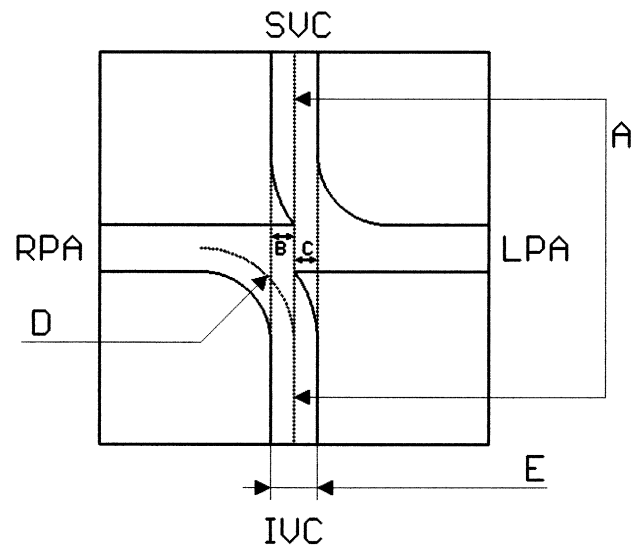


Fig 2. Scheme of the modified curved cavopulmonary connection. (A = caval offset; B+C = anastomotic offset of half a diameter of each caval vein resulting in an anastomotic offset of one caval diameter; D = radius of curvature; E = diameter; SVC = superior vena cava; IVC = inferior vena cava; RPA = right pulmonary artery; LPA = left pulmonary artery.)

Simms, Ing Ltd, Bangor, County Down, Northern Ireland). Pulmonary flow split could be chosen by varying the level of two afterload overflow reservoirs. Pressure was measured continuously at a distance of 20 duct diameters at both caval veins and pulmonary arteries by standpipes. A mixture of 40% glycerine and 60% demineralized water was used as test fluid. To ensure a constant viscosity of  $\eta = 3.6 \cdot 10^{-3}$  Pa·s and a density of  $\rho = 1,090$  kg/m<sup>3</sup> the test fluid was kept at 24°C by temperature control. Experiments were done at a fixed total flow of 2, 3, 4, and 5 L/minute to simulate rest and exercise. The IVC/SVC ratio was varied between 50/50 and 67/33 because at age 4 years the caval flow split is on its transition from infant to adult conditions which are reached at age 6.6 years [19]. The pulmonary flow split between RPA and LPA was altered in the range of 20/80, 30/70, 40/60, 45/55, 50/50, and vice versa to simulate various pulmonary resistances.

To evaluate the distribution of IVC fluid to each lung, the set-up was extended by a second reservoir with temperature control and two thermometers in the right and left pulmonary arteries. Demineralized water at 19°C in the IVC and 30°C in the SVC was used as test fluid. Total flow was adjusted for viscosity keeping the Reynolds number constant. At each setting of caval and pulmonary flow split, the temperatures in the pulmonary arteries were measured and recorded simultaneously to calculate the percentage of IVC fluid in each pulmonary artery.

Furthermore, to determine the rate of flow to each lung without fixed pulmonary artery flow ratios, the caval flow rates were adjusted by two preload reservoirs and the pulmonary resistance kept equal by two afterload reservoirs in a second test circuit. Right and left pulmonary artery flow rates were litered out volumetrically, and pressures in the caval veins were recorded simultaneously (Hewlett Packard 38742A, Boise, ID).

#### Data Analysis

For each quadruple of flow values, measured in the first test circuit, a quadruple of pressure values was recorded simultaneously. The complexity of data was reduced to scalar values by calculating the power loss ( $P_{loss}$ ), which is the sum of static and kinematic power consumption. Kinematic power consumption results from the product of flow  $Q$  and Bernoullian dynamic pressure  $p_{kin} = \frac{1}{2}\rho v^2$ . The velocity ( $v$ ) results from  $v = Q/A$ , where  $A$  is the total cross sectional area. Hence the kinematic power loss is calculated as  $P_{loss,kin} = \frac{1}{2}\rho Q^3/A^2$  and is, therefore, totally independent of measured pressure values and model flow patterns. Thus, the kinetic power loss is insignificant for comparison in the models and can be disregarded, as stated by Sharma and associates [14]. For that reason we only regarded the static power loss, calculated as follows:

$$P_{loss,static} = (Q_{IVC} \cdot p_{IVC} + Q_{SVC} \cdot p_{SVC}) \\ - (Q_{RPA} \cdot p_{RPA} + Q_{LPA} \cdot p_{LPA}).$$

