Assessment of Ventricular Contractile State and Function in Patients With Univentricular Heart

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To elucidate the ventricular contractile state and function in patients with univentricular heart, the ventricular volume, mass, ejection phase index, and wall stress were evaluated with biplane ventriculography and pressure measurement in 41 patients: 18 with left ventricular (LV) type (age, 6.4±6.1 years) and 23 with right ventricular (RV) type (age, 5.7±4.1 years), and data from patients with univentricular heart were compared with data from 19 normal control subjects (age, 7.2±4.3 years). Although the end-diastolic and end-systolic volumes were significantly greater in both types of univentricular heart than in the normal control group, the volumes for the LV and RV type patients did not differ from each other. The ejection fraction (EF) was depressed in both patient types of univentricular heart and was significantly (p<0.005) lower in the RV type than in the LV type patients (0.56±0.05 for LV type, 0.50±0.07 for RV type, and 0.64±0.03 for the control group). The ventricular mass was larger in both patient types of univentricular heart than in that of the control group, whereas the ratio of ventricular mass to end-diastolic volume was significantly (p<0.001) lower in the RV type patients than in the LV type patients and the control group (0.79±0.18 g/ml for LV type, 0.51±0.10 for RV type, and 0.82±0.13 for control group). End-systolic stress was significantly elevated in both types of univentricular heart (241±45 for LV type, 328±52 for RV type, and 205±26 kdynes/cm² for the control group) and significantly (p<0.001) greater in the RV type than in the LV type patients. There was a significant inverse correlation (p<0.001) between end-systolic stress and the ratio of mass to end-diastolic volume in all the patients. In 27 patients (12 patients for LV type, 15 for RV type) the mean normalized systolic ejection rate corrected for heart rate (MNSERc) clearly fell below the 95% confidence limit of the normal end-systolic stress–MNSERc relation. The end-systolic stress–end-systolic volume ratio was also significantly depressed in both patient types of univentricular heart (3.49±1.77 for LV type, 4.07±2.13 for RV type, and 7.20±1.32 for the control group). In these variables, however, there were no significant differences between LV and RV type patients of univentricular heart. Thus, despite the absence of significant difference either in preload or myocardial contractile function between LV and RV type patients, afterload was significantly increased in RV type patients compared with LV type patients. Therefore, impaired ejection performance in RV type compared with that in LV type patients may be responsible for afterload mismatch caused by inadequate ventricular hypertrophy rather than by myocardial contractile dysfunction. (Circulation 1989;79:1247–1256)

Patients with univentricular heart have various potential problems relating to abnormal ventricular function before and after surgical interventions. These include chronic volume overload, chronic hypoxemia, anatomic derangement, and perioperative myocardial damage. Ventricular dysfunction may be one of the major determinants of the prognosis in patients with this defect.1–5 It is, therefore, important to assess the ventricular function accurately to manage each patient adequately before irreversible ventricular dysfunction develops. There have been many reports regarding ventricular function in patients with univentricular heart with or without surgical treatments.6–11 These studies, however, have been limited mainly to evaluating variables related to pump function that are dependent on loading conditions. Therefore, similar to chronic aortic or mitral regurgitations in adults, assessment of the contractile state by considering...
end-systolic stress and by estimating the myocardial function by using the relation between end-systolic stress and either ejection phase indexes or end-systolic volume may be important.

We have shown the presence of inadequate ventricular hypertrophy in response to volume load in patients with right ventricular (RV) type of univentricular heart compared with that in patients with left ventricular (LV) type. We hypothesize that inadequate hypertrophy of the myocardium results in afterload mismatch, which is the major determinant of depressed pump function in this subset of univentricular heart. In this study, therefore, the ventricular volume, mass, ejection phase index, and wall stress were evaluated in patients with univentricular heart by comparing these with normal values obtained by cineangiography and pressure measurement. The contractile state and function were thereby elucidated in patients with univentricular heart.

