Comparison of somatic development and status of conduit after extracardiac Fontan operation in young and older children*

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Abstract

Objective: We set out to examine whether the extracardiac Fontan operation (ECFO) in young children is beneficial for the early postoperative course and whether it has a negative impact on the mid-term hemodynamics and growth of the children due to absent growth potential of the prosthetic conduit. Therefore we compared our medium-term experience with ECFO in children under 4 years of age to that in older children regarding the incidence of postoperative complications, somatomotoric development and conduit status.

Methods and results: Between 11/95 and 12/02 ECFO was performed in 30 children under 4 years of age and 21 older children aged 4–13 years. There were no deaths in children under 4 years of age and two older children died. No prolonged support (>72 h) of suprarenin was required in small children compared to 4 older children. In twenty-seven children, who underwent postoperative heart catheterization no pulmonary artery or systemic vein distortion occurred. One re-operation and one transcatheter intervention were performed because of the partial conduit stenosis. During the median follow-up of 4.8 years a manifestly accelerated postoperative weight gain was observed in children operated on under 4 years of age, compared to that in older children (up to the 50 vs. 10th percentile, P<0.05).

Conclusions: The ECFO could be performed in young children with low morbidity and mortality rates. In the majority of patients, implanted prosthetic grafts maintain stable form without the development of stenosis. Accelerated somatic development, especially in small children, is to be observed after completion of the Fontan circulation.

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1. Introduction

We assume that the early removal of cyanosis and volume overload in functionally single ventricle is not only beneficial for the early postoperative course but also provides the optimal basis for normal somatic development of the children. The original selection criteria used by Choussat have been significantly modified during the past decade and many authors have described good early results after both intracardiac and extracardiac modified Fontan operation in small children [1–4]. However, it is still a cause of concern that the inability of the extracardiac prosthetic conduit to grow—in length as well as in diameter—might in time lead to pulmonary artery distortions or flow disturbances in the conduit, resulting in failed Fontan hemodynamics, protein-losing enteropathy, failed somatic development and need for surgical conduit revision. Attempts to implant a maximal sized conduit, such as would be sufficient for adults, in young children could lead to suboptimal Fontan hemodynamics, as we reported previously [5]. Therefore, we analyzed our early and medium-term experience with the extracardiac Fontan operation (ECFO) in children under 4 years of age regarding

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the incidence of early postoperative complications, status of the extracardiac conduit and pulmonary arteries and somatic development after early palliation. The results were compared with those achieved in older children.

2. Methods

2.1. Patients

Between 11/1995 and 12/2002 60 consecutive patients with single ventricle physiology underwent ECFO at our institute. Thirty patients were in median 3 (range: 1.3–4, group A) years of age with a median body weight of 13 (range: 8.8–17.0) kg at the time of completion of ECFO. The other 21 older children had a median age of 5.5 (range: 4.6–13, group B) years and weighed preoperatively a median of 20 (13–37) kg. The median body weight was preoperatively in the 25th percentile in both groups. The median body weight at birth was 3.1 and 3.2 kg, respectively (between 25 and 50th percentile). A total of 99 previous operations were performed without differences between group A (1.9 operations/patient) and group B (2.0 operations/patient). Bi-directional cavopulmonary shunt (BCPS) was performed in 28 (87%) of the 30 small children and in 19 (87%) of the 21 older children. The median body weight at the time of BCPS was slightly different with 8.7 kg (10th percentile) in group A and 11 kg (3rd percentile) in group B (Fig. 1).

The age distribution in the patient population was similar over the total study and no selection criteria for Fontan candidates were changed during this time period. The main cardiac diagnosis and heterotaxia syndrome showed no statistical differences in both groups (Table 1). There were no differences regarding the preoperative pulmonary artery indices, arterial oxygen saturation, systemic ventricular end diastolic pressure or distribution of the patients with left or right morphology of the systemic ventricle between the two groups. The pulmonary artery pressure was higher in older children, but all preoperative parameters in all patients were within our standard values for acceptance for the Fontan operation (Table 2) [6]. In the majority of children with delayed operation the reasons were of social or demographic character or they came from abroad. Nine adults (>16 years of age) were excluded from this comparative study.

