Comparison of hemodynamics between Norwood procedure and systemic-to-pulmonary artery shunt for single right ventricle patients

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Abstract

Objective: Despite that surgical outcomes of patients with hypoplastic left heart syndrome have improved, one of the problems remaining is the high interstage mortality after a stage I Norwood procedure. The purpose of this study was to determine the hemodynamic characteristics of hypoplastic left heart syndrome after a Norwood procedure. We examined the perioperative hemodynamic differences of the staged operation between the first stage of the Norwood procedure and systemic pulmonary shunt for single right ventricle patients.

Methods: Data from 39 patients who underwent a Norwood procedure (right ventricle to pulmonary artery conduit: 19, Blalock-Taussig shunt, 20) were analyzed. There were nine early and seven interstage deaths. Bidirectional cavopulmonary shunt was performed in 15 patients and the Fontan procedure in 9 (group H). We defined the control group as 26 patients who underwent the first stage of a systemic pulmonary shunt for a single ventricle. Bidirectional cavopulmonary shunt was performed in 14 patients and the Fontan procedure in 8 (group C). We compared the perioperative hemodynamics of the staged operation between the two groups.

Results: Cardiothoracic ratio and single ventricular diastolic dimension before bidirectional cavopulmonary shunt were acutely increased in group H ($P < 0.02$, $< 0.001$). There was no significant difference between the two different types of Norwood procedures. The pulmonary artery index for the right heart bypass operation was lower in group H than in group C ($P < 0.001$). Oxygen saturation before bidirectional cavopulmonary shunt in group H decreased ($P < 0.001$) and thus was lower than that in group C ($P = 0.003$). Mortality and the postoperative clinical parameters of the right heart bypass operation were not different between the two groups.

Conclusions: Patients with hypoplastic left heart syndrome showed hemodynamic instability of acutely increased cardiothoracic ratio, and single ventricular diastolic dimension despite decreased oxygen saturation interstage after stage I of a Norwood procedure. This suggests that this hemodynamic characteristics in hypoplastic left heart syndrome correlates with the higher mortality before second stage palliation than in found with single right ventricle patients.

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Keywords: Hypoplastic left heart syndrome; Norwood procedure; Single ventricle; Right ventricle to pulmonary artery conduit; Blalock-Taussig shunt; Cardiothoracic ratio; Single ventricular diastolic dimension

1. Introduction

Surgical outcomes of patients with hypoplastic left heart syndrome (HLHS) have been improved by the introduction of the staged Fontan strategy and several other new techniques. Despite the improved early outcomes after the Norwood procedure, one of the problems of the staged Norwood strategy is the relatively high incidence of death before the second stage of palliation [1-4]. To determine the cause of the high mortality interstage after a stage I Norwood procedure, we hypothesized that single right ventricular function and pulmonary blood supply interstage after a Norwood procedure in HLHS patients would be different from single right ventricle non-HLHS patients who required additional pulmonary flow through a graft. We report comparisons of hemodynamic parameters and operative results of the staged operation for patients with HLHS, with single right ventricle patients who had decreased pulmonary flow as a neonate or early infant and required a systemic-to-pulmonary artery shunt in the first stage of single ventricle palliation.

2. Patients and methods

2.1. Patient population

The records of 39 consecutive patients who underwent the Norwood procedure between November 1993 and March 2000 at the Fukuoka Children’s Hospital were reviewed retrospectively (group H). Cardiac transplantation for HLHS is uncommon in Japan, and we excluded patients with high risks using cardiopulmonary bypass due to severe ductal shock or heart failure (DIC, etc.). We defined the control
The patient, cause of late death, cardiothoracic ratio (CTR), and weight at the time of the staged operation, status of Fukuoka Children’s Hospital and reviewed retrospectively. Pulmonary atresia were retrieved from the database of a systemic-to-pulmonary artery shunt at the first stage of a staged Fontan procedure (group C). Patient profiles are shown in Table 1. To compare single right ventricular function between two groups, we excluded patients diagnosed with a single ventricle mainly occupied morphologically by a left ventricle (double inlet left ventricle, tricuspid atresia, and pulmonary atresia with intact ventricular septum, etc.) from group C.

