Clinical assessment of diastolic retrograde flow in the descending aorta for high-flow systemic-to-pulmonary artery shunting

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ABSTRACT

Objective: To investigate whether echocardiographic characteristics in the descending aorta of patients with cyanotic congenital heart disease who have received a systemic-to-pulmonary artery (SP) shunt can indicate shunt flow volume and predict postoperative adverse events related to high-flow shunting.

Methods: Among the 73 consecutive patients who received an SP shunt between 2010 and 2014, data for 53 patients who underwent postoperative Doppler echocardiographic assessment of diastolic retrograde flow in the descending aorta (dAo-RF) were reviewed retrospectively.

Results: The mean dAo-RF ratio was 0.50 ± 0.15 at intensive care unit admission and reached its peak level (0.56 ± 0.12) at 24 hours after surgery. All of the patients with a maximal dAo-RF ratio of ≥0.80 had experienced acute heart failure or cardiogenic shock due to postoperative high-flow shunting and required emergent surgical interventions to reduce pulmonary blood flow. Pulse oximetry–measured oxygen saturation and serum lactate level were significantly correlated with dAo-RF ratio, but they had some clinical dispersion to match the postoperative adverse events.

Conclusions: The dAo-RF ratio is a simple, repeatable, and noninvasive index for postoperative assessment of SP shunt flow volume. A high dAo-RF ratio is a significant predictor of postoperative adverse events of high-flow shunting.

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Early primary intracardiac repair of cyanotic congenital heart defects has been evolving in recent years, but systemic-to-pulmonary artery (SP) shunts continue to play a pivotal role in the management of some patients with ductal-dependent pulmonary circulation or inadequate pulmonary blood flow. Despite progressive advances in perioperative management, overall outcomes of the SP shunt remain unsatisfactory, with a mortality rate ranging from 2.3% to 16%.1,2 According to the 2012 annual report of the Japanese Association for Thoracic Surgery, the overall hospital mortality rate was 3.4% in 654 SP shunt operations performed nationwide.3 Patients who undergo palliative surgery with the creation of an SP shunt are at risk for high-flow shunting as well as shunt thrombosis. Excessive shunt flow contributes to increased diastolic runoff, ventricular volume overload, and low cardiac output syndrome, resulting in hemodynamic instability during the early postoperative period.4 Recently, Alsoufi et al5 reported that increased shunt size-to-weight ratio is a significant risk factor for mortality.
related to pulmonary overcirculation and systemic or coronary steal after the creation of modified Blalock-Taussig shunt. Numerous factors can affect this risk, including shunt size and length, proximal arterial inflow site, alternate pulmonary blood flow source, and pulmonary vascular resistance. These factors should be considered at the time of SP shunt placement and efforts taken to avoid pulmonary overcirculation. Previous studies of the SP shunt have not reported research pertaining to clinical methodology for the postoperative assessment of high-flow shunting, however.

Doppler echocardiography is one available modality for evaluating diastolic blood flow. A previous study showed that diastolic retrograde flow in the descending aorta (dAo-RF) can signify impaired systemic perfusion in patients with patent ductus arteriosus (PDA). We hypothesized that echocardiographic characteristics in the descending aorta can indicate the flow volume of the SP shunt postoperatively, and that the dAo-RF ratio can help predict postoperative events related to high-flow SP shunting.

PATIENTS AND METHODS Patients

Between April 2010 and August 2014, 73 consecutive patients underwent SP shunt placement at Kobe Children’s Hospital, with postoperative Doppler echocardiography assessment of dAo-RF. Of these, 3 patients undergoing the Norwood procedure with an SP shunt and 17 patients with incomplete dAo-RF data were excluded from the present study. The remaining 53 patients were enrolled in this study. Data collection involved a retrospective review of clinical medical records and databases. This study was conducted with the approval of the hospital’s Institutional Review Board (registration no. R27-22), and the need for individual consent was waived in view of the study’s retrospective nature.

