SURGERY FOR CONGENITAL HEART DISEASE

EFFECT OF VOLUME UNLOADING SURGERY ON CORONARY FLOW DYNAMICS IN PATIENTS WITH AORTIC ATRESIA

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Objectives: The objectives of this study were to define physiologic effects on and a clinical correlate to coronary blood flow during volume unloading surgery in patients with aortic atresia. **Methods:** Twenty-two patients with aortic atresia (group I, 13 patients with stage I reconstruction undergoing hemi-Fontan operation; group II, 9 patients with hemi-Fontan undergoing Fontan operation) underwent perioperative transesophageal echocardiography. Doppler spectral patterns, peak velocity, velocity time integral, and blood flow in the native ascending aorta were measured. Preoperative hemodynamics and postoperative clinical data were analyzed. Significance was defined as $p < 0.05$. **Results:** Higher values of coronary blood flow (982.9 ± 321.7 vs 548.6 ± 333.8 ml/min per square meter), velocity time integral (20.7 ± 5.6 vs 12.6 ± 4.0 cm), and peak velocity (96.1 ± 21.4 vs 51.0 ± 18.2 cm/sec) were found before operation in group I than after operation and in group II at both times. Flow changed from predominately systolic in preoperative group I to both systolic and diastolic after operation and in group II. Before operation in groups I and II, a number of hemodynamic parameters such as superior vena cava oxygen saturation correlated with coronary blood flow dynamics. After operation in group II, urine output ($r = 0.86$) and central venous pressure ($r = -0.85$) correlated with coronary blood flow dynamics. **Conclusion:** Coronary blood flow parameters were higher in group I as a result of the increased energy needs required to pump to two circulations. No changes were found in group II. A number of coronary blood flow parameters correlated with preoperative hemodynamics and postoperative clinical data. These parameters appear to be useful in assessing the performance status of the myocardium after the Fontan operation, consistent with the notion that myocardial perfusion relates directly to ventricular function. (J Thorac Cardiovasc Surg 1997; 113:718-27)

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Coronary blood flow is regulated by hydrostatic forces, anatomic factors, metabolic control, and autoregulation.¹ It correlates well with myocardial oxygen consumption,² which is, in turn, mostly determined by myocardial tension development, external work, heart rate, and contractility.¹ A decrease in coronary blood flow in the normal metabolic state results in reduced ventricular performance.³⁻⁵

One of the ultimate goals in the surgical management of the functional single ventricle is to achieve normal volume work. In linking coronary blood flow with the volume work done by the functional single ventricle, hypoplastic left heart syndrome affords a

unique opportunity to study coronary blood flow and volume loading. By necessity, in patients with aortic atresia, an aortic-pulmonary anastomosis must be constructed to maintain coronary blood flow via retrograde flow in the native ascending aorta.⁶ In these patients, the native pulmonary artery is used as the systemic semilunar valve and the patients eventually undergo staged Fontan reconstruction.⁷ In the first stage, the aortic-pulmonary anastomosis is constructed and pulmonary blood flow is via a systemic-pulmonary artery shunt, which places a volume load on the ventricle.⁸⁻¹¹ After hemi-Fontan¹⁰⁻¹⁴ and Fontan⁷ procedures, this volume load is removed by channeling blood from one or more vena caval vessels into the pulmonary artery and bypassing the ventricle.^{8-11, 13} Our institution has advocated reduction in the volume work early in the patient's course to achieve a better clinical result.¹³

We hypothesized that the ventricular volume load would increase myocardial oxygen consumption and coronary blood flow. Because the native ascending aorta acts as the only conduit for coronary blood flow, it follows that its retrograde flow dynamics reflect coronary flow. We further hypothesized that retrograde flow in the native ascending aorta might partly determine ventricular performance. This study used transesophageal echocardiography before and after operation to evaluate the effects of volume unloading operation on coronary flow dynamics in the patient with functional single ventricle with aortic atresia (hemi-Fontan procedure is volume unloading; conversion to Fontan circulation is thought not to be volume unloading⁸⁻¹³). An attempt to determine a functional correlate to the flow in the native ascending aorta was done by comparing Doppler data with hemodynamics at cardiac catheterization and clinical data after operation.