Methods

Patients

Forty-one children with univentricular heart were investigated in this study. The diagnosis of univentricular heart was confirmed by cineangiograms and cross-sectional echocardiograms. Ventricular type of univentricular heart was determined by the trabecular pattern of the main and rudimentary chamber and the position of the rudimentary chamber. Of 41 patients, 37 had a rudimentary chamber clearly shown on angiograms or echocardiograms. In these patients, the position and trabecular pattern of the rudimentary chamber enable the ventricular type to be determined. Sixteen patients had the LV type of univentricular heart with a rudimentary RV anteriorly, whereas 21 were the RV type with a rudimentary LV posteriorly. In the remaining four patients, two had a main LV chamber characterized by a smooth trabecular architecture similar to the other 16 patients with the LV type of univentricular heart, and two had a main RV chamber characterized by a rough trabeculation. The latter two patients were confirmed to have the RV type of univentricular heart at later open-heart surgeries. Consequently, 18 patients had the LV type of univentricular heart, and 23 had the RV type. No patients with indeterminate type or common ventricular type of univentricular heart were included in this study. In addition, all cineangiograms were reexamined to classify the main ventricle as LV or RV type on a blinded basis by two pediatric cardiologists (T.M. and F.K.) not involved in this study. The ventricular types classified by the two observers completely agreed with our classification in all patients.

The anatomic findings and previous surgical treatments are summarized in Table 1. Two atrioventricular valves were more common in patients with the LV type than with the RV type of univentricular heart (72% vs. 13%), whereas a common atrioventricular valve was more frequent in patients with the RV type than in the LV type (65% vs. 28%). All but six patients with LV type had varying degrees of pulmonary outflow obstruction. Fifty-six percent of the patients with LV type and 57% of those with RV type had undergone surgical procedures to regulate pulmonary blood flow such as systemic-to-pulmonary shunt operation or pulmonary artery banding. No patients with significant atrioventricular valvular regurgitation on the ventriculogram were included in this study so that ventricular function could be compared in the two groups under similar hemodynamic and volume-overload conditions. Fourteen patients with splenic syndrome (two with the LV type and 12 with the RV type) were included in the study. Two with the LV type and 10 with the RV type were asplenia, and two with the RV type were polysplenia.

A comparison of the basic clinical and hemodynamic data in the groups is shown in Table 2. The age at the time of investigation ranged from 2 days to 18 years in the LV type and from 3 months to 15 years in the RV type patients. Hypoxemia and polycythemia were found in both LV and RV type patients. There were no significant differences between the groups in age, hemoglobin concentration, systemic oxygen saturation, ventricular pressure, or pulmonary to systemic blood flow ratio.

The normal control group included 19 infants and children who underwent cardiac catheterization to rule out congenital heart defects including atrial septal defect, patent ductus arteriosus, and aortic stenosis in 18 with a heart murmur or abnormal results on the electrocardiogram (incomplete right bundle branch block) and to rule out coronary artery disease in one patient with atypical chest.

### Table 1. Cardiac Anatomy and Previous Palliations

<table>
<thead>
<tr>
<th>Main ventricular chamber (n)</th>
<th>AV valves</th>
<th>Pulmonary outflow</th>
<th>Palliations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Common</td>
<td>Double inlet</td>
<td>AV valve atresia</td>
</tr>
<tr>
<td>LV type (18)</td>
<td>5</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>(28%)</td>
<td>(72%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RV type (23)</td>
<td>15</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>(65%)</td>
<td>(13%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

AV, atrioventricular; S-P shunt, systemic-to-pulmonary shunt; PAB, pulmonary artery banding; LV, left ventricular; RV, right ventricular.
Table 2. Clinical and Hemodynamic Data