Patient characteristics are summarized in Table 1. The median age and body weight at the time of surgery was 2.0 months (range, 6 days to 11.9 months) and 4.1 kg (range, 2.7 to 9.2 kg), respectively. There were 23 males and 30 females. Cardiac defects included double-outlet right ventricle (n = 14; 26.4%), Tetralogy of Fallot (n = 9; 17.0%), single ventricle (n = 9; 17.0%), pulmonary atresia with ventricular septal defect (PA/VSD) (n = 6; 11.3%), pulmonary atresia with intact ventricular septum (n = 5; 9.4%), transposition of the great arteries (n = 5; 9.4%), and Ebstein’s anomaly (n = 3; 5.7%). Thirty-two patients (60.4%) had duct-dependent pulmonary circulation, and 7 (13.2%) had a history of a previous SP shunt. Aortic regurgitation was absent in 51 patients (96.2%) and trace in 2 patients (3.8%).

Surgical Procedure

The surgical procedure for SP shunt placement is summarized in Table 2. Placement was performed through a median sternotomy in 37 patients (69.8%), through a right thoracotomy in 9 patients (17.0%), and through a left thoracotomy in 7 patients (13.2%). Cardiopulmonary bypass was used in 27 patients (50.9%). The surgical approach and use of cardiopulmonary bypass were determined based on the patient’s anatomy, anastomotic site of the shunt, and clinical condition. Inflow vessels of the SP shunt included the brachiocephalic artery in 28 patients (52.8%), the subclavian artery in 19 patients (35.8%), and the common carotid artery in 6 patients (11.3%). Outflow vessels included the right pulmonary artery in 29 patients (54.7%), the left pulmonary artery in 16 patients (30.2%), and the main (central) pulmonary artery in 8 patients (15.1%).

A thin-walled Gore-Tex stretch vascular graft, configured for a pediatric shunt (W. L. Gore & Associates, Tokyo, Japan), was implanted as the SP shunt in an end-to-side fashion with a 7-0 polypropylene continuous suture parallel to the direction of flow as possible, with appropriate angle correction if necessary. After a Doppler waveform of 3 beats in the descending aorta was recorded, velocity-time integrals (VTIs) of systolic antegrade flow and diastolic retrograde flow in the descending aorta were measured by tracing the curves above and below the baseline, respectively (Figure 1). The mean diastolic retrograde flow VTI was divided by the mean systolic antegrade flow VTI to calculate the dAo-RF ratio. The study endpoint was defined as postoperative adverse events, including heart failure (eg, tachycardia, oliguria), cardiogenic shock, and cardiac arrest, due to high-flow SP shunting that necessitated emergent reduction of pulmonary blood flow. The dAo-RF ratio was measured at
### TABLE 1. Patient characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tbody>
<tr>
<td>Sex, male/female, n</td>
<td>23/30</td>
</tr>
<tr>
<td>Age at surgery, months, median (range)</td>
<td>2.0 (0.2-11.9)</td>
</tr>
<tr>
<td>Weight at surgery, kg, median (range)</td>
<td>4.1 (2.7-9.2)</td>
</tr>
<tr>
<td>Diagnosis, n (%)</td>
<td>Double-outlet right ventricle 14 (26.4), Tetralogy of Fallot 9 (17.0), Single ventricle 9 (17.0), PA/VSD 6 (11.3), PA/IVS 5 (9.4), TGA 5 (9.4), Ebstein anomaly 3 (5.7), Other 2 (3.8)</td>
</tr>
<tr>
<td>Duct-dependent pulmonary circulation, n (%)</td>
<td>32 (60.4)</td>
</tr>
<tr>
<td>Previous SP shunt, n (%)</td>
<td>7 (13.2)</td>
</tr>
<tr>
<td>Aortic regurgitation, n (%)</td>
<td>2 (3.8)</td>
</tr>
</tbody>
</table>

### Statistical Analysis

Data are given as mean ± standard deviation or median and range, as appropriate. Time-related data for the dAo-RF ratio and other postoperative parameters (diastolic BP, SpO₂, serum lactate level, and peak shunt flow velocity) were analyzed by 1-way repeated-measures analysis of variance (ANOVA). The Bonferroni test was performed for multiple comparisons of these data among each time point. Univariate and multivariate regression analyses were performed to evaluate the associations between dAo-RF ratio and other postoperative parameters. Data were analyzed using Stat View J 5.0 (SAS Institute, Cary, NC) and Prism version 5.0 (GraphPad Software, San Diego, Calif). Differences were considered statistically significant at P < .05.

