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Original Article

Characterization and treatment of systemic venous to pulmonary venous collaterals seen after the Fontan operation

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Abstract *Objectives:* To determine the anatomical characteristics of systemic venous collaterals formed after the Fontan operation, and the efficacy of a transcatheter strategy for management. *Methods:* We reviewed retrospectively the data from cardiac catherization of 50 persistently cyanotic patients after the Fontan operation. *Results:* A total of 54 transcatheter interventions were performed, at a mean age of 6.3 ± 3.5 years, a mean interval of 2.7 ± 2.9 years from completion of the Fontan circulation. Of 38 patients who had fenestration of the baffle at the time of surgery, 25 had patency of the fenestration, and 24 had the fenestration occluded with a device at the time of interventional treatment for associated venous collaterals. We identified a total of 68 systemic venous collateral channels, of which 36 (53%) were supracardiac, 12 (18%) cardiac, and 20 (29%) infracardiac in origin. The most common site of origin was the brachiocephalic vein (44%), followed by the left phrenic vein (25%). A longer time from surgery, at 3.3 ± 3.4 years, was associated with the identification of collaterals having a diameter larger than 4 mm ($p < 0.01$). The mean pulmonary arterial pressure was higher in those with larger compared to those with smaller collaterals (13.3 ± 2.8 versus 11.1 ± 2.0 mmHg, $p < 0.01$). Coils were used for occlusion of 61 vessels, and a Rashkind™ occluder for the remaining 7. After exclusion of the patients undergoing simultaneous closure of their fenestration, systemic saturation of oxygen increased from 89 ± 6% to 95 ± 3% ($p < 0.01$). *Conclusion:* Venous collateral channels are common in patients suffering progressive cyanosis in the setting of the Fontan circulation. The collaterals increase in size with time, and are associated with higher pulmonary arterial pressures. Transcatheter treatment is feasible, and results in resolution of cyanosis. Only continuing follow-up will show whether further collateralization occurs in time.

Keywords: Venous collateral channels; cavopulmonary connections; cyanosis; coil embolization; Rashkind™ Occluder; interventional catheterization

THE FONTAN PROCEDURE HAS NOW BEEN performed for more than 30 years as the attempted final palliation for patients with functionally univentricular physiology. Attrition related to the resultant circulation is a complex multifactorial phenomenon, resulting from subtle, but continuous, changes within various circulatory compartments.[1] Deterioration may occur due to ventricular dysfunction, either primary or due to volume overload, development of left-to-right shunts, atrioventricular valvar regurgitation, or atrial arrhythmias. In addition, recurrent or progressive cyanosis can develop due to the formation of systemic-to-pulmonary venous collateral channels, baffle leaks, or pulmonary arteriovenous malformations.[2–5]

In patients with a bidirectional cavopulmonary anastomosis, several investigators have described the hemodynamic and anatomical characteristics predating development of venous collaterals, and their subsequent transcatheter management.[6–10] From these reports, angiographic examination has revealed that approximately one-third of the patients have collateral channels between the systemic and pulmonary venous systems after a bidirectional cavopulmonary anastomosis. Such collaterals commonly originate from the

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brachiocephalic vein, and are associated with the severity of the pressure gradient between the pulmonary arterial circulation and the pulmonary atrium.[7,9] The overall characteristics of the venous collaterals that develop after a Fontan procedure, however, remain largely unknown. Our study, therefore, sought to establish the mechanisms underscoring the development of systemic-to-pulmonary venous collaterals after a Fontan procedure, and their optimal treatment.

Materials and methods

Between November, 1992 and August, 2001, we performed interventional procedures in 53 patients with systemic-to-pulmonary venous or atrial collaterals after a Fontan procedure. The data for these patients were obtained from the computerized cardiac database at The Hospital for Sick Children, Toronto. We reviewed angiograms and hemodynamic data from studies before the Fontan surgery, and the records of interventional catheterizations carried out after surgery, as well as the clinical data from the hospital medical records. Early in the experience, patients were brought to the catheterization laboratory only as the clinical need arose for closure of a known surgical fenestration, or assessment of the development of cyanosis, ventricular function, or pulmonary arterial anatomy. Presently, such studies are routinely performed 6 months after surgery for elective closure of fenestrations, or after 18 months for elective anatomical assessment regardless of symptoms. Patients with symptoms, or an increasing severity of cyanosis, are studied earlier on the basis of clinical need.