Methods

Patients. We prospectively studied 22 consecutive patients with hypoplastic left heart syndrome and aortic atresia by means of transesophageal echocardiography both before and after operation between December 12, 1994, and August 3, 1995. No patient had aortic stenosis. All patients had aorta-pulmonary artery anastomosis done by one surgeon. Thirteen patients (group I) had undergone stage I Norwood reconstruction only and were undergoing a hemi-Fontan procedure (anastomosis of one or both superior vena caval vessels to the pulmonary artery with right atrial exclusion and takedown of the systemic-pulmonary artery shunt). Nine patients (group II) had undergone the hemi-Fontan procedure^{13, 14} and were undergoing Fontan completion.⁷ Twelve patients had mitral atresia and 11 patients had mitral stenosis. Two

Table I. Patient characteristics and hemodynamic and postoperative data in both surgical groups

Parameter	Group I	Group II
Age (mo)*	6.0 ± 0.8	20.2 ± 0.8
Weight (kg)*	5.7 ± 1.0	10.7 ± 1.3
Height (cm)*	65.4 ± 6.3	80.6 ± 3.7
BSA (m ²)*	0.3 ± 0.04	0.48 ± 0.05
RA pressure (mm Hg)*	4.5 ± 1.9	6.4 ± 1.2
RVEDP (mm Hg)*	6.1 ± 2.2	9.3 ± 2.4
SVC saturation (%)*	48.0 ± 5.8	60.2 ± 8.4
PA pressure (mm Hg)	12.4 ± 2.6	12.2 ± 2.3
Ao syst. (mm Hg)	110.6 ± 18.3	102.8 ± 13.1
Ao mean (mm Hg)	75.9 ± 10.2	74.9 ± 9.0
Ao saturation (%)*	79.3 ± 4.3	85.9 ± 2.8
Qp (L/min/m ²)*	4.4 ± 1.3	2.4 ± 0.9
Qs (L/min/m ²)	2.6 ± 0.8	—
Qp/Qs	1.8 ± 0.6	—
Rs (WU)	31.8 ± 10.6	—
Rp (WU)*	1.7 ± 0.6	2.4 ± 1.2
Rp/Rs	0.056 ± 0.02	—
Hemoglobin (mg/dl)	15.4 ± 1.3	15.0 ± 1.0
pH*	7.38 ± 0.03	7.35 ± 0.02
Pco ₂ (mm Hg)	42.9 ± 2.7	42.8 ± 2.7
Po ₂ (mm Hg)*	46.1 ± 4.0	56.0 ± 6.5
Hospital days*	10.2 ± 5.7	36.3 ± 32.7
CVP (mm Hg)	6.3 ± 2.0	6.9 ± 1.3
UO (ml/kg/hr)*	3.2 ± 1.0	2.4 ± 0.7
Intubation hours	20.7 ± 1.9	20.5 ± 2.8
HR (beats/min)	123.1 ± 17.8	121.8 ± 12.6
HR std (beats/min)*	8.8 ± 3.9	13.8 ± 5.2

Group I patients are those who had undergone stage I Norwood reconstruction only and were undergoing hemi-Fontan procedure (superior vena cava or venae cavae to pulmonary artery anastomosis with right atrial exclusion and takedown of the systemic-pulmonary artery shunt). Group II patients are those who had undergone the hemi-Fontan procedure and were undergoing Fontan completion. Systemic blood flow (*Qs*), the ratio of systemic to pulmonary blood flow (*Qp/Qs*), systemic vascular resistance (*Rs*), and the ratio of pulmonary to systemic vascular resistance (*Rp/Rs*) were not calculated for group II because there is no good value for the mixed systemic venous oxygen saturation in the hemi-Fontan reconstruction. *BSA*, body surface area; *RA pressure*, right atrial mean pressure; *RVEDP*, right ventricular end-diastolic pressure; *SVC*, superior vena cava; *PA pressure*, pulmonary artery mean pressure; *Ao*, aorta; *Ao syst.*, peak aortic systolic blood pressure; *Ao mean*, mean aortic blood pressure; *sat*, oxygen saturation of blood; *Qp*, pulmonary blood flow; *Qs*, systemic blood flow; *Rs*, systemic vascular resistance; *WU*, Wood units; *Rp*, pulmonary vascular resistance; *Pco₂*, carbon dioxide tension; *Po₂*, oxygen tension; *CVP*, central venous pressure; *UO*, urine output; *HR*, heart rate; *std*, standard deviation.