### RESULTS

#### Postoperative Outcomes

The median follow-up period after the SP shunt was 1.8 years (range, 2.3 months to 4.7 years). Of the 53 patients with the SP shunt, 22 (41.5%) underwent biventricular repair, and 17 (32.1%) underwent univentricular repair (Fontan completion in 9 and bidirectional Glenn palliation in 8). There was 1 in-hospital death due to liver dysfunction in a patient with Ebstein’s anomaly, along with 2 late deaths, 1 due to respiratory failure in a patient with PA/VSD and tracheostomy and the other due to sudden circulatory collapse in a patient with Ebstein’s anomaly.

#### dAo-RF Ratio

Time-course changes in the dAo-RF ratio after SP shunting are shown in Figure 2. The mean dAo-RF ratio was 0.50 ± 0.15 at ICU admission, 0.56 ± 0.12 at 24 hours after surgery, 0.55 ± 0.14 at 48 hours after surgery, and 0.45 ± 0.11 at 7 days after surgery. The dAo-RF ratio reached a peak at 24 hours after surgery, with the highest ratio occurring during 7 days after SP shunting. There was a significant difference in the time course change in dAo-RF ratio during the first 7 days after surgery (P < .0001, 1-way repeated measures ANOVA). The dAo-RF ratio at 7 days after surgery was significantly lower than that at ICU admission (P = .0419) and at 24 hours after surgery (P < .0001).

#### Other Postoperative Parameters

Time course changes in diastolic BP, SpO₂, serum lactate level, and peak shunt flow velocity are illustrated in Figure 3. During the first 48 hours after surgery, there were no statistically significant differences in diastolic BP, serum lactate level, or peak shunt flow velocity at each time point. Mean values of diastolic BP, serum lactate, and peak shunt flow velocity were 41.7 ± 5.2 mmHg, 1.3 ± 0.6 mmol/L, and 2.9 ± 0.6 m/s, respectively. The mean SpO₂ was 80.3 ± 6.2% at ICU admission and 84.2 ± 3.7% at 48 hours after surgery. The increase in...
SpO₂ during the first 48 hours after surgery was gradual but statistically significant (\(P = .0003,\) 1-way repeated-measures ANOVA).

Associations Between dAo-RF Ratio and Other Postoperative Parameters

On univariate regression analyses, the maximum dAo-RF ratio was correlated with maximum SpO₂ and serum lactate level during the first 48 hours after surgery (SpO₂, \(r = 0.302, P = .0278;\) lactate, \(r = 0.305, P = .0266\)), whereas there was no statistically significant correlation between dAo-RF ratio and any postoperative parameter on the multivariate regression analysis.

Shunt-Related Events

Postoperative adverse events due to high-flow SP shunting occurred between 6 and 87 hours after surgery in 4 patients, including acute heart failure in 1 and cardiogenic shock in 3. All cases of cardiogenic shock occurred during or after tracheal suctioning, and 1 of the 3 affected patients experienced cardiac arrest requiring extracorporeal membrane oxygenation support. Demographic data for these patients are summarized in Table 3. The shunt size was 3.5 mm in 2 patients and 4.0 mm in 2 patients. As an additional source of pulmonary circulation after SP shunting, the 3.8-kg infant with a 3.5-mm shunt had residual PDA flow and the 5.6-kg infant with a 4.0-mm shunt had blood flow through a previous right modified Blalock-Taussig shunt. The maximum dAo-RF ratio during the first 48 hours was >0.80 in all 4 patients (Figure 4). Emergent surgical interventions to reduce pulmonary blood flow, including PDA banding in 1 patient, shunt banding in 2 patients, and shunt clamping in 1 patient, were performed in the ICU.

DISCUSSION

Balancing blood flow between pulmonary and systemic circulation is imperative to stabilize hemodynamics in

FIGURE 1. Doppler echocardiographic assessment of diastolic retrograde flow in the descending aorta. VTIs of systolic antegrade flow and diastolic retrograde flow were measured by tracing the curves above and below the baseline, respectively. VTI, Velocity-time integral.

