Aortic Reservoir Function After Arterial Switch Operation in Elementary School-Aged Children

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Background After the arterial switch procedure, decreased distensibility of the aortic root has been reported, which means impaired aortic reservoir function of the coronary circulation, but there have been no reports regarding the relationship of this issue to myocardial perfusion. Therefore, in the present study the aortic reservoir function and coronary supply-demand balance were examined in patients after undergoing the arterial switch operation (ASO) around the time of entering elementary school.

Methods and Results Diastolic runoff (DR), which is the percentage of diastolic blood flow to total cardiac output, was measured as the index of aortic reservoir function. The subendocardial viability ratio was investigated as the index of coronary supply—demand balance. In the patient group, the aortic root was dilated (p<0.0001) and distensibility was impaired (p<0.0001) in comparison with an age-matched control group. However, there was no difference between the 2 groups in DR or subendocardial viability ratio.

Conclusions Coronary supply—demand balance was preserved in the pediatric ASO patients, despite the aortic root dysfunction. The preserved DR suggests that dilation of the aorta compensates for aortic reservoir function. Because large artery dysfunction predicts future cardiovascular diseases, careful follow-up is crucial. (Circ J 2008; 72: 1291–1295)

Key Words: Aortic root function; Arterial switch operation; Coronary blood flow; Subendocardial ischemia; Transposition of great arteries

The arterial switch operation (ASO) is recognized as the procedure of choice for treating children with transposition of the great arteries. Although the mid- and long-term outcomes of the procedure are excellent, some studies have demonstrated long-term postoperative problems, one of which is an abnormality of the aortic root. Specifically, dilated aortic roots with decreased distensibility after the ASO have been reported. Although a relationship between aortic root dilation and aortic regurgitation has been reported, there are no reports regarding the influence of the decreased distensibility of the aortic root.

Decreased distensibility of the aorta relates to decreased reservoir function of the aorta. The aorta serves predominantly as a cushioning reservoir of blood during systole, expelling it to the peripheral circulation during diastole. One of the most important organs to be supplied blood in diastole is the heart. Watanabe et al have reported that decreased aortic compliance increases the risk of subendocardial ischemia and recent studies have shown a relationship between aortic reservoir function and ischemic heart disease. However, there are no data regarding the hemo-dynamic influence on the coronary circulation by damaged distensibility of the aorta in patients after the ASO.

Recent nuclear studies have demonstrated that myocardial perfusion is not completely normal in some patients after the ASO. Although Oskarsson et al reported normal coronary flow velocity reserve in children after an ASO, using an intracoronary Doppler flow wire, Gagliardi et al, also using an intracoronary Doppler flow wire, found that coronary flow volume reserve was consequently reduced. We thus analyzed the aortic reservoir function and coronary supply—demand balance in pediatric patients after an ASO.

Methods

Subjects We enrolled 24 patients who had undergone an ASO for complete transposition or double outlet right ventricle with subpulmonary ventricular septal defect (16 males, 8 females; mean age: 6.5±1.1 years, range 5–9 years, height: 113.5±8.0 cm, 98.3–132.7 cm; weight: 20.4±4.8 kg, 16.0–33.9 kg; body surface area: 0.80±0.11 m², 0.65–1.07 m²). Seven patients underwent the operation with the 2-staged arterial switch method; namely, pulmonary artery banding with or without Blalock-Taussig shunt was performed before the ASO. The postoperative course was uneventful with no clinical signs of myocardial ischemia or electrocardiographic (ECG) changes at rest.

The control subjects were 1-to-1, age-matched patients with small left-to-right shunt disorders (10 patients with ventricular septal defect, 13 with atrial septal defect, 1 with partial anomalous pulmonary venous connection without...
atrial septal defect). Their pulmonary-to-systemic flow ratio was 1.4±0.3 (range 1.0–1.9). They were also asymptomatic and given no medication. There were no differences in height (115.3±8.7 cm), weight (21.1±4.4 kg) or body surface area (0.82±0.11 m²) compared with the patients after the ASO. All subjects gave written informed consent, and the study was approved by the institutional ethics committee.

Data Acquisition

Data were obtained from follow-up cardiac catheterization and angiographic investigations conducted around the time of the patients entering elementary school. The mean time interval between the ASO and the present study for all children was 6.1±1.4 years. After conventional right and left cardiac catheterization, including measurement of cardiac output by the thermodilution method, a pressure sensor mounted catheter (Millar, SPC-464D) was inserted from the femoral artery. The ascending aortic pressure waveform and the ECG were simultaneously recorded on a hard disk through an analog–digital converter. After pressure measurement, angiography of the left ventricle, right ventricle, pulmonary artery, ascending aorta and coronary arteries was performed.

Aortic Diameter Measurements

The aortic diameter was measured in the lateral view of the left ventriculogram (60 frames/s). In order to minimize the direct influence of contrast material injection on the hemodynamics, the measurements were made after 1 of the first 2 beats after the injection of contrast medium into the ventricles. The angiogram with the ventricular ectopic beat was not used. The measurements of aortic diameter were made at the sinus of Valsalva: the largest systolic and smallest diastolic diameters were measured.