Surgical data

The type of Fontan procedure was recorded, as where any additional surgical procedures. Right atrial to pulmonary arterial anastomoses, or lateral tunnel procedures, were performed early in the series, while more recently extracardiac conduits were fashioned. The age at the Fontan operation, and the interval from the completion of the operation to the catheterization, were noted and compared with other clinical data.

Cineangiogram analysis

Cardiac catheterizations were performed under sedation or general anesthesia following standard techniques. Venography was initially performed in the inferior and superior caval veins, brachiocephalic vein and Fontan baffle. Further selective studies were performed by hand injection of contrast material (Isovue 300, Bracco Canada, Montreal), frequently with balloon occlusion techniques or subselective injections.[11] Systemic-to-pulmonary venous collaterals were defined as those venous channels allowing flow from the Fontan circuit into either the pulmonary atrium or veins. The location, origin, and course of such channels were recorded.

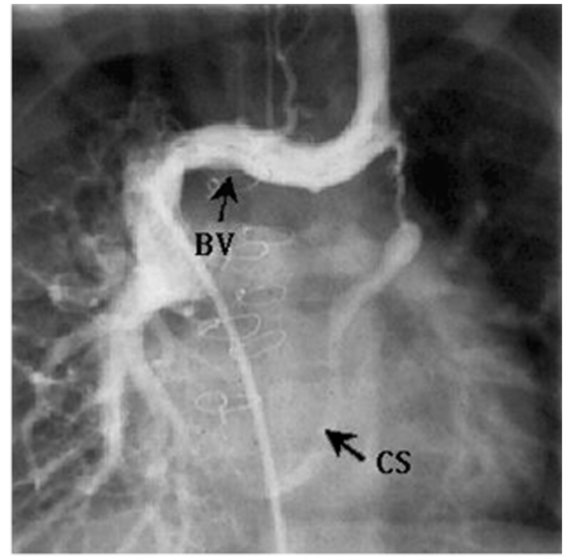

Figure 1.
This venous collateral, of supracardiac type, originated from the brachiocephalic vein and drained to the coronary sinus.

The origins of the collaterals were divided into 3 groups as follows:

- Supracardiac, originating from the superior caval vein or one of its tributaries (Fig. 1);
- Cardiac, originating between the superior caval vein and inferior caval vein (Fig. 2);
- Infracardiac, originating from the inferior caval vein or one of its tributaries (Fig. 3).

Furthermore, the termination of each collateral was recorded, as either to the pulmonary atrium or vein. The collaterals were further characterized as single or multiple and whether they drained into the right or left thoracic cavity. The size of collaterals were estimated at its origin, and compared with the known catheter diameter. Those smaller than 4 mm were classified as small, and greater than or equal to 4 mm as large.

Analysis of hemodynamics

Mean pressures were recorded in the pulmonary artery and aorta, together with the end-diastolic pressure of the dominant ventricle from the study before and after surgery, as were saturations of oxygen in the systemic and pulmonary arteries. The majority of patients were breathing room air. Several patients, however, were ventilated in an enriched mixture of oxygen, and therefore, statistical analysis of saturations of oxygen was limited to those who were breathing room air.

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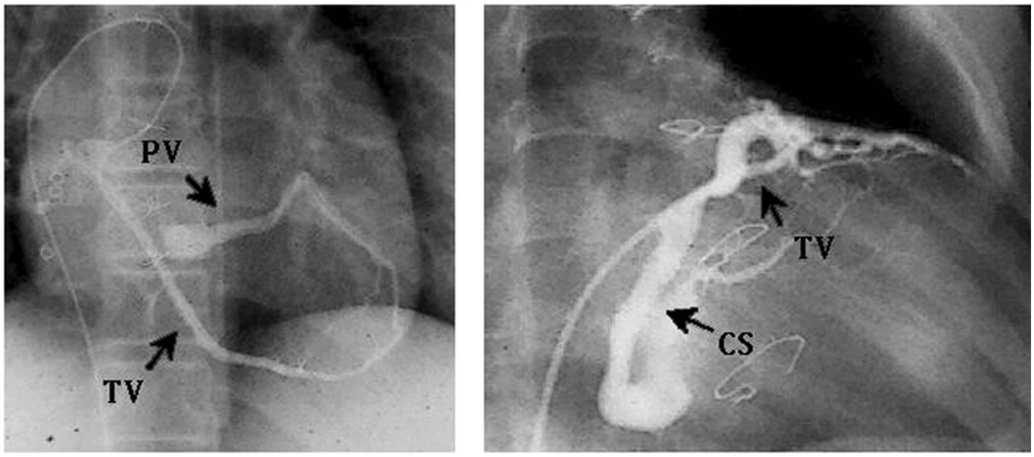

Figure 2.
This venous collateral, of cardiac type, originated from a thebesian vein and drained to the new left atrium.