FIGURE 2. Time-course changes in diastolic retrograde flow ratio in the descending aorta (dAo-RF ratio) after systemic-to-pulmonary artery shunting. Data of individual patients are represented with grey dots and lines. Data of patients who had postoperative adverse events related to high-flow shunting are separately represented with red dots and lines. Black dots and lines denote means and standard deviations. Black dashed lines denote 95% confidence intervals. ICU, Intensive care unit.
patients with an SP shunt. Excessive pulmonary circulation through the shunt may be associated with impaired coronary artery and end-organ perfusion because of increased diastolic runoff and volume overload of the heart and lungs. Therefore, assessment of blood flow balance is important in the management of postoperative intensive care in these patients. The major finding of this study is that a high dAo-RF ratio on Doppler echocardiography was significantly associated with postoperative events related to high-flow SP shunting, and can be a useful indicator of blood flow volume through the SP shunt. To the best of our knowledge, this is the first report of echocardiographic assessment of SP shunts using the dAo-RF ratio.

Diastolic retrograde flow in the aorta has been well studied in preterm infants with PDA. Groves and colleagues reported that dAo-RF is a reliable marker of high-volume ductal shunting, strongly associated with increased left ventricular output. Carlo and colleagues reported that persistent diastolic retrograde flow in the abdominal aorta is associated with an increased risk of necrotizing enterocolitis in infants with congenital heart disease. Recently, Rychik and colleagues evaluated circulatory maldistribution after the Norwood procedure for hypoplastic left heart syndrome by using diastolic retrograde flow in the reconstructed aorta. The ratio of the retrograde-flow VTI to the forward-flow VTI in the descending aorta was significantly associated with the pulmonary/systemic blood flow ratio on the basis of the systemic arterial oxygen saturation levels (Qp/Qs). In addition, we recently showed a significant positive linear correlation between the dAo-RF ratio by echocardiography and the postoperative Qp/Qs by cardiac catheterization (unpublished data).

The present study demonstrate that the dAo-RF ratio increased and reached the peak at 24 hours after SP shunting, and gradually declined until postoperative day 7. Three of 4 postoperative adverse events related to

![FIGURE 3. Time-course changes in diastolic BP, SpO2, shunt Vp, and serum lactate levels after systemic-to-pulmonary artery shunting. Data of individual patients are represented by gray dots and lines. Data for patients who experienced postoperative adverse events related to high-flow shunting are represented separately by red lines. Black dots and lines denote means and standard deviations. Black dashed lines denote 95% confidence intervals. BP, Blood pressure; Vp, peak flow velocity; SpO2, pulse oximeter oxygen saturation; ICU, intensive care unit.](image-url)
high-flow SP shunting occurred within the first 24 hours after surgery. The remaining event occurred at 87 hours after surgery, but 18 hours after delayed sternal closure. In general, patients who undergo pediatric cardiac surgery with cardiopulmonary bypass are prone to the development of extravascular fluid overload and subsequent lung impairment with increased pulmonary vascular resistance. Because a postoperative reduction in extravascular fluid through increased diuresis can improve lung compliance and gas exchange with an increase in pulmonary blood flow, a negative fluid balance after surgery may be related to a postoperative increase in the dAo-RF ratio during the first 24 hours owing to improved lung condition. Close attention should be paid to the dAo-RF ratio and postoperative adverse events related to high-flow SP shunting during this period.

Clinical signs, such as low diastolic BP, high SpO₂, and increased serum lactate level, have been conventionally used as postoperative parameters for assessment of high-flow SP shunting. Di Filippo and colleagues identified serum lactate level as a useful marker related to the low circulatory syndrome linked to pulmonary overcirculation and/or myocardial dysfunction. Although SpO₂ and serum lactate level were significantly correlated with dAo-RF ratio, there has been some clinical dispersion of these parameters to match the postoperative adverse events in the present study. This study showed that all patients with a maximum dAo-RF ratio of ≥0.8 had postoperative adverse events related to high-flow SP shunting, and that these adverse events did not occur in any patients with a maximum dAo-RF ratio of <0.8. Although the limited sample size of the adverse events prevents us from providing a conclusive cutoff points for them, we propose that a dAo-RF ratio of 0.80 could be an appropriate cutoff value for postoperative adverse events. Patients with an SP shunt placement should be managed using the dAo-RF ratio in addition to the conventional postoperative parameters.