*Significant differences between groups I and II at *p* < 0.05.

patients who underwent Fontan completion died before leaving the hospital and seven of the nine patients had some degree of pleural effusion during the hospital stay. After operation, no inotropic agents were used in any patient. Patient characteristics are summarized in Table I.

Echocardiography. All studies were done via transesophageal echocardiography. Preoperative studies were done in the operating room after induction of general anesthesia and postoperative studies were done in the intensive care unit within 2 to 4 hours of completion of the operation. A comprehensive two-dimensional biplane transesophageal echocardiographic examination was done

Aorta-Pulmonary Artery Anastomosis

Fig. 1. A, Two-dimensional image of the aorta-pulmonary artery anastomosis in a longitudinal view in a patient with hypoplastic left heart syndrome with previous hemi-Fontan procedure. Doppler sample volume was placed below the insertion site of the native ascending aorta into the pulmonary artery. *nAo*, Native ascending aorta; *P*, posterior; *PV*, pulmonary valve; *RV*, right ventricle; *S*, superior. **B,** Doppler spectral recordings in the native ascending aorta of a patient after stage I reconstruction (*top panel*) and after hemi-Fontan procedure (*bottom panel*). Note how most of the blood flow in the patient after stage I reconstruction is systolic and the peak velocity occurs in systole, whereas in the patient after the hemi-Fontan procedure, most of the blood flow is diastolic and the peak velocity occurs in diastole. *m/s*, Meters/second.

on each patient with either a Hewlett Packard 77020 phased array ultrasonographic system (Sonos 1000) or an Acuson 128XP system with 7.5 and 5.0 MHz transducers. All studies were recorded on ½-inch super VHS format videotapes and were available for retrospective off-line analysis. The native ascending aorta was identified in both planes; however, only the longitudinal (vertical) plane enabled a long-axis view of the native ascending aorta (Fig. 1, *A*). The probe was manipulated either retroflexed or anteflexed to obtain the best image parallel to the

retrograde path of flowing blood. Color-flow mapping was done to further localize the retrograde path of flowing blood and a pulsed Doppler sample volume was placed in the native ascending aorta below the insertion site of the native ascending aorta into the pulmonary artery. Doppler spectral recordings were analyzed off-line with use of a personal computer and Digisonics software (Digisonics Inc.).

Doppler spectral recordings (Fig. 1, *B*) were used to derive the velocity time integral (VTI), peak velocity, and R-R interval. Peak velocity was characterized not only quantita-

tively but also as to where in the cardiac cycle it occurred. Coronary blood flow was calculated by the following formula¹⁵ after the diameter of the native ascending aorta was measured on the two-dimensional image:

$$\text{Blood flow (L/min)} = \frac{V_{\text{mean}} (\text{cm/sec}) \times \text{CSA} (\text{cm}^2) \times 60 \text{ sec/min}}{1000 \text{ ml/L}}$$

where V_{mean} is mean velocity (VTI/R-R interval), CSA is cross sectional area of flow (native aortic diameter squared $\times [\pi/4]$). Each measurement on the Doppler spectral recording (velocity time integral, peak velocity, and R-R interval) and the two-dimensional image (aortic diameter) was done on three heartbeats and the results averaged.

Cardiac catheterization and postoperative data. All patients were sedated for catheterization with sodium pentobarbital (Nembutal) 4 mg/kg and meperidine (Demerol) 3 mg/kg given orally. Additional sedatives such as midazolam were given as needed. All studies were done within 24 hours of echocardiography. A summary of the hemodynamic and postoperative data by surgical group is listed in Table I.

Statistics. Significance was defined as $p < 0.05$. Comparison between values for coronary flow dynamics obtained before and after operation in the same patient were made by the paired Student's t test, and comparisons between the two groups were made with the unpaired Student's t test. Correlation between coronary flow dynamics with preoperative hemodynamic data and postoperative functional data was done by Pearson's correlation coefficient. Statistical analysis was done on a personal computer with use of JMP version 3.1.4 software (SAS Institute, Cary, N.C.).