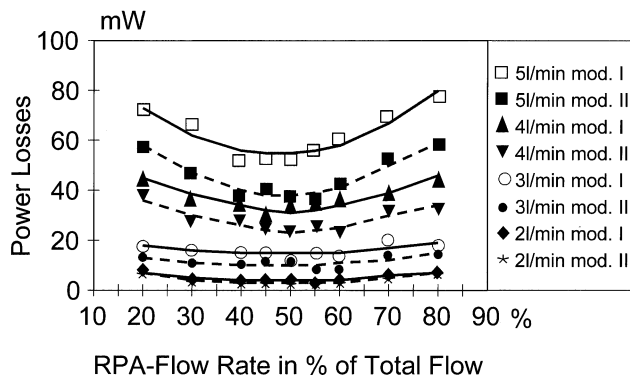


Fig 3. Significantly lower power losses of the curved configuration (model II) than of the crosslike cavopulmonary connection (model I) at an inferior to superior caval flow ratio of 50/50. The symbols are measured points and the lines are least square fits of parabola for illustration. (RPA = right pulmonary artery.)

Statistics

All measurements were repeated five times at steady state conditions and the average value taken. The maximal error of power loss determination was low, between 1 and 5.2 mW depending on increasing total flow. Therefore we analyzed the differences of the corresponding levels of power losses between both models comparing the mean of power losses at each corresponding flow rate using the Mann-Whitney U test. The level of significance was  $\alpha$  of 0.05 or less for the one-sided test.

Results

We found that curvature reduced power losses significantly in all experimental conditions. At symmetric caval flow ratios the lowest power losses in both models occurred at RPA/LPA flow ratio between 45/55 and 55/45, whereas more asymmetric pulmonary flow splits resulted in higher power losses (Fig 3).

At a caval flow ratio of IVC/SVC = 67/33 the power losses increased in the curved model if RPA flow was reduced (Fig 4). Major differences in power losses regarding the absolute values were observed at high flow rates, whereas the percentage of power loss was not dependent on flow rates (Figs 3, 4).

With an IVC/SVC flow ratio of 67/33 and an adverse pulmonary artery flow split such as RPA/LPA = 20/80, power loss was reduced by at least 20% by curvature, whereas an RPA/LPA flow ratio of 80/20 led to a reduction of power loss up to 40% (Fig 4). At a high total flow rate of 5 L/minute and a caval flow ratio of IVC/SVC = 67/33 minimal power loss of 40 mW was found at a physiologic RPA/LPA flow ratio of 55/45 in the curved configuration. Conversely, with the crosslike anastomosis and identical experimental conditions the least power loss was 67 mW, which was measured at an RPA flow rate of 45% to 55%. The reduction of power losses by curvature was most successful in asymmetric caval and normal pulmonary flow ratios and at high total flow rates (Fig 4).

In the crosslike model at symmetric as well as at

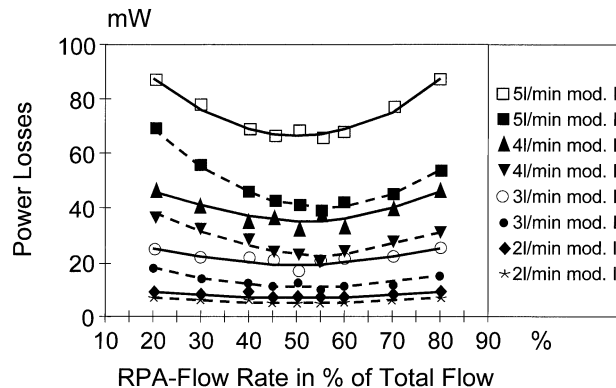


Fig 4. Significantly lower power losses of the curved configuration (model II) than of the crosslike cavopulmonary connection (model I) at an inferior to superior caval flow ratio of 67/33. The symbols are measured points and the lines are least square fits of parabola for illustration. (RPA = right pulmonary artery.)