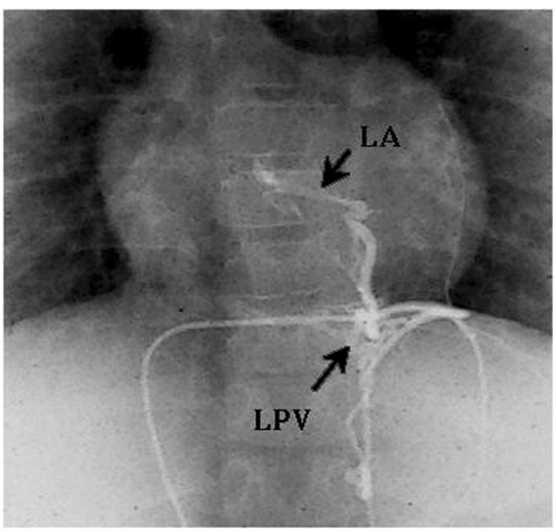

Figure 3.
This venous collateral, of infracardiac type, originated from the left phrenic vein and drained to pericardial vein.

Catheter treatment

Progressive cyanosis, or a qualitatively large shunt flow, were considered indications for therapeutic intervention. Prior to occlusion of any collateral, any potential obstructive elements within the baffle circulation were sought and corrected with balloon angioplasty or implantation of stents. Whereas most small collaterals were occluded with coils (Gianturco type, Cook Inc, Bloomington, IN; IDC type, Target Inc, Fremont, CA), most large collaterals were occluded with a Rashkind PDA™ occluder (C.R, Bard Inc, Bellerica, MA). At the same procedure, the surgical fenestration or systemic-to-pulmonary arterial collaterals were occluded as needed. All complications were recorded.

Statistical analysis

The characteristics of our population are reported as frequency and mean with standard deviation. Differences between groups were compared using unpaired student's t-test, one-way ANOVA, or Chi squared analysis using the StatView 5.0 program when appropriate. Differences were considered significant when the p value was less than 0.05.

Results

Profile of patients

There were a total of 54 transcatheter interventions for closure of systemic-to-pulmonary venous collaterals in 50 patients after their Fontan procedure. There were 28 males and 22 females. The age at catheterization ranged from 2.4 to 14.9 years, with a mean of 6.3 ± 3.5 years. The interval between the Fontan procedure and catheterization ranged from 1 day to 10.2 years, with a mean of 2.7 ± 2.9 years. The dominant ventricle was of left morphology in 32 patients, right in 16 patients, and indeterminate in 2 patients. The principal diagnoses are shown in Table 1.

Demographic and anatomical data

Of the 50 patients, 2 had an anastomosis from the right appendage to the pulmonary arteries, 29 a lateral tunnel procedure, 16 an extracardiac Fontan procedure, and 1 each a Bjork procedure, a direct anastomosis of the right atrium to the pulmonary trunk, an anastomosis of the right superior caval vein to the pulmonary trunk, and an anastomosis of the right atrium to the left pulmonary artery. A Damus–Kaye–Stansel procedure was performed in 5 patients

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Table 1. Principal diagnosis (n = 50).

Diagnostic category	n
Double inlet left ventricle	14
Double outlet right ventricle	9
Univentricular connection, left ventricular type, absent right connection	5
Pulmonary atresia with intact ventricular septum	4
Hypoplastic left heart syndrome	4
Unbalanced atrioventricular septal defect	1
Ventricular discordance with hypoplastic right ventricle	3
Right isomerism	2
Left isomerism	2
Ebstein's anomaly	1
Other	5
Total	50

Table 2. Hemodynamic data prior to and after the Fontan procedure (n = 50).

