Ventricular Volume Characteristics in Double-Inlet Left Ventricle Before and After Septation

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Septation is one of the surgical choices for double-inlet left ventricle, yet postoperative hemodynamics have not been well defined. We studied ventricular volume characteristics in 10 patients with double-inlet left ventricle before and after septation. Preoperative end-diastolic volume (EDV) of the ventricle was 291±111% (±SD) of normal and ejection fraction (EF) was 0.59±0.07. Postoperatively, EDV of the right-sided ventricle (RV) was 82±24%, and EDV of the left-sided ventricle (LV) was 153±41%. Ejection fraction of the RV was 0.77±0.10, and LVEF was 0.49±0.13. On the short-axis view of two-dimensional echocardiography, fractional change of the cross-sectional area was 0.65±0.16 for the RV and 0.23±0.11 for the LV. Fractional shortening of the septum-to-ventricular free wall axis was 0.51±0.17 in the RV and −0.05±0.09 in the LV. Analysis of the curvature of the new septum during cardiac cycle on two-dimensional echocardiography revealed that the septum shifted to the right side during systole in all patients in whom the systolic LV/RV pressure ratio was larger than 1.0. The septum shifted toward the LV during diastole in eight patients in whom end-diastolic pressure in the RV was higher than or equal to that in the LV, whereas it remained in the right side in two patients with higher left-side pressure. The cardiac index of these two patients was 2.4 and 2.6 l/min/m², respectively, whereas it averaged 4.4±1.0 l/min/m³ in the other eight patients. High filling pressure of the LV should have restrained the crucial diastolic shift of the new septum. We conclude that the paradoxical motion of the septum and the unevenly divided ventricles bring about favorable postoperative hemodynamics in these patients. (Circulation 1990;81:1537-1543)

Septation operation is one of the choices in surgical management for double-inlet left ventricle with left anterior outlet chamber (DILV)\textsuperscript{1,2}. Postoperative ventricular function and the functional significance of the prosthetic noncontractile ventricular septum after septation, however, is not completely understood. Several reports have shown that the new septum shows a paradoxical movement\textsuperscript{3–5} although the role of the shift of the septum during a cardiac cycle on ventricular function and factors that affect the movement of the septum have not been precisely defined. Therefore, the purpose of the present study was to clarify the dynamics of the noncontractile septum and ventricular volume characteristics after septation in patients with DILV. The result would also be helpful in selecting patients for septation.

Methods

The present study included 10 patients with DILV who underwent ventricular septation since April 1980\textsuperscript{6} and who had satisfactory preoperative and postoperative hemodynamic data. Seven patients had previous palliations, that is, there was pulmonary artery banding in seven patients, subclavian flap method for coarctation of the aorta in one patient, Blalock-Hanlon atrioseptostomy in one patient, pacemaker implantation in one patient, and ligation of the patent ductus arteriosus in two patients. One patient with pulmonary artery banding had subsequently undergone Blalock-Taussig anastomosis for hypoxemia. The other three patients did not have palliations and had subpulmonary or valvular pulmonary stenosis, or both. Two patients had narrow bulboventricular foramen (Table 1).

The operation was accomplished through the atrial approach\textsuperscript{5,6} in all patients, at ages in the range of 23
months to 24 years. Aortic cross-clamp time averaged 102±22 minutes (Table 1). A permanent pacemaker of VVI type was newly implanted in eight patients; however, sinus rhythm returned spontaneously at several days to 2 months after surgery in all patients. The remaining patient did not require pacemaker implantation. Only one patient with congenital heart block was on a pacemaker at the time of this study.

Procedures

A standard right- and left-heart catheterization was performed with a fluid-filled catheter system, and cineventriculography was performed in the anteroposterior and lateral projections with a film speed of 60 frames/sec. Preoperatively, the volume of the main chamber of the morphological left ventricle was calculated with the area-length method and that of the rudimentary chamber of the morphological right ventricle with Simpson's rule by the method of Graham et al. Both were added to obtain the total volume, which was compared with the expected normal value for the left ventricle. The ventricular free wall thickness was measured on the anteroposterior projection of the ventriculogram with which ventricular muscle mass was calculated according to the conventional method for only the main chamber and was expressed as a percentage of normal for each patient.