asymmetric caval and pulmonary flow ratios, the LPA fluid consisted of inferior caval fluid in the range of 30% to 70%. In the curved model at balanced caval and pulmonary flow ratios, LPA fluid contained at least 5% IVC fluid and up to 44% if the IVC/SVC flow ratio was 67/33. At varying pulmonary artery flow splits the part of IVC fluid within the LPA varied consecutively. At a caval flow ratio of IVC/SVC = 67/33 and equal right and left pulmonary artery resistances, at different total flow rates there was no significant relationship between both models and pulmonary artery flow distribution (Fig 5). Pressure oscillations with amplitudes up to 3 mm Hg within the caval veins could be detected in all experimental conditions but only at the crosslike model (Fig 6).

Comment

One of the major problems in the very complex circulation of commonly used crosslike total cavopulmonary

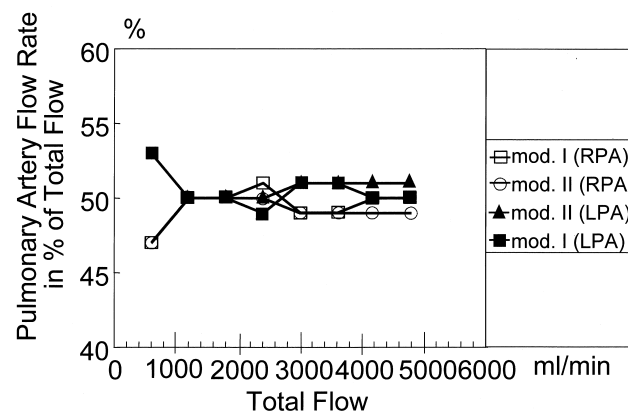


Fig 5. Right to left pulmonary artery flow at an inferior to superior caval flow ratio of 67/33 and equal right and left pulmonary artery resistances. There was no maldistribution of pulmonary artery flow in the crosslike model (model I) or in the curved model (model II). (RPA = right pulmonary artery; LPA = left pulmonary artery.)

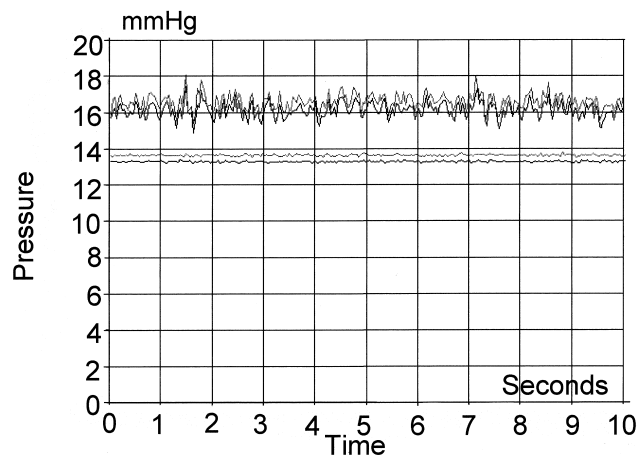


Fig 6. Pressure oscillations in the caval veins with the crosslike cavopulmonary connection (model I, upper curves) and with the curved configuration (model II, lower curves) at a total flow of 5,600 mL/minute, an inferior to superior caval flow ratio of 50/50, and identical right and left pulmonary resistances. Note the reduced oscillations in the curved model.