	Prior to Fontan	After Fontan	p value
Age (yr)	3.3 ± 1.9	6.3 ± 3.5	NS
mPAP (mmHg)	11.2 ± 2.8	12.2 ± 2.7	NS
mVEDP (mmHg)	6.9 ± 2.4	7.2 ± 2.4	NS
SaO_2 (%)	85 ± 4	88 ± 6	NS

Abbreviations: SaO_2: systemic arterial oxygen saturation; mPAP: mean pulmonary artery pressure; mVEDP: mean ventricular end-diastolic pressure

having the lateral tunnel procedure, and in 4 patients with the extracardiac Fontan procedure. The age at the time of the Fontan operation was 3.6 ± 2.1 years, 42 patients previously having had a staged bidirectional cavopulmonary anastomosis. A fenestration was performed in 24 of the patients with a lateral tunnel, and in 14 of those with an extracardiac baffle. In 11 patients, the fenestration had closed spontaneously. In 2 patients, the fenestration had been previously closed by a transcatheter technique prior to the catheter intervention that addressed the venous collaterals. In 24 patients, the fenestration was occluded at the same catheter intervention as for the venous collaterals. In the remaining patient, severe cyanosis persisted after the Fontan procedure. A large venous collateral, originating from brachiocephalic vein and draining to the coronary sinus was found within 24 h after surgery. It was closed with a Rashkind™ duct so as to reduce the severity of cyanosis, the fenestration in the baffle being left patent.

Hemodynamic data

Hemodynamic data prior to and after Fontan operation are summarized in Table 2. The catheterization study prior to the Fontan procedure was performed at the mean age of 3.3 ± 0.9 years, an average of 4 months prior to surgery. There were no significant differences in pulmonary arterial and end-diastolic pressures between the two catheterization studies.

Anatomical characteristics of the venous collaterals

The characteristics of the venous collateral channels are detailed in Table 3. A total of 68 collaterals were occluded, 43 being single and 25 multiple. Of the channels, 36 (53%) were supracardiac, 12 (18%) cardiac, and 20 (29%) infracardiac in origin. Of the 36 collaterals of supracardiac origin, 30 originated from the brachiocephalic vein and 6 from the superior caval vein. Of the 12 collaterals of the cardiac type, 11 originated from thebesian veins and connected to the functional left atrium, with 1 collateral originating from the coronary sinus and draining to a thebesian vein in a patient in whom the coronary sinus opened into the right atrium. Of the infracardiac type, 17 of 20 collaterals originated from left phrenic vein. One collateral came from the portal vein, which connected through a patent vertical vein to the pulmonary venous confluence in a patient also undergoing repair of totally anomalous pulmonary venous connection. One collateral originated from the inferior caval vein, and 1 from the right phrenic vein. The most common site of origin was the brachiocephalic vein (44%), followed by the left phrenic vein (25%). Of the 68 collaterals, 18 drained directly into pulmonary veins, while the remainder drained into the functional left atrium. The majority of the collaterals (93%) developed within the left thoracic cavity. In 8 patients, collaterals were found originating from the brachiocephalic vein, or from a left superior caval vein draining to the coronary sinus, and draining to the pulmonary venous atrium, none of which were detected at the study prior to the Fontan procedure. Including these patients, 10 patients had collaterals which drained to the coronary sinus.

There was no correlation between the characteristics of the venous channels, the morphology of the dominant ventricle, or the type of the Fontan procedure, although those undergoing an extracardiac Fontan procedure, as a matter of course, could not have cardiac venous collaterals. In patients with both the lateral tunnel and extracardiac Fontan conduits, nonetheless, the number of the supracardiac collaterals was approximately twice as frequent as those of infracardiac origin (Table 4). The cardiac collaterals were significantly larger than either infra or supracardiac collaterals ($p < 0.02$), and all but one of the 11 collaterals was single (Table 3). A longer interval between the Fontan procedure and catheter intervention was observed, at 3.3 ± 3.4 years versus 1.3 ± 1.2 years, $p < 0.01$, in patients with larger

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Table 3. Characteristics of the systemic pulmonary venous collaterals (n = 68).

		Size		Number		Device	
Category	Origin	Small	Large	Single	Multiple	Coil	Rashkind™
Supracardiac (n = 36)	Brachiocephalic vein	22(5)	8(3)	17(7)	13(1)	28(6)	2(2)
	SCV	2	4	3	3	5	1
Cardiac (n = 12)	Thebesian vein	2(1)	10(2)	11(3)	1	9(2)	3(1)
Infracardiac (n = 20)	Phrenic vein	11	7	10	8	17	1
	ICV	1		1		1	
	Portal vein		1	1		1	

(): Collateral drains toward the coronary sinus
Abbreviations: SCV: superior caval vein; ICV: inferior caval vein

Table 4. Relationship between Fontan modification and venous collaterals (n = 68).

	Supracardiac	Cadiac	Infracardiac
Lateral tunnel	21	9	12
Extracardiac	13	0	6
Others	2	3	2

Table 5. Comparison between collateral size (n = 68).

