Is there a role for extracorporeal life support after stage I Norwood?∗

C. Pizarro∗, D.A. Davis, R.M. Healy, P.J. Kerins, W.I. Norwood

Nemours Cardiac Center, Alfred I. DuPont Children Hospital, 1600 Rockland Road, Wilmington, DE 19899, USA

Received 8 October 2000; received in revised form 1 December 2000; accepted 29 December 2000

Abstract

Objectives: Controversy still surrounds the use of extracorporeal life support (ECLS) in patients with single ventricle physiology. An analysis of the experience with a group of neonates who underwent stage I Norwood palliation and received ECLS is reported. Methods: A retrospective review of hospital records, operative notes and perfusion data was performed in a group of 12 consecutive patients undergoing ECLS in the perioperative period after stage I. An analysis to identify risk factors for poor outcome was performed. Results: The mean age and weight were 3.9 days (1±14) and 2.6 kg (1.4±3.8), respectively. There were 3/12 patients under 2.5 kg and four patients were under 35 weeks of gestation. The most common diagnosis (7/12) was hypoplastic left heart syndrome with aortic atresia. Associated extracardiac anomalies were present in four patients. Three patients had an additional cardiac defect and two of these required an additional surgical procedure besides the stage I Norwood. The mean circulatory arrest was 56 min (46±63). ECLS was initiated preoperatively in one, intraoperatively in nine, and postoperatively in two patients. The indication for support was: arrhythmia (one), low output (six), cardiac arrest (three), unbalanced circulation (one), and hypoxemia (two). The mean duration of support was 68 h (24±192). Eight patients were weaned off support, and six were discharged home in good condition. Morbidity included sepsis in five, renal failure in five, neurologic sequelae in three, and bleeding in two. Prematurity, renal dysfunction and the initiation of ECLS outside the operating room were significantly associated with poor outcome. Residual hemodynamic effect, low birth weight and neurologic event showed a tendency towards poor outcome, but did not reach statistical significance. Conclusions: Although the use of ECLS in patients with single ventricle physiology still carries a significant risk, prompt initiation of support can improve the outcome in a group of patients with impaired cardiopulmonary function after stage I palliation. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Hypoplastic left heart syndrome; Norwood procedure; Extracorporeal support; Pediatric; Cardiac surgery

1. Introduction

Extracorporeal membrane oxygenation (ECMO) has emerged as an effective technique for the mechanical support of many patients with refractory cardiac dysfunction following surgical repair of their congenital heart defect. After considerable experience with this technique in various centers, the reported success rate for hospital survival of patients who were on ECMO approximates 40% [1–8]. Patients with a single ventricle physiology constitute a particularly challenging subgroup of patients, with a reportedly worse overall outcome. The lower survival rate in these patients has been, in part, attributed to an imbalance between systemic and pulmonary perfusion, and its associated impact on coronary perfusion due to the diastolic run-off into the pulmonary bed. In addition, because the initial stage of this palliation requires an arterial communication, some degree of volume overload to the single pumping ventricle occurs. These features further complicate the recovery of a dysfunctional myocardium when weaning from cardiopulmonary bypass (CPB) and may explain why patients with a single ventricle type physiology, have a worse overall outcome.

Due to the limited experience with extracorporeal support and the poorer overall outcome with this particular patient population, single ventricle physiology has been considered a relative contraindication for post-cardiotomy support [6,7]. In this review, we report our experience with ECMO support after the stage I Norwood procedure.

2. Materials and methods

A retrospective review of 12 consecutive newborns that received extracorporeal circulatory support after stage I...
surgical palliation between January 1998 and September 1999 was performed. This review included hospital records, operative notes, as well as anesthesia and perfusion data. Multiple clinical variables were analyzed for their impact on survival to hospital discharge. These clinical variables included demographic factors, certain aspects of CPB, and details regarding the management of the extracorporeal support and its complications (Appendix A).

The decision to initiate extracorporeal support was based on the presence of low cardiac output, persistent acidosis, difficulty to balance pulmonary/systemic circulation (Qp/Qs), severe hypoxemia, the presence of arrhythmia, and/or cardiac arrest in the perioperative period. We did not use a specific algorithm or clinical pathway to dictate when extracorporeal support would be employed. Our practice was to employ intravenous (dopamine and sodium nitroprusside) and/or inhalational (CO₂/N₂) therapies to either redistribute or improve the cardiac output. When these maneuvers were insufficient, then extracorporeal support was provided to the patient. All patients are represented in Table 1.