connections is the collision of inferior and superior caval flow. The results of Sharma and associates [14] and Shandas and associates [20] as well as our flow visualization studies showed that this caval flow collision creates helically rotating vortices within the pulmonary arteries. De Leval and colleagues [10] also described small oscillations at postoperative cardiac catheterizations in patients with the total cavopulmonary connection and related them to left atrial and systemic ventricular events, contraction of the residual atrial wall, or respiratory fluctuations. Although our test circuit was nonpulsatile and not influenced by respiration, similar oscillations were observed in the crosslike model (Fig 6). Thus the oscillations in this model probably were generated by alternations of vortices that are caused by the frontal collision of caval flows. The observed helically rotating vortices not only induce oscillations but also represent an energy-consuming process measured as pressure losses. In this regard, flow separation of the caval inlets should provide some advantages as mentioned by Sharma and associates [14]. There are three approaches to gain this flow separation, augmentation, offsetting, and curvature. Numeric approaches to improve geometry by enlarging the IVC anastomosis toward the RPA using a polytetrafluoroethylene patch showed reduced power losses [12]. Sharma and associates [16] described the behavior of models with 0.5 and 1 diameter offset combined with 5.5-cm radii of curvature. The IVC was curved toward the RPA and the SVC toward the LPA. They found a benefit of curvature only at optimal flow ratios, such as an RPA/LPA flow split of 70/30, whereas adverse flow ratios such as RPA/LPA = 30/70 caused increased power losses.

From a hydrodynamic perspective, it seems obvious that the radius of curvature is a major determinant of pressure losses and flow patterns. If the radius is too small it leads to caval flow collision, and if it is too large acute angles are created between IVC and LPA and

between SVC and RPA, both conditions leading to power losses. As a rationale these parameters as well as the potential for surgical practicability formed the basis of our modification with a small caval curvature that prevents acute angles, caval offset, and caval flow collision. Power losses were lower in this model than in the crosslike anastomosis. This small curvature did not create increased power losses at adverse pulmonary flow splits (Figs 3, 4), as observed by Sharma and associates [16], and it did not lead to a maldistribution of pulmonary artery flow in the case of unfixed pulmonary flow split at equal lung resistance (Fig 5). The effect of curvature was most evident at high flow rates simulating exercise.

Srivastava and colleagues [15] previously reported that pulmonary arteriovenous malformations are a known complication caused by hepatic venous maldistribution in the lungs after some types of cavopulmonary connection. At identical right and left pulmonary artery resistances and a symmetrical caval flow ratio resembling flow conditions of infants [19], most IVC fluid simulating hepatic venous return was directed toward the RPA in the curved connection. At adult caval flow ratios, a certain dispersion of the IVC fluid toward both pulmonary arteries with an LPA flow containing up to 44% IVC fluid could be measured. The influence of various caval flow ratios on the distribution of inferior caval blood in the curved cavopulmonary connection is an important finding of this study. In young children a lack of hepatic blood in the left lung can occur because of impaired caval blood mixing in this type of connection. During the growth period the caval flow split is in transition from neonatal conditions to the adult caval flow ratio of IVC/SVC = 67/33, thus improving the mixing of superior and inferior caval blood, which might protect against pulmonary arteriovenous malformations [15]. The amount of mixing that is adequate for prevention of arteriovenous malformations is still unknown. Nevertheless, the potential for reduced perfusion of the left lung with hepatic blood and the possible development of arteriovenous malformations in curved anastomosis must be taken into consideration. Especially in the very young, further investigations are necessary to optimize mixing and power losses across curved cavopulmonary connections preferably with physiologic conditions including respiration.

Power losses in the curved model are lower compared with those of the crosslike configuration. In absolute values of power losses, this effect is most obvious during exercise. Conversely, the distribution of hepatic fluid from the IVC to the right and left pulmonary arteries is less balanced in the curved model especially for caval flow conditions that simulate young age. The reduction of anastomotic offset might induce a more balanced distribution of hepatic venous return.

The major limitation of this study is that this in vitro investigation is comparable to in vivo conditions only with certain reservations. The tubes were rigid allowing no compliance mechanisms that might alleviate peak pressures, for example, the observed pressure oscillations. De Leval and colleagues [10], however, recorded

similar oscillations in patients, suggesting that the rigidity was not of consequence. We did not consider the effects of respiratory changes on caval flow and pulmonary resistance that might also cause pressure losses and mixing of IVC and SVC fluid.

