BIDIRECTIONAL SUPERIOR CAVOPULMONARY ANASTOMOSIS IMPROVES MECHANICAL EFFICIENCY IN DILATED ATRIOPULMONARY CONNECTIONS

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Objective: Few therapeutic options exist for patients with failing dilated atriopulmonary connections. We addressed the hypothesis that a bidirectional superior cavopulmonary anastomosis will improve the hemodynamic efficiency of dilated atriopulmonary connections while maintaining physiologic pulmonary flow distributions. **Methods:** Dilated atriopulmonary connections with and without a bidirectional superior cavopulmonary anastomosis were created in explanted sheep heart preparations and transparent glass models. A mechanical energy balance and flow visualization were performed for 6 flow rates (1-6 L/min), both with and without the bidirectional superior cavopulmonary anastomosis, and were then compared. A novel contrast echocardiographic technique was used to quantify inferior vena cava flow (hepatic venous return) distributions into the pulmonary arteries. **Results:** The rate of fluid-energy dissipation was $52\% \pm 14\%$ greater in the dilated atriopulmonary anastomosis than in the bidirectional superior cavopulmonary anastomosis model over the range of flow rates studied ($P = 6.3E^{-3}$). Total venous return passing to the right pulmonary artery increased from $41\% \pm 2\%$ to $47\% \pm 3\%$ ($P = 9.7E^{-3}$) and that for inferior vena cava flow decreased from $42\% \pm 3\%$ to $12\% \pm 4\%$ ($P = 3.3E^{-4}$) after addition of the bidirectional superior cavopulmonary anastomosis. Flow visualization confirmed more ordered atrial flow in the bidirectional cavopulmonary anastomosis model, resulting from a reduction of caval flow stream collision and interaction. **Conclusions:** A bidirectional cavopulmonary anastomosis reduces fluid-energy dissipation in atriopulmonary connections, provides a physiologic distribution of total flow, and maintains some hepatic venous flow to each lung. This approach may be a technically simple alternative to atriopulmonary takedown procedures and conversions to total cavopulmonary connections in selected patients. (J Thorac Cardiovasc Surg 1999;118:681-91)

Shortly after the description of the first successful right ventricular bypass operation for tricuspid atresia,¹ Kreutzer and associates² demonstrated that the entire venous return could be diverted to the pulmonary circulation through a single valveless atriopulmonary

connection (APC). Although the modified Fontan operation has been used widely to separate the systemic and pulmonary circulations in patients with complex congenital heart disease, several early and late postoperative complications associated with this procedure³⁻⁵ have diminished its use in place of more hemodynamically efficient total cavopulmonary connections (TCPCs).⁶ Although TCPC has virtually replaced APC in many centers, late postoperative survivors with dilated APCs and failing circulations present a significant clinical management problem. We have previously demonstrated that progressive right atrial dilatation decreases the hemodynamic efficiency of the APC.⁷ Although conversion to a TCPC has been advocated to improve flow dynamics and reduce the risk of supraventricular arrhythmias and thrombus formation,

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Fig 1. A, Modified Fontan APC for tricuspid atresia. B, APC with a BSCA. C, A photograph of the APC with BSCA glass model with geometric vessel and chamber sizes specifications. The inferior vena cava entered the right atrium posteriorly at an angle of 70°. APC, Atriapulmonary connection; BSCA, bidirectional superior cavopulmonary anastomosis; IVC, inferior vena cava; SVC, superior vena cava; MPA, main pulmonary artery; RPA, right pulmonary artery; LPA, left pulmonary artery; LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