### Table 1

<table>
<thead>
<tr>
<th>Patient</th>
<th>Dx</th>
<th>Age (days)</th>
<th>Weight (kg)</th>
<th>Procedure</th>
<th>Shunt size (mm)</th>
<th>DHCA (min)</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HLHS critical AS renal dyspl</td>
<td>6</td>
<td>2.6</td>
<td>Stage I</td>
<td>4</td>
<td>49</td>
<td>Intraoperative</td>
</tr>
<tr>
<td>2</td>
<td>HLHS (mh, as) papvd</td>
<td>1</td>
<td>3.1</td>
<td>Stage I</td>
<td>4</td>
<td>Intraoperative</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>HLHS (ma, aa)</td>
<td>4</td>
<td>2.8</td>
<td>Stage I</td>
<td>4</td>
<td>46</td>
<td>Intraoperative</td>
</tr>
<tr>
<td>4</td>
<td>Dilated cardiomyopathy</td>
<td>5</td>
<td>3.0</td>
<td>Stage I batista</td>
<td>4</td>
<td>54</td>
<td>Intraoperative</td>
</tr>
<tr>
<td>5</td>
<td>HLHS (dorv, ma) Chromosome 11 deletion</td>
<td>1</td>
<td>3.8</td>
<td>Stage I after arch rep paband</td>
<td>4</td>
<td>50</td>
<td>Preoperative</td>
</tr>
<tr>
<td>6</td>
<td>HLHS (ma, aa) 33 wks</td>
<td>3</td>
<td>1.5</td>
<td>Stage I</td>
<td>3.5</td>
<td>63</td>
<td>Intraoperative</td>
</tr>
<tr>
<td>7</td>
<td>HLHS (ma, aa) cor triatrium premie</td>
<td>2</td>
<td>2.6</td>
<td>Stage I</td>
<td>3.5</td>
<td>56</td>
<td>Postoperative</td>
</tr>
<tr>
<td>8</td>
<td>HLHS (ms, aa) triplets premie</td>
<td>14</td>
<td>1.4</td>
<td>Stage I</td>
<td>3.5</td>
<td>58</td>
<td>Postoperative</td>
</tr>
<tr>
<td>9</td>
<td>HLHS (ma, aa) cdh, scimitar</td>
<td>4</td>
<td>2.9</td>
<td>Stage I</td>
<td>4</td>
<td>Intraoperative</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>HLHS (ms, as)</td>
<td>5</td>
<td>3.3</td>
<td>Stage I</td>
<td>4</td>
<td>58</td>
<td>Intraoperative</td>
</tr>
<tr>
<td>11</td>
<td>HLHS (dorv ma) tapvc</td>
<td>1</td>
<td>3.3</td>
<td>Stage I repair of tapvc</td>
<td>4</td>
<td>60</td>
<td>Intraoperative</td>
</tr>
<tr>
<td>12</td>
<td>HLHS (mh, as) Turner Mosaic</td>
<td>1</td>
<td>2.0</td>
<td>Stage I</td>
<td>4</td>
<td>60</td>
<td>Intraoperative</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Patient</th>
<th>Indicat</th>
<th>ECMO run (h)</th>
<th>Shunt</th>
<th>Weaned</th>
<th>Length of stay (days)</th>
<th>Mortality</th>
<th>Late neurol fx</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lco</td>
<td>48</td>
<td>Partially closed</td>
<td>Yes</td>
<td>32</td>
<td>Survived</td>
<td>Normal</td>
</tr>
<tr>
<td>2</td>
<td>Lco</td>
<td>24</td>
<td>Open</td>
<td>Yes</td>
<td>20</td>
<td>Survived hemifont</td>
<td>Normal</td>
</tr>
<tr>
<td>3</td>
<td>Unbal Qp/Qs</td>
<td>24</td>
<td>Open</td>
<td>Yes</td>
<td>19</td>
<td>Survived hemifont</td>
<td>Normal</td>
</tr>
<tr>
<td>4</td>
<td>Lco</td>
<td>120</td>
<td>Open</td>
<td>1 failed, 2 yes</td>
<td>53</td>
<td>Survivor hemifont</td>
<td>Normal</td>
</tr>
<tr>
<td>5</td>
<td>Cardiac arrest</td>
<td>112</td>
<td>Closed/open</td>
<td>Yes</td>
<td>36</td>
<td>Death sepsis, atn, ich</td>
<td>Normal</td>
</tr>
<tr>
<td>6</td>
<td>Lco</td>
<td>102</td>
<td>Closed</td>
<td>Taken off</td>
<td>7</td>
<td>Death, asc ao obst, ich</td>
<td>Normal</td>
</tr>
<tr>
<td>7</td>
<td>Arrest POD #1</td>
<td>70</td>
<td>Closed</td>
<td>Taken off</td>
<td>5</td>
<td>Death, no cardiac fx</td>
<td>Normal</td>
</tr>
<tr>
<td>8</td>
<td>Apnea, arrest</td>
<td>48</td>
<td>Open/closed</td>
<td>Failed</td>
<td>6</td>
<td>Death, nec, atn</td>
<td>Normal</td>
</tr>
<tr>
<td>9</td>
<td>Lco, severe hypoxia</td>
<td>192</td>
<td>Open</td>
<td>Failed X 2</td>
<td>14</td>
<td>Death, atn, lung failure;</td>
<td>Normal</td>
</tr>
<tr>
<td>10</td>
<td>SVT</td>
<td>24/66</td>
<td>Open/closed/open</td>
<td>Yes; 2 yes</td>
<td>13</td>
<td>Death, pulm hemorrhage, sepsis</td>
<td>Normal</td>
</tr>
<tr>
<td>11</td>
<td>Hypoxia</td>
<td>24</td>
<td>Open</td>
<td>Yes</td>
<td>12</td>
<td>Survivor, hemifont</td>
<td>Normal</td>
</tr>
<tr>
<td>12</td>
<td>Lco</td>
<td>24</td>
<td>Open</td>
<td>Yes</td>
<td>14</td>
<td>Survivor, hemifont late death 7/10/00</td>
<td>Normal</td>
</tr>
</tbody>
</table>