Results

Volume unloading operation and coronary flow dynamics. Fig. 2, A through C, displays the three coronary flow parameters measured both before and after operation in group I (volume unloading operation in patients undergoing hemi-Fontan). Significantly higher values of velocity time integral (20.7 ± 5.6 vs 12.6 ± 4.0 cm, $p = 0.00004$), peak velocity (96.1 ± 21.4 vs 51.0 ± 18.2 cm/sec, $p = 0.000002$), and coronary blood flow (982.9 ± 321.7 vs 548.6 ± 333.8 ml/min per square meter, $p = 0.000009$) were noted in patients with volume-loaded stage I Norwood reconstruction than in those after conversion to the hemi-Fontan circulation. No significant difference in heart rate was noted between preoperative and postoperative measurements (R-R interval of 462 ± 74 vs 491 ± 114 msec, respectively) or in native aortic diameter (3.9 ± 0.7 vs 3.6 ± 0.9 mm, respectively).

In group II patients (conversion of hemi-Fontan circulation to Fontan reconstruction, not constituting volume unloading⁸⁻¹⁴), no significant difference was noted in the velocity time integral (12.3 ± 6.9 vs $10.5 \pm$

Fig. 2. The effect of volume unloading operation on A, velocity time integral; B, peak velocity; and C, coronary blood flow. Note how all parameters appear to decrease from stage I to the hemi-Fontan stage.

3.7 cm), peak velocity (43.3 ± 29.9 vs 43.1 ± 13.5 cm/sec), or coronary blood flow (411.7 ± 180.0 vs 445.5 ± 193.0 ml/min per square meter). Although no significant difference existed between native aortic

diameters before and after operation in the patients undergoing Fontan reconstruction (4.5 ± 0.9 mm before vs 4.6 ± 0.7 mm after), the heart rate was faster after operation than before operation (R-R interval 460 ± 88 msec vs 578 ± 78 msec, respectively, $p = 0.007$). No significant differences were noted in values of the velocity time integral, peak velocity, or coronary blood flow between group I after operation (immediately after hemi-Fontan procedure) and group II (hemi-Fontan condition before operation and Fontan after operation).

Before operation, group I patients (volume loaded) displayed Doppler spectral patterns in which coronary blood flow occurred mostly in systole ($>75\%$ of velocity time integral occurred between the QRS and end of the T wave; Fig. 1, *B, top panel*), whereas after operation group I and group II patients (no volume load) displayed flow distributed throughout the cardiac cycle with a majority of the flow in diastole (Fig. 1, *B, bottom panel*). A nadir of flow was noted in late systole. Furthermore, group I patients before operation peak velocities were demonstrated to occur in systole (Fig. 1, *B, top panel*). After operation, peak velocities were demonstrated to occur in eight patients in late systole and in four patients in diastole (Fig. 1, *B, bottom panel*), and one had a peak velocity in systole and diastole. Peak velocities were demonstrated to occur in four group II patients in late systole and in one in diastole, and four had a peak velocity in systole and diastole.

Correlations between coronary flow dynamics and hemodynamics/postoperative data. In group I patients, preoperative superior vena caval oxygen saturation correlated with both preoperative peak velocity ($r = 0.56, p = 0.04$) (Fig. 3, *A*) and coronary blood flow ($r = 0.55, p = 0.05$) (Fig. 3, *B*). Interestingly, the preoperative aortic oxygen saturation had a positive correlation with the postoperative velocity time integral ($r = 0.54, p = 0.05$) whereas the preoperative cardiac index and the pulmonary-to-systemic vascular resistance ratio had an inverse relationship with the postoperative velocity time integral ($r = -0.61, p = 0.03$ and $r = -0.59, p = 0.03$, respectively).

