Fate of pulmonary arteries following Norwood Procedure

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Abstract

Objective: This study evaluated the requirement for surgical reoperation and catheter-based reintervention to central pulmonary arteries (CPAs) following Norwood Procedure (NP). We sought to identify the influence of various surgical techniques employed during NP on subsequent interventions.

Methods: Between 1993 and 2004, 226 patients underwent Stage II following NP. Ninety-eight patients (43%) had completion of Fontan circulation (Stage III) and a further 107 (47%) are on course for Fontan completion with 21 (9%) inter-stage deaths. During NP, the aortic arch was reconstructed without additional material (n = 91, 40%) or with a pulmonary homograft patch (n = 135, 60%). Pulmonary blood flow was supplied by modified Blalock–Taussig shunt (n = 177, 78%) or right ventricle to pulmonary artery conduit (RV-PA; n = 49, 22%). The CPAs defect was closed directly (n = 69, 31%) or with a patch (n = 157, 69%). Complete resection of coarctation was performed in 126 patients (56%).

Results: Ninety-seven patients (43%) required surgical reoperation to CPAs during Stage II. Actuarial freedom from reoperation was 60 ± 3%, 52 ± 4% and 50 ± 4% at 1, 5 and 10 years, respectively. On multivariable analysis, NP with RV-PA increased risk of reoperation (LR 8.3, 5.3–13.2; p < 0.001). Forty-one patients (18%) required catheter-based reintervention on CPAs. Actuarial freedom from reintervention was 98 ± 1%, 72 ± 4% and 58 ± 6% at 1, 5 and 10 years, respectively. CPA problems were almost exclusively limited to the proximal Left pulmonary artery. On multivariable analysis, catheter-based reintervention became more common with time. Complete resection of coarctation increased risk of reintervention (LR 3.9, 1.6–9.6; p < 0.005).

Arch reconstruction and CPAs repair techniques did not affect risk of reoperation or reintervention on CPAs.

Conclusions: CPA stenoses and hypoplasia need surgical attention in approximately half of all patients undergoing the NP. The need for reoperation is increased when using the RV-PA conduit technique (although the majority of these are performed as part of the Stage II procedure). Catheter reinterventions are almost exclusively confined to the left CPA and are increased when the arch is shortened by resection of the coarctation tissue at time of NP.

Keywords: Norwood; Pulmonary arteries; Surgical technique

1. Introduction

Hypoplastic left heart syndrome (HLHS) describes a group of congenital cardiac abnormalities, characterised by severe stenosis or atresia of the mitral and aortic valves, a diminutive ascending aorta and left ventricular hypoplasia [1]. In 1983, William Norwood reported the first successful surgical palliation of HLHS [2], which involved an initial Norwood Procedure (NP) followed by the Fontan procedure. A bidirectional cavo-pulmonary anastomosis was subsequently introduced as an intermediate stage [3]. This three-stage surgical palliation remains the most commonly used method for the treatment of patients with HLHS.

In the recent years, there has been a substantial improvement in the outcome following surgical palliation for HLHS. This has been attributed to modifications in the surgical strategies and technique [4], and particularly to the reemergence of the right ventricle to pulmonary artery (RV-PA) conduit as an alternative to the modified Blalock–Taussig shunt (MBTS) as the source of pulmonary blood flow [5]. The RV-PA conduit is associated with more stable postoperative haemodynamics [6–9], improved ventricular function [9] and superior early survival in our own and other reported series [10,11]. The early survival following the Norwood Procedure in contemporary series varies between 73% and 90% [12–16]. As early survival improves, attention is increasingly being turned towards later morbidity, and the preservation of a well-developed pulmonary vascular tree is paramount to ensuring good outcomes from Stages II and III surgery.

Previous reports have suggested that the RV-PA conduit is associated with better development of the branch pulmonary arteries than the classical technique [17]. However, we have
found that despite this, a greater proportion of patients required subsequent central pulmonary arteries (CPAs) patch augmentation [17] at the time of Stage II. The aim of this study was to determine the requirement for reoperation and catheter-based reintervention to the CPAs following NP and the influence of different surgical strategies and techniques employed at our Institution for all patients with classical HLHS or systemic outflow tract obstruction associated with either right or left ventricular hypoplasia. We have focused particularly on the aortic arch reconstruction and on the type of shunt used.