* HLHS, hypoplastic left heart syndrome; AS, aortic stenosis; mh, mitral hypoplasia; aa, aortic atresia; ma, mitral atresia; dorv, double outlet right ventricle; wks, weeks; cor triatria, cor triatriatum; tapvc, total anomalous pulmonary venous connection; cdh, congenital diaphragmatic hernia; lco, low cardiac output; unbal qpsqs, unbalanced pulmonary/systemic circulation; pod, postoperative day; svt, supraventricular tachycardia.
2.1. ECMO circuit

2.1.1. Circuit components

The CPB circuit consisted of a 0.25-inch PVC tubing and a Carmeda-coated Minimax Plus oxygenator/heat exchanger (Medtronic Cardiopulmonary, Inc., Anaheim, CA), an open Micro venous/cardiotomy reservoir (Cobe Laboratories, Arvada, CO), and roller pumps (Sarns/3M Healthcare, Ann Arbor, MI). The system was configured to allow full CPB in the operating room with the option to provide postoperative ECMO or ventricular assist (VAD) without the interruption of blood flow or gas exchange when adjusting the level of support, thus eliminating exposure of the perfusate to new surfaces or interrupting the support.

2.1.2. Priming components

The priming volume is approximately 450 cc, consisting of Plasma-lyte A which is displaced by fresh whole blood (approximately 24–48-h-old) to achieve a pump hematocrit of 20%. Additional medications include heparin (100 units/kg), solumedrol (30 mg/kg), lasix (1 mg/kg), mannitol (0.5 g/kg), NaHCO₃ (10 mEq), oxacillin (25 mg/kg), and gentamycin (2.5 mg/kg). In addition, 100 units/kg of heparin are administered to the patient just prior to cannulation.

2.1.3. Perfusate pathway

Fig. 1 illustrates the pathway for blood during conventional CPB in the operating room. From the venous cannulation, blood drains by gravity to the venous reservoir, then is pumped by the arterial roller pump to the integrated heat exchanger and oxygenator which has ports for laboratory sampling and volume administration. From the oxygenator, blood travels to the arterial cannula; this line includes an arterial to venous bridge which allows recirculation of the A–V loop. This bridge is configured with straight 0.25-inch tubing connectors with luer adapters, stopcocks and 0.25-inch perfusion adapters. This allows the bridge to remain closed to the A–V loop and crystalloid primed until needed, negating the need to ‘flash’ the bridge routinely.

Fig. 1. The complete CPB circuit as it is set up in the operating room. Dashed lines represent crystalloid primed components.

Fig. 2. The steps needed to remove the venous cardiotomy reservoir without interrupting support while converting to ECMO support. A 0.25-inch straight connector is positioned in the venous reservoir loop in place of the venous reservoir.

Fig. 3. The blood path during ECMO support.
When ECMO is needed following surgical repair, the venous reservoir is removed from the circuit by utilizing the reservoir bypass loop which facilitates the smooth transition from CPB to ECMO (Fig. 2). Fig. 3 illustrates the blood path during ECMO, this includes a 4-inch VAD line that is clamped and crystalloid primed for conversion to VAD, if desired. An additional 6-foot line is clamped and crystalloid primed to provide a closed loop to recirculate the bypassed oxygenator during the VAD. Fig. 4 illustrates the circuit configuration during VAD, by moving the clamp positions; conversion from ECMO to VAD is achieved without interruption of support.