Size	Age (yr)	Interval period (yr)*	SaO_2 (%)	mPAP (mmHg)
Small (n = 38)	4.8 ± 2.3	1.3 ± 1.2	89 ± 7	11.1 ± 2.0
Large (n = 30)	7.3 ± 3.9	3.3 ± 3.4	87 ± 7	13.3 ± 2.8
p value	$p < 0.01$	$p < 0.01$	NS	$p < 0.01$

*Interval between Fontan surgery and study after sugery

collaterals. Additionally, such collaterals were associated with significantly higher mean pulmonary arterial pressures, at 13.3 ± 2.8 mmHg, than the values of 11.1 ± 2.0 mmHg found in patients with smaller collaterals ($p < 0.01$; Table 5). The collaterals that connected to the coronary sinus were more commonly single than multiple ($p < 0.05$; Table 4). Patients who had such collaterals had a significantly lower systemic saturation of oxygen than did those with other types of venous collaterals (83 ± 3% versus 89 ± 53%; $p < 0.05$). Whether or not a fenestration was present at the time did not influence the characteristics of the venous channels (Table 6).

Catheter intervention data

Coils were used for occlusion of 61 collaterals, and a Rashkind™ occluder for the remaining 7 vessels. All were totally or subtotally occluded after transcatheter treatment. At the same time, 24 patients underwent closure of fenestrations, 22 patients with a Rashkind™ occluder, 1 patient with a coil, and 1 patient with a CardioSeal™ septal occluder (NMT Inc, Boston, MA). In 2 patients, either a stent was implanted or a balloon used to dilate pulmonary arterial stenosis, while 2 patients underwent coil embolization of systemic arterial collateral channels.

Excluding the patients undergoing simultaneous closure of a fenestration, systemic saturations of oxygen significantly increased from 89 ± 6% to 95 ± 3% ($p < 0.01$). In the patients undergoing both closure of a fenestration and occlusion of a venous collateral, the systemic saturation of oxygen significantly increased from 87 ± 6% to 96 ± 2% ($p < 0.01$).

One patient with concordant ventriculo-arterial connections but with an anterior left-sided aorta (so-called "anatomically corrected malposition") acquired complete atrioventricular block, which spontaneously reversed to sinus rhythm within 24 h of the procedure.

Discussion

Mechanism of the development of the venous collaterals

The etiological development of systemic-to-pulmonary venous collaterals is unsettled. It may be due to new angiogenesis, or result from the reopening of preexisting channels. During normal embryological development, the bilateral anterior cardinal venous system evolutes into a unilateral right-sided system. The left cardinal venous system largely disappears, leaving the coronary sinus as its distal remnant. Persistence of the left superior caval vein, however, is relatively common in the patients with congenital cardiac disease, being seen in one-tenth of such patients, and in almost three-quarters of those with isomerism of the atrial appendages.[12–14] This feature plays an important role in the pathophysiology of the patients with complex congenital cardiac disease.[15] In our study, no left-sided caval vein that became apparent after operation was demonstrated prior to the Fontan procedure. This suggests that increasing systemic venous pressures reopened the rudiments of the left superior caval venous system after surgery. Balloon occlusion angiography may identify such venous collaterals,

Table 6. Comparison of interatrial communication (n = 50).

					Size	
Interatrial communication	**n**	**Interval (yr)***	**SaO_2 (%)**	**mPAP (mmHg)**	**Small**	**Large**
No fenestration	12	4.9 ± 4.4	88 ± 8	12.1 ± 2.8	3	9
Previous closure	13	2.6 ± 1.3	90 ± 3	12.8 ± 2.7	6	7
Patent fenestration	25	1.3 ± 1.1	87 ± 6	12.2 ± 2.6	14	11
p value		$p < 0.05$	NS	NS	NS	

*Interval between Fontan surgery and study after surgery
Abbreviations: SaO_2: systemic arterial oxygen saturation; mPAP: mean pulmonary artery pressure

but only if the channel is patent; not potentially patent.[11] In patients undergoing the Fontan procedure, the mechanism of development of venous collaterals is also different from that of arterial collaterals.[16,17] Arterial collaterals primarily develop in the lung, in order to supplement a deficit pulmonary blood flow, or are associated with previous surgical palliation, such as a Blalock-Taussig shunt or cavopulmonary anastomosis. Venous collaterals, in contrast, develop in the posterior mediastinum, and drain to the functional left atrium or pulmonary veins in response to an elevated systemic venous pressure. They do not seem to be associated with previous surgical palliation.