2. Patients and methods

Between November 1992 and August 2004, 367 patients with functionally single ventricle anatomy and systemic outflow tract obstruction underwent NP at the Diana Princess of Wales Children's Hospital, Birmingham, United Kingdom. More than 90% of the patients had a right ventricular dependent systemic circulation (n = 333). The median age at operation was 4 days (range, 0–217 days). Early mortality for the entire series was 28% (n = 103) and there were 28 inter-stage deaths prior to Stage II procedure (cavo-pulmonary anastomosis). Exponentially Weighted Moving-Average (EWMA) identified a continued improvement in early outcome with an estimated early mortality of 10% in June 2004 [18]. Two hundred and twenty-six patients (61.5%) underwent Stage II procedure and these patients represent our study group (Table 1). To date, 98 patients (43%) have subsequently had completion of Fontan circulation (Stage III).

In previous studies from our institution [11, 17, 19–22], we have already described the surgical techniques and strategies employed during NP. Arch reconstruction was performed with two established techniques: the original technique, which involves arch reconstruction without the use of additional patch material, as previously reported by other authors [19–21]. In summary, all the duct and coarctation tissues were excised from the aorta, disconnecting the descending aorta from the arch. The aortic arch was opened along the inner aspect of the ascending aorta, down to the level of the divided proximal pulmonary artery, and a complex anastomosis was then constructed between aortic arch, proximal pulmonary artery and descending aorta. This technique was used in 40% (n = 91) of our study population.

The second technique involved arch reconstruction with a pulmonary homograft patch, as described by Jonas et al. [22]. The duct tissue was completely excised only in presence of severe coarctation, and the aortic back wall was left in continuity in all the other cases. The arch was open in the inner aspect of the ascending aorta and was then reconstructed with pulmonary homograft material cut to a teardrop shape. The proximal pulmonary artery was then anastomosed to a longitudinal incision in the allograft patch on the underside of the reconstructed neo-aorta. In these cases where the coarctation tissue was excised, the back wall of distal aortic arch and proximal descending aorta were joined directly and then the underside of the neo-aortic arch augmented with allograft material. This technique was used in 60% of patients (n = 135) and the duct and coarctation tissue was completely resected only in 35 patients. Amongst all study patients (n = 226), coarctation was completely resected in 126 patients (56%).

Pulmonary blood flow was supplied using a modified Blalock–Taussig shunt (n = 177, 78%) or a right ventricle to pulmonary artery conduit (n = 49, 22%). The MBTS was made with a polytetrafluoroethylene (PTFE) tube conduit (GORE-TEX®, W.L. Gore & Associates (UK) Ltd., Livingston, Scotland) from the innominate artery to pulmonary artery and the majority of patients had either a 3.5 mm (59%, n = 104) or a 3 mm shunt (37.2%, n = 65), depending on the pre-operative body weight. In patients where an MBTS was used, the central distal pulmonary artery defect was closed directly (29%, n = 51) or by a patch (71%, n = 126) of various materials (autologous pericardium, bovine pericardium, pulmonary homograft).

The RV-PA conduit was introduced in 2002. Initially, the RV-PA conduit was taken to the left side of the ascending aorta, as described by Sano et al. [5] and this was the technique used in the first 23 patients. In the last 26 cases of this group, the RV-PA conduit was passed on the right side of the ascending aorta. Forty-five patients (92%) had a 5 mm and four patients had a 4 mm RV-PA conduit, depending again on the pre-operative body weight.

In patients receiving an RV-PA conduit, the defect in the central distal pulmonary artery was closed by tailoring the distal end of the RV-PA conduit (37%, n = 18) or by a separated patch (63%, n = 31). Amongst all patients (n = 226), CPAs defect was closed directly in 69 patients (31%) and with a separate patch in 157 patients (69%) (Table 2).

Cardiac catheterisation was routinely undertaken prior to the creation of cavo-pulmonary shunt (Stage II) and completion of Fontan circulation (Stage III). Balloon angioplasty of the reconstructed aortic arch was performed in cases with a peak systolic gradient in excess of 10 mmHg. The CPAs after Norwood Procedure were assessed in detail to judge the need for surgical reconstruction during Stage II. Cardiac catheterisation prior to Stage III surgery was routinely performed from right internal jugular vein approach. CPAs stenosis was treated by balloon angioplasty and, increasingly, by stent implantation.