2.2. Anticoagulation

A continuous heparin sodium infusion was used in order to maintain an activated clotting time of 180–200 s. Hemoglobin was maintained at 10 mg/dl during full support, and greater than 14 mg/dl when partial support was used or when weaning from the circuit was anticipated. Fresh whole blood was used during surgery and in the immediate postoperative period in order to achieve hemostasis. Subsequently, packed red blood cells were used to increase the hematocrit as needed. All blood was tested for human immunodeficiency virus and hepatitis C.

2.3. Cannulation

All patients received cannulation via median sternotomy using a single right atrial cannula and an arterial cannula in the main pulmonary artery or reconstructed neo aorta. No left atrial cannula was placed for additional drainage if there was an unobstructed intra-atrial communication. In the case of intraoperative institution of support, the patient was kept on the same circuit used for the surgery. The cannulae were kept in place, the pursestrings were controlled with a tourniquet and surgical clips, the chest was closed with a silastic patch, and a direct wall suction catheter was used to evacuate shed mediastinal blood. Adequate cardiac decompression was evaluated by direct inspection and/or echocardiogram. If the patient left the operating room without support, but was considered likely to require it in the immediate postoperative period, then the pursestrings and tourniquets were secured with a surgical clip and left in the chest. This action would facilitate rapid recannulation and the institution of extracorporeal support when needed.

2.4. Flows

The primary goal of the extracorporeal support in this patient population with their parallel circulations was to maintain adequate tissue perfusion, minimize pulmonary overcirculation, and provide time for the myocardial and/or lung dysfunction to recover. The flows (which ranged between 50 and 150 ml/kg per min) were titrated according to each patient’s needs, maintaining adequate gas exchange, tissue perfusion and acceptable acid base status. Accordingly, the mechanical ventilatory support and the gas flow through the oxygenator were adjusted to achieve acceptable levels of alveolar gas exchange. While on extracorporeal support, all inotropic medications were discontinued.

2.5. Ventilator

After the initiation of the circulatory support, manipulations in the inspired gas mixture on the ventilator were made to achieve acceptable arterial blood gases. The mechanical ventilatory support was titrated according to the amount of extracorporeal support. If the baby was on greater than 75 cc/kg flow per min, the ventilator would typically be set to provide a 20 cc/kg tidal volume at ten breaths/min with an attendant end expiratory pressure of 10 cm of H2O. The patients received a remifentanil infusion for sedation.

2.6. Shunt management

The prevailing strategy during this experience was to leave the aorta–pulmonary shunt open during the period of support, unless there was a significant degree of run-off towards the pulmonary circuit. If there was a significant fall in the mean arterial pressure (particularly diastolic pressure) and/or significant cardiac distention, the shunt was partially occluded until hemodynamic recovery occurred, at which point the shunt was reopened. The size of the shunt was 4.0 mm, unless the baby was prematurely born, in which case, the shunt was 3.5 mm in size.

2.7. Fluid management

Depending on their fluid status and renal function, these
patients were managed with fluid restriction, diuretics and/or ultrafiltration in an effort to decrease interstitial edema and improve cardiopulmonary function. Electrolytes were kept within the normal range and nutritional support was provided.

2.8. Weaning

Once signs of cardiopulmonary recovery were evident as judged by improved hemodynamic parameters, an increase in arterial override, improved cardiac contractility by direct inspection, a well balanced Qp/Qs, and adequate alveolar gas exchange, the extracorporeal support was lowered. The ventilator support was increased and inspired carbon dioxide, low dose dopamine and sodium nitroprusside may have been administered in order to achieve a balance in systemic and pulmonary circulations. This process was monitored by frequent clinical observation and arterial blood gas analysis. Delayed sternal closure was usually performed 24 h after decannulation.

2.9. Statistical analysis

Data analysis was performed using SPSS (SPSS, Inc., Chicago, IL). The cross-tabulation procedure and Fisher’s exact test were used for all the discrete variables. The continuous variables were analyzed with a Mann–Whitney test. Statistical significance was determined at $P < 0.05$.

3. Results

The mean age in this group of patients was 3.9 days, with a range of 1–14 days. The mean weight was 2.6 kg, with a range of 1.4–3.8 kg. There were 13 runs of extracorporeal support in 12 patients. The mean duration was 67 h, with a median of 48 and a range of 24–192 h. After the support, 8/12 patients were successfully weaned off the support and 6/12 were discharged home.

