Pulmonary/Systemic Flow Ratio in Children After Cavopulmonary Anastomosis

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Objectives. **This study attempted to provide a formula for calculation of the pulmonary/systemic flow ratio in children after bidirectional cavopulmonary anastomosis.**

Background. **With the bidirectional cavopulmonary anastomosis, only the superior vena cava blood is oxygenated by the lungs. The inferior vena cava flow recirculates into the systemic circulation. The ratio of these flows will determine systemic arterial saturation.**

Methods. **According to the Fick principle, 1) Systemic cardiac output (liters/min) = Pulmonary venous flow + Inferior vena cava flow; 2) Systemic blood oxygen transport (ml/min) = Pulmonary venous blood oxygen transport + Inferior vena cava blood oxygen transport. By substituting the first equation into the second, Pulmonary/systemic flow ratio = (Systemic saturation − Inferior vena cava saturation)/(Pulmonary venous saturation − Inferior vena cava saturation).**

Results. **We applied the third formula to data obtained from 34 catheterizations in 29 patients after bidirectional cavopulmonary anastomosis. Mean [±SD] age at operation was 1.70 ± 1.43 years, and mean age at catheterization was 2.95 ± 1.65 years. The pulmonary/systemic flow ratio calculated for all 29 patients was 0.58 ± 0.09. Of 17 patients with aortography, 10 had systemic to pulmonary collateral vessels. Patients with collateral vessels had a significantly higher pulmonary/systemic flow ratio (0.61 ± 0.07 vs. 0.53 ± 0.07, respectively, $p < 0.02$) and systemic saturation (88 ± 4% vs. 82 ± 4%, respectively, $p < 0.002$) than those without collateral vessels. The pulmonary/systemic flow ratio in those patients with no collateral vessels was similar to the previously reported echocardiographically derived superior vena cava/systemic flow ratio in normal children.**

Conclusions. **The pulmonary/systemic flow ratio after bidirectional cavopulmonary anastomosis can be calculated. Pulmonary blood flow in these patients determines systemic saturation and accounts for the majority of venous return in young children.**

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Bidirectional cavopulmonary anastomosis is used as a staged palliative procedure en route to the ultimate Fontan repair in selected patients with cyanotic congenital heart disease (1). As such, bidirectional cavopulmonary anastomosis reduces the volume load on the systemic ventricle and allows a smoother postoperative course before and after the Fontan procedure (2). Since its inception (3,4), the technique of cavopulmonary anastomosis has changed, but not the basic physiologic concept. Superior vena cava flow, by virtue of being the effective pulmonary blood flow, determines systemic saturation. The contribution of the superior vena cava flow to total cardiac output in normal children was recently described (5) and was dependent on the age of the child. We hypothesized that superior vena cava flow in children after bidirectional cavopulmonary anastomosis is not different from that in normal children and that it accounts for most of the systemic venous return in young children.

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Methods

The contribution of pulmonary to systemic blood flow in patients with cavopulmonary anastomosis is unknown. To calculate the pulmonary to systemic flow in patients with a cavopulmonary shunt, a formula was derived using the Fick principle (see Appendix for details). The basic assumptions are the following: 1) Systemic cardiac output (liters/min) = Pulmonary venous flow (liters/min) + Inferior vena cava flow (liters/min); 2) Systemic blood oxygen transport (ml/min) = Pulmonary venous blood oxygen transport (ml/min) + Inferior vena cava blood oxygen transport (ml/min). Thus, Pulmonary/systemic flow ratio = (Systemic saturation − Inferior vena cava saturation)/(Pulmonary venous saturation − Inferior vena cava saturation).