For the purposes of this study, actuarial freedom from subsequent patch augmentation on CPAs and actuarial freedom from subsequent catheter-based intervention on CPAs were used as outcome measures. These were analysed using univariable and multivariable analyses. The risk factors
analysed were: type of shunt used as pulmonary blood supply, duct and coarctation tissue resection, arch reconstruction technique (with or without pulmonary homograft), CPAs repair (defect closed with or without a patch), age at NP, age at Stage II, interval between Stages I and II, year of NP and year of Stage II.

This study involved the retrospective review of hospital records and echocardiographic and cardiac catheterisation data. All patients have been followed up since discharge from hospital by a paediatric cardiologist either in our own unit or in the patients’ referring hospital. Follow-up was complete with a median interval of 22 months (range, 32 days–11.6 years).

2.1. Statistical analysis

Data have been examined by analysis of variance using a commercial statistical software package (SPSS for Windows, version 12; SPSS Inc., Chicago, IL). Continuous variables are expressed as medians and ranges, and comparative univariable analyses were carried out using either the Mann–Whitney U-test or the Wilcoxon signed-rank test. Binomial or ordinal data were expressed as percentages, and comparative univariable analyses were conducted with the chi-squared test, the two-sided Fisher exact test or binomial logistic regression, as appropriate.

Actuarial freedom from reoperation and freedom from catheter-based reintervention were estimated by using the Kaplan–Meier product limit method. These results have been expressed as a probability estimate ±1 SEM. The influence of surgical strategies on these actuarial outcome measures have been made with the log-rank test and a stepwise Cox regression analysis. Results of these multivariate analyses have been expressed as likelihood ratios (LR) with 95% CI for variables with a p < 0.05.

3. Results

Ninety-seven patients (43%) needed reoperation on CPAs during cavo-pulmonary anastomosis (Stage II) (Table 3). Actuarial freedom from reoperation was 60 ± 3%, 52 ± 4% and 50 ± 4% at 1, 5 and 10 years following NP, respectively (Fig. 1). On univariable analysis, the risk factors for CPAs arterioplasty were: the use of an RV-PA conduit (rather than MBTS, p = 0.001); arch reconstruction with pulmonary homograft (p = 0.001); more recent date of NP (p = 0.001) and Stage II (p < 0.001). Multivariable analysis showed that only RV-PA conduit substantially increased risk of reoperation. Actuarial freedom from reoperation on CPAs during cavo-pulmonary anastomosis was 76 ± 5% for patients with MBTS and 3 ± 3% for patients with RV-PA conduit, at 1 year (LR 8.3, 5.3–13.2; p < 0.001) (Fig. 1).

Forty-one patients (18%) required catheter-based reintervention on CPAs. All these interventions were made between Stages II and III and/or after Stage III. Twelve patients required two consecutive catheter-based reintervention and three patients had three consecutive reintervention. Twenty-four patients (10.6%) required the implantation of stents after previous balloononing of the narrowed CPAs. Interestingly, 98% of these catheter-based interventions were directed towards the left pulmonary artery (LPA) and were related more to hypoplasia rather than discrete stenoses. Actuarial freedom from reintervention was 98 ± 1%, 72 ± 4% and 58 ± 6% at 1, 5 and 10 years following NP, respectively. On univariable analysis, the risk factors were younger age at NP (p = 0.04) and more recent date of Stage II (p = 0.03).

Multivariable analysis showed that catheter-based reintervention has become more common with time. Amongst all

Table 2
Surgical strategies and techniques used in our study group (n = 226) for arch reconstruction, pulmonary blood supply and central pulmonary arteries repair during Norwood Procedure

<table>
<thead>
<tr>
<th>Arch reconstruction techniques</th>
<th>n</th>
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<tbody>
<tr>
<td>Without homograft patch</td>
<td></td>
</tr>
<tr>
<td>Duct and CoA tissue completely excised</td>
<td>91 (40%)</td>
</tr>
<tr>
<td>With homograft patch</td>
<td></td>
</tr>
<tr>
<td>Aortic backwall left in continuity</td>
<td>100</td>
</tr>
<tr>
<td>Duct and CoA tissue completely excised</td>
<td>35</td>
</tr>
<tr>
<td>Pulmonary blood supply</td>
<td></td>
</tr>
<tr>
<td>Modified Blalock–Taussig shunt</td>
<td>177 (78%)</td>
</tr>
<tr>
<td>RV-PA conduit</td>
<td>49 (22%)</td>
</tr>
<tr>
<td>Central pulmonary arteries reconstruction at NP</td>
<td></td>
</tr>
<tr>
<td>With patch</td>
<td>157 (69%)</td>
</tr>
<tr>
<td>Direct closure</td>
<td>69 (31%)</td>
</tr>
</tbody>
</table>

CoA: coarctation; RV-PA: right ventricle to pulmonary artery.