2.2. Surgery

All operations were performed by one surgeon (V. A-M). The anastomosis between the inferior vena cava (IVC) and the pulmonary artery was established using a Gore-Tex® (W.L. Gore and Associates, Inc, Flagstaff, AZ, USA) conduit with a median diameter of 18 (16–24) mm.
in young children and 20 (16–24) mm in older children. In 40 children the operation was performed on the beating heart with normothermic cardiopulmonary bypass (median duration 91 (30–274) min). Cardioplegia (CP) and mild hypothermia were used selectively in 11 patients for additional intracardiac repair. The diameter of the extracardiac conduit in the last 40 patients was ascertained according to the diameter of the IVC, trying not to oversize it by more than 25% [5].

There was no difference in duration of CPB or use of cardioplegia between the young and older children (CP in five and six patients, respectively). Fenestration was performed in 14 patients without differences between younger (n = 8) and older (n = 6) children. Eleven patients received a fenestrated conduit routinely at the beginning of the study period and the last three because of intraoperatively elevated pulmonary artery pressure.

### Table 1

Main cardiac diagnosis

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Age &lt;4 years</th>
<th>Age &gt;4 years</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tricuspid atresia</td>
<td>11</td>
<td>9</td>
<td>n.s.</td>
</tr>
<tr>
<td>Double inlet left ventricle</td>
<td>5</td>
<td>2</td>
<td>n.s.</td>
</tr>
<tr>
<td>Complex anatomy with double outlet right ventricle</td>
<td>1</td>
<td>2</td>
<td>n.s.</td>
</tr>
<tr>
<td>Pulmonary atresia with intact interventricular septum</td>
<td>5</td>
<td>1</td>
<td>n.s.</td>
</tr>
<tr>
<td>Unbalanced complete atrioventricular septal defect</td>
<td>3</td>
<td>3</td>
<td>n.s.</td>
</tr>
<tr>
<td>Other complex form of single ventricle</td>
<td>5</td>
<td>4</td>
<td>n.s.</td>
</tr>
<tr>
<td>Heterotaxia syndrome</td>
<td>2</td>
<td>4</td>
<td>n.s.</td>
</tr>
</tbody>
</table>

### Table 2

Pre-operative heart catheterization data

<table>
<thead>
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<th></th>
<th>Preoperative</th>
<th>Postoperative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n=30</td>
<td>n=21</td>
</tr>
<tr>
<td>PAI (Nakata)</td>
<td>(mm²/m²)</td>
<td>(mm²/m²)</td>
</tr>
<tr>
<td>LLI (mm²/m²)</td>
<td>143 (94–299)</td>
<td>169 (104–516)</td>
</tr>
<tr>
<td>Mean PAP (mmHg)</td>
<td>10 (6–14)</td>
<td>12 (3–19)</td>
</tr>
<tr>
<td>SVEDP (mmHg)</td>
<td>6 (2–10)</td>
<td>7 (2–14)</td>
</tr>
<tr>
<td>Arterial oxygen saturation (%)</td>
<td>83 (68–90)</td>
<td>82 (55–89)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Postoperative</td>
<td>n=12</td>
<td>n=14</td>
</tr>
<tr>
<td>PAI (Nakata) (mm²/m²)</td>
<td>275 (147–489)</td>
<td>251 (118–462)</td>
</tr>
<tr>
<td>LLI (mm²/m²)</td>
<td>183 (98–341)</td>
<td>166 (71–478)</td>
</tr>
<tr>
<td>Mean PAP (mmHg)</td>
<td>10 (6–13)</td>
<td>13.5 (4–20)</td>
</tr>
<tr>
<td>SVEDP (mmHg)</td>
<td>6.5 (3–9)</td>
<td>5 (2–12)</td>
</tr>
<tr>
<td>Arterial oxygen saturation (%)</td>
<td>97 (90–100)</td>
<td>95 (88–100)</td>
</tr>
</tbody>
</table>

PAI, pulmonary artery (Nakata) index; LLI, lower lobe index; PAP, pulmonary artery pressure; SVEDP, systemic ventricular end diastolic pressure.

* Two outliers, described in the text.

### 2.3. Development of pulmonary arteries and status of conduit

The postoperative diameter of the pulmonary arteries (pulmonary artery indices), the IVC and the conduit was defined using contrast angiography. Also the postoperative relation between the diameters of the IVC and the conduit in the posterio-anterior and lateral view was measured and compared.