## References

1. Fontan F, Baudet E. Surgical repair of tricuspid atresia. *Thorax* 1971;26:240-8.
2. Bridges ND, Jonas RA, Mayer JE, Flanagan MF, Keane JF, Castaneda AR. Bidirectional cavopulmonary anastomosis as interim palliation for high-risk Fontan candidates. *Circulation* 1990;82(4):170-6.
3. Cowgill LD. The Fontan procedure: a historical review. *Ann Thorac Surg* 1991;51:1026-30.
4. Furuse A, Brawley RK, Gott VL. Pulsatile cavo-pulmonary artery shunt. Surgical technique and hemodynamic characteristics. *J Thorac Cardiovasc Surg* 1972;63:495-500.
5. Giannico S, Corno A, Marino B, et al. Total extracardiac right heart bypass. *Circulation* 1992;86(5):110-7.
6. Hashimoto K, Kurosawa H, Tanaka K, et al. Total cavopulmonary connection without the use of prosthetic material: technical considerations and hemodynamic consequences. *J Thorac Cardiovasc Surg* 1995;110:625-32.
7. Lins RFA, Lins MFA, Cavalcanti C, Miranda RP, Mota JH. Orthoterminal correction of congenital heart disease: double cava-pulmonary anastomosis. *J Thorac Cardiovasc Surg* 1982;84:633-5.
8. Robicsek F. An epitaph for cavopulmonary anastomosis. *Ann Thorac Surg* 1982;34:208-20.
9. De Leval MR. Right heart bypasses operations. In: Stark J, de Leval MR, eds. *Surgery for congenital heart defects*. Philadelphia, Pennsylvania: W.B. Saunders Company, 1994: 565-79.
10. De Leval MR, Kilner P, Gewillig M, Bull C. Total cavopulmonary connection: a logical alternative to atriopulmonary connection for complex Fontan operations. *J Thorac Cardiovasc Surg* 1988;96:682-95.
11. Kirklin JW, Fernandez G, Fontan F, et al. Therapeutic use of right atrial pressure early after the Fontan operation. *Eur J Cardiothorac Surg* 1990;4:2-7.
12. De Leval MR, Dubini G, Migliavacca F, et al. 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;111:502-13.
13. Van Haesdonck JM, Mertens L, Sizaire R, et al. Comparison by computerized numeric modeling of energy losses in different Fontan connections. *Circulation* 1995;92:322-26.
14. Sharma S, Goudy S, Walker P, et al. 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;27:1264-9.
15. Srivastava D, Preminger T, Lock JE. Hepatic venous blood and the development of pulmonary arteriovenous malformations in congenital heart disease. *Circulation* 1995;92: 1217-22.
16. Sharma S, Ensley A, Chatzimavroudis G, Fontaine AA, Yoganathan AP. Does the addition of curvature at the total cavopulmonary connection (TCPC) site reduce power losses? *J Am Coll Cardiol* 1997;29 (Suppl A):427-8A.
17. Köttgen U, Bolt W. *Kreislauf*. In: Brock J, ed. *Biologische Daten für den Kinderarzt*. Berlin: Springer-Verlag, 1954:356-88.
18. Sievers HH, Onnasch DGW, Lange PE, Bernhard A, Heintzen PH. Dimensions of the great arteries, semilunar valve roots, and right ventricular outflow tract during growth: normative angiocardigraphic data. *Pediatr Cardiol* 1983;4: 189-96.
19. Salim MA, DiSessa TG, Arheart KL, Alpert BS. Contribution of superior vena caval flow to total cardiac output in children. *Circulation* 1995;92:1860-5.
20. Shandas S, DeGroff CG, Kwon J, Valdest-Cruz L. Vortex structures within the modified Fontan connection play a primary role in energy loss. In vitro digital particle image velocimetry studies. *J Am Coll Cardiol* 1997;29(Suppl A): 427A.

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