### 2.2. Operative technique and management

Descending aortic cannulation, which avoids the need for circulatory arrest, and right ventricle to pulmonary artery conduit [5–8] for Norwood procedure, was introduced in 1998 in our institution. Postoperative management using a low resistance strategy was also introduced in 1998 [9]. The Norwood procedure was performed without circulatory arrest in 23 patients (67%) [10,11]. The mean diameter of an ascending aorta at Norwood procedure for HLHS patients was 2.8 ± 1.1 (1.5–6) mm. Hypoplastic ascending aortas under 2 mm were 42% and ascending aortas under 3 mm in diameter were 78% in group H. No patients required takedown of bidirectional cavopulmonary shunts (BCPS) and Fontan procedure caused by high pulmonary resistance. Operative profiles are shown in Table 2.

### 2.3. Additional procedures during right heart bypass surgery

The incidence of required additional procedures during BCPS was higher in group H than group C (P = 0.014). There was no difference in the frequency of additional procedures for the Fontan procedure. Additional procedures are shown in Table 3.

### 2.4. Data analysis

Surgical, hemodynamic, and laboratory data for all of the patients who underwent the first stage palliation for HLHS and single right ventricle with pulmonary stenosis or pulmonary atresia were retrieved from the database of Fukuoka Children’s Hospital and reviewed retrospectively. The diagnosis, operation and additional procedures, age and weight at the time of the staged operation, status of the patient, cause of late death, cardiothoracic ratio (CTR), single ventricle diastolic dimension (SVDd), atroventricular valve regurgitation (AVVR), pulmonary artery (Nakata) index (PAI), mean pulmonary artery pressure (MPAP), pulmonary resistance index (Rpl), right atrial pressure (RAP), single ventricle end-diastolic pressure (SVEDP), single ventricular ejection fraction (SVEF), cardiac index (CI), oxygen saturation (Sat O2), and postoperative clinical parameters were analyzed. Data were sampled at the examination immediately after stage I palliation, at the preoperative examination before BCPS and Fontan procedure, and at the latest catheterization after Fontan procedure. These are the regular diagnostic procedures in our hospital. Early death was defined as death within 30 days of surgery, and late death was defined as death occurring more than 30 days after surgery. For each parameter, we performed a subset analysis of right ventricle to pulmonary artery conduit vs. Blalock-Taussig (BT) shunt Norwoods and single right ventricle with pulmonary stenosis vs. single right ventricle with pulmonary atresia.

All data are expressed as the mean ± SD. Two group comparisons were performed with an unpaired, two-tailed t-test for means of normally distributed variables and with Wilcoxon rank sum tests for skewed data. The χ² or Fisher exact test was used to analyze differences among the categorical data. A P value of less than 0.05 was considered significant. Statistical analysis was performed with Statview version 5.0J software.
3. Results

3.1. Mortality

As assessed in February 2002, there were nine early deaths (23%) and seven late deaths (18%) in 39 stage I palliation patients in group H. There were no early deaths but there were three late deaths in the 26 stage I palliation patients in group C. No early or late deaths occurred in patients who underwent BCPS in either group. There were no early deaths in either group but there was one late death in group C in patients who underwent Fontan procedure. One patient with severe atrioventricular valve regurgitation who underwent concomitantly atrioventricular valve replacement died from an acute increase in pulmonary resistance 2 months after undergoing the Fontan procedure.

3.2. Late death after stage I palliation

There were seven late interstage deaths after stage I palliation in group H and three in group C. Cardiac failure was the primary cause of death in group H, tricuspid regurgitation in two patients and right ventricular failure, and coronary ischemia, hypoxia, arrhythmia, and recurrence of coarctation of the aorta in one patient each. In contrast, respiratory infection was the cause of death in two patients and right ventricular failure was the cause of death in one patient in group C.

