Dynamics of right heart flow in patients after Fontan procedure

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ABSTRACT In seven patients who underwent Fontan procedures but in whom no valves were inserted, dynamics of right heart flow were evaluated with the use of a catheter-tipped velocity transducer, pulsed Doppler echocardiography, and angiography. Right atrial (RA) contraction caused a forward flow to the pulmonary artery (PA) and a backward flow to the inferior vena cava (IVC). Backward flow to the superior vena cava (SVC) was minimal. As the right atrium relaxed, a rapid forward flow occurred at the IVC and SVC that filled the atrium and a small amount of pulmonary regurgitant flow was observed. Subsequently, a forward flow was observed at the IVC, SVC, and PA during RA diastole. Angiographically determined RA stroke volume (SV) was less than 40% of the left ventricular (LV) SV in three patients in whom the postoperative increase in atrial “a” wave pressure (Δp) was greater than 8 mm Hg, while it was similar to or greater than LVSV in four patients in whom Δp was 6 mm Hg or less. In all patients LV end-diastolic volume was 107 ± 27(SD)% of normal but LV ejection fraction was 0.53 ± 0.07, resulting in the reduced cardiac output (2.8 ± 0.7 l/min/m²). There was no correlation between the RASV or RA ejection fraction and cardiac output. These data show that the RA contraction causes a forward flow to the PA and that pulmonary regurgitation is not significant after Fontan procedure even when valves are not inserted. Also, the postoperative increase in the RA afterload may depress RA function. The contribution of atrial contraction to output of the right heart may not be a major determinant of cardiac output.


SINCE Fontan et al.1 and Kreutzer et al.2 reported the surgical procedure of physiologic correction of tricuspid atresia, this type of operation has been successfully applied to various congenital heart diseases.3–5 Postoperative hemodynamic studies6-12 have revealed that right atrial (RA) pressure is increased, especially in the “a” wave, which is transmitted to the pulmonary artery (PA), and that the pulmonary valve is found to open at the time of atrial contraction. Although these observations imply that RA contraction may play an important role in postoperative hemodynamics in these patients, dynamics of right heart flow have not been studied in depth. This study was undertaken to determine dynamics of right heart flow as well as RA and left ventricular (LV) volume characteristics in patients who have undergone Fontan procedure. Data were obtained with a catheter-tipped velocity transducer and by pulsed Doppler echocardiography and angiography.

Subjects and methods

Seven patients who had undergone a modified Fontan procedure were studied during a period of from 4 weeks to 4 years after the operation. Their ages at the time of surgery ranged from 2 to 19 years. The diagnoses and surgical procedures for each patient are summarized in table 1. Valves were not inserted in any of the patients. The preoperative hemodynamic data are also presented in table 2.

Right and left heart catheterizations were performed after patients were premedicated with 2 mg/kg meperidine and 1 mg/kg hydroxyzine pamoate. Cineangiocardiograms were recorded after injection of contrast medium into the inferior vena cava (IVC) and the main PA. The cine records served to determine the RA and LV volumes. Both volumes were calculated by the methods reported by Graham et al.,13, 14 RA and LV ejection fractions (EFs) were obtained with the equation: (maximum volume − minimum volume) ÷ maximum volume. The maximum RA and LV end-diastolic volumes (EDVs) observed were compared with the expected normal values (RA volume = 54.6 × body surface area [BSA]15,23 LVEDV = 72.5 × BSA14,25) and were expressed as a percentage of normal. Cardiac output was determined by the thermodilution method.

In six of the seven patients, a catheter-tipped velocity transducer (Miller, Model VPC-663A) was introduced into the right side of the heart. Blood flow velocity was measured with an
electromagnetic flowmeter (Narco, Model RT-500) with a 30 Hz filter before angiographic examination.

In all patients, pulsed Doppler echocardiography was performed to determine blood flow patterns at the IVC, hepatic vein, superior vena cava (SVC), and right and left PAs. The system used was a Toshiba SSH-11A combined with an SDS-10A. The high-pass filter of the pulsed Doppler instrument was set at 200 or 400 Hz. The measurements were made at the end of expiration while patients were in the supine position. The transducer was placed in the subxiphoid region to obtain the flow pattern at the IVC and hepatic vein, the SVC flow pattern was recorded from the suprasternal approach, and the pulmonary flow pattern was obtained from the third left intercostal space. The effect of deep inspiration was studied in five patients by recording the flow pattern at the point of maximum inspiration.