To test our hypothesis we retrospectively reviewed the data from two institutions of all patients who underwent catheterization after cavopulmonary anastomosis. The data included saturation and pressure measurements in the superior and inferior vena cavae, pulmonary artery and veins, left and right

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Table 1. Summary of Demographic and Hemodynamic Data

	Mean ± SD	Range
Age at operation (yr)	1.70 ± 1.43	0.41–5.77
Follow-up (yr)	1.25 ± 0.90	0.02–3.59
At catheterization		
Age (yr)	2.95 ± 1.65	0.56–7.28
Weight (kg)	12.62 ± 4.63	4.94–26.6
Height (cm)	87 ± 16	62–120
Body surface area (m^2)	0.47 ± 0.18	0.19–0.93
Mean SVC pressure (mm Hg)	12 ± 3	7–20
Mean LA pressure (mm Hg)	6 ± 3	1–12
Systemic resistance (Woods units·m^2)	17.19 ± 5.47	8.75–28.31
Pulmonary resistance (Woods units·m^2)	2.45 ± 1.08	0.60–5.07

LA = left atrial; SVC = superior vena cava.

Table 2. Comparison of Patients With and Without Systemic to Pulmonary Collateral Vessels

	With Collateral Vessels (n = 10)	Without Collateral Vessels (n = 7)	p Value
Total catheterizations	12	10	
Age at cavopulmonary anastomosis (yr)	1.3 ± 1.5	1.6 ± 1.2	0.59
Age at catheterization (yr)	2.4 ± 1.5	3.2 ± 1.3	0.22
Saturation in distal PA (%)	64 ± 7	61 ± 7	0.50
Aortic saturation (%)	88 ± 4	82 ± 4	< 0.002
SVC saturation (%)	65 ± 8	58 ± 4	< 0.04
SVC pressure (mm Hg)	10 ± 2	13 ± 2	< 0.04
Q_P/Q_S	0.61 ± 0.07	0.53 ± 0.07	< 0.02
Previous B-T shunt	4	3	0.86

Data presented are mean value ± SD, unless otherwise indicated. B-T = Blalock-Taussig; PA = pulmonary artery; Q_P/Q_S = pulmonary/systemic flow ratio; SVC = superior vena cava.

atria and a systemic artery. We used the equations 1 to 5 (Appendix) to evaluate the pulmonary as well as the superior and inferior vena cava flows and to calculate the pulmonary/systemic flow in patients with a cavopulmonary anastomosis. Pulmonary flow was also calculated according to the Fick principle, using an assumed oxygen consumption and saturation levels from the distal pulmonary artery and pulmonary vein.

Calculated flow data were correlated with systemic saturation, age at surgery and catheterization and body surface area. The presence of systemic to pulmonary collateral vessels, as well as their relation to the measured saturation and calculated flows, was also assessed.

Statistics. Data analyses were performed on a Macintosh computer using commercially available software (StatView 4.0). Paired and unpaired Student *t* tests were utilized where applicable. Regression analysis was used to evaluate significant correlation of independent variables. A p value < 0.05 was considered significant, and data are presented as mean value ± SD.

Results

Patients. A total of 29 patients (13 female, 16 male) from the University of Tennessee and the Medical University of South Carolina met the inclusion criteria of this study and had a total of 34 catheterizations (two patients had three catheterizations each, and one had two). The diagnosis was pulmonary atresia with intact ventricular septum (three patients); double-inlet single ventricle (seven patients); single ventricle with left atrioventricular valve atresia (two patients); double-outlet right ventricle (five patients); double-outlet left ventricle (one patient); hypoplastic left heart syndrome (five patients); and tricuspid atresia (six patients) (Table 1).

Saturation data. Only one patient underwent catheterization in the postoperative first week because of poor hemodynamic status. The remaining 28 patients underwent catheterization ≥2 months after operation. Mean hemoglobin was 15.5 ± 1.9 g/dl (range 10.0 to 18.2), and mean systemic saturation was 84 ± 5% (range 70% to 92%). Superior and inferior vena cava saturation data were available for 25 and 28 catheterizations, respectively: 61 ± 8% (range 38% to 80%) and 65 ± 8% (range 41% to 79%). Saturation data for both the superior and inferior vena cava were available from the same catheterization in 22 patients, and mean superior vena cava saturation was five percent points lower than mean inferior vena cava saturation (p < 0.0007). Pulmonary vein or left atrial saturation, or both, was available for 27 catheterizations and was 98 ± 2% (range 95% to 100%). We assumed a pulmonary venous saturation of 97% for the remaining seven catheterizations. The pulmonary/systemic flow ratio for all 29 patients, calculated according to equation 3 in the Appendix, was 0.58 ± 0.09. Neither pulmonary/systemic flow ratio nor systemic saturation had any significant correlation with age at cavopulmonary anastomosis surgery or age, height, weight and body surface area at catheterization.