#### 2.4. Somatic development

The development of weight and length in children according to the percentiles was studied with respect to the different somatic development for gender (26 m, 25 f), different races (6 patients of Turkish ancestry) and trisomy 21 (1 patient), from birth throughout the surgical history with staged single ventricle palliation and during the follow-up after Fontan operation.

### 3. Statistical analysis

To compare the two different age groups with regard to the length of ventilatory support and hospital stay, pre- and post-operative oxygen saturation, pulmonary artery and end diastolic ventricular pressure and pulmonary artery indices, the Mann–Whitney test was used. The postoperative differences in length and weight gain were also compared with the Mann–Whitney test. To detect differences between the two groups with regard to the incidence of postoperative complications, the χ²-test was employed.

The data were analyzed with the software SPSS for Windows 9.0 (SPSS Inc, Chicago, III). A P-value of 0.05 or less was considered statistically significant.

### 4. Results

#### 4.1. Early postoperative course

Mortality. None of the 30 children under 4 years of age died. Two older children (2/21 = 9.5%) died early postoperatively. The total hospital mortality rate was 3.9% (Table 3).

No prolonged support (for more than 72 h) or high dosage of suprarenin was required in children operated on under 4 years of age while they were needed in 19% (4 patients) of older children (P = 0.039). Acute renal failure and supraventricular tachyarrhythmias occurred rarely in small children but the difference from the older children did not reach statistical significance. There was no difference between the younger and older children regarding the duration of mechanical ventilation (median <24 h), incidence of prolonged pleural effusions or chylothorax and hospital stay (median <3 weeks).
4.2. Follow-up

There were no late deaths during the total median follow-up period of 4.8 (range: 1.3–7.7) years. The anticoagulation was established with marcumar (INR 2.5-3) for at least 1 year after surgery (currently in 19 children) and life-long with acetylsalicylic acid (3–5 mg/kg/d).

Heart catheterization was performed in 27 patients (55%) 0.3–7.2 years (median 1.5 years) after surgery. In all except one patient, in whom elevated pulmonary artery pressure persisted, the fenestration was closed \((n=2)\) or recognized as spontaneously closed. The hemodynamic data (Table 2) showed no statistically significant differences between the younger and older children.

4.3. Development and status of the pulmonary arteries

Despite the maximal height gain of up to 64 cm no pulmonary artery or systemic vein distortions were observed in any patient (Fig. 2).

Stable or increased pulmonary artery indices (based on the body surface area) were measured in all patients despite the increase of the body surface area during the follow-up from preoperatively 0.61 (0.42–0.81) to 0.72 (0.55–1.23) \(m^2\) (Table 2).

In one child operated on at 4.5 years of age slightly distorted pulmonary arteries were observed 12 months after surgery without pressure gradient and without clinical symptoms. Repeated catheterization 6 years after surgery demonstrated still excellent hemodynamics with low pulmonary artery pressure and without pressure gradient in the Fontan circuit. The child shows normal somatic development and is doing well.

4.4. Status of the extracardiac conduit

In 24 out of 27 patients (89%) who underwent postoperative angiography the clear contour of the extracardiac conduit without wall thrombosis or stenosis of the anastomosis was noted.

The median angio graphically measured lateral to anterior conduit diameter ratio was 1.4 (range: 1.0–2.3).

Therefore we observed an ellipsoid intrapericardial form of the conduit with a tendency to slight lateral compression in the middle (Fig. 2).

The median angiographically measured conduit-to-IVC diameter ratio in posterior-anterior view was 1.2 (range: 0.76–1.66) and in lateral view 1.4 (range: 0.89–2.14).
The angiographically measured conduit-to-IVC diameter ratio in children operated on under 4 years of age was a median of 1.3 for the postero-anterior and 1.5 for the lateral view and therefore was slightly larger than in older children (1.1 for postero-anterior and 1.3 for lateral, respectively) but this difference did not reach statistical significance ($P = 0.8$). In seven patients (five younger and two older children) conduit oversizing of more than 40% (ratio: 1.45–1.74) was measured. We saw no differences in flow pattern within the conduit between younger and older children.