Postoperatively, volumes of the right-sided ventricle (RV) and the sinus portion of the left-sided ventricle (LV) were determined by the area-length method. Because the outflow tract of the LV is originally the rudimentary outlet chamber with the morphological right ventricle, Simpson's rule was applied to calculate its volume. The volume of the LV was the total of the sinus and outflow portions. End-diastolic volume (EDV), the largest volume during a cardiac cycle, was expressed as a percentage of the expected normal values for the respective ventricle. From EDV and end-systolic volume, the smallest volume during a cardiac cycle, we calculated stroke volume and ejection fraction (EF) in the usual manner.

Echocardiography was done within a few days of the invasive study. On the short-axis view obtained at the level of tendinous chords of the atrioventricular valves, right and left ventricular cross-sectional areas were integrated at end diastole and end systole, from which fractional change of the area for each ventricle was calculated by the following equation: fractional change=(end-diastolic area−end-systolic area)/(end-diastolic area). On the same cross-sectional view, a transverse axis (A1) and a short axis (A2) were drawn (Figure 1), and fractional shortening of each axis was calculated for each ventricle. To further characterize the passive motion of the noncontractile septum, the curvature of the septum was evaluated by the S/L ratio (deviation ratio) (Figure 1). This ratio was obtained at end diastole and end systole in both the cross-sectional view and the apical four-chamber view and was expressed as positive when the septum shifted to the right ventricular side.

We have been following all the patients at our clinic with follow-up periods in the range of 8–36 months (mean, 24±10 months). Their clinical conditions were reviewed to evaluate the medium-term follow-up result.

Data were expressed as mean±1 SD. We analyzed the data using Student's t test, and the difference was considered significant when the p value was less than 0.05.

Results

Preoperative Hemodynamics and Volume Characteristics

Mean pulmonary artery blood pressure averaged 27±13 mm Hg, and pulmonary vascular resistance (PVR) was 3.4±3.0 units·m². Three patients had PVR higher than 4.0 units·m², which was reduced by tazoline–hydrogen chloride infusion (Table 2). Two patients (patients 1 and 7) had pressure gradients of 85 and 10 mm Hg, respectively, at the narrow bulbo-
FIGURE 1. Echocardiographic study of a short-axis view (upper panels) and apical four-chamber view (middle panels). Lower panels: The longest axes (A1) are drawn parallel to the septum of both right-sided and left-sided ventricles (RV and LV, respectively), and the septoventricular free wall axes (A2) are drawn perpendicular to A1s. Fractional shortening of each axis is calculated. The areas and fractional changes of RV and LV were calculated in short-axis view. Curvature was quantified by taking the ratio of S/L as in the figure. L is line connecting both ends of the prosthetic septum, and S is longest distance from the line to the septum. The ratio was obtained at both end diastole and end systole.

Table 2. Preoperative Hemodynamic Data

<table>
<thead>
<tr>
<th>Patient</th>
<th>PA systolic/diastolic pressure (mm Hg) (mean)</th>
<th>PVR* (units · m²)</th>
<th>Ventricular pressure (peak/EDP) (mm Hg)</th>
<th>Qp/Qs</th>
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</thead>
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<tr>
<td>1</td>
<td>27/15 (22)</td>
<td>1.6</td>
<td>180/19†</td>
<td>1.6</td>
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<tr>
<td>2</td>
<td>37/10 (25)</td>
<td>2.1</td>
<td>86/7</td>
<td>2.9</td>
</tr>
<tr>
<td>3</td>
<td>40/12 (22)</td>
<td>2.9</td>
<td>115/7</td>
<td>2.1</td>
</tr>
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<td>4</td>
<td>64/32 (50)</td>
<td>5.6 (1.8)</td>
<td>90/5</td>
<td>2.3</td>
</tr>
<tr>
<td>5</td>
<td>35/12 (24)</td>
<td>2.3</td>
<td>88/8</td>
<td>2.3</td>
</tr>
<tr>
<td>6</td>
<td>54/12 (30)</td>
<td>11 (4.3)</td>
<td>125/11</td>
<td>1.3</td>
</tr>
<tr>
<td>7</td>
<td>40/12 (23)</td>
<td>2.1</td>
<td>103/8‡</td>
<td>1.7</td>
</tr>
<tr>
<td>8</td>
<td>20/8 (11)</td>
<td>1.2</td>
<td>105/8</td>
<td>1.7</td>
</tr>
<tr>
<td>9</td>
<td>26/10 (17)</td>
<td>1.2</td>
<td>80/10</td>
<td>2.2</td>
</tr>
<tr>
<td>10</td>
<td>65/30 (48)</td>
<td>4.1 (2.9)</td>
<td>112/9</td>
<td>2.1</td>
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</tbody>
</table>

PA, pulmonary artery; PVR, pulmonary vascular resistance; EDP, end-diastolic pressure; Qp/Qs, pulmonary-to-systemic blood flow ratio.