Aortography. Of 17 patients who underwent aortography, 10 had systemic to pulmonary collateral vessels, whereas 7 had no collateral vessels. None of these collateral vessels was considered large enough to require embolization. Patients with and without collateral vessels are compared in Table 2. The subgroups differed significantly in pulmonary/systemic flow ratio and superior vena cava saturation and pressure but did not differ in age at operation or catheterization or in the use of a Blalock-Taussig shunt for palliation before the cavopulmonary anastomosis.

Pulmonary/systemic flow. We calculated the predicted pulmonary/systemic flow according to the equation (Superior vena cava flow/Cardiac output = $-0.013 \times [\text{Age}^2] + 0.064 \times \text{Age} + 0.478$) derived from our echocardiographic study (5) (i.e., Pulmonary flow = Superior vena cava flow). For the group with no collateral vessels, there was agreement between the predicted and calculated pulmonary/systemic flow ratio (0.53 ± 0.03 vs. 0.53 ± 0.07, respectively, p > 0.7). However, for the group with collateral vessels, there was a significant difference between the two values (0.53 ± 0.05 predicted vs. 0.61 ± 0.07 calculated, $p < 0.005$). Thus, the catheterization-derived pulmonary/systemic flow ratio reported herein confirms the results of the echocardiographic–Doppler assessment of superior vena cava flow previously reported by our group (5).

Superior vena cava flow according to equation 4 (Appendix) was 2.26 ± 0.80 liters/min per m^2. This independent determination of pulmonary blood flow had a significant correlation with systemic saturation ($r = 0.60$, $p < 0.007$). Cardiac index derived from equation 5 was 4.10 ± 0.94 liters/min per m^2. Superior vena cava saturation correlated positively with cardiac index ($r = 0.69$, $p < 0.001$).

Pressure measurements. Transpulmonary pressure gradient was 5 ± 1.6 mm Hg (range 2 to 10). Mean pulmonary artery pressure varied inversely with systemic saturation ($r = -0.50$, $p < 0.007$) and positively with indexed pulmonary resistance ($r = 0.54$, $p < 0.02$), that is, patients with higher pulmonary artery pressure had higher pulmonary resistance and lower systemic saturation. Pulmonary arteriolar resistance values were normal (≤4 Woods units·m^2) in all patients but one. Mean pulmonary resistance excluding this patient, who did not survive and had a resistance of 5.07 Woods units·m^2, was 2.15 ± 0.72 Woods units·m^2 (range 0.60 to 3.27).

Discussion

In the normal child at rest, the saturation difference between the arterial and mixed venous blood is approximately 25%, and all of the systemic venous return passes through the lungs and becomes fully oxygenated (6). In the cavopulmonary shunt circulation, only the venous blood returning via the superior vena cava passes through the lungs and becomes oxygenated before it reaches the systemic circulation. The inferior vena cava blood, on the other hand, reenters the systemic circulation without passing through the lungs and mixes with the fully saturated blood returning via the pulmonary veins. This mixture, a physiologic right-to-left shunt, is responsible for the systemic desaturation in patients with a cavopulmonary shunt. We were unable to find a formula, other than the one reported herein, which describes the relationship between superior vena cava and systemic arterial flow.

All patients. Our data from 29 patients demonstrated that pulmonary venous flow after cavopulmonary anastomosis was 58% of total systemic venous return. Moreover, normal pulmonary venous saturation excluded the presence of significant pulmonary arteriovenous fistulae in these patients (7). Thus, the calculated pulmonary/systemic flow ratio only included that portion of the pulmonary flow that became oxygenated (i.e., the effective pulmonary blood flow).