In one patient with an atrioventricular septal defect, heterotaxia, and left IVC, operated on at 7 years of age, a partial stenosis of the conduit developed because of compression of the retrocardiac conduit by the vena cava without significant pressure gradient but with significant ascites. After interventional balloon dilatation of the conduit stenosis there was complete normalization of the conduit diameter and control magnet resonance imaging 4 months later showed normalized laminar and antegrade flow pattern (maximal velocity 22 ml/s in the inferior caval vein) through the conduit.

One other 3-year-old child (reported elsewhere) with significantly oversized and bent conduit developed conduit thrombosis and severe protein-losing enteropathy [5]. At re-operation the conduit was replaced with a smaller one and the acute symptoms disappeared.

In the other 24 patients, who are awaiting postoperative catheterization, the echocardiographic check-up examinations in our outpatient department do not reveal any signs of conduit or pulmonary artery stenosis.

4.5. Flow pattern in extracardiac conduit

Laminar flow with rapid transport of contrast medium from the conduit into the pulmonary arteries was observed in 23 out of 27 patients. In 4 patients (2 children from group A and 2 from group B) we found slowed flow through the conduit with a period of storage of the contrast medium in the conduit. All these patients had single or combined risk factors: limited ventricle function (in 2), elevated pulmonary artery pressure (17–20 mmHg; in 3), paralysis of the phrenic nerve (in 3), conduit stenosis (in 2) and oversizing of more than 40% of the conduit compared to the IVC (in 2) were observed.

4.6. Somatic development in children

The median absolute weight gain in children was 2.5 (1.5–5) kg/year after the Fontan operation and the median absolute weight was 23 (13–50) kg at the end of the follow-up of 4.8 (range: 1.3–7.5) years. In terms of percentiles the median body weight in children operated on under 4 years of age was 50 (3–97)th and in older children it was 10 (3–75)th. The weight course in both groups was similar with a characteristic decrease of weight gain after birth up to the Glenn and Fontan operation. However, the ‘post-Fontan’ acceleration of weight gain in children operated on under 4 years of age (median 25, range 3–94%) compared to those with delayed Fontan palliation (median 0, range –25 to 50%) was significant ($P < 0.028$; Fig. 1).

There was no statistically significant impact on the postoperative weight gain in children with oversizing of the conduit compared with the IVC diameter of more than 40% ($n = 7$).

The post-Fontan length gain in children operated on under 4 years of age was accelerated, compared to that in older children, with a tendency toward normal height, but the difference did not reach statistical significance (Fig. 1). The absolute length gain of the children was 21.5 ± 15.3 (median 15, range 3–64) cm and the tallest child at the end of the follow-up measured 153 cm at the age of 9 years, 7 years after ECFO.

5. Discussion

5.1. Early postoperative outcome

Young age at the time of Fontan operation is no longer considered a risk factor and, furthermore, the early removal of cyanosis and volume overload was postulated to be beneficial for the postoperative course [3,7]. Various authors have reported on the modified Fontan operation or total cavopulmonary connection in children under 4 or even under 2 years of age with good results [2–4]. However an early mortality rate of up to 9%, late mortality of up to 18% and a relatively high incidence of postoperative arrhythmias were reported [3,4].

In our series we observed that the patients who received ECFO at an early age (under 4 years) showed a better early postoperative outcome with significantly lower need for inotropic support compared to children operated on at an older age. We, like others, assume that long-term volume overload of the single ventricle, especially under cyanosis, leads to ventricular hypertrophy, myocardial fibrosis and limited diastolic and systolic ventricular function [7,8].

We believe, as we reported previously, that the avoidance of cardioplegia and reduction of the cardiopulmonary bypass time is important to preserve ventricular function in the early postoperative period, but ventricular hypertrophy and structural myocardial changes in older patients still remain a significant limiting factor for the successful Fontan operation [6,7]. Furthermore the diminished postoperative ventricular function could additionally increase the risk for acute renal failure, that we frequently observed in older children [9].