Fig 2. Symmetric bifurcation model illustrating the general principles of the measurement technique used to determine the pulmonary distribution of flow from the IVC. A 1.0-mL bolus of contrast agent is injected into the main branch proximal to the bifurcation and time-intensity curves constructed from short-axis echocardiographic views placed through the main (input function) and right branch (output function). Since the area under the input time-intensity curve represents the total number of particles injected into the system, monitoring changes in the area under the branch time intensity curve allows for quantification of pulmonary flow distributions. N_{branch} , Number of particles passing through branch; N_{trunk} , number of particles passing through trunk; $Area_{branch}$, area under branch time-intensity curve; $Area_{trunk}$, area under trunk time-intensity curve; Q_{branch} , branch flow rate; Q_{trunk} , trunk flow rate.

this procedure is technically demanding and associated with approximately a 10% mortality.⁸⁻¹²

The bidirectional superior cavopulmonary anastomosis (BSCA) is commonly performed as a part of the staged surgical management of children with complex congenital heart disease who will ultimately undergo a complete Fontan operation. This procedure diverts upper extremity venous return directly into the pulmonary arteries and therefore may offer a number of specific advantages for improving the hemodynamic status of patients with dilated APC. Although previous studies have compared flow dynamics of APC and TCPC,^{6,13} the use of a BSCA to improve the flow dynamics of dilated APC has not been previously proposed or studied. Accordingly, the purpose of this study was to address the hypothesis that addition of a BSCA

will improve the hemodynamic efficiency of the right heart and pulmonary circulation in dilated APC, while maintaining a physiologic distribution of both total and inferior vena cava (IVC) flow (normally containing hepatic venous return) to the pulmonary vasculature.

Methods

Flow models

Tissue. Modified APCs were performed on fresh explanted sheep heart and lung preparations (30.3 ± 2.1 kg; body surface area, 1.2 ± 0.2 m²) by means of standard surgical techniques.¹⁴ After an oblique incision, the right atrial appendage was connected to the transected proximal main pulmonary artery (Fig 1, A). Simulation of right atrial dilation was achieved surgically by creating an incision in the anterior wall of the right atrium and sewing a glutaraldehyde-fixed patch of pericardial tissue into the right atrial chamber as pre-

Fig 3. Fluorescence particle-tracking flow visualization apparatus (see text for details).

viously reported.⁷ After the dilated APC had been studied, a BSCA was performed on these same models by transecting the superior vena cava (SVC) and connecting its proximal end to the superior aspect of the right pulmonary artery in an end-to-side fashion (Fig 1, B). Thus each model served as its own control ($n = 12$).

Transparent glass replicas. Geometrically correct glass models of the dilated APC connection with and without a BSCA were constructed from blown Pyrex glass (Corning, Inc, Corning, NY) with vessel and right atrial chamber dimensions equivalent to those of the explanted tissue preparations with a tolerance of ± 1 mm. Pressure taps were placed in the caval veins and right atrium, across the atriopulmonary anastomosis and pulmonary artery bifurcation, and along the length of the branch pulmonary arteries in 1-cm steps. Fig 1, C, is a photograph of the APC-BSCA glass model with vessel and chamber dimensions and geometric parameters (see legend to Fig 1).

Flow conditions and hemodynamic measurements. Tissue and glass models were studied in an in vitro flow loop described previously.⁷ Models were perfused with a blood analog fluid (33% glycerin/water, viscosity 3.5 cP) with a steady centrifugal pump at 6 flow rates (1–6 L/min), producing a range of physiologic right heart Reynolds' numbers (ratio of inertial to viscous forces) and velocities of approximately 200 to 2300 and 20 to 65 cm/s, respectively. SVC and IVC flows were set to 35% and 65% of the total flow rate, respectively, to account for the greater flow contribution of the IVC in older children.¹⁵ In tissue models, nonrestrictive atriopulmonary anastomoses were confirmed by simultane-