Characteristics of systemic venous collaterals

We found supracardiac venous collaterals originating from the brachiocephalic vein to be the most common, followed by those originating from the infracardiac left phrenic vein. We speculate that the development of such vessels is related to long standing elevation in venous pressure beginning with the creation of the bidirectional cavopulmonary anastomosis, as supracardiac collaterals have been shown to develop before the Fontan operation, while collaterals from cardiac or infracardiac origins appear only to develop after the procedure. Although such venous collaterals originating from superior caval vein or brachiocephalic veins were occluded before the Fontan procedure, additional venous collaterals may develop after the procedure. As shown in our study, this is a time-related phenomenon.

Collaterals communicating with the coronary sinus were frequent. Interestingly, in our population, such collaterals were not detected before the Fontan operation, but developed into significant channels after the procedure, again reflecting the stimulus provided by an increased venous pressure. If identified, these should be addressed at the preoperative study. Balloon occlusion techniques could be helpful in improving visualization.[11] The collaterals originating from thebesian veins were generally single and large, as compared with other collaterals. If identified, they too should be addressed by catheter intervention, as they may enlarge with time.

The termination of collaterals in the patient after a Fontan procedure is different from those after a bidirectional cavopulmonary anastomosis. From previous studies, more than half of collaterals were found to drain to the inferior caval vein after a bidirectional cavopulmonary anastomosis.[6–10] After the Fontan procedure, such vessels drained to the pulmonary vein or functional left atrium. This observation may have a hemodynamic basis, influenced by venous angiogenesis or the reopening of preexistent venous channels, where now the difference in pressure between vascular compartments becomes the driving force. Venous channels from the superior caval or brachiocephalic veins draining to the inferior caval vein in patients after a bidirectional cavopulmonary anastomosis were not occluded before the Fontan procedure because such shunts do not result in cyanosis after completion of the Fontan circulation. It would be necessary to occlude them, however, if their site of drainage changed prior to or following the procedure, if cyanosis was a clinical concern, and if their presence reduced effective pulmonary blood flow. As such, further observation and follow-up is recommended.

We have shown that patients with higher pulmonary arterial pressures developed larger venous collaterals. Magee et al.[7] reported that the elevation of pulmonary arterial pressure was also associated with the development of venous collaterals after a bidirectional cavopulmonary anastomosis. We have now shown that the time interval between the Fontan operation and catheter intervention was related to the characteristics of the venous collaterals, suggesting that such vessels may continue to develop as a component of the natural history of a Fontan circulation. The eventual development of cyanosis after the procedure may be a long term finding in this susceptible population.

Fenestration of the baffle was introduced to prevent the systemic venous pressure from rising excessively in patients considered to be at high risk during the perioperative period. It was postulated that such fenestrations would prevent or reduce the development of venous collaterals. We were unable to confirm this postulate. Indeed, many fenestrations closed spontaneously or became increasingly restrictive with time, such that the mean systemic venous pressure was not significantly different from those patients with an intact baffle. Additionally, the frequency of venous collaterals was the same in patients with and without a fenestration.

Indications for catheter intervention

In the absence of obstruction to the systemic venous pathway, the presence of large decompressing collateral vessels, associated with resting desaturation, is generally considered an indication for intervention. Indications for the closure of smaller collaterals, in contrast, particularly when the baffle has been fenestrated, are less clear. In our opinion, catheter intervention should be based upon a combination of individual circumstances, the degree of cyanosis, and the anatomical characteristics of the collateral vessels. Additionally, in patients without resting desaturation, if desaturation developed while exercising, investigation into the presence of the venous collaterals should be considered.

Efficacy and complications of catheter intervention

After performing such procedures, all collaterals were occluded acutely, either totally or subtotally. In the absence of a fenestration, arterial saturations of oxygen significantly increased after interventional treatment. Such techniques were performed without difficulties, although 1 patient had transient complete atrioventricular block.

Limitation

Our results may be biased, as we could not review all patients who underwent a Fontan procedure during the period of investigation, since not all had had postoperative studies. Thus, we did not address the incidence and characteristics of collateral vessels in patients without resting desaturation. Furthermore, the accuracy of measurement of the diameter of the vessels was limited by the method of calibration. The definition of significant decompressing veins was judged based mainly on the arterial saturations of oxygen and their size. Finally, the long-term efficacy of our therapeutic strategy was not addressed, as follow up studies are as yet unavailable.

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