Collateral vessels. The incidence of systemic to pulmonary collateral vessels in a subgroup of patients who had angiography in the current study (59%) is comparable to that reported by Triedman et al. (8). Our data indicate that superior vena cava flow is the sole contributor to pulmonary flow in patients without collateral vessels and a major contributor in patients with collateral vessels. The predicted pulmonary/flow ratio was significantly greater in patients with than without collateral vessels. Therefore, in patients with a cavopulmonary anastomosis, collateral vessels may contribute as much as 8% of cardiac output (or 13% of pulmonary blood flow). In patients without systemic to pulmonary collateral vessels, superior vena cava flow was 53 ± 7% of systemic flow. This flow ratio was identical to the noninvasive estimation of superior vena cava flow in normal children of the same age previously reported (5).

Age. Previously reported data (5) in normal children demonstrated a slow decline in the contribution of the superior vena cava flow to total cardiac output with increasing age. This phenomenon was not observed in the current study. A reasonable explanation lies in the narrow age range of the patients under examination.

Study limitations. The major limitation of the proposed formula for calculation of the pulmonary/systemic flow ratio is the accurate sampling of the inferior vena cava blood for determination of saturation. Saturation in the inferior vena cava can change markedly with minimal variation in the position of the sampling catheter. Other limitations of the study include its retrospective nature and lack of uniformity in the performance of the catheterizations in the two institutions involved. Consequently, selected data were absent for a few patients. In addition, the oxygen consumption used in the calculation of flow was estimated rather than measured. These limitations would be avoided in a prospective study of patients after bidirectional cavopulmonary anastomosis.

Summary. We demonstrated that the pulmonary/systemic flow ratio can be calculated in patients after cavopulmonary anastomosis. Superior vena cava flow in children <3 years old comprises >50% of total cardiac venous return. The presence of collateral vessels increases pulmonary blood flow and systemic saturation. These data are critical to the understanding of flows after cavopulmonary anastomosis.

Appendix

Derivation of Equations Used in the Study

Assuming no systemic to pulmonary shunt and a nonsignificant coronary sinus blood flow, Superior vena cava flow = Pulmonary flow (Q_P) = Pulmonary venous flow. However, in the presence of a systemic to pulmonary shunt, pulmonary venous flow would be larger than superior vena cava flow. Systemic cardiac output (liters/min) (Q_S) = Pulmonary venous flow (Q_P) + Inferior vena cava flow (Q_{IVC}):

$$Q_S = Q_P + Q_{IVC}; \qquad Q_{IVC} = Q_S - Q_P. \qquad [1]$$

The total volume of oxygen transported (ml/min) by the blood in a given circuit is a function of the oxygen content of the blood per unit of volume as well as the number of units of blood volume passing through the circuit per minute.

For the systemic circulation, the volume of oxygen transported per minute equals the oxygen content of 1 liter of blood at the systemic saturation times the systemic blood flow (i.e., cardiac output = Q_S).

Systemic blood oxygen transport = Oxygen-carrying capacity of blood × Systemic arterial saturation (SA_{sat}) × Systemic blood flow.

Pulmonary venous blood oxygen transport = Oxygen-carrying capacity of blood × Pulmonary venous saturation × Pulmonary venous flow.

Inferior vena cava blood oxygen transport = Oxygen-carrying capacity of blood × Inferior vena cava saturation × Inferior vena cava flow.

Oxygen delivered to the systemic circulation is the sum of the oxygen delivered by the pulmonary veins and the oxygen remaining in the inferior vena cava blood.

Systemic blood oxygen transport = Pulmonary venous blood oxygen transport + Inferior vena cava blood oxygen transport. Thus, Oxygen-carrying capacity of blood × Systemic arterial saturation × Systemic blood flow = (Oxygen-carrying capacity of blood × Pulmonary venous saturation (PV_{sat}) × Pulmonary venous return) + (Oxygen-carrying capacity of blood × Inferior vena cava saturation (IVC_{sat}) × Inferior vena cava flow):

$$Q_S \times (O_2\text{-carrying capacity}) \times SA_{sat} = Q_P \times (O_2\text{-carrying capacity}) \times PV_{sat} + Q_{IVC} \times (O_2\text{-carrying capacity}) \times IVC_{sat}. \quad [2]$$