3.3. Transient changes in CTR, SVDd, and AVVR before BCPS

CTR increased significantly after the Norwood procedure before BCPS in group H (mean interval between stages I and II palliation: 8.4 months, from 56.2 ± 5.1 to 61.9 ± 4.1%, P = 0.02). There were no significant differences between CTR after the systemic-to-pulmonary artery shunt and before BCPS in group C (mean interval between stages I and II palliation: 18.5 months, from 59.5 ± 5.7 to 58.8 ± 7.3%). Increasing CTR was found during a shorter interval in group H (Fig. 1A). SVDd increased significantly

<table>
<thead>
<tr>
<th>Group H</th>
<th>Group C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional procedure on BCPS (n=15)</td>
<td>Additional procedure on BCPS (n=14)</td>
</tr>
<tr>
<td>TAP</td>
<td>3</td>
</tr>
<tr>
<td>ASD enlargement</td>
<td>3</td>
</tr>
<tr>
<td>Asc. Ao. graft replacement</td>
<td>1</td>
</tr>
<tr>
<td>Aortoplasty</td>
<td>1</td>
</tr>
<tr>
<td>Balloon angioplasty (re-CoA)</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>12</td>
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</table>

<table>
<thead>
<tr>
<th>Group H</th>
<th>Group C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional procedure on Fontan (n=9)</td>
<td>Additional procedure on Fontan (n=8)</td>
</tr>
<tr>
<td>TAP</td>
<td>2</td>
</tr>
<tr>
<td>ASD enlargement</td>
<td>1</td>
</tr>
<tr>
<td>Aortoplasty</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>4</td>
</tr>
</tbody>
</table>

Group H, hypoplastic left heart syndrome; Group C, controls; n, number of patients; BCPS, bidirectional cavopulmonary shunt; n, number of patients; TAP, tricuspid annuloplasty; TAPVD, total anomalous pulmonary venous drainage; ASD, atrial septal defect; AVV, atrioventricular valve; Asc.Ao., ascending aorta; CoA, coarctation of the aorta; NS, not significant.

Fig. 1. Changes in the cardiothoracic ratio and single ventricle diastolic dimension before bidirectional cavopulmonary shunt surgery. BCPS, bidirectional cavopulmonary shunt; SP, systemic pulmonary; CTR, cardiothoracic ratio; SVDd, single ventricle diastolic dimension.
after the Norwood procedure before BCPS in group H (mean interval between stages I and II palliation: 8.4 months, from 21.7±5.8 to 32.3±6.2 mm, P<0.001). There were no significant differences between after systemic-to-pulmonary artery shunt and before BCPS in group C (mean interval between stages I and II palliation: 18.5 months, from 25.6±7.4 to 31.8±6.6 mm). Increasing SVDd was found during a shorter interval in group H (Fig. 1B). Despite that patients who underwent BCPS were younger in group H than in group C, CTR and SVDd increased in a shorter period in group H. AVVR was 0.6±0.8 Sellers degrees (0-2) immediately after Norwood and 1.1±1.0 Sellers degrees (0-3) before BCPS in group H, 1.1±0.9 Sellers degrees (0-2) immediately after systemic-to-pulmonary artery shunt and 1.1±0.8 Sellers degrees (0-2.5) before BCPS in group C. In both groups, the changes in AVVR were not significant. In this study, there were no significant differences in CTR and SVDd in the subset analysis of right ventricle to pulmonary artery conduit vs. BT shunt Norwoods (CTR; 61.0±4.8% before BCPS in right ventricle to pulmonary artery conduit Norwood vs. 60.1±4.0% before BCPS in BT shunt Norwood, SVDd; 29.2±4.5 mm before BCPS in right ventricle to pulmonary artery conduit Norwood vs. 33.5±6.6% before BCPS in BT shunt Norwood).

### 3.4. Preoperative PAI, MPAP, Rpl, RAP, SVD, SVEDP, SVEF, and CI

The PAI values of group H at the time of BCPS and the Fontan procedure were significantly lower than in group C (Fig. 2A). MPAP of group H at the time of BCPS in the right ventricle to pulmonary artery conduit Norwood vs. 60.1±4.0% before BCPS in right ventricle to pulmonary artery conduit Norwood vs. 60.1±4.0% before BCPS in right ventricle to pulmonary artery conduit Norwood vs. 29.2±4.5 mm before BCPS in right ventricle to pulmonary artery conduit Norwood vs. 33.5±6.6% before BCPS in BT shunt Norwood).