Aortic distensibility was calculated using the following formula:

\[ 2 \times \frac{(D_s - D_d)}{D_d} \times \frac{(P_s - P_d)}{P_s} \]

where \(D_s\) = aortic systolic diameter, \(D_d\) = aortic diastolic diameter, \(P_s\) = aortic systolic pressure, and \(P_d\) = aortic diastolic pressure.

The use of this formula to estimate distensibility of vessels with thin walls in relation to lumen, such as the aorta, has already been reported.13,14

Subendocardial Viability Ratio (Fig 1)

The subendocardium is thought to be more sensitive to shortage of blood supply than the subepicardium. Buckberg et al demonstrated that the ratio of the diastolic phase area (diastolic pressure time index) to the area of the systolic phase (tension time index) in the central aortic pressure profile has a close correlation with the blood supply to the subendocardium.15,16 That ratio was designated as the subendocardial viability ratio:

Subendocardial viability ratio = diastolic pressure time index/tension time index.

The tension time index was obtained by measuring the area under the aortic systolic pressure curve, and it equals the mean aortic systolic pressure multiplied by the duration of systole. The diastolic pressure time index was obtained by measuring the area under the diastolic aortic pressure curve and subtracting from it the mean left atrial pressure (assumed to be equal to the left ventricular diastolic pressure) multiplied by the diastolic time. When the left atrial pressure was not recorded, we used the pulmonary capillary wedge pressure instead.

Diastolic Runoff (DR, Fig 2)

DR is defined as the portion of the stroke volume that is stored in the large arteries during systole and then flows into the small peripheral arteries during diastole by means of the elastic properties of arterial walls. When expressed as
Aortic Reservoir Function After ASO

Table 1 Hemodynamic Data

<table>
<thead>
<tr>
<th></th>
<th>ASO</th>
<th>Control</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBP (mmHg)</td>
<td>99.7±11.3</td>
<td>90.9±8.9</td>
<td>0.013</td>
</tr>
<tr>
<td>DBP (mmHg)</td>
<td>58.7±8.7</td>
<td>57.8±7.3</td>
<td>NS</td>
</tr>
<tr>
<td>MAP (mmHg)</td>
<td>78.2±9.8</td>
<td>75.2±8.0</td>
<td>NS</td>
</tr>
<tr>
<td>PP (mmHg)</td>
<td>40.9±6.1</td>
<td>33.1±5.3</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>SAC (ml/mmHg)</td>
<td>0.88±0.25</td>
<td>0.96±0.38</td>
<td>NS</td>
</tr>
<tr>
<td>LVEF (%)</td>
<td>63.2±5.0</td>
<td>68.0±6.9</td>
<td>NS</td>
</tr>
<tr>
<td>SV (ml)</td>
<td>42.0±9.6</td>
<td>36.7±8.8</td>
<td>NS</td>
</tr>
<tr>
<td>HR (beats/min)</td>
<td>87.3±11.8</td>
<td>91.2±14.4</td>
<td>NS</td>
</tr>
<tr>
<td>DT/RR</td>
<td>0.59±0.04</td>
<td>0.57±0.04</td>
<td>NS</td>
</tr>
</tbody>
</table>

Values are mean±SD. Abbreviation see in Table 1.

Table 2 Aortic Distensibility, Subendocardial Viability Ratio and Percent Diastolic Runoff

<table>
<thead>
<tr>
<th></th>
<th>ASO</th>
<th>Control</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aortic diameter (mm)</td>
<td>29.5±3.4</td>
<td>22.1±3.4</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Aortic distensibility (dynes/cm²)</td>
<td>1.7±0.8</td>
<td>8.1±2.0</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Tension time index</td>
<td>25.6±3.4</td>
<td>23.7±2.4</td>
<td>0.0089</td>
</tr>
<tr>
<td>Diastolic pressure time index</td>
<td>25.6±3.7</td>
<td>24.0±2.5</td>
<td>NS</td>
</tr>
<tr>
<td>Subendocardial viability ratio</td>
<td>99.7±14.6</td>
<td>101.4±19.4</td>
<td>NS</td>
</tr>
<tr>
<td>Diastolic runoff (%)</td>
<td>53.3±4.4</td>
<td>51.9±4.4</td>
<td>NS</td>
</tr>
</tbody>
</table>

Values are mean±SD. Abbreviation see in Table 1.

Fig 3. Relationship between the percentage of diastolic runoff and the subendocardial viability ratio in patients after the arterial switch operation (○) and in the control group (□).

diastolic runoff percentage (%)  

Discussion

Our findings indicate that the reservoir function of the

endocardial viability ratio. A p-value <0.05 was considered to be statistically significant.