ous pressure measurements immediately proximal and distal to the right atrium–main pulmonary artery and SVC–right pulmonary artery connections at several flow rates. The anastomosis was determined to be nonrestrictive for pressure gradients less than 1 mm Hg for flow rates up to 6 L/min. Caval vein, pulmonary artery, and right atrial pressures were measured with fluid-filled catheter pressure transducers interfaced to a personal computer via an analog-to-digital board and custom software (Lab View Software, National Instruments, Austin, Tex) for automated data acquisition. Additionally, pressure was mapped in 1-cm steps from the right atrium to the pulmonary artery bifurcation and then bidirectionally along the branch pulmonary arteries for each configuration. Caval vein and pulmonary artery flows were measured with an ultrasonic flowmeter and 10- to 14-mm flow probes (Transonic Systems, Inc, Utica, NY) placed loosely around the circumference of each vessel or a latex ultrasound window. Total flow was measured with a calibrated rotameter inserted in the flow loop proximal to the model. Average velocities were determined by means of instantaneous flow values and vessel cross-sectional areas (measured at full vessel distention in tissue models).

Pulmonary flow distribution of IVC flow. A novel contrast echocardiographic measurement technique derived from indicator-dilution theory was used to quantify the distribution of IVC flow (and hence hepatic venous return) into the branch pulmonary arteries. Details of the mathematical model and measurement technique have been published elsewhere.^{16–18} Fig 2 demonstrates the general features of the model for a simple symmetric bifurcation (see legend to Fig 2). An albumin-

Fig 4. Absolute rate of fluid-energy dissipation versus flow rate for the APC connection both with and without BSCA. APC, Atriopulmonary connection; BSCA, bidirectional superior cavopulmonary anastomosis.

Table I. Absolute pressure data for each model at all flows

		Mean pressure data (mm Hg)							
	Q_T	P_{SVC}	P_{IVC}	P_{RPA}	P_{LPA}	$P_{SVC}-P_{LPA}$	$P_{SVC}-P_{RPA}$	$P_{IVC}-P_{RPA}$	$P_{IVC}-P_{LPA}$
APC	1.0	2.0	2.1	1.8	2.0	0.0	0.2	0.3	0.1
	2.0	5.1	5.0	4.4	4.4	0.7	0.8	0.6	0.6
	3.0	9.1	9.1	7.5	7.7	1.4	1.5	1.5	1.4
	4.0	13.9	13.5	11.9	12.0	1.9	2.0	1.6	1.5
	5.0	18.4	18.2	16.0	15.9	2.5	2.4	2.2	2.3
	6.0	25.1	25.0	21.7	21.5	3.7	3.4	3.3	3.5
APC-BSCA	1.0	2.0	1.9	1.9	1.9	0.1	0.1	0.0	0.0
	2.0	4.8	4.8	4.2	4.4	0.4	0.6	0.6	0.4
	3.0	8.7	8.9	7.9	8.1	0.5	0.8	1.1	0.8
	4.0	13.8	14.1	12.7	13.0	0.8	1.1	1.5	1.1
	5.0	18.7	19.6	17.4	18.0	0.8	1.3	2.1	1.6
	6.0	25.3	26.4	23.4	24.1	1.2	1.9	2.9	2.2

The pressure drop from the caval veins to the branch pulmonary arteries was consistently greater in the APC model at all flow rates and combinations studied ($P < 0.01$) and was a function of total flow. Standard deviations for all pressure data did not exceed 0.38 mm Hg. P_{IVC} , inferior vena cava pressure; P_{SVC} , superior vena cava pressure; P_{RPA} , right pulmonary artery pressure; P_{LPA} , left pulmonary artery pressure. Standard deviation < 0.28 mm Hg for all samples.

encapsulated perfluoropropane echocardiographic contrast agent (Optison, Mallinckrodt Medical, St Louis, Mo) was used as an intravascular flow tracer to mimic hepatic venous return. After a 2-mL bolus injection into the IVC, time-intensity curves were constructed from short-axis echocardiographic views placed through the IVC (input function) and distal right pulmonary artery (output function) with a 2.5-MHz transducer and clinical ultrasound system (Sonos 2500, Hewlett-Packard, Andover, Mass). By using the derived model (see equation in Fig 2), the number of particles passing

through the right pulmonary artery relative to the total number of particles injected into the system could be determined.