In group II, the preoperative peak velocity correlated with preoperative pulmonary artery pressure ($r = 0.68, p = 0.04$; Fig. 3, *C*) and pulmonary blood flow ($r = 0.73, p = 0.02$) (Fig. 3, *D*). Postoperative coronary blood flow had a strong positive correlation with urine output ($r = 0.86, p = 0.003$; Fig. 3, *E*) and a strong inverse correlation with central venous pressure ($r = -0.85, p = 0.007$; Fig. 3, *F*). Interestingly, the postoperative peak velocity had a positive

correlation with preoperative pulmonary artery pressure ($r = 0.81, p = 0.007$) and pulmonary blood flow ($r = 0.70, p = 0.03$).

Discussion

Coronary blood flow is an important feature in ventricular performance.²⁻⁵ We hypothesized that the increased volume load placed on the functional single ventricle heart with aortic atresia in the first stage of reconstruction⁸⁻¹¹ would be reflected in increased myocardial oxygen demand and an increase in coronary blood flow. Further, because coronary blood flow is an important feature in ventricular performance, we hypothesized that its dynamics of flow might have a hemodynamic or physiologic correlate. This study addressed these issues with the conversion of the functional single ventricle heart from stage I reconstruction (volume-loaded ventricle) to the hemi-Fontan condition (no volume load). Coronary flow dynamics in patients undergoing conversion of the hemi-Fontan to Fontan condition (both no volume load) were also studied.

Volume unloading operation and coronary flow dynamics. We demonstrated that in patients with functional single ventricle who have undergone stage I Norwood reconstruction there are significantly increased values of coronary blood flow, velocity time integral, and peak velocity. This increased coronary blood flow is a result of the increased volume load placed on the heart, which increases myocardial oxygen consumption and serves to increase myocardial contractile force and systolic ventricular stiffness.¹⁶ This effect has been shown to be clinically relevant because those patients with hypoplastic left heart syndrome and larger coronary artery cross-sectional areas (presumably on the basis of increased flow) have a higher likelihood of survival than those with smaller cross-sectional areas.¹⁷

The increase in values of coronary blood flow, velocity time integral, and peak velocity demonstrated in patients who have undergone stage I Norwood reconstruction is consistent with similar findings in patients with a similar physiologic condition: aortic insufficiency.¹⁸⁻²⁰ In both, a volume load is imposed and a low diastolic blood pressure is present (diastolic runoff as a result of flow into the ventricle in aortic insufficiency and flow into the pulmonary vascular bed via the systemic-pulmonary artery shunt in stage I Norwood reconstruction).

The majority of coronary blood flow to the normal left ventricle occurs during diastole.^{2, 21-24} There is

Fig. 3. Correlations between preoperative hemodynamics and postoperative clinical status with coronary flow dynamics. There were positive correlations in group I (patients with stage 1 reconstruction who underwent the volume-unloading hemi-Fontan operation) between preoperative superior vena cava (SVC) oxygen saturation and (A) peak velocity and (B) coronary blood flow. In group II (patients who underwent Fontan completion; no volume change), there was a positive correlation between the preoperative peak velocity and (C) the preoperative pulmonary artery pressure and (D) the preoperative pulmonary blood flow. After operation, a strong positive correlation existed between (E) coronary blood flow and urine output and a strong negative correlation existed between (F) coronary blood flow and central venous pressure. *R*, Pearson's correlation coefficient; *SEE*, standard error of the estimate.

also a small amount of antegrade flow that occurs throughout systole, with a short period of flow reversal at the beginning and the end of systole.¹ In the normal right ventricle, however, flow is continuous throughout the cardiac cycle with systolic flow somewhat greater than diastolic flow.¹ This was demonstrated to change to a more left ventricular profile when right ventricular pressure rises to systemic pressure.^{1, 24} In our study, the morphologic right ventricle is the systemic ventricle and should mimic the flow pattern in the normal left ventricle. Our findings indicate, however, that in the volume-loaded state, the coronary flow pattern of the systemic right ventricle does not mimic that of the normal left ventricle with flow mostly in systole. This is, again, more consistent with the findings in aortic regurgitation, in which coronary blood flow was found to change from predominantly diastolic to predominantly systolic with increasing degrees of aortic insufficiency.¹⁸⁻²⁰ The presumed mechanism of predominantly systolic flow and decreased diastolic flow into the coronary arteries in patients who have a systemic-pulmonary artery shunt or with aortic regurgitation is a "diastolic steal" from these runoff lesions.