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (yr)</th>
<th>Hb (g/dl)</th>
<th>SaO₂ (%)</th>
<th>Qp/Qs</th>
<th>VPSP (mm Hg)</th>
<th>VEDP (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV type</td>
<td>6.4±6.1</td>
<td>15.4±4.1*</td>
<td>81±6*</td>
<td>1.16±0.46</td>
<td>103±18</td>
<td>8±3</td>
</tr>
<tr>
<td>RV type</td>
<td>5.7±4.1</td>
<td>16.3±2.1*</td>
<td>77±9*</td>
<td>0.85±0.40</td>
<td>105±16</td>
<td>7±3</td>
</tr>
<tr>
<td>Control</td>
<td>7.2±4.3</td>
<td>11.9±1.2</td>
<td>94±2</td>
<td>ND</td>
<td>109±19</td>
<td>6±2</td>
</tr>
</tbody>
</table>

Hb, hemoglobin concentrations; SaO₂, systemic oxygen saturation; Qp/Qs, pulmonary-to-systemic flow ratio; VPSP, ventricular peak systolic pressure; VEDP, ventricular end-diastolic pressure; LV, left ventricular; RV, right ventricular; ND, not done.

*p<0.001 vs. control.

pain. Echocardiographic investigation was not available for 12 children before 1982, and seven others were not able to be diagnosed by this noninvasive device. Informed consent to permit catheterization was obtained for each patient. All children in the control group were thus found to have no cardiac abnormalities, normal blood pressure, and a left ventricular ejection fraction of 0.60 or greater. The age at the time of the investigation ranged from 3 months to 13 years, with a mean age of 7.2±4.3 years (mean±SD).

Cardiac Catheterization and Ventriculography

All patients underwent cardiac catheterization and biplane 35-mm cineangiography (PolyDiagnost C system, Philips, Eindhoven, Netherlands) under mild sedation (pethidine hydrochloride and hydroxyzine). Mild anesthesia was introduced with a single administration of ketamine chloride (1 mg/kg i.m.) in 17 patients or with a single administration of thiopental sodium (1 mg/kg i.v.) in 14 patients. Pressure measurement and ventriculography were performed under stable hemodynamic conditions at least 90 minutes after anesthesia. Aortic and ventricular pressures were recorded just before ventriculography through a well-flushed fluid-filled catheter connected to a Statham strain gauge (P23Db or P23ID, Cleveland, Ohio). After pressure measurement and oxymetry were performed, ventriculograms were filmed in the posteroanterior and lateral projections at 60 or 90 frames/sec after injection of contrast medium (diatrizoate 76%, at 1.0–1.2 ml/kg) into the main ventricular chamber. Immediately after the ventriculogram was obtained, a steel sphere 30 mm in diameter was filmed, for calibration purposes, at the spatial location that the ventricle had occupied.

Measurements and Calculations

The border of the ventricular cavity in both projections was traced manually at end diastole and end systole during the sinus rhythm on the recorded selective ventriculogram (Figure 1). The largest ventricular projection was assumed to represent end diastole, and the smallest was assumed to represent end systole. Ventricular volumes were

Figure 1. Posteroanterior angiogram from a patient with right ventricular type of univentricular heart, illustrating the ventricular cavity border (dotted line) and the ventricular wall (arrow) used to calculate the ventricular volume, mass, and wall stress.
calculated from the posteroanterior and lateral projections using the area-length method with calibration for radiographic magnification with the steel sphere 30 mm in diameter. No regression equation was applied to either the univentricular heart or the normal left ventricle. The ventricular volume was expressed as the indexed value for the body surface area.

Ejection fraction (EF) and mean normalized systolic ejection rate corrected for heart rate (MNSERc) were then calculated as ejection phase indexes. MNSERc was computed as MNSERc=EF/ETc, where ETc is ejection time corrected for heart rate, which was obtained after ventricular ejection time was rate-corrected to a heart rate of 60 beats/min by dividing by the square root of the RR interval. Both ventricular ejection time and RR interval were measured from the number of frames on the ventriculogram.