Fluid-energy dissipation. To quantify the fluid dynamic efficiency of each model, we analyzed the rate of fluid-energy loss over a physiologic range of flow rates and conditions for each model. This analysis requires knowledge of pressure, flow, and velocity at the inlets and outlets of the right side of the heart and is particularly useful since it includes all potential sources of loss: static and kinetic energy losses due to flow expansion and contraction, and viscous dissipation loss-

Fig 5. Total mechanical efficiency (fluid-energy dissipation divided by total energy available for flow) for each configuration studied. Over the range of physiologic flow rates, the APC with the BSCA dissipated only 8% of the total fluid energy available versus 15% for the APC. APC, Atriopulmonary connection; BSCA, bidirectional superior cavopulmonary anastomosis.

es due to flow collision and mixing. The energy dissipation analysis is simply a fluid-energy balance over the flow model that states the fluid energy entering the model is equal to the fluid energy leaving the model plus any incurred loss:

$$E_{loss} = \sum E_{in} - \sum E_{out} \quad (\text{Eq 1})$$

where the total rate of fluid energy for vessel i is given by the equation:

$$E_i = Q_i \left(P_i + \frac{1}{2} \rho v_i^2 \right) \quad (\text{Eq 2})$$

for i = superior vena cava (svc), inferior vena cava (ivc), right pulmonary artery (rpa), or left pulmonary artery (lpa). Equation 2 represents both static and kinetic energy contributions where Q is the flow rate in cubic meters per second, P is the static pressure in Newtons per square meter, v is the average velocity in meters per second, and ρ is the fluid density in kilograms per cubic meter. Combining equations 1 and 2, we arrive at an equation that represents the total energy dissipation occurring across each model:

$$E_{loss} = q_{svc} \left(P_{svc} + \frac{1}{2} \rho v_{svc}^2 \right) + Q_{ivc} \left(P_{ivc} + \frac{1}{2} \rho v_{ivc}^2 \right) - Q_{rpa} \left(P_{rpa} + \frac{1}{2} \rho v_{rpa}^2 \right) - Q_{lpa} \left(P_{lpa} + \frac{1}{2} \rho v_{lpa}^2 \right) \quad (\text{Eq 3})$$

Although the rate of fluid-energy dissipation provides useful information regarding relative performance of different

procedures, the clinical significance of absolute loss values is less obvious. Accordingly, an additional parameter was defined and referred to as the overall efficiency coefficient (η_E), which reflects the effect of flow geometry on the total fluid-energy dissipation as a fraction of the total energy available for fluid motion ($0 < \eta_E < 100$):

$$\eta_E + 100 \cdot \left(1 - \frac{E_{loss}}{Q_{svci} \left[P_{svc} + \frac{1}{2} \rho v_{svc}^2 \right] + Q_{ivc} \left[P_{ivc} + \frac{1}{2} \rho v_{ivc}^2 \right]} \right) \quad (\text{Eq 4})$$

Laser-induced particle tracking flow visualization. To identify areas of flow separation and turbulence that were associated with quantitative fluid-energy losses, transparent flow models were qualitatively analyzed by means of the technique of laser-induced fluorescence particle tracking. A schematic of the setup is shown in Fig 3. Neutrally buoyant 30- μm fluorescent microspheres (Duke Scientific, Palo Alto, Calif) were injected into the flow field and observed by means of a fluorescence illumination technique. An 18-W argon ion laser passes through an optical regulator and then is reflected off a mirror and through a cylindric lens that splits the beam into a 1.1-mm sheet of light. This sheet passes through the transparent model in a plane parallel to flow and excites the neutrally buoyant particles that follow the streamlines of flow. Particle excitation results in an emission of light at a longer wavelength (611 nm) than the transmitted light. Particle motion and streamlines were recorded by

Fig 6. Pulmonary flow distribution of (A) total venous return to the right pulmonary artery and (B) inferior vena cava flow to the right pulmonary artery for both configurations studied. RPA, Right pulmonary artery; APC, atrio-pulmonary connection; BSCA, bidirectional superior cavopulmonary anastomosis.

means of a high-resolution digital camera (Eastman Kodak, Rochester, NY) through a high-pass optical filter. Each condition was recorded on super VHS videotape for off-line analysis.