Further investigations are necessary to establish whether earlier volume reduction of the single ventricle in young
5.2. Medium-term status of the conduit and somatic development

Beyond the early postoperative period and apart from the preservation of sinus rhythm, which was described previously by us and others, follow-up studies after ECFO regarding the status of the extracardiac conduit and the growth potential of children after the implantation of prosthetic tissue into the Fontan circuit are not available [6,7,12]. The long-term status of the extracardiac prosthetic conduit, blood flow within it, and the growth potential of children after the implantation of prosthetic tissue into the Fontan circuit remains unclear. Therefore we saw a need for this follow-up data, with which we can confirm that the maximal body length gain in children of up to 64 cm (absolute maximal body length of 153 cm at the end of the follow-up) did not lead to distortions of the conduit-to-RPA anastomosis.

During the angiographic check-ups we observed in the majority of patients optimal forwards flow in the extracardiac conduit without turbulence, with an equal distribution of the superior and inferior venous flow pattern to the right and left pulmonary artery which support the in vitro results of Lardo et al. [13]. Slowed flow in the conduit aggravated by oversizing, bending, or compression of the conduit may lead to thrombosis and protein loss, such as in two of our patients.

On follow-up catheterization we observed low pulmonary artery pressure and adequate growth of the arteries in the majority of patients. Together with good ventricular function these provide optimal Fontan hemodynamics. Furthermore, we note no significant reduction of the pulmonary artery indices (based on the body surface area) despite growth of the children with increase of the body surface area during the follow-up. This indirectly represents the adequate development of the pulmonary arteries despite the absence of pulsatile flow in the Fontan circuit after operation.

The somatic development and growth in childhood remain the basic indicators of adequate therapy of congestive heart failure in congenital heart disease. During the era before the Fontan operation many investigators showed that somatic development of children with chronic cyanosis was frequently inadequate compared to that of the healthy population [14–16]. Our results support this, with the dramatic deceleration of weight and length gain according to the percentiles after birth and before Fontan operation in all children, which is probably related to congestive heart failure and cyanosis [14–16]. Stenborg et al. described significantly improved physical growth following the total cavopulmonary connection but Cohen et al. showed significantly decreased weight and length in children who had undergone Fontan operation, compared to their healthy peers [16]. Our results in older children operated on after 4 years of age were similar to those of Cohen. These patients showed only slight improvement of their weight and stature during the median follow-up of 4 years after surgery and remained significantly underweight. However, the ‘post-Fontan’ acceleration of weight gain toward normal in children operated on under 4 years of age compared to those with delayed palliation was significant in our series. Also Stenbog et al. saw, similar to our results, equal increases in weight and height only in children operated on before the age of 5 years [17]. Probably the early establishment of Fontan circulation protected heart function and allowed the growth of children to catch up [18]. Otherwise the insufficient height gain in older children may be caused by the delayed bone age, which seems to be affected by chronic hypoxemia during the children ages and which correlates directly with the low height percentile [15]. In contrast to the results of Day et al. the improvement of the height and weight gain in our series was more significant not after BCPS, but after completion of the Fontan circulation [19]. Regarding the optimal time for the ECFO, we would consider not only the age limit (about 2–4 years of age), but also a body weight of 10–14 kg, as long as the inferior vena cava is adequately developed, as we reported previously, and all other selection criteria for optimal Fontan operation are fulfilled [5]. Protein-losing enteropathy, accompanied by chronic ascites and hypoalbuminemia, could be a significant factor influencing the normal height gain [16,19,20]. The optimal laminar flow pattern in the extracardiac conduit may prevent the development of protein-losing enteropathy and thus maintain the normal growth in children. In particular, the potential for ‘catch-up’ growth is greater at a young age. We believe that early palliation provides better long-term ventricular function and, combined with the earlier removal of cyanosis, a better starting position for normal somatic development of children without hypoxemia. On the other hand, Day et al. have described the long-term results with a maximal follow-up of 18 years and final results after the ECFO remain to be seen [19].

6. Conclusions

The mid-term results after ECFO show low morbidity and mortality rates, especially after palliation in small children. Implantation of a conduit with a diameter sufficient for long-term Fontan hemodynamics is possible in young children. In the majority of patients, implanted prosthetic grafts maintain stable form without the development of stenosis or thrombosis. Accelerated somatic development, with normalization of weight and height in
small children, is to be observed after completion of the Fontan circulation. The long-term results are still to be awaited.

Acknowledgements

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References