Table 3
Reoperations on central pulmonary arteries (CPAs) at cavo-pulmonary shunt (Stage II) and catheter-based reintervention after Stage II in our study group (n = 226)

<table>
<thead>
<tr>
<th>Reoperation on CPAs during Stage II</th>
<th>n</th>
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<tbody>
<tr>
<td>Modified Blalock–Taussig shunt</td>
<td>50/177</td>
</tr>
<tr>
<td>RV-PA conduit</td>
<td>47/49</td>
</tr>
<tr>
<td>Reintervention on CPAs after Stage II</td>
<td></td>
</tr>
<tr>
<td>Two patients had two consecutive reintervention</td>
<td></td>
</tr>
<tr>
<td>Three patients had three consecutive reintervention</td>
<td></td>
</tr>
<tr>
<td>Reintervention on LPA after Stage II</td>
<td>40/41</td>
</tr>
</tbody>
</table>

Most of catheter-based reintervention were directed towards left pulmonary artery (LPA).
study patients, complete coarctation resection independently increased risk of reintervention. Actuarial freedom from catheter-based reintervention on CPAs following cavo-pulmonary anastomosis was 82 ± 7% for patients with coarctation tissue left in continuity and 68 ± 5% for patients with coarctation completely resected at 5 years (LR 3.9; 95% CI, 1.6—9.6; p = 0.003) (Fig. 2).

A more recent date of NP independently increased risk of reintervention (p = 0.001). Arch reconstruction technique or CPA repair technique (i.e. direct closure vs patch repair, and type of patch repair used) did not affect risk of reoperation or reintervention on CPAs.

4. Discussion

Several studies have demonstrated the recent improvements in survival after NP. However, these patients need a very close follow-up to exclude medium-term complications. CPA stenosis after NP with an RV-PA conduit was the commonest problem we encountered and although this is a potential drawback of the technique, the growth of the branch PAs has been excellent as previously reported [17].

At our institution, the vast majority of RV-PA patients required subsequent CPAs patch augmentation in contrast to patients who received an MBTS, with 48 out of 49 patients having a CPA patch at Stage II [11]. As demonstrated in the results section, the only risk factor for CPAs patch augmentation was the use of RV-PA conduit, which was associated with a more than eight-fold increase compared to an MBTS.

Recently, the RV-PA conduit regained popularity as an alternative to MBTS, as it eliminates the diastolic ‘runoff’ from the systemic to the pulmonary circulation, which characterises the MBTS. This, in turn, raises diastolic pressure and increases coronary perfusion pressure, and may also ensure a more balanced haemodynamic state, as reported by several authors [5—10]. It may also create more pulsatile pulmonary artery flow and encourage development and growth of the pulmonary vasculature. The usage of the RV-PA conduit has become the standard at our institution since 2002.

In a previous study, we have shown an improvement in early survival following the usage of RV-PA conduit [11]. However, we remained concerned about the frequency and the severity of CPAs stenosis at the site of insertion of the conduit in this group of patients.

We initially considered that the surgical technique used was unsatisfactory, leading to a distortion of the CPAs. The surgical reconstruction of severe CPAs stenosis to the left side of neo-aorta is difficult and hazardous. Therefore, we have modified our technique by placing the distal end of RV-PA conduit on the right side of the neo-aorta. This technique was employed routinely since February 2003. Despite this modification in the technique, the same proportion of patients required subsequent patch augmentation of CPAs. However, the right sided conduit is much more accessible for the surgeon and provides easier access to the CPAs than a left sided shunt. At 6 months following the Norwood Procedure, the freedom from CPAs reconstruction was 18 ± 12% and 22 ± 7% in the left and right sided RV-PA groups, respectively (p = 0.98).

Although this observation seems to be in contradiction with an increased rate of reoperation and catheter-based reintervention in more recent Norwood Procedures (right sided RV-PA conduit), this could be time-related and only long-term follow-up could help to elucidate this difference.