Statistical analysis. Fluid-energy dissipation data are expressed as the mean value of 6 consecutive measurements at the same flow conditions. Differences in the rate of fluid-energy dissipation, right pulmonary artery pressures, and total and IVC pulmonary flow distributions with and without the BSCA and with flow rate were compared by 2-way analysis of variance with replication ($P < .01$).

Results

Fluid-energy dissipation. Absolute energy dissipation versus flow rate for each model studied is shown

in Fig 4. Losses increased exponentially with increasing flow rate ($r = 0.96$) and were 52 ± 14 greater in the APC model than in the dilated APC with a BSCA over the range of flows ($P = 6.3E^{-3}$). No significant changes in mean pulmonary artery pressure between the APC and BSCA configurations were noted for flow rates up to 5 L/min ($P = .194$). At a flow rate of 6 L/min, however, pulmonary artery pressure increased 1.3 ± 0.1 mm Hg ($P = 4.5E^{-3}$) after incorporation of the BSCA. The rate of fluid energy passing through the right atrium decreased $62\% \pm 23\%$ over the range of flow rates studied after the construction of the BSCA ($P = 3.4E^{-3}$). Table I shows absolute pressure data for each model at all flows. Standard deviations for all data were less than

Fig 7. Flow visualization images from (A) APC and (B) APC with BSCA at a flow rate of 4 L/min. Without the BSCA, flow is characterized by chaotic particle dynamics in the right atrium due to caval stream collision and mixing. After incorporation of the BSCA, flow through the right atrium is more ordered. C, A plane through the pulmonary artery bifurcation in the APC model. Note the formation of helical flow in the left pulmonary artery. For the APC-BSCA model (D) the flow competition region can be visualized as shown by the arrow. For abbreviations see Fig 1.

0.28 mm Hg. The pressure drop from the caval veins to the branch pulmonary arteries was consistently greater in the APC model at all flow rates and combinations studied ($P = 6.7 \times 10^{-3}$) and was a function of total flow ($P = 8.4 \times 10^{-4}$). Total efficiency coefficients for each model are shown in Fig 5, where the y-axis represents the rate of fluid-energy dissipation divided by the total fluid energy available to drive flow across the pulmonary circulation (carried by the IVC and SVC inlet streams). For the most physiologic flow rates between 3 and 5

L/min, the APC model dissipated up to 15% of the total input fluid energy compared with only 8% when the BSCA was incorporated into the circulation.

Total and IVC pulmonary flow distributions. The distribution of total and IVC pulmonary flow was also affected by the BSCA (Fig 6). For the APC model, an average of $41\% \pm 3\%$ of the total venous return was directed toward the right pulmonary artery, which increased to $47\% \pm 2\%$ for the APC-BSCA model ($P = 9.7 \times 10^{-3}$, Fig 6, A). The distribution of pulmonary flow

was independent of total flow rate over the flow range of 2 to 6 L/min ($P = 2.5e^{-2}$). Since there was excellent mixing in the right atrial chamber from violent caval vein stream interactions (see next section), the pulmonary distribution of flow that would normally contain hepatic venous return was approximately equal to that measured for total flow distributions (approximately 40%). Fig 6, *B*, shows a comparison of the total bubbles passing through the right pulmonary artery for each flow rate studied. The distribution of IVC flow decreased from $42\% \pm 3\%$ for the APC alone model to $12\% \pm 4\%$ for the APC-BSCA model ($P = 3.2e^{-4}$) and was independent of total flow rate ($P = 2.1e^{-1}$).