Ventricular wall thickness was calculated as the average of 30–50 wall thickness measurements of the middle third of the lateral ventricular free wall at end diastole (Figure 1). The ventricular mass was calculated by the following formula12,15:

$$\text{VMV} = \frac{4}{3} \pi \left( \frac{d}{2} + h \right) \times \frac{d l}{2} \times \frac{1}{2} + h \times \left( \frac{l}{2} + h \right) - \frac{4}{3} \pi \frac{d}{2} \times \frac{d l}{2} \times \frac{1}{2} \times \frac{1}{2}$$

where da is transverse diameter calculated from the posteroanterior projection, dl is transverse diameter calculated from the lateral projection, h is end-diastolic wall thickness, l is maximum length of the long axis whether on the posteroanterior or lateral projection, and VMV is ventricular mass volume.

The ventricular mass volume was converted to the ventricular mass by multiplying the volume by the specific gravity of the heart muscle (1.05). The ventricular mass was expressed as the ventricular mass index corrected for the body surface area and the ratio of ventricular mass to end-diastolic volume.

End-systolic circumferential wall stress (ESS) was calculated by Mirsky’s formula16 and expressed as kilodynes per square centimeter:

$$\text{ESS} = \frac{P_b}{H} \left( 1 - \frac{H}{2b} - \frac{b^2}{2a^2} + \frac{H^2}{8a^2} \right)$$

where a and b are ventricular midwall semimajor and semiminor axes at end systole, H is end-systolic wall thickness, and P is ventricular systolic pressure.

ESS was expressed as kilodynes per square centimeter by multiplying it by 1.332 kdynes/cm² per mm Hg. The end-systolic wall thickness was calculated by Hugenholtz’s method,17 which assumes that ventricular mass remains constant during the cardiac cycle. In this study, the ventricular peak systolic pressure was substituted for the end-systolic pressure.

End-diastolic circumferential wall stress was calculated by the same formula, where a and b are ventricular midwall semimajor and semiminor axes at end diastole, H is end-diastolic wall thickness, and P is end-diastolic ventricular pressure.

These measurements and calculations were processed with a digitizer (PC-8875, NEC, Tokyo, Japan) connected to a computer (PC-9801, NEC).

**Statistical Analysis**

All data are expressed as the mean±SD. Statistically significant differences in the ventricular function data among the three groups were determined by one-way analysis of variance (ANOVA), followed by a Newman-Keuls test if the ANOVA probability (p) value was less than 0.05. Linear regression analysis, when performed, was calculated by the least-squares method. Fisher’s exact test or the χ² test, when applicable, was used for nonparametric data comparisons.

**Results**

**Ventricular Volume and Mass**

The ventricular volume and mass variables for the subjects in each group are listed in Table 3. The end-diastolic and end-systolic volume indexes in the LV and RV type patients were much greater than those in the normal control group (p<0.001) but were not different from each other. The ejection fraction varied widely within the LV type (0.46–0.63) and RV type patients (0.37–0.62) but was significantly depressed in both univentricular heart groups compared with the normal control group (p<0.001). The EF was significantly lower in RV type than in LV type patients (p<0.005). The patients with RV type had a significantly lower value of ventricular mass index than those with LV type (p<0.001), although both types had a significantly increased index compared with the normal control group (p<0.001 for control vs. LV type,

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**Table 3. Ventricular Volume and Mass Data**

<table>
<thead>
<tr>
<th>Group</th>
<th>EDVI (ml/m²)</th>
<th>ESVI (ml/m²)</th>
<th>EF</th>
<th>VMI (g/m²)</th>
<th>VM/EDV (g/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV type</td>
<td>180±60**</td>
<td>79±28**</td>
<td>0.56±0.05**</td>
<td>139±42**</td>
<td>0.79±0.18</td>
</tr>
<tr>
<td>RV type</td>
<td>191±63**</td>
<td>95±35**</td>
<td>0.50±0.07**</td>
<td>99±36*</td>
<td>0.51±0.10**</td>
</tr>
<tr>
<td>Control</td>
<td>79±17</td>
<td>28±5</td>
<td>0.64±0.03</td>
<td>65±20</td>
<td>0.82±0.13</td>
</tr>
</tbody>
</table>

EDVI, end-diastolic volume index; ESVI, end-systolic volume index; EF, ejection fraction; VMI, ventricular mass index; VM/EDV, ventricular mass/end-diastolic volume ratio.