*Values in parentheses are PVR after trazoline infusion.
† and ‡There were pressure gradients of 85 and 10 mm Hg, respectively, at the narrow bulboventricular foramen.
ventricular foramen. The pulmonary-to-systemic blood flow ratio was 2.0±0.5.

EDV of the ventricle was in the range of 174–570% of normal, averaging 291±111%. The patient (patient 1) with severe subaortic stenosis had the largest EDV. EF was in the range of 0.47±0.68, with an average of 0.59±0.07. Ventricular muscle mass was in the range of 158–355% of normal. The ratio of the mass to the volume was in the range of 0.62–0.96 when the “percentages-of-normal” data were used, and was in the range of 0.82–1.44 when we used values of EDV in milliliters and mass in grams (Figure 2).

Postoperative Findings of Cardiac Catheterization and Cineangiography

Systolic pressure of the RV was in the range of 29–75 mm Hg, which was lower than the pressure of the LV in each patient. Diastolic pressure was higher in the RV than in the LV throughout diastole in eight patients (Figure 3) in whom end-diastolic pressure (EDP) of the RV was equal to or higher than the pressure of the LV; however, it was higher for the LV than the RV in the remaining two patients. Mean right atrial pressure averaged 12±2 mm Hg. Cardiac index, determined by the thermodilution method, was 3.9±1.2 l/min/m², and it was 2.4 and 2.6 l/min/m², the lowest among the subjects, in the two patients (patients 7 and 8) whose EDP of the LV was higher than that of the RV (Table 3). EDV of the RV averaged 82±24% of normal, which was smaller than that of the LV in each patient, and the latter averaged 153±41% of normal. The ratio of absolute EDV value of the RV to the LV averaged 35:65 (the RV was 35±6%), and the ratio of EDVs of

FIGURE 2. Plotting showing preoperative ventricular volume data. The largest EDV is of the patient (patient 1) with severe bulboventricular obstruction. EDV, end-diastolic volume; EF, ejection fraction; M, ventricular mass; % normal, % of expected normal (see text).

FIGURE 3. Simultaneous recording of ventricular pressure of RV and LV. Pressure is higher in the RV throughout diastole than in the LV in eight patients who had relatively good cardiac output. RV, right-sided ventricle; LV, left-sided ventricle.
Echocardiographic Findings After Septation

Fractional shortening of the transverse axis (A1) was 0.27±0.13 for the RV and 0.25±0.08 for the LV, and the fractional shortening of the short axis (A2) was 0.51±0.17 and -0.05±0.09, respectively (Figure 5).

The fractional change of the cross-sectional area was 0.65±0.16 in the RV, which was significantly higher than 0.23±0.11 in the LV (Figure 5). The deviation ratio was higher at end systole than at end diastole in each patient (Figure 6). This ratio averaged 0.29±0.11 at end systole and 0.03±0.12 at end diastole in the short-axis view, and 0.19±0.09 and -0.06±0.07, respectively, in the apical four-chamber view.

The two patients (patients 7 and 8) with higher EDP of the LV than of the RV had low fractional change of the area and the A2 axis of the RV, as indicated by the open circles in Figure 5. In these patients, the deviation ratio was positive throughout a cardiac cycle in both views (Figure 6). These two patients had the lowest cardiac index among the subjects, as previously stated.

FIGURE 5. Plotting showing fractional changes of the axes and area in 2DE. Fractional shortening of A1 axes of both ventricles was similar; however, fractional shortening of A2 of the LV was negative as a whole and significantly lower than the fractional shortening of the RV. Fractional change of area of the LV was significantly lower than the fractional change of the RV. The open circle indicates that end-diastolic pressure of the LV was higher than end-diastolic pressure of the RV in these patients. Note these two patients had low fractional change of the area of the RV, A1, longest ventricular axes; A2, septoventricular free wall axes; LV, left-sided ventricle; RV, right-sided ventricle.