#### Table 4

<table>
<thead>
<tr>
<th>Preoperative Rpl, RAP, and SVDp</th>
<th>Group H</th>
<th>Group C</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rpl (wood U/m²) Before BCPS</td>
<td>2.1±1.2</td>
<td>2.0±1.4</td>
<td>NS</td>
</tr>
<tr>
<td>Before Fontan</td>
<td>1.7±1.2</td>
<td>1.0±0.5</td>
<td>NS</td>
</tr>
<tr>
<td>RAP (mmHg) Before BCPS</td>
<td>5.0±3.2</td>
<td>4.6±2.2</td>
<td>NS</td>
</tr>
<tr>
<td>Before Fontan</td>
<td>4.5±2.7</td>
<td>3.2±2.4</td>
<td>NS</td>
</tr>
<tr>
<td>SVDp (mmHg) Before BCPS</td>
<td>4.9±2.6</td>
<td>3.8±2.2</td>
<td>NS</td>
</tr>
<tr>
<td>Before Fontan</td>
<td>3.9±2.7</td>
<td>3.1±2.3</td>
<td>NS</td>
</tr>
<tr>
<td>SVEF (%) Before BCPS</td>
<td>58.9±11.3</td>
<td>63.7±15.1</td>
<td>NS</td>
</tr>
<tr>
<td>Before Fontan</td>
<td>61.7±8.7</td>
<td>64.4±11.7</td>
<td>NS</td>
</tr>
<tr>
<td>CI (l/min per m²) Before BCPS</td>
<td>4.2±1.3</td>
<td>4.0±1.3</td>
<td>NS</td>
</tr>
<tr>
<td>Before Fontan</td>
<td>4.1±0.9</td>
<td>4.1±0.9</td>
<td>NS</td>
</tr>
</tbody>
</table>

Group H, hypoplastic left heart syndrome; Group C, controls; n, number of patients; Rpl, pulmonary resistance index; BCPS, bidirectional cavopulmonary shunt; NS, not significant; RAP, right atrial pressure; SVDp, single ventricle end-diastolic pressure; SVEF, single ventricular ejection fraction; CI, cardiac index.

(Fig. 2B). Preoperative Rpl, RAP, SVDp, SVEF, and CI are shown in Table 4. In this study, there were no significant differences between the right ventricle to pulmonary artery conduit and BT shunt Norwoods in PAI, MPAP, Rpl, RAP, SVDp, SVEF, and CI.

### 3.5. Transient changes in Sat O₂

Sat O₂ after the Norwood procedure decreased compared to before BCPS in group H (Fig. 3, P<0.001). Although significant differences were not found after stage I palliation between the two groups, the value in group H was significantly lower than in group C before BCPS (P=0.03). Sat O₂ in group H was lower than in group C before the Fontan procedure (P=0.03). At late follow-up, no significant difference was found in Sat O₂ between group H and group C.

### 3.6. Postoperative changes in MPAP

MPAP after BCPS at the time of admission to the intensive care unit (ICU) was higher in group H than in group C (Fig. 4,
3.7. Postoperative course

The duration of mechanical ventilation after BCPS was 11.0 ± 12.0 h (2–48) in group H and 11.0 ± 8.3 h (2–24) in group C, and 11.8 ± 13.5 h (1–41) in group H and 9.8 ± 7.5 h (1–19) in group C after the Fontan procedure. The stay in ICU stay after BCPS was 2.6 ± 3.0 days (1–11) in group H and 2.9 ± 3.7 days (1–15) in group C, and 2.1 ± 1.4 days (1–5) in group H and 2.2 ± 1.5 days (1–6) in group C after the Fontan procedure. The duration of chest drainage after BCPS was 3.5 ± 1.2 days (2–6) in group H and 3.3 ± 0.9 days (2–5) in group C, and 8.3 ± 4.0 days (2–15) in group H and 7.8 ± 6.0 days (3–21) in group C after the Fontan procedure. In this study, none of the postoperative parameters were different between the two groups.