*p<0.005 vs. control, **p<0.001 vs. control; tLV type vs. RV type.

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and \( p<0.005 \) for control vs. RV type). The ratio of ventricular mass to end-diastolic volume in the RV type patients was significantly lower than in the LV type \( (p<0.001) \) and in the normal control group \( (p<0.001) \), whereas there was no significant difference in this index between the LV type and the normal control group.

**Ventricular Wall Stress**

Figure 2 illustrates the circumferential end-systolic and end-diastolic stress for the three groups. End-systolic stress ranged from 176 to 362 kdynes/cm\(^2\) \((241 \pm 45 \text{ kdynes/cm}^2)\) in the LV type patients and ranged from 236 to 416 kdynes/cm\(^2\) \((328 \pm 52 \text{ kdynes/cm}^2)\) in the RV type patients. Both values were significantly greater than the normal control value \((205 \pm 26 \text{ kdynes/cm}^2)\); \(p<0.025\) for control vs. LV type, and \(p<0.001\) for control vs. RV type. In addition, end-systolic stress in the RV type was significantly greater than in the LV type \( (p<0.001) \).

End-diastolic stress ranged from 6 to 58 kdynes/cm\(^2\) \((35 \pm 14 \text{ kdynes/cm}^2)\) in the LV type and from 10 to 69 kdynes/cm\(^2\) \((42 \pm 16 \text{ kdynes/cm}^2)\) in the RV type. Both values were significantly greater than the normal control value \((26 \pm 10 \text{ kdynes/cm}^2)\); \(p<0.05\) for control vs. LV type, and \(p<0.005\) for control vs. RV type, but they did not differ from each other.

A significant inverse correlation was observed between end-systolic stress and the ratio of ventricular mass to end-diastolic volume in all the patients with univentricular heart \((r=0.84, p<0.001)\), indicating a characteristic increase in end-systolic stress with a decrease in the ratio of ventricular mass to end-diastolic volume (Figure 3).

**Ventricular Contractile Function**

A significant inverse correlation between end-systolic stress and ejection fraction was present in all three groups: LV type, \(E_F=0.76-0.00080\text{ESS} \ (r=-0.68, p<0.002)\); RV type, \(E_F=0.80-0.00091\text{ESS} \ (r=-0.68, p<0.001)\); and normal control group,

\[E_F=0.87-0.0011\text{ESS} \ (r=-0.81, p<0.001)\]. There were no significant differences in the slopes of the regressions among the three groups by analysis of covariance (Figure 4).

As shown in the bottom panel of Figure 4, in 12 patients with univentricular heart \((29\%)\) the ejection fraction value clearly fell below the 95% confidence limit band of the end-systolic stress and ejection fraction relation of the normal controls. Those 12 patients included seven of 18 with LV type \((39\%)\) and five of 23 with RV type \((22\%)\), respectively. Although disproportionate impairment of ejection fraction in relation to end-systolic stress tended to be more frequent in LV type than in RV type patients, the difference was not statistically significant by nonparametric tests.

A significant inverse correlation between end-systolic stress and MNSERc was also found in all three groups: LV type, \(\text{MNSERc}=2.8-0.0035\text{ESS} \ (r=-0.82, p<0.001)\); RV type, \(\text{MNSERc}=2.7-0.0036\text{ESS} \ (r=-0.74, p<0.001)\); and normal control group, \(\text{MNSERc}=2.8-0.0026\text{ESS} \ (r=-0.55, p<0.02)\). The elevations of the regression lines were significantly \((p<0.05)\) lower in both univentricular heart groups than in the normal control group but did not differ from each other by analysis of covariance (Figure 5).