TABLE 3. Hemodynamic Data in Patients After Septation

<table>
<thead>
<tr>
<th>Patients</th>
<th>LV peak/EDP pressure (mm Hg)</th>
<th>RV peak/EDP pressure (mm Hg)</th>
<th>RAP (mm Hg)</th>
<th>Cardiac index (l/min/m²)</th>
<th>Remarks</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>112/10</td>
<td>32/13</td>
<td>13</td>
<td>3.3</td>
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<td>64/15</td>
<td>9</td>
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<td>PH</td>
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<tr>
<td>8</td>
<td>95/16</td>
<td>33/14</td>
<td>12</td>
<td>2.4</td>
<td>Qp/Qs=2</td>
</tr>
<tr>
<td>9</td>
<td>90/8</td>
<td>29/8</td>
<td>12</td>
<td>3.5</td>
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<tr>
<td>10</td>
<td>96/8</td>
<td>75/11</td>
<td>8</td>
<td>4.5</td>
<td>PH</td>
</tr>
</tbody>
</table>

LV, left-sided ventricular; RV, right-sided ventricular; RAP, mean right atrial pressure; EDP, end-diastolic pressure; PH, pulmonary hypertension; Qp/Qs, pulmonary-to-systemic blood flow ratio of residual shunt.

FIGURE 4. Plotting showing postoperative ventricular volume characteristics. End-diastolic volume was larger and ejection fraction was lower for the LV than for the RV in each patient. LV, left-sided ventricle; RV, right-sided ventricle.

only the main ventricular portion, excluding the rudimentary chamber, was 41:59 (the RV was 41±10%). EF of the RV was 0.77±0.10, which was higher than that of the LV, with an average of 0.49±0.13 in each patient (Figure 4). The patient who had LVEF of 0.74 had residual ventricular shunt with a pulmonary-to-systemic flow ratio of 2.0. Four patients who had the lowest EF of the RV among the subjects warrant further elaboration. Two patients (patients 7 and 6) with EF of 0.58 and 0.72, respectively, were those patients whose EDP of the LV was higher than the EDP of the RV – one patient (patient 1) with 0.67 had the largest preoperative EDV, and the other patient (patient 6) with 0.70 was on a pacemaker. Stroke volume was 30±10 ml/m² for the RV and 31±14 ml/m² for the LV, excluding the one patient with a residual shunt.

End-diastolic pressure was significantly higher in the RV than in the LV (Figure 4). The mean pressure was 0.51±0.17 and 0.49±0.13, respectively, for the LV and RV. The end-diastolic pressure was significantly higher in the RV than in the LV (Figure 4).
Follow-up Study

No patient died during the follow-up period, and none has required additional surgery. Two patients are on diuretics and vasodilators; one patient (patient 1) had had severe narrowing of the bulboventricular foramen, and the other patient (patient 2) had been the youngest patient; however, the patients' parents and the patients, themselves, do not notice any difficulty in their physical activity at their ages of 7 and 4 years, respectively. Two of the other eight patients are in New York Heart Association class II, and the remaining six are in class I. Cardiopulmonary ratio on chest reoncogram was in the range of 0.55 to 0.73, with an average of 0.61 ± 0.06.

Discussion

The postoperative data revealed that hemodynamics at rest after septation were satisfactory. Cardiac output was normal in the majority of the subjects although filling pressure of the RV and right atrial pressure were higher than normal. We have previously reported that in patients after Fontan procedure, the other surgical choice for DILV, cardiac output averaged 2.97 l/min/m² at a right atrial pressure of 15 ± 3 mm Hg.11 This difference indicates the superiority of septation over Fontan procedure although the final conclusion should be reached only after a long-term follow-up study.

It should be noted that the volume measurement in the present study had some drawbacks. The morphology of the new RV and LV was obviously different from normal, and we compared EDVs of the new ventricles with expected normal values obtained from subjects with normal ventricular morphology. The basic concept using this computation was that certain standardization must be adopted to compare the size of ventricles among patients of greatly differing body size and to know, regardless of precision, how volume characteristics deviate from normal because of the presence of a noncontractile ventricular septum. Yet, the most conspicuous finding of the present study was an imbalance of EDVs with the RV:LV ratio of 35:65, which was compensated for by the differences in EF, resulting in an identical stroke volume in both ventricles. The low and high EF of the LV and the RV, respectively, resulted from a paradoxical movement of the interventricular septum.4,12