In the volume-unloaded state (hemi-Fontan and Fontan reconstruction), the coronary flow pattern is continuous with much of the flow in diastole, most consistent with the flow pattern in the normal left ventricle.¹ Only one nadir of flow was noted, in late systole, as compared with the normal left ventricular flow pattern in which two nadirs are noted (beginning and end systole).

There are a number of reasons the coronary flow patterns in the ascending aorta in hypoplastic left heart syndrome may be different. Measurement of retrograde flow in the ascending aorta reflects flow in both the right and left coronary arteries, whereas the flows described in the literature single out either the right or left coronary artery.^{1, 2, 18-24} Additionally, the increased pressure in the cavity and substance of the myocardium of the hypoplastic left ventricle may add to the distortion in the flow profiles. Further, morphologic coronary artery abnormalities noted in hypoplastic left heart syndrome may contribute to the overall alterations in flow dynamics.²⁵⁻²⁷ Finally, ventricular-ventricular interactions²⁸⁻³⁰ may be another reason for the difference in coronary flow patterns. Alternatively, the change in coronary flow patterns may be the reason for altered strain and wall motion patterns observed in single right ventricles compared with those in sys-

temic right ventricles in a dual-chambered circulation.³⁰

Noteworthy is the relative consistency in coronary flow dynamics in postoperative group I and group II. Although there may have been some hemodilution from cardiopulmonary bypass, this did not appear to affect coronary flow dynamics. In addition, the amount of hemoglobin in both groups before operation was the same (Table I), which confirms that the change in coronary flow dynamics was not caused by a change in hemoglobin level.

Correlations between coronary flow dynamics and hemodynamics/postoperative data. In both groups, a number of hemodynamic parameters correlated with coronary flow dynamics. Before operation in group I, superior vena caval oxygen saturation had a positive relationship with coronary blood flow and peak velocity presumably because the increased myocardial perfusion gave rise to an increased cardiac index. In group II, increased pulmonary blood flow was associated with a higher peak velocity, reflective of increased oxygen delivery to the myocardium and therefore better myocardial performance. The increased pulmonary blood flow may be the reason for the positive correlation between pulmonary artery pressure and peak velocity (the higher the pulmonary blood flow, the greater the pulmonary artery pressure).

It is interesting that multiple preoperative hemodynamic parameters in both groups had a correlation with postoperative coronary flow dynamics. This is not surprising inasmuch as the preoperative hemodynamics reflect the status of the cardiovascular system and the suitability of the patient for operation. It would follow that the better the candidate for operation, the better on average the patient would do after operation.

In group II, some postoperative clinical data correlated with coronary flow dynamics. The strong positive correlation of coronary blood flow with urine output and strong negative correlation with central venous pressure are reflections of increased myocardial perfusion giving rise to increased ventricular performance.

Finally, we are unsure why group II patients had correlations between postoperative clinical data and postoperative coronary flow dynamics whereas group I patients did not. It may be that the physiologic status of the hemi-Fontan operation is "more robust" than that of the Fontan because not all the systemic venous return needs to traverse the lungs to maintain cardiac output. Because of this, coronary

blood flow may not be as tightly linked to clinical status, which uncouples this relationship in group I patients.

Limitations of the study. In obtaining Doppler information in the native ascending aorta, the flow of blood was not always perfectly parallel to the Doppler cursor. This may have caused a small error in our measurements; however, we do not think that this would have substantially changed our results or conclusions. This study focused on the difference in coronary blood flow measured by the same technique when the ventricle was changed from a volume-loaded to unloaded state. Further, all aorta-pulmonary artery anastomoses were done by the same surgeon with the same technique, which standardized the geometry of the anastomotic connection when these patients were grouped. In addition, hemi-Fontan and Fontan operations do not involve the aorta-pulmonary artery anastomosis, so the geometry of this connection does not change. Because the geometry is similar in all patients and between operations, measurement errors and bias are the same for both physiologic states and should cancel each other out when one looks at differences.