There were three patients with a weight of 2 kg or less. Four patients had gestational ages of less than 35 weeks at birth, and two of these patients were products of multiple pregnancy (twins and triplets, respectively). Another patient in this group had a diagnosis of congenital diaphragmatic hernia, hypoplastic left lung and scimitar syndrome, in addition to hypoplastic left heart syndrome. This patient underwent stage I Norwood palliation 3 days after his diaphragmatic hernia repair.

The most common cardiac diagnosis was hypoplastic left heart syndrome of the mitral atresia, aortic atresia variant. One patient with critical aortic stenosis underwent a failed balloon valvuloplasty and had stage I Norwood 2 days later. Another patient had a prenatal diagnosis of severely dilated and poorly functioning left ventricle, associated with mitral valve hypoplasia and mitral regurgitation. The aortic arch was unobstructed but there was retrograde flow via the ductus into the arch. This baby had a stage I palliation at 5 days of age [9].

Other associated cardiac anomalies were present in five patients and included cor triatriatum, dilated myopathy, scimitar syndrome and partial and total anomalous pulmonary venous connection. Additional surgical procedures were performed in two of these patients: a partial ventriculectomy and the repair of total anomalous pulmonary venous drainage, respectively.

Associated non-cardiac diagnoses included: Turner syndrome in one patient, chromosome 11 deletion in another patient, renal dysplasia in a third, and a congenital diaphragmatic hernia as well as scimitar syndrome in the fourth patient.

The mean duration of deep hypothermic circulatory arrest was 56 min, with a range between 46 and 63 min. A comparison of the pre-support variables is shown in Table 2.

The most common indication for support was myocardial dysfunction, followed by cardiac arrest, inability to balance Qp/Qs, pulmonary dysfunction and arrhythmia. The institution of support was most commonly performed at the conclusion of the surgical repair (9/12). One patient was placed on support after a cardiac arrest before her stage I, and two other patients were supported after suffering a cardiac arrest in the postoperative period.

All of the patients who were hospital survivors had initiation of support in the operating room. Subsequently, five of these patients are known to have completed their second stage (hemifontan or bi-directional Glenn). Unfortunately, one of them died at home after his second stage.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Pre-support variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
<td>Survivors</td>
</tr>
<tr>
<td>Age</td>
<td>3</td>
</tr>
<tr>
<td>Weight</td>
<td>2.8</td>
</tr>
<tr>
<td>Prematurity</td>
<td>0/6</td>
</tr>
<tr>
<td>Low birth weight</td>
<td>1/6</td>
</tr>
<tr>
<td>Associated cardiac dx</td>
<td>3/6</td>
</tr>
<tr>
<td>Associated non-cardiac dx</td>
<td>2/6</td>
</tr>
<tr>
<td>Circulatory arrest</td>
<td>53</td>
</tr>
<tr>
<td>Residual defect</td>
<td>0/6</td>
</tr>
</tbody>
</table>

a NS, no statistical significance.

Table 3

<table>
<thead>
<tr>
<th>Initiation of support variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
</tr>
<tr>
<td>Shunt open at cannulation</td>
</tr>
<tr>
<td>Support in ICU</td>
</tr>
<tr>
<td>Support in OR</td>
</tr>
<tr>
<td>Support for cardiac arrest</td>
</tr>
</tbody>
</table>

b $P < 0.056$. 

גיבוש אינטרגלי נתרן ב-398 ימים, עם نطاق 1–14 ימים. המשקל הממוצע היה 2.6 קг, עם نطاق 1.4–3.8 קג. היו 13 תיליניSKTOP שבהם 12 נפגעים. הנקבה הממוצעת של הקריון נמשכה 67 שעות, עם מדיה של 48 שעות וטווח של 24–192 שעות. לאחר הקריון, 8 מתוך 12 נפגעים הצליחו לשוער מהקריון והושארו בבית החולים לחופש." "There were three patients with a weight of 2 kg or less. Four patients had gestational ages of less than 35 weeks at birth, and two of these patients were products of multiple pregnancy (twins and triplets, respectively). Another patient in this group had a diagnosis of congenital diaphragmatic hernia, hypoplastic left lung and scimitar syndrome, in addition to hypoplastic left heart syndrome. This patient underwent stage I Norwood palliation 3 days after his diaphragmatic hernia repair.

The most common cardiac diagnosis was hypoplastic left heart syndrome of the mitral atresia, aortic atresia variant. One patient with critical aortic stenosis underwent a failed balloon valvuloplasty and had stage I Norwood 2 days later. Another patient had a prenatal diagnosis of severely dilated and poorly functioning left ventricle, associated with mitral valve hypoplasia and mitral regurgitation. The aortic arch was unobstructed but there was retrograde flow via the ductus into the arch. This baby had a stage I palliation at 5 days of age [9].