The presence of an additional source of pulmonary circulation through a residual PDA after SP shunting complicates postoperative echocardiographic evaluation of the dAo-RF ratio. Because PDA flow itself is characterized by the dAo-RF, the dAo-RF ratio is influenced by both shunt and residual PDA flows. In this study, 1 of 5 patients who had residual PDA flow after SP shunting had a maximum dAo-RF ratio of 0.85 and experienced cardiogenic shock due to pulmonary overcirculation. Close management of pulmonary circulation is necessary.
in patients who have both an SP shunt and PDA with a higher dAo-RF ratio. Forward blood flow across the pulmonary valve or major aortopulmonary collateral artery also complicates the evaluation of pulmonary circulation after SP shunting. Further study of the dAo-RF ratio in the presence of additional sources of pulmonary blood flow is needed to determine hemodynamic stability of both the systemic and pulmonary circulation.

Appropriate regulation of the SP shunt flow is important to avoid pulmonary overcirculation. In the present study, emergent surgical interventions to reduce pulmonary blood flow, such as shunt banding and clipping, were required in patients who experienced a postoperative adverse event due to high-flow SP shunting. These interventions will be more beneficial for patients at high risk for pulmonary overcirculation if they are performed before the occurrence of the adverse events. We recently attempted to evaluate the dAo-RF ratio after SP shunt placement using intraoperative epicardial Doppler echocardiography. When a high dAo-RF ratio is noted in the operating room, it might be possible to immediately downsize the shunt with banding or clipping at that time. Further study is needed to determine whether this technology can be adopted in the operating room, and how the dAo-RF ratio can be significant in guiding downsizing of the shunt.

Although in this study we defined postoperative adverse events as events related to presumed pulmonary overcirculation and requiring emergent reduction of pulmonary blood flow, some patients with high-flow SP shunting will require augmented inotropic support, mechanical ventilation, and diuresis without emergent surgical interventions. In the present study, there was a tendency for the patients with a higher dAo-RF ratio to require medical treatment for pulmonary overcirculation. Moreover, we recently found that a dAo-RF ratio of >0.80 was almost equal to a Qp/Qs of >2.0 after SP shunting (unpublished data). We could detect patients with overcirculation through echocardiographic evaluation of the dAo-RF ratio before the onset of adverse events requiring an emergent reduction of pulmonary blood flow.

This study has some limitations that must be acknowledged. The single-center retrospective study design impedes the generalizability of our results. Patient exclusion because of incomplete dAo-RF ratio in the postoperative echocardiographic assessments may be a potential source of selection bias, but the excluded patients did not experience any postoperative adverse events related to high-flow SP shunting. The dAo-RF is an echocardiographic index of aortic regurgitation severity, and thus can be affected by the presence of aortic regurgitation. In the present study, however, most of the patients had no aortic regurgitation, and 2 patients had only trace aortic regurgitation. Although our proposal that a dAo-RF ratio of 0.80 could be an appropriate cutoff value for postoperative adverse events, we were not able to achieve an adequate statistical analysis with the limited effective sample size of 4. It remains to be confirmed in larger study with a larger effective sample size.

In summary, the dAo-RF ratio is a useful index for postoperative assessment of the flow volume of an SP shunt. This technique is simple, noninvasive, and repeatable at the bedside. Based on our findings, a high dAo-RF ratio would be a significant predictor of postoperative adverse events of high-flow SP shunting. Using this index, the flow volume of the SP shunt could be peripherally adjusted to decrease the risk of postoperative adverse events.

Conflict of Interest Statement
Authors have nothing to disclose with regard to commercial support.

References

Key Words: systemic-to-pulmonary artery shunt, high-flow shunting, diastolic retrograde flow in the descending aorta