As shown in the bottom panel of Figure 5, in 27 patients \((12\text{ with LV type, 15 with RV type})\), the MNSERc value clearly fell below the 95% confidence limit band of the ESS=MNSERc relation of the normal controls with an incidence of 66% as a whole group. The incidence of the disproportionate impairment of MNSERc in relation to end-systolic stress was 67% in LV type and 65% in RV type patients. There was no significant difference in the
incidence of this abnormal MNSERc in the two groups of patients with univentricular heart.

Figure 6 illustrates the ratio of end-systolic stress to the end-systolic volume index (ESS/ESVI), which is another index for estimation of myocardial inotropic state, in the patients with univentricular heart and the normal control subjects. ESS/ESVI ranged from 1.58 to 9.57 (3.49±1.77) in LV type and from 1.92 to 11.0 (4.07±2.13) in RV type patients. Those values in both types of patients with univentricular heart were significantly (p<0.001) lower than ESS/ESVI in the normal control group (7.20±1.32), but values for LV and RV type patients did not significantly differ from each other.

In an attempt to determine which factors contributed to an observed low ESS/ESVI, analyses of subgroups divided arbitrarily by various factors such as age, preload, or cyanosis were performed. When the patients were arbitrarily divided into 26 patients under 8 years old (mean, 3.3 years) and into 15 patients over 8 years old (mean, 12.9 years), the ESS/ESVI ratio did not significantly differ between the subgroups (<8 years, 4.00±2.30; and >8 years, 3.48±1.27). There was also no significant difference in the ESS/ESVI ratio between 16 patients whose systemic oxygen saturation was under 80% (mean, 74%) and in 25 patients with over 80% (mean, 84%) (3.54±1.50 and 3.44±1.27, respectively). However, the ESS/ESVI ratio was significantly (p<0.05) lower in 14 patients whose end-diastolic volume index was greater than 200 ml/m² (mean, 248 ml/m²) than in 27 patients with less than 200 ml/m² (mean, 154 ml/m²) (2.54±0.49 and 4.47±2.15, respectively).

**Discussion**

Although many reports of ventricular pump dysfunction in patients with univentricular heart have been presented, there are no reports on estimation of afterload or ventricular contractile function in patients with this defect. The most important findings in our study were the significant increase in ventricular systolic wall stress in patients with...
univentricular heart, particularly in those with the RV type, and an insignificant difference in the preload or the extent of myocardial contractile dysfunction between the two types of univentricular heart. Ventricular pump performance is determined by the interaction among preload, afterload, and myocardial contractility. The preload did not differ between patients with the LV and RV type of univentricular heart because of insignificant differences in the pulmonary to systemic flow ratio, the end-diastolic volume, and the end-diastolic wall stress between the two types. On the other hand, despite ventricular hypertrophy in both LV and RV type patients, end-systolic stress increased more than the mean+2 SD value in the normal control group (250 kdynes/cm²) in one third of the patients with LV type and in most of those with RV type. These data show that ventricular hypertrophy is insufficient to maintain normal wall stress, that is, "afterload mismatch," in those patients with univentricular heart. In addition, the more severe the degree of insufficient hypertrophy to ventricular volume was, the more the afterload increased, and afterload mismatch was found much more frequently in patients with the RV type univentricular heart than in those with the LV type.