Substituting equation 1 in equation 2 yields:

$$Q_S \times (O_2\text{-carrying capacity}) \times SA_{sat} = Q_P \times (O_2\text{-carrying capacity}) \times PV_{sat} + (Q_S - Q_P) \times (O_2\text{-carrying capacity}) \times IVC_{sat}.$$

The oxygen-carrying capacity is constant for the same hemoglobin in the same patient during catheterization and cancels out of the formula as follows:

$$Q_S \times SA_{sat} = Q_P \times PV_{sat} + Q_S \times IVC_{sat} - Q_P \times IVC_{sat};$$

$$Q_S \times SA_{sat} - Q_S \times IVC_{sat} = Q_P \times PV_{sat} - Q_P \times IVC_{sat};$$

$$Q_S \times (SA_{sat} - IVC_{sat}) = Q_P \times (PV_{sat} - IVC_{sat});$$

$$\frac{Q_P}{Q_S} = \frac{SA_{sat} - IVC_{sat}}{PV_{sat} - IVC_{sat}}. \quad [3]$$

The calculation of the pulmonary/systemic flow ratio is valid, even in the presence of collateral vessels, because the pulmonary venous flow, not the superior vena cava flow, was used for this calculation.

In the absence of collateral vessels, the superior vena cava saturation will equal the pulmonary artery saturation (PA_{sat}), and pulmonary flow may be calculated according to the Fick formula (equation 4) as follows:

$$Q_P = \frac{\text{Oxygen consumption}}{(PV_{sat} - PA_{sat}) \times \text{Blood oxygen-carrying capacity}}; \quad [4]$$

otherwise, the most distal pulmonary artery saturation should be used in equation 4. Systemic cardiac output can then be calculated from the known systemic/pulmonary flow ratio (equation 3):

$$Q_S = \frac{\text{Oxygen consumption} \times (PV_{sat} - IVC_{sat})}{\text{Blood oxygen-carrying capacity} \times (PV_{sat} - PA_{sat}) \times (SA_{sat} - IVC_{sat})}. \quad [5]$$

With the calculation of the systemic and pulmonary flows, the inferior vena cava flow is derived from equation 1.

References

1. Hopkins RA, Armstrong BE, Serwer GA, Peterson RJ, Oldham HN. Physiologic rationale for a bidirectional cavopulmonary shunt. A versatile complement to the Fontan principle. J Thorac Cardiovasc Surg 1985;90:391–8.
2. Pridjian AK, Mendelsohn AM, Lupinetti FM, et al. Usefulness of the bidirectional Glenn procedure as staged reconstruction for the functional single ventricle. Am J Cardiol 1993;71:959–62.
3. Carlon CA, Mondini PG, DeMarchi R. Surgical treatment of some cardiovascular diseases (a new vascular anastomosis). J Int Coll Surg 1951;16:1–10.
4. Glenn WWL. Circulatory bypass of the right side of the heart. IV. Shunt between superior vena cava and distal right pulmonary artery—report of clinical application. N Engl J Med 1958;259:117–20.
5. Salim MA, DiSessa TG, Arheart KL, Alpert BS. The contribution of superior vena caval flow to total cardiac output in children: a Doppler echocardiographic study [abstract]. Circulation 1994;90 Suppl I:I-156.
6. Vargo TA. Cardiac catheterization-hemodynamic measurements. In: Garson A Jr., Bricker JT, McNamara DG, editors. The Science and Practice of Pediatric Cardiology. Philadelphia: Lea and Febiger, 1990:913–45.
7. McFaul RC, Tajik AJ, Mair DD, Danielson GK, Seward JB. Development of pulmonary arteriovenous shunt after superior vena cava right pulmonary artery (Glenn) anastomosis. Circulation 1976;55:212–6.
8. Triedman JK, Bridges ND, Mayer JE, Lock JE. Prevalence and risk factors for aortopulmonary collateral vessels after Fontan and bidirectional Glenn procedure. J Am Coll Cardiol 1993;22:207–15.