**Results**

**Velocity patterns of blood flow obtained by the catheter method**

*Patients who underwent direct RA-PA anastomosis. A representative tracing is presented in figure 1. At the main PA, a forward flow was detected along with a pressure elevation that began to rise immediately after the onset of the P wave on the electrocardiogram (ECG). At the same time, a backward flow was detected at the IVC while at the SVC a continuous forward flow was interrupted or reversed slightly. The graphic representation of this flow was designated the A wave and its peak coincided with the peak of the a wave of the atrial pressure. A rapid forward flow then followed at the IVC and SVC and its graphic representation was designated the R wave. The peak of this wave coincided with a dip in the atrial pressure. At this time, there was a slow and transient backward flow detected at the PA. Subsequently, a slow forward flow was noted at each site. This flow was observed to begin during the ST segment on the ECG and continued until the next A wave and was called the D wave.*

*Patient 4, who underwent direct anastomosis of the RA-right ventricular (RV) outflow tract. At the main PA, an additional forward flow was recorded between the A and D waves. The wave representing this flow was designated the V wave and it began 70 to 80 msec after the QRS complex and terminated at the time when a sharp and small notch was recorded on the pressure tracing. At

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Diagnosis</th>
<th>Previous palliation</th>
<th>Surgical procedure</th>
<th>Age at the surgery</th>
<th>Interval after the surgery</th>
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<tbody>
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<td>1</td>
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<td>BT at 2 yr</td>
<td>RA-PA anastomosis</td>
<td>8 yr</td>
<td>1 mo</td>
</tr>
<tr>
<td>2</td>
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<td>RA-PA anastomosis</td>
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<td>1 yr</td>
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<td>RA-PA anastomosis</td>
<td>9 yr</td>
<td>1 mo</td>
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<tr>
<td>7</td>
<td>TA lb</td>
<td>Potts at 1 yr</td>
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<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>Preoperative hemodynamic data</th>
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- RAP = right atrial pressure; PAP = mean pulmonary arterial pressure; PVW = mean pulmonary vein wedge pressure; LAP = mean left atrial pressure; NA = not available.
- Cineangiography was not performed in this patient.
the IVC and SVC the flow patterns were essentially the same as in the patients who underwent direct RA-PA anastomosis (figure 2).

Patient 5, who underwent direct RA-PA anastomosis and tricuspid orifice closure. This patient had a forward flow similar to the V wave (figure 3). At the IVC and SVC, the flow pattern was similar to that in the other patients.

Blood velocity pattern obtained with pulsed Doppler echocardiography. In all patients the flow pattern values obtained by echocardiography were identical to those obtained by the catheter method described above (figure 4). As illustrated in figure 5, the forward flow was increased at the PA and IVC by deep inspiration.

Postoperative hemodynamic data and volume characteristics. The data are summarized in table 3. None of the patients had intracardiac or extracardiac residual shunt. Cardiac output ranged from 1.6 to 3.7 l/min/m², with an average of 2.8 ± 0.7(SD) l/min/m². RA pressure increased in all patients. Mean PA pressure was normal. The pressure gradient between the mean RA and PA pressures was 4 mm Hg or less. There were no patients in whom PA wedge pressure was higher than normal. LVEDV was 107 ± 27% of normal and LVEF was 0.53 ± 0.07. The maximum RA volume increased in five patients and was normal in two. RA EF ranged from 0.18 to 0.40, with an average of 0.28 ± 0.08. This parameter was inversely correlated with postoperative increase in the atrial a wave (Δp) (r = −.77, p < .05; figure 6). The RA stroke volume (SV)/LV SV ratio was less than 0.4 in patients in whom Δp was greater than 8 mm Hg, while this ratio was more than 0.8 in patients in whom Δp was 6 mm Hg or less (figure 6).

Discussion

Although it is generally accepted that atrial contraction is important for maintenance of the pulmonary and systemic circulations in patients after Fontan procedure, results of some experimental and clinical

FIGURE 1. Flow velocity pattern as determined by the catheter method. An elevated a wave was associated with a forward flow to the main PA (mPA) and a backward flow to the IVC and SVC. This was designated the A wave. Subsequently a rapid forward flow (the R wave) was observed at the IVC and SVC, along with a dip in the pressure. During this period little regurgitant flow was detected at the mPA. These waves were followed by a slow forward flow (the D wave) at the IVC, SVC, and PA.
studies suggest that atrial contraction may not be essential.\textsuperscript{16–19} Data obtained at cardiac catherterization in these patients have shown that atrial contraction produces a large wave in the right atrium, which transmits well to the PA.\textsuperscript{5–12,18} The echocardiographic studies have shown that the pulmonary valve opens at the beginning of the atrial contraction.\textsuperscript{10} Furthermore, it has been reported that a closing sound of the pulmonary valve is recorded on the phonocardiogram at the end of atrial contraction.\textsuperscript{20} This is indirect evidence that atrial contraction contributes to the production of a forward flow into the pulmonary circulation. Our results confirm that it is directly related to the A wave in the PA. We also found that there was another forward flow into the PA (the D wave) during the period between two successive atrial contractions.