Our data showed no significant difference for any of the postoperative parameters (CTR, SVDd, AVVR, PAI, MPAP, RpI, RAP, SVEDP, Sat O2, and MPAP) in the subset analyses of right ventricle to pulmonary artery conduit vs. BT shunt Norwoods and single right ventricle with pulmonary stenosis vs. single right ventricle with pulmonary atresia.

4. Discussion

4.1. The type of ventricular chamber and pulmonary flow supply

In this study, the morphological chamber of the all of HLHS group was the right ventricle, because all our patients are ‘classical HLHS’ and HLHS variant with single right ventricle. To assess single right ventricular function of HLHS, we excluded patients diagnosed with a single left ventricle from the control group. Although not all patients were occupied by only a morphological right ventricle component, patients in both groups had mainly occupied single right ventricle. We selected single right ventricle requiring systemic-to-pulmonary shunt as the first stage operation as the control group for pulmonary blood supply, because pulmonary flow is supplied through the conduit in Norwood procedure. We assessed single right ventricular function between HLHS and a ‘normal’ single right ventricle.

4.2. Associated lesions

The frequency of associated cardiac lesions, such as coronary ischemia [12], tricuspid regurgitation [13], restrictive ASD [14], and recoarctation of the aorta were high in HLHS, which would be associated with increased mortality [13] and responsible for decreased cardiac function. In this study, the number of additional procedures on stage II palliation was higher in the HLHS group in this study, implying that there was an additional hemodynamic load from associated lesions in the HLHS group. In contrast, in the single right ventricle group, associated cardiac lesions were low and the cause of two interstage deaths was respiratory infection.

4.3. Lower PAI in HLHS patients

Our data showed lower PAI at each right heart bypass operation in the HLHS group. Pulmonary arteries are commonly exposed by systemic high pressure before Norwood procedure in HLHS patients, and pulmonary artery pressure before stage I palliation in the single ventricle group was lower than the HLHS group. We suggest one of the cause of lower PAI in HLHS is pulmonary hypertension before Norwood procedure. Another cause is suggested to be from congenital alveolar capillary dysplasia with HLHS [15]. There is also some possibility of high pulmonary vascular resistance due to the pulmonary vascular embryological characteristics of HLHS etiology.

4.4. Sat O2 transition before stage II palliation

Although the size of the shunts and Qp/Qs were different, the oxygen saturation after stage I palliation in both groups was similar; there was a lower degree of hypoxia before BCPS in patients with HLHS. We believe that the causes of lower saturations before BCPS in group H could be due to decreased cardiac output. Although a lower mixed venous saturation would be another cause, sampling was not performed in this study. Our data suggests that poor contractility of the single right ventricle could cause unstable hemodynamics after Norwood procedures and HLHS is not a ‘normal single right ventricle’.

4.5. CTR and SVDd before stage II palliation

In this study before BCPS, an acute increase in CTR, and SVDd without significant development of atrioventricular valve regurgitation, suggested a decrease in cardiac function. The acute increases in CTR and SVDd accompanied by progressive hypoxia in the current study are difficult to explain. Based on the data, we hypothesized that decreased cardiac function occurs first, causing secondary hypoxia.
4.6. Pathophysiology

We believe that coronary ischemia caused by a narrowed ascending aorta may be one of the cause of hemodynamic instability. Some reports have shown that the presence of a hypoplastic ascending aorta is correlated with mortality in patients who underwent a Norwood procedure [16]. In this study, a narrowed ascending aorta under 3 mm was found in 78% of HLHS patients. Impaired diastolic coronary flow after undergoing the Norwood procedure [17] could be another possible mechanism.

Interestingly, CTR and SVDd in the interstage between stage I palliation and BCPS acutely increased in patients with HLHS while no change occurred in the non-HLHS group. These data indicate that HLHS cannot accommodate volume overload. Another cause for the data in HLHS is the reduced fibrous matrix of the HLHS ventricle [16], which causes ventricular weakness in response to volume load. In pulmonary atresia with intact ventricular septum, ischemic exposure to the heart induces collagensynthesis [18] but our study demonstrated progressive hypoxia in the setting of HLHS.