This study used only retrograde flow in the ascending aorta as a measure and reflection of coronary blood flow. There was, however, a small component of blood flow that was directed in the antegrade direction during the cardiac cycle (5 patients, all of whom had velocity time integrals of the antegrade flow <6% of the retrograde flow). This may be a reflection phenomenon: blood propelled against the aortic plate with a component entering the coronary arteries and a component directed back toward the aorta-pulmonary artery anastomosis. Because this component was small, we again do not think this would have substantially changed our results or conclusions.

Conclusion. Values of coronary blood flow, the velocity time integral, and peak velocity are higher in patients who have undergone stage I Norwood reconstruction before they undergo the hemi-Fontan operation than in other stages, as a result of the increased energy needs required to pump to two circulations. No changes were found in patients who had undergone the hemi-Fontan procedure and underwent Fontan reconstruction. A number of coronary blood flow parameters correlated with preoperative hemodynamics and postoperative clinical data. These parameters appear to be useful in assessing the performance status of the myocardium after operation in patients undergoing Fontan re-

construction, consistent with the notion that myocardial perfusion relates directly with ventricular function.

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Commentary

Anatomic and functional coronary abnormalities in patients undergoing palliative operations for hypoplastic left heart syndrome have been understudied. The article by Fogel and his colleagues is an important first step toward better understanding of the interaction between coronary flow dynamics and cardiovascular pathophysiology after palliative surgery for hypoplastic left heart syndrome. Using transesophageal echocardiography before and after the operation in patients with aortic valve atresia, the investigators demonstrated that unloading procedures were associated with concomitant decreases in flow in the native aortic root, which serves as a conduit for blood entering the coronary ostia.

Although the authors discuss some of the potential limitations of the method used in their study, several aspects of it deserve further consideration. By sampling flow velocity in the native aortic root and calculating flow rate, the authors suggest that most of that flow enters the coronary circulation and is reflective of coronary blood flow. It should be realized, however,

that this assumption has not been validated and the proportion of native aortic root flow entering the coronary arteries is unknown. As noted in the article, some of the blood that enters the native ascending aorta is reflected and does not enter the coronary circulation. Inasmuch as spectral Doppler echocardiography displays the summed average flow velocity and direction along the beam path, it cannot accurately resolve instantaneous flow in opposite directions. By using Doppler flowmetry in the native ascending aorta, one is currently unable to resolve the relative proportions of circular flow and coronary flow. Other inherent limitations of Doppler echocardiography might further complicate its use in the infant with aortic atresia who has undergone palliation. These technical limitations, including dependency on angle of interrogation, an assumed circular shape of the native ascending aorta, respiratory and cardiac motions that shift the region of interrogation, and other limitations, further illustrate the need for studies to determine the validity and accuracy of Doppler echocardiography in this particular anatomic-physiologic setup.

Future research on coronary blood flow dynamics and its relation to surgical treatment in patients with hypoplastic left heart syndrome may correlate parameters that are obtainable in the cardiac catheterization laboratory or during the operation with noninvasive techniques. For example, coronary blood flow can be estimated by means of transvascular intracoronary imaging and Doppler ultrasonography. This technique has been successfully used in the pediatric age group, as demonstrated by Hamaoka and Onouchi.¹ Another approach is to measure coronary sinus blood flow using either catheter-tipped flowmetry or intravascular Doppler ultrasonography. The metabolic state of the myocardium, which reflects coronary supply/demand ratio, can also be assessed by measuring lactate, pH, and other metabolic parameters in coronary sinus blood samples.² An attractive noninvasive alternative to Doppler echocardiography is magnetic resonance imaging (MRI). Recent technologic advances in flow imaging and quantification by MRI make this modality a promising research tool in the study of coronary flow dynamics.³ In particular, multidimensional phase velocity mapping MRI is capable of resolving flow velocity throughout the cardiac cycle in three spatial dimensions. This technique has shown a promising prospect when applied to coronary arteries in adults.⁴ In addition, MRI is also capable of evaluating myocardial perfusion and ventricular function.⁵

Dr. Fogel and his colleagues took the first step in a long journey toward better understanding of a complex interplay between coronary flow dynamics and pathophysiology of the palliated cardiovascular system in patients with various forms of hypoplastic left heart syndrome. Such improved understanding is essential for future improvements in surgical management of these patients.

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