Other associated cardiac anomalies were present in five patients and included cor triatriatum, dilated myopathy, scimitar syndrome and partial and total anomalous pulmonary venous connection. Additional surgical procedures were performed in two of these patients: a partial ventriculectomy and the repair of total anomalous pulmonary venous drainage, respectively.

Associated non-cardiac diagnoses included: Turner syndrome in one patient, chromosome 11 deletion in another patient, renal dysplasia in a third, and a congenital diaphragmatic hernia as well as scimitar syndrome in the fourth patient.

The mean duration of deep hypothermic circulatory arrest was 56 min, with a range between 46 and 63 min. A comparison of the pre-support variables is shown in Table 2.

The most common indication for support was myocardial dysfunction, followed by cardiac arrest, inability to balance Qp/Qs, pulmonary dysfunction and arrhythmia. The institution of support was most commonly performed at the conclusion of the surgical repair (9/12). One patient was placed on support after a cardiac arrest before her stage I, and two other patients were supported after suffering a cardiac arrest in the postoperative period.

All of the patients who were hospital survivors had initiation of support in the operating room. Subsequently, five of these patients are known to have completed their second stage (hemifontan or bi-directional Glenn). Unfortunately, one of them died at home after his second stage.

There were no hospital survivors in the group of patients...
who underwent institution of extracorporeal support outside
the operating room, either in the pre- or postoperative period
(Table 3). All 12 patients had a systemic to pulmonary shunt depen-
dent pulmonary circulation. The degree of pulmonary over-
circulation, the adequacy of systemic and coronary perfusion, and the degree of cardiac distortion influenced
the shunt management. Eight patients were managed with
their shunts open throughout the period of their extracorpore-
al support. Among these eight patients, six were success-
fully weaned off support and five became hospital survivors.

Four patients required partial closure or total shunt occlu-
sion at the initiation of the support due to the excessive
pulmonary overcirculation and inadequate systemic perfusion
pressure despite high flows. Only one patient was weaned successfully after 48 h of support, and was eventu-
ally discharged from the hospital.

Two patients had a devastating neurological complication
and were taken off support. A third patient had no recovery
of cardiac function after 5 days on the circuit and was simili-
arily removed from support.

The incidence and comparison of major complications
between survivors and non-survivors is shown in Table 4. Non-survivors were more likely to have sustained renal,
neurologic, respiratory and bleeding complications, although renal dysfunction was the only event associated
with poor outcome \( (P < 0.05) \). All of the neurologic events
were present in the non-survivor group, however, this factor
did not reach statistical significance. Sepsis was evenly
distributed among survivors and non-survivors.

There were no long-term neurologic, renal or pulmonary
sequelae in any of the survivors.

4. Discussion

Currently, extracorporeal membrane oxygenator (ECMO)
has become a well established form of cardiac support for
children with myocardial dysfunction after surgical repair of
congenital heart defects \([1–8]\). The appropriate selection of
pediatric patients for extracorporeal circulatory support
continues to be a matter of controversy, especially in condi-
tions associated with single ventricle physiology \([6,7]\). The

<table>
<thead>
<tr>
<th>Complication</th>
<th>Patients</th>
<th>Survivors/non-survivors</th>
<th>Significance*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sepsis</td>
<td>5</td>
<td>2/3</td>
<td>NS</td>
</tr>
<tr>
<td>Renal failure</td>
<td>5</td>
<td>0/5</td>
<td>( P &lt; 0.05 )</td>
</tr>
<tr>
<td>Ultrafiltration</td>
<td>5</td>
<td>0/5</td>
<td>( P &lt; 0.05 )</td>
</tr>
<tr>
<td>Neurologic</td>
<td>3</td>
<td>0/3</td>
<td>NS(^{b})</td>
</tr>
<tr>
<td>Respiratory</td>
<td>3</td>
<td>0/3</td>
<td>NS</td>
</tr>
<tr>
<td>Bleeding</td>
<td>2</td>
<td>0/2</td>
<td>NS</td>
</tr>
<tr>
<td>Circuit complication</td>
<td>1</td>
<td>1/0</td>
<td>NS</td>
</tr>
</tbody>
</table>

\(^{a}\) NS, no statistical significance.

\(^{b}\) \( P < 0.056 \).

Extracorporeal Life Support Organization’s (ELSO) registry
uses a mixture of anatomic and physiologic criteria to define
eight different subgroups of cardiac patients. Hypoplastic left
heart syndrome is listed as having a worse overall outcome
when ECMO is used. This is based on the experience of 209
accumulated cases, with an average run-time of 126 h and a
reported survival of only 27%. Similarly, when looking at
patients having a stage I Norwood procedure, this registry
reports a 26% hospital survival rate for a group of 97 patients
treated \([10]\).