4.7. Surgical procedures

Despite improved outcome using a right ventricle to pulmonary artery conduit for the modified Norwood procedure [5-7], our data did not show a significant difference in CTR, SVDd, and pulmonary artery size between BT shunt and right ventricle to pulmonary artery conduit. Similarly, there are no significant difference in CTR, SVDd, and pulmonary artery size between pulmonary stenosis and atresia. There is a difference in shunt sizes both between as well as in the groups, and further studies will be required to determine the relationship of shunt size and a complete subset analysis of each of the groups.

4.8. Interstage death in HLHS

Other problems before stage II palliation have been reported as impairment of coronary perfusion, unstable pulmonary blood flow, and neoaortic obstruction [19]. One of the greatest problems of the staged Fontan procedure for HLHS is unexpected death interstage before stage II palliation, with a reported frequency of 4-15% [1,20]. The factors that correlate with unexpected death in the interstage after Norwood procedure are yet to be clearly determined.

In this study, the main cause of late deaths after Norwood procedure was cardiac failure due to associated cardiac lesions, and the frequency of additional procedures of stage II palliation were high in HLHS patients. Our results showed that one of the causes of interstage death are acute progressive associated lesions. In pulmonary circulation, a lower oxygen saturation and PAI on right heart bypass operation were detected in HLHS. We suggest that hemodynamic instability characterized by low pulmonary flow and ventricular weakness indicates acute increasing of CTR and SVDd and is another cause of the higher frequency of interstage death in HLHS patients than in non-HLHS patients.

4.9. Right heart bypass operation for HLHS

Although satisfactory results have been achieved with cavopulmonary shunts [21,22] and hemi-Fontan procedures [23] in stage II palliation, the optimal timing of stage II palliation for HLHS is undetermined. The merit of early right heart bypass [21,24] is to protect the pulmonary artery from systemic arterial pressure and to decrease volume loading on the single right ventricle. On the other hand, if cavopulmonary shunting is performed in a setting of high pulmonary resistance, the right heart bypass operation could fail due to pulmonary immaturity. To add shunts to the pulmonary flow to treat progressive hypoxia in the interstage after the Norwood procedure, we need to determine whether decreased cardiac function will permit volume overload.

Our data showed that MPAP is higher after BCPS in patients with HLHS and that the effect of high pulmonary resistance decreases gradually as the patient reaches adulthood. Postoperative courses, which were assessed by clinical parameters, showed no significant differences in either group. Once right heart bypass circulation is achieved, there is a low mortality in patients with HLHS [25]. There was lower mortality after right heart bypass operation in HLHS and non-HLHS patients in this study, consistent with previous studies [17]. Our staged Fontan strategy of stage II palliation performed by BCPS and the Fontan completion mainly performed by extracardiac conduit [14] resulted in excellent outcomes.

4.10. Study limitations

In this study, on stage I palliation, all patients of the Norwood group were neonates, while there were three neonates in the single ventricle group. Interstage deaths were not included in the comparisons of the results and there were 23 patients, without decreased patients, each in the Norwood and shunt groups. In the surgical procedures, half of the patients had right ventricle to pulmonary artery shunt for pulmonary blood supply in our Norwood modification. Therefore, this study was not a strict comparison of BT shunts between patients with HLHS or single right ventricle. We selected patients who had systemic-to-pulmonary artery shunt performed without a comparable intracardiac procedure as the control group: the Norwood procedure performed by BCPS and the Fontan completion mainly performed by extracardiac conduit [14] resulted in excellent outcomes.
5. Conclusions

In summary, HLHS patients showed acutely increased CTR, SVDd and decreased Sat O₂ in the interstage period after a Norwood procedure. Smaller pulmonary artery size and a tendency to higher MPAP were also found more in HLHS than single right ventricle patients. The frequency of associated cardiac lesions requiring an additional procedure on stage II palliation was high in HLHS patients. These results may indicate greater interstage hemodynamic instability in HLHS patients than in single right ventricle patients. This suggests that the weakened hemodynamics of HLHS could be one of the causes of the high mortality before stage II palliation. Outcomes improve following right heart bypass operation using a staged Fontan strategy, with no significant differences in the clinical postoperative course between HLHS and single right ventricle patients.

References