Flow visualization. Flow visualization experiments demonstrated marked differences in right atrial and pulmonary flow dynamics between the 2 models, which helped explain differences in quantitative measurements of energy dissipation. Flow in the dilated APC connection was characterized by violent collision and interaction between caval flow streams and disordered flow, with recirculation zones along the lateral and medial walls of the dilated right atrial chamber (Fig 7, *A*). Additionally, large vortices were present in the main pulmonary artery with chaotic particle dynamics at the pulmonary artery bifurcation. After the addition of the BSCA, right atrial flow dynamics improved substantially as demonstrated by more ordered, lower-velocity flow from the IVC to APC connection (Fig 7, *B*), although some swirling right atrial flow was noted due to the angle of inflow from the IVC into the right atrium. In the APC model, the degree of chaotic flow in the right atrium increased with increasing flow rate and increased flow separation regions distal to the IVC. The result was the formation of a recirculation region and vortices in the main and right pulmonary arteries over a flow range of 2 to 4 L/min (Fig 7, *C*). Unstable main and branch pulmonary vortices were not present in the BSCA model for flow rates up to 4 L/min (Fig 7, *D*) and were less pronounced than in the APC model at higher flow rates (5–6 L/min). Pulmonary flow competition was clearly visualized in the APC-BSCA model and was characterized by a slow flow recirculation region located between the BSCA and main pulmonary artery (arrow in Fig 7, *D*). IVC flow containing hepatic venous return was directed bidirectionally to the branch pulmonary arteries, and no SVC flow reached the left pulmonary artery.

Discussion

The Fontan procedure has evolved substantially over the past 3 decades, but no designs have been directed at improving the mechanical efficiency of the APC per se,

particularly once atrial dilatation has occurred. In light of the number of patients with APC having symptoms in the late postoperative period, such an approach is warranted. In a recent study we⁷ showed that progressive right atrial dilatation, as occurs in many patients with long-standing APC, results in a decrease in hemodynamic efficiency and an increase in effective pulmonary vascular resistance. Be'eri and associates¹⁹ recently studied flow dynamics in vivo using magnetic resonance imaging velocity mapping and confirmed poor right atrial flow dynamics and adverse caval stream interaction in patients with APC. Conversion of the APC to a lateral tunnel TCPC through both an intra-atrial and an extracardiac approach has been suggested to improve right heart flow dynamics and ideally improve exercise performance while reducing the incidence of thrombus formation and supraventricular arrhythmias.^{8–12} Although we²⁰ have recently demonstrated specific hemodynamic advantages of the extracardiac TCPC over intra-atrial techniques, conversion procedures are technically demanding, require cardiopulmonary bypass, and usually involve additional atrial suture lines, all of which may be associated with significant morbidity and mortality in this group of very sick patients.

In this study, we evaluated the effect of a bidirectional superior cavopulmonary anastomosis on the flow dynamics of dilated atriopulmonary connections. Results from these studies indicate that a BSCA may be a simple technique for improving the mechanical efficiency and flow dynamics of dilated atriopulmonary connections.

Source of improved flow efficiency. The improved mechanical efficiency observed with the BSCA can most likely be attributed to elimination of caval flow interaction in the dilated right atrium. As was observed in flow visualization data, IVC and SVC flows collide in the right atrium and result in large flow separation and stagnation zones along the lateral and septal walls of the atrium. Additionally, high-velocity flow through the right atrium resulted in large vortices in the main pulmonary artery and recirculation zones in the branch pulmonary arteries. In the APC with the BSCA, however, SVC flow is diverted directly into right pulmonary artery and thus does not interact with IVC flow entering the right atrium. Less fluid stream interaction results in a reduction of kinetic energy loss, viscous dissipation, and flow stagnation and separation zones and reduces flow conditions thought to be conducive for thrombus formation. In addition, the presence of competing flows in the pulmonary arteries may also contribute to the superior efficiency of this configuration by eliminating flow separation distal to the pul-