During diastole, the noncontractile interventricular septum shifted toward the LV side, obviously the result of pressure difference between the two ventricles. The two patients whose filling pressure of the LV was higher than right-side pressure did not have the diastolic leftward shift as presented in the echocardiographic study (Figure 5). This “nonparadoxical” motion should have been advantageous to the pump function of the LV but obviously was not advantageous for the total hemodynamics because these two patients had the lowest cardiac outputs among the subjects, together with low fractional change of the cross-sectional area of the RV. Thus, we considered that the diastolic leftward movement of the septum is crucial for “earning” of diastolic volume of the RV. The importance of this action was also suggested by the fact that the only patient who died during the series had had an excessive ventricular hypertrophy with the mass:volume ratio (g/ml) of 3.7. We have speculated that the low compliance of the ventricle13 caused high filling pressure of the LV after septation, which restrained the diastolic leftward septal movement, thus resulting in circulatory failure. Barber et al14 showed that ventricular wall thickness determined on the echocardiogram was thicker in nonsurvivors of corrective surgery for DILV than in survivors. They included three patients who underwent ventricular septation although details were not presented.

During systole, the septum shifted toward the RV. This finding had already been shown by echocardiographic studies.3–5 This paradoxical motion of the septum obviously reduces pump function of the LV, as evidenced by its low EF,12 but augments pump function of the RV, as shown by its high EF.4,12 Thus, the paradoxical septal movement is an essential factor for systolic function of the RV and also to equalize stroke volume of the two ventricles with different EDVs. The most important factor in producing this shift of the septum is, again, the pressure difference between the two ventricles. As a matter of fact, it has been known that pulmonary stenosis and pulmonary hypertension are risk factors of this procedure1 because they could cause right ventricular hypertension after septation. In the present study, three patients had pulmonary hypertension that persisted after operation; however, the pulmonary artery pressure was below the systemic level (Table 3). This indicates that pulmonary hypertension is not an absolute contraindication to this procedure if it is expected that the pulmonary pressure will decline below the systemic pressure after septation. In this regard, we emphasize the importance of measuring

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**Figure 6.** Plotting showing cyclic change in curvature of the septum. S/L ratio (see text) was higher at end systole (●) than at end diastole (○) in each patient. Patients 7 and 8 had higher end-diastolic pressure of the LV than of the RV, and patient 9 had end-diastolic pressures in the two ventricles that were equal.
pulmonary vascular resistance and evaluating reversibility with the trazolene test when resistance is high. We are not able to establish from this study the safety limit of pulmonary vascular resistance for septation; however, we expect it to be similar to the evaluation of pulmonary hypertension associated with large left-to-right shunt disease, such as ventricular septal defect.

These facts indicate the importance of dividing the single ventricle unevenly. Shimazaki et al. found that the right-to-left EDV ratio was 3:4 to 2:3 after septation for type C single ventricle. McGoon et al. also stated that there seemed to be variably smaller cavity volume for the right-sided ventricular chamber than for the left-sided chamber in most patients after the septation procedure although they recommended that partitioning should be done by placing the septum as far to the left side as possible, citing the experimental studies of Seki et al. in dogs, which showed that the single ventricle should be divided into two equal-sized chambers. Their subsequent theoretical consideration suggested that a prosthetic septum should be constructed not on the midline but further left to the midpoint by 8% of the total circumferential length of the heart. Their study was, however, based on a condition in which the heart has two (right and left) structurally separate ventricles with no interventricular septum, which is markedly different from DILV; they also did not consider the diastolic dynamics of the septum. Our data suggest that the single ventricle should be divided unevenly with the RV:LV EDV ratio being approximately 4:6. Additionally, because the insertion of a noncontractile prosthesis as a part of the ventricular wall should compromise pump function of the LV, EDV must be larger than normal to maintain normal cardiac output. This was the case in the present study as the normal cardiac output resulted from the large EDV in the presence of a low EF.

We conclude that good postoperative hemodynamics will result from septation by dividing the main ventricle unevenly to produce the right-to-left chamber size ratio of 4:6, and that septation is not recommended in patients in which the paradoxical septal motion will be restrained by residual right ventricular hypertension or excessive ventricular hypertrophy.

Acknowledgments

We are grateful to Barbara Levine and Esther Eshkol for their editorial assistance with this manuscript.

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KEY WORDS • ventricle, single • septation operation • ventricular function • ventricular septum
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Circulation. 1990;81:1537-1543
doi: 10.1161/01.CIR.81.5.1537

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