Our results demonstrate that in the group of patients who
required extracorporeal support after stage I Norwood
palliation, 66% \((8/12)\) of them could be successfully weaned
from extracorporeal support, and 50% \((6/12)\) were
discharged home in good condition. The presence of a resi-
dual hemodynamic defect determined a poor outcome in
one of our patients. This is consistent with the ECMO litera-
ture \([5,6,8]\) that states that extracorporeal support cannot
overcome the handicap of an inadequate repair. If the
patients with residual surgical defects were excluded, then
the overall success rate to hospital discharge was improved
to over 50% in our series.

These results may be directly related to the indications,
timing and threshold for the initiation of extracorporeal
support. Contrary to the experience of other centers,
where the intraoperative initiation of support was associated
with worse outcomes \([3,6,11]\), our experience revealed the
opposite. In fact, we had a lack of survivors when patients
were placed on extracorporeal support out of the operating
room, and a much better outcome in those patients placed
on support in the operating room. This experience is similar to
that reported by Jaggers et al. \([12]\), where the early institu-
tion of extracorporeal support in the operating room was
associated with a better chance of survival to hospital
discharge in a cohort of patients, including ten patients
with single ventricle. There is little doubt that patients
with single ventricle physiology are more vulnerable to
myocardial damage and tolerate dysfunction less than
other patients who do not have the added demands of balan-
cing two circulations and adapting to an increased volume
burden. Therefore, it is not surprising that these patients
would require some cardiac support postoperatively. By
providing mechanical circulatory support in a timely way,
this patient population is afforded time to adjust to the
increased demands to its ventricle.

Our strategy of maintaining the shunt open during the
extracorporeal support is based on clinical and laboratory
evidence that antegrade pulmonary blood flow is beneficial
\([12,13]\). Of course, it is difficult to conclude that leaving a
shunt patent during extracorporeal support is the cause of the
improved outcome in our patients. Perhaps those patients
who were able to have their shunts open had more favorable
hemodynamics and that is the explanation for their improved
outcome. In fact, those with the worse hemodynamics and the
most significant myocardial dysfunction, had low perfusion
pressures and significant compromise of their coronary
perfusion. In this scenario, closure of the shunt provided temporary improvement of the hemodynamic conditions by increasing the systemic perfusion pressure and coronary blood flow, and decreased the amount of pulmonary over-circulation and cardiac distension. Not surprisingly, in our experience, the patients who required shunt occlusion at the institution of extracorporeal support had the worse hemody-namic profile and required the highest amount of support. We had only one survivor in the group of patients who had their shunts occluded during their support and this patient had his shunt only temporarily occluded. This patient was eventually weaned off and discharged home. Despite the fact that it appeared that occluding the shunt would be associated with a poor outcome, this variable did not reach statistical signifi-cance as a risk factor for mortality.

Although not used in our particular patient population, the VAD device is another form of circulatory support to be used when only myocardial dysfunction is present. A recent report by Thuys et al. [14] included 12 patients with hypoplastic left heart syndrome who were managed with this form of support. Although their report only had a 25% hospital survival rate (3/12), it demonstrated the advantages of this form of support: effective reduction in preload and wall stress, decrease in anticoagulation needs, decrease in inflammatory effects related to the device and simplicity [14,15]. This is an attractive modality assuming the lung function and the ability to balance the systemic and pulmonary circulations are adequate.

Despite our reported improvement in survival in this patient population, the morbidity in these patients remains quite high. When looking at different potential risk factors for poor outcome, renal dysfunction was the only factor that reached statistical significance. This is consistent with other reports [5,12]. Bleeding was not a common problem in our experience as opposed to most series [3,5,8,12]. This finding may be related to the use of fresh whole blood in the immediate postoperative period and the use of a heparin-coated circuit, which allowed the maintenance of lower activated clotting times. Consequently, the need for mediastinal exploration was infrequent.

Neurologic complications were mostly related to intracranial bleeding, which is not surprising given this younger aged group. Those infants with neurologic complications were also the ones who had their support instituted after having had a cardiac arrest. The presence of neurologic dysfunction showed a tendency towards a poor outcome, but it did not reach statistical significance, perhaps because of a small sample size.