The velocity transducer system used in the present study had a phase shift with a time delay of 37 \pm 3 msec in the frequency range of 1 to 30 Hz, as reported by Kolettis et al.\textsuperscript{21} Taking into account this time delay, we give a detailed explanation of the flow dynamics in the right heart of patients who have undergone Fontan procedure; as the right atrium contracts, blood is ejected out toward every outlet, both in a forward flow to the PA and in a backward flow to the IVC and SVC. This corresponds to the A wave. The flow into the SVC was less than that into the IVC. This could be related to the fact that the capacity of the SVC system is less than that of the IVC. Another possibility could be that the action potential recorded at the proximal portion of the SVC\textsuperscript{22} indicated the existence of an atrial muscle and that the junction of the RA and SVC contracted to become stenotic by atrial contraction. These mechanisms may impede the flow from the right atrium to the SVC. As blood returns to the IVC and SVC, pressure in these vessels increases. Subsequently, when the right atrium relaxes the pressure falls sharply and blood flows rapidly into the atrium like water that has been dammed up and is suddenly released. Therefore, the atrial contraction may have a "damming-up" effect on the systemic venous return. However, the rapid flow illustrated by the R wave barely, if at all,
reaches the PA. Instead it is largely consumed by the right atrium. During this period there is slow and transient pulmonary regurgitation, but it is surprisingly less than that expected for patients in whom valves are not inserted. Thereafter, the systemic venous return flows directly into the pulmonary circulation during atrial diastole; this produces the D wave.

In patient 4, in whom the RV outflow tract was used, the V wave was observed as a forward flow in the main PA in addition to the A and D waves. This wave was observed during the ST segment on the ECG, and was accompanied by a pressure elevation that terminated at the time when the notch indicating closure of the pulmonary valve was recorded on the pressure tracing. This is probably produced by a contraction of the ventricle. The RA pressure in this patient was the lowest among the patients studied, thus implying a beneficial role of the ventricle. However, this patient also had the lowest cardiac output. Therefore it can not be concluded from this single case whether the existence of the right ventricle is really beneficial or not. The mechanism of the V wave in patient 5 is not clear, but a possible explanation is that the surgically closed tricuspid valve was lifted up into the right atrium by ventricular contraction, thus creating an effect similar to that of atrial contraction.

Pulsed Doppler echocardiography was found to be useful for detection of these intracardiac flow patterns. However, this method failed to detect the slow and transient pulmonary regurgitant flow, probably because the velocity of the flow was so slow that it was cut off by the high-pass filter used in this study. As illustrated in figure 5, the effect of deep inspiration was shown with the use of this method. It might be argued

FIGURE 4. The pulsed Doppler echocardiogram shows a flow velocity pattern at each site almost identical to that shown by the catheter method. HV = hepatic vein; I-PA = left PA; r-PA = right PA.

FIGURE 5. The pulsed Doppler echocardiogram shows that the forward flow increases at the IVC during deep inspiration.
that this phenomenon could be due to a change in the position of the sampling point or in the direction of the Doppler beam. In fact, the sampling point could be moved by deep inspiration from the center of the vessel to the periphery, where the velocity of the flow is usually slower than at the center. Nevertheless, in this study the velocity was shown to be increased by this maneuver. Furthermore, since the change in the angle between the Doppler beam and the flow was negligible, the increase in the flow could not be related to the angular change.

Flow velocity is determined not only by the amount of flow but also by the size of the site at which the flow is determined. Because the size of anastomosis between the right atrium or ventricle and the PA varies from patient to patient and will change during the cardiac cycle, the velocity data alone is not sufficient to allow quantification of the amount of flow. The RASV/LVSV ratio was used to evaluate the contribution of the atrial contraction to right heart output, although it must be noted that the RASV might be greater than the amount of forward flow due to atrial contraction. It was shown that this ratio correlated with the postoperative increase in the a wave, indicating that the contribution of the atrial contraction was attenuated by an increase in atrial afterload (figure 6). In addition, the RAEF was inversely related to the magnitude of the increase in the a wave. This finding is in agreement with that in the study of Janos et al., in which radionuclide angiography was used. Because, as shown in this study and in other studies, postoperative atrial pressure is at fairly constant level in patients after Fontan procedure, the data in figure 6 may indicate that the contribution of atrial contraction is larger in patients who have had high preoperative atrial pressure than in patients whose atrial pressure has been low. In the latter patients, therefore, the flow during atrial diastole would be a major fraction of the right heart output. In this study there was no significant correlation between RASV or RAEF and cardiac output, which suggests that RA function may not be a major determinant of cardiac output.

References

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**TABLE 3**
Postoperative hemodynamic and volume data

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<tr>
<th>Patient No.</th>
<th>CI (l/min/m²)</th>
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<th>PAW cc</th>
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<th>% of normal LVEF</th>
<th>RASV cc</th>
<th>RAf cc</th>
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<td>9</td>
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<td>129</td>
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</tbody>
</table>

CI = cardiac index (l/min/m²); max RAV = maximum RA volume; other abbreviations are as in table 2 and text.

**FIGURE 6.** RAOF inversely correlated with the postoperative increase in the atrial a wave (Δp). The RASV/LVSV ratio was smaller in patients with high Δp (more than 8 mm Hg) than in those with low Δp.
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