The relation between end-systolic stress and either ejection phase indexes or end-systolic volume has been used to estimate myocardial contractility of the left ventricle under chronic pressure or volume overload in both adults with valvular heart diseases19–22 and children with congenital heart defects.23–25 There was no significant difference in ESS/ESVI ratio or the frequency of patients with a disproportionately lower ejection fraction or MNSERc than the predicted value from the normal relations. Myocardial contractile function, therefore, may not differ between the LV and RV type patients. Ejection performance was depressed in the RV type patients compared with that in the LV type patients, and this difference in the extent of pump dysfunction in the two types of univentricular heart may be responsible for the afterload mismatch caused by insufficient ventricular hypertrophy rather than myocardial contractile dysfunction.

Methodologic Limitations

There may be some controversial points in methodology concerning the accuracy of measurements of ventricular volumes and wall thickness in univentricular heart in this study, particularly of its validation. For validation of our method, we evaluated echocardiographic internal dimensions and wall thickness of the main ventricles in 18 patients from this study group (six with the LV type and 12 with the RV type) in whom clear short-axis view images were obtained by cross-sectional echocardiography, and we compared these to the data obtained by ventriculography. There was close correlation between the ventriculographic minor axis (y, mm) in posteroanterior projection and the echocardiographic transverse diameter (x, mm) on the short-axis view: \( y = 1.02x - 0.07, r = 0.97, \text{SEE} = 3.9 \text{ mm} \). Between the ventriculographic minor axis in lateral projection and the echocardiographic anteroposterior diameter, there was also significant linear correlation: \( y = 1.03x + 0.63, r = 0.98, \text{SEE} = 3.0 \text{ mm} \). Between the wall thickness data obtained by ventriculographic and echocardiographic examinations, there was also close correlation: \( y = 1.07x - 0.49, r = 0.99, \text{SEE} = 0.20 \text{ mm} \). In addition, there were no significant differences in correlations between the LV and RV types of univentricular heart in terms of these parameters.

Another point of controversy regarding methodology of measuring ventricular volumes is the necessity of applying regression equations. In this study, no regression equation was applied in ventricular volume calculations. It was mainly because of the lack of any reliable regression equation for univentricular heart measurement at the present time. There is as yet no generally approved quantitative correlation of the main chamber of each type of univentricular heart to the normal LV or RV regarding the ventricular geometry or trabecular structure. For example, the shape of the main chamber of a univentricular heart appears to be elliptical or spherical even in patients with the RV type and accordingly is quite different from the normal RV shape. The adoption of the basic equations used for normal LV or RV may be inappropriate in this situation. Therefore, it seems to be more reasonable to analyze the calculated volume data without regres-
sion equations rather than with the regression equations for normal LV or RV to avoid methodologic invalidity. The calculated volume data without regression equations seem to be at least comparable among the three groups. In other factors affecting the accuracy of our mass or stress data, dyskinetic wall motion of the ventricular chamber and extreme asymmetrical ventricular hypertrophy were not found in any cineangiograms or echocardiograms.

There may be small errors in our stress measurements attributable to the use of a fluid-filled catheter system, the use of peak systolic pressure instead of end-systolic pressure, and not simultaneously recording the pressure with ventriculography. As discussed by Taniguchi et al.\textsuperscript{26} and other investigators\textsuperscript{27,28} in previous studies of LV function in adults with valvular heart diseases, the method used here has sufficient validity. First, the difference in peak systolic pressure with a well-flushed fluid-filled catheter and micromanometer-tipped catheter is small,\textsuperscript{26} and the time delay in transmission of pressure through fluid-filled catheters has also been shown to be quite short (about 10 mm/sec).\textsuperscript{29} Second, our stress data may not be identical to end-systolic stress because peak systolic pressure was substituted for end-systolic pressure. Some investigators showed an absolute difference between peak and end-systolic pressures.\textsuperscript{30,31} However, under basal conditions without hemodynamic interventions, the difference may be constant over a large range of afterload conditions,\textsuperscript{30} and the results in this study comparing the groups may not be greatly influenced. Reichek et al.\textsuperscript{26} also showed a close correlation between the LV peak systolic and the end-systolic pressure (\(r=0.97\)), and in addition, Marsh et al.\textsuperscript{27} and Borow et al.\textsuperscript{30} found close correlations (\(r=0.99\) and \(r=0.95\), respectively) between the slope of the pressure and volume or dimension relation obtained with the peak systolic pressure and the slope obtained with the end-systolic pressure. We, therefore, concluded that the methods we used to measure the ventricular pressure introduced no serious error in the estimation of end-systolic wall stress. Despite some methodologic limitations and assumptions necessary for use of this technique, the end-systolic stress data in this study are believed to represent the true afterload of a univentricular heart.