monary artery bifurcation and serving to facilitate efficient flow transfer into the branch pulmonary arteries. Interestingly, the efficiencies measured for the APC-BSCA configuration in this study were equal to efficiencies previously reported for the lateral tunnel TCPC both in our laboratory and by others.^{16,21} This surprising result lends further insight into the etiology of energy losses in the APC and suggests that caval flow collision and mixing in the right atrium represents the primary source of flow inefficiency, perhaps more so than inherent differences in connection geometry.

Factors affecting pulmonary flow distributions.

The pulmonary flow distribution of both total and hepatic venous return may have important implications regarding the long-term functional status of patients with single ventricle physiology. An appropriate pulmonary ventilation-perfusion match is an important determinant of optimal gas exchange and exercise performance, and pulmonary deprivation of hepatic venous return may result in arterial venous malformations in patients with unidirectional and bidirectional superior cavopulmonary connections.^{22,23} In the APC-BSCA model, flow competition between the IVC and SVC resulted in a more favorable distribution of total venous return into the pulmonary arteries and significantly altered the distribution of IVC flow. The later parameter is largely dependent on the ratio of IVC and SVC flow and the angle between the main pulmonary artery and the branch pulmonary arteries. In the current study, these parameters were 35%/65% and 60° (pointing toward the left pulmonary artery), respectively, representing an older patient with normally related great vessels. IVC flow is transmitted directly to the main pulmonary artery, where it flows bidirectionally into the branch pulmonary arteries. Since this flow stream is greater than SVC flow, the portion of IVC flow directed to the right pulmonary artery has sufficient fluid momentum to "win" the flow competition with half of the SVC stream, thus permitting some (approximately 12%) IVC flow to pass to the right lung and with no SVC flow reaching the left lung. Clearly, pulmonary flow distributions in a clinical setting depend on a variety of factors, including the actual caval flow ratio, individual anatomy, and respiratory-induced changes in flow with inspiration.

Clinical implications. Construction of a palliative BSCA in patients with right atrial dilation offers several theoretical and practical advantages over complex TCPC conversion procedures and thus may have clinical merit. This approach may improve hemodynamic efficiency and stop the cycle of increasing resistance and decreasing output commonly seen in this group of

patients without significant elevations in pulmonary artery pressure. Since poor right atrial flow dynamics have been shown to result in a resistance to pulmonary flow, which is in addition to the inherent pulmonary arteriolar resistance,⁷ an improvement in hemodynamic efficiency of the APC may significantly improve exercise capacity. Additionally, this approach is technically straightforward, can be performed without cardiopulmonary bypass, and does not require additional atrial suture lines or the placement of potentially thrombogenic prosthetic material.

Study limitations. As was mentioned in the discussion, the APC-BSCA models studied represented patients with normally related great arteries. As the main pulmonary artery angle and the distance between the bidirectional cavopulmonary anastomosis and main pulmonary artery are very different in patients with transposed great arteries, it is likely that flow distribution characteristics would also be very different from those measured in this study. Also, in addition to individual geometry, the pulmonary distribution of total and hepatic venous return in the clinical setting is likely dependent on the actual caval flow ratio, effects of respiration, pulmonary vascular resistance, and left ventricular function. More advanced in vitro modeling techniques will be required to isolate the effect of these potentially important parameters.

Conclusions

These studies indicate that incorporation of a BSCA with dilated APC improves flow dynamics and provides a physiologic distribution of total flow, while maintaining some IVC flow (hepatic venous return) into each lung. This procedure is technically simple, does not require additional atrial suture lines, and can be performed quickly without cardiopulmonary bypass. A BSCA may be a logical and effective alternative to complicated APC takedown procedures and conversions to total cavopulmonary connections in selected patients.

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