As mentioned above, a recent study performed at this Institution [17] showed that despite an almost constant narrowing at the site of its insertion on the CPAs, the use of RV-PA conduit seems to provide a better growth of distal pulmonary arteries compared to MBTS.

We propose that the narrowing that occurs with the RV-PA conduit at the site of conduit insertion is a problem inherent to this technique. We hypothesised that the purely systolic flow inside the RV-PA conduit could cause turbulence, which could be particularly high at the site of conduit insertion into CPAs. In MBTS, the blood flow occurs throughout all the cardiac cycle and the turbulence should be less compared to a RV-PA conduit where large amount of blood is shifted into conduit in one third of the time (systole only). Therefore, this high turbulence could lead to a ‘chronic’ stimulus for an inflammatory reaction, which, in turn, may cause fibrosis and narrowing. This appears to be an inherent risk of the RV-PA conduit but we do not believe it is sufficient reason to change practice in view of the potential benefits of improved survival and better branch PA development. We have accepted that CPA patching is often necessary at Stage II and have had zero mortality amongst these patients.

CPA repair technique, direct closure or patch closure did not affect risk of subsequent reoperation or reintervention on CPAs. Similarly, the arch reconstruction technique, per se, did not affect risk of subsequent reoperation or reintervention on CPAs, but multivariable analysis showed that complete duct tissue and coarctation resection independently increased the risk of catheter-based reintervention of the CPAs (LR 3.9; 95% CI, 1.6—9.6) after Stage II. This is thought to be related to a degree of compression of left pulmonary artery after extensive aortic arch reconstruction. Actuarial freedom from catheter-based reintervention was 98 ± 1% and 72 ± 4% at 1 and 5 years, respectively.
References


Appendix A. Conference discussion

Dr M. Magalhoes (Lisbon, Portugal): I just want to give you a hint. We have been doing a mushroom with a 0.4 thickness pericardium patch of Gore-Tex, and then we implant the Gore-Tex tube in the centre of it. And we use the size of the mushroom as the bifurcation, or the size of the bifurcation of pulmonary artery, and we didn’t have any case so far of central stenosis. Dr Griselli: Well, it is remarkable, to say that we have been looking for the reasons of this narrowing on the central pulmonary arteries. That’s why the right ventricle-to-pulmonary artery conduit has changed position over the years from the left side to the right side, believing that the right side, if we have to face this problem almost constantly, then it is easy to operate, particularly the Stage II. Initially, it was a problem, basically, if we are sizing correctly the length of the shunt. It may be too long, compressing the PA; it may be too short and pulling the PA and causing trouble. But it wasn’t the case. We believe that very much, probably, from other studies, the turbulence inside the right ventricle-to-pulmonary artery conduit may be superior than the one in modified Blalock–Taussig shunt, and long term can give you chronic inflammation and stenosis.
Dr T. Tlaskal (Prague, Czech Republic): Do you have any explanation for the increased risk of re-coarctation after resection of coarctation?

Dr Griselli: No. What we experienced is that the arch reconstruction per se, as a patch or no patch, is not an increased risk for reoperation or reintervention either on the arch or on the pulmonary arteries. It’s just when you resect the coarctation, probably, in the short term, when you resect the coarctation, due to flexibility or elasticity of neonatal tissue, there are no problems. But long term, probably, that space, that corner, which basically at the time of our coarctation resection becomes too tight, causes compression on the left pulmonary artery mainly. So I think it is more likely to be a long-term problem than a short-term problem, as has been demonstrated by our data.

Dr G. Stellin (Padova, Italy): Obviously, we are curious to know the middle long-term results of this modification with RV-PAs conduit placed on the right side. I am wondering whether you have found a higher incidence of right pulmonary artery stenosis placing your conduit to the right rather than to the left of the neoascending aorta?

Dr Griselli: No, there is no difference in terms of right or left. What I can tell you for sure, because we examined this problem as well, that if we put a conduit in the right side, the freedom from reoperation at 6 months is slightly better than left side. The left side is about 14% at 6 months, in the right side it’s 22% but is of no statistical importance. So it’s been better but not very much better.

Dr V. Tsang (London, United Kingdom): Can I follow on your reconstruction of the arch with no foreign tissue? What was the reason you stopped that approach, using native tissue for reconstruction?

Dr Griselli: We stopped using homograft material you mean?

Dr