Myocardial Contractile Function in Univentricular Heart

A significant incidence as high as 66% of depressed MNSERc relative to end-systolic stress along with a lower ESS/ESVI ratio indicates the existence of myocardial contractile dysfunction in both types of univentricular heart. On the contrary, the ESS-EF relation showed an incidence of depression as low as 29%. This difference may be partly due to the characteristics of ejection fraction as a partially preload-dependent index. All patients with univentricular heart had volume overload and were consequently under an increased preload condition. This increased preload may result in an increased ejection fraction and underestimation of contractile dysfunction. On the other hand, MNSERc is less a preload-dependent index than is ejection fraction as the rate-corrected velocity of shortening described by Colan et al.\textsuperscript{32} The ESS-MNSERc relation, thereby, seems to be more sensitive to distinguish depressed contractility than does the ESS-EF relation under volume-overloading conditions in patients with a univentricular heart.

There are many possible factors causing myocardial contractile dysfunction in patients with univentricular heart, including chronic hemodynamic volume overload, chronic hypoxemia with polycythemia (myocardial hypoxia or ischemia), perioperative myocardial damage after open-heart surgery, and chronic pressure overload in some cases associated with subaortic obstruction. It remains unclear which of the factors mentioned above are primarily responsible for this myocardial dysfunction in this study. In these factors, the influence of chronic volume overload on contractile function is still controversial.\textsuperscript{33,34} In this study, the ESS/ESVI ratio was significantly lower in patients with greatly increased end-diastolic volume (>200 ml/m\(^2\)) than in patients with moderate ventricular enlargement (<200 ml/m\(^2\)), suggesting that volume overload seems to be one of the major factors causing an impaired inotropic state in the univentricular heart. Thus, myocardial contractile dysfunction appears to be present in a significant number of patients with univentricular heart. Of particular interest in this study, however, was that no significant difference occurred in myocardial contractility between the two types of ventricular structures in univentricular heart.

Clinical Implications

In this study, it was shown that the pump function tends to be more impaired by the afterload mismatch in patients with the RV type univentricular heart than with the LV type defect. In previous studies, we showed that patients with the RV type of univentricular heart and with low ratio of ventricular mass to end-diastolic volume had an increased risk of late death due to congestive heart failure after a Blalock-Taussig shunt and an increased risk of perioperative death due to severely low cardiac output after a modified Fontan operation.\textsuperscript{3-5} These poor results of surgical treatment for the RV type of univentricular heart may be mainly related to the reduced reserve or poor adaptation of ventricular function due to the afterload mismatch that we revealed in this study. Application of systemic-to-pulmonary artery shunt operations has to be considered carefully for RV type patients with afterload mismatch, and when performed, volume overload or consequent increase of afterload should be minimized by such as a low-flow shunt or other surgical procedures. Although the survival rate of patients with RV type of univentricular heart with or without surgical interventions is still discou-
aging,35–37 our data of an insignificant difference in myocardial contractility between the LV and RV types shows that it may be possible to improve the long-term prognosis of the RV type of univentricular heart by effective afterload reduction therapy or a more definitive surgical procedure.

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References


KEY WORDS • ventricular wall stress • afterload mismatch • inadequate ventricular hypertrophy • myocardial contractile dysfunction
Assessment of ventricular contractile state and function in patients with univentricular heart.
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