In reviewing our experience, we believe that satisfactory results can be achieved when using ECMO support for patients after stage I Norwood palliation. It is clear that failure to wean from CPB after the procedure is not a contra-indication to this therapy, assuming there are no residual hemodynamic defects. The institution of support after cardio-vascular collapse has occurred, unfortunately, remains a significant factor for poor outcome. Early initiation of mechanical circulatory support should be considered when signs of hemodynamic instability are developing. Utilizing the same circuit during surgery or having a circuit primed and ready in case it is needed in the intensive care unit, are some of the techniques that allow for the prompt utilization of this therapy. Unfortunately, in our series of patients, although this plan has minimized the time to cannulation in an emergency situation, the survival for post-arrest support remains poor.

5. Summary

We believe that extracorporeal support provides a valid treatment option in the management of patients with cardiopulmonary dysfunction after stage I Norwood palliation, especially if initiated early. The results of our experience demonstrate that the use of extracorporeal support can rescue some patients and provide an additional increase in the survival rate after surgery for this complex form of congenital heart disease. New modifications of extracor-poreal support in the subgroup of patients with single ventricle physiology are being explored. Hopefully, this progress will result in improved outcomes for some patients who other-wise would have been lost.

6. Limitations

The retrospective nature of this study and the small number of patients are important factors that need to be considered, due to the fact that statistical power is lacking in many of the comparisons made. Also the lack of a random-ized patient allocation process to the strategy described and the lack of a control group make the analysis difficult and susceptible to error. Although the extracorporeal support provided was quite uniform, the lack of a consistent protocol detailing the selection and management of these patients makes the data interpretation more difficult.

Acknowledgements

The authors thank Stacey R. Armatti for her valuable assistance in the statistical analysis of these data.

References

manage similar children, and we recently published in the Annals this month our experience, and we have a 40% survival in children after the Norwood stage I procedure. We have struggled with appropriate management of the shunt, and I see that in the majority of your cases, you left the shunt open and said that you would close the shunt or partially occlude the shunt based on evidence of adequate systemic perfusion.

I would like to just ask you, what are your criteria for this? Is it based on lactic acid, mean arterial blood pressure, do you measure mixed venous oxygen? How do you determine that systemic perfusion is inadequate and that you need to partially or completely occlude the shunt?

Dr Pizarro: Certainly, the issue of shunt management has been raised by different groups, and it looks like the patients who had the shunt closed since the inception of the support tended to do poorly and some people attributed that to the fact that if you leave the shunt closed, then you have some problems with pulmonary complications, reperfusion injury and so forth.

I think that part of the problem is the fact that patients select out themselves. If you need to close the shunt because the run-off is excessive, the diastolic blood pressure and coronary perfusion are compromised and the overall systemic perfusion is also inadequate, those patients are certainly the sickest patients who need the largest amount of support for the most prolonged time. It is fairly difficult to manage those patients, and whatever you do, probably your outcome is going to be worse than if you are able to leave the shunt open.

Our approach has been to watch for mean arterial blood pressure, a minimum diastolic blood pressure, in the 25–30 range, normalization of the ECG, and, avoid cardiac distension, and for that we will just have a quick look at the echocardiogram or direct cardiac inspection if we are exploring the patient and make sure the heart is decompressed. If we can’t decompress the heart because there is large run-off through the lungs, then that heart is going to have a fairly large end diastolic volume and the chances of recovery are going to be very poor. So that is basically what we used.

Dr A. Corno (Lausanne, Switzerland): I have two questions. As a result of this retrospective study, how did you change your policy on indication for ECMO after a Norwood? For instance, I noticed in prematurity you have all failures of the ECMO application. Are you now intending to refuse ECMO for a premature child after a Norwood?

And the second question, of course you are dealing with a patient who is cyanotic after a Norwood procedure; saturation is generally 73%. How do you begin and how do you run the ECMO, with a normoxic style or hypoxic cyanotic after a Norwood procedure; saturation is generally 73%. How do you begin and how do you run the ECMO, with a normoxic style or hypoxic style?

Dr Pizarro: First, premature babies or babies with low birth weights, CBR, IUGR, are certainly the most difficult subset of patients, and we actually had no survivors among those. However, I would say that before we would declare somebody dead if somebody crashes and has a significant collapse, our first initial response now is going to be to place them on support and see what happens in the first 48 h, and that is how actually this whole experience began. It turned out that some patients did well, and certainly premature babies, so far we haven’t been able to rescue any of them.

In reference to your second question, we normally put the patient on full flow or whatever flow is necessary for adequate systemic perfusion, and let’s say if we have a flow of over 75 ml/kg per min, we tend to set the ventilator at resting mode, ten breaths/min and between room air and 30%. We will just run that patient normoxic with hematorcrits between 30 and 35. The difficulty begins when you try to start weaning and that transition between the patient, assuming cardiopulmonary function and then you are decreasing the amount of support, that is where trying to balance the two circulations, it gets very tricky, and some patients fail in that stage.