Results

The left ventricular ejection fraction was 63.2±5.0% in the patients after the ASO; none demonstrated significant aortic regurgitation on aortography. In addition, none of the patients had any anatomical problems, such as stenosis or aneurysm of their coronary arteries on coronary angiography. The diastolic pressure waveforms were exponential curves in both the patients (mean r value: 0.9960) and the control subjects (mean r value: 0.9947). Table 1 shows the hemodynamic data. Systolic blood pressure (99.7±11.3 vs 90.9±8.9 mmHg; p=0.013) and pulse pressure (40.9±6.1 vs 33.1±5.3 mmHg; p<0.0001) were significantly higher in the patients than in the controls. Heart rate and diastolic time, which was corrected by the RR interval, showed no difference between the groups. In the patient group, the aortic diameter was significantly large (29.5±3.4 vs 22.1±3.4 mm; p<0.0001) and distensibility was low (1.7±0.8 vs 8.1±2.0 dynes/cm²; p<0.0001). There was no difference in the subendocardial viability ratio (97.3±19.0 vs 101.4±19.4%) or percentage of DR (52.9±5.0 vs 52.1±4.4%) between the groups (Table 2). The tension time index, which is the workload of the left ventricle, was significantly higher in the patient group (25.7±3.4 vs 23.7±2.4; p=0.0089). Fig 3 demonstrates the relationship between the percentage of DR and the subendocardial viability ratio in both groups. In each group, strong correlations were observed between these 2 parameters (patient group: r²=0.761, p<0.0001; control group: r²=0.915, p<0.0001). In addition, there was no difference between the groups in the relationship of these 2 parameters.

Our findings indicate that the reservoir function of the

Discussion

Our findings indicate that the reservoir function of the
aorta and the coronary supply—demand balance were pre-
erved in the patients after the ASO, despite their measur-
able aortic root dysfunction. The relationship between aortic
distensibility and coronary circulation has been shown and
Fig 3 demonstrates the strong correlation between the per-
centage of DR and the subendocardial viability ratio in this
study. Our result shows that diastolic blood, which is stored
in the aorta during systole, is 1 of the most important deter-
minants of coronary blood flow. Thus, decreased blood
storage in the aorta during systole accounts for impaired
corony circulation in patients with decreased aortic disten-
sibility. The reason why the aortic reservoir function was
maintained in the present patients may be that the aorta was
dilated. Although its distensibility is decreased, an expanded
aorta may be able to store enough blood during systole,
which resembles the compensation of a failing heart; that is,
although the left ventricular ejection fraction is decreased,
the increased left ventricular end-diastolic volume can main-
tain sufficient cardiac output. The dilated aorta may assist
in maintaining blood flow in diastole, especially coronary
blood flow, so when considering the coronary circulation,
the influence of aortic root function must be taken into
account.

There have been some reports regarding the effects of de-
creased aortic distensibility on cardiac pulsatile work. Kelly
et al showed that myocardial oxygen demand increases in
conjunction with vascular stiffening. The reason for the in-
creased myocardial oxygen demand is augmentation of the
pulsatile power output of the left ventricle. The increased
pulse pressure and tension time index seen in the present
patients suggests increased myocardial oxygen demand
after the ASO. Indeed, many studies have demonstrated that
myocardial blood flow at rest is increased in patients after
an ASO.

Ohtsuka et al have reported that decreased aortic disten-
sibility contributes to a decrease in the coronary flow
reserve. Other reports have shown good long-term clinical
outcomes in patients after an ASO, but decreased coronary
flow reserve without concomitant coronary arterial stenosis
has been demonstrated. That is, myocardial oxygen de-
mand increases and coronary flow reserve decreases in pa-
 


cients after the ASO. Although our data showed a balanced
coronary demand—supply relationship while resting, an im-
balance may occur during exercise. More examinations are
thus required, although Weindling et al reported that myo-
cardial perfusion was adequate during the physiological
stress of exercise in children up to 8 years after an ASO.

Our data demonstrated that systolic blood pressure and
pulse pressure significantly increased in the patients after
the ASO, most likely because of decreased elasticity of the
aorta. Recent studies regarding hypertension have under-
lined the importance of large elastic arterial distensibility in
cardiovascular diseases. As the walls of the large arteries
stiffen, systolic pressure increases, diastolic pressure de-
creases, and pulse pressure increases in the central aorta for
a given pattern of left ventricular ejection. This pattern of
hypertension, which is referred to as “isolated systolic hypertensio
”, is typical in older individuals, and is associ-
ated with an appreciably increased risk for coronary heart
disease. Moreover, reduced arterial elasticity in normo-
tensive persons, independent of blood pressure, predicts the
future development of hypertension. Patients after an
ASO may be candidates for future cardiovascular diseases
and therefore careful observation of our patients beyond the
time of entering elementary school will be important.

In conclusion, our data demonstrated preserved aortic
reservoir function in pediatric patients after an ASO, despite
dilation and decreased distensibility of the aorta. Decreased
aortic distensibility is observed in many conditions, such as
in the aorta of elderly persons and individuals with Marfan
syndrome and in cases of tetralogy of Fallot. However,
those patients do not necessarily demonstrate insufficient
coronary perfusion and under such conditions, aortic dilata-
tion has also been reported. A dilated aorta may therefore
help to maintain diastolic blood flow, especially coronary
blood flow. Further investigations are needed to clarify the
relationship between large-artery hemodynamics and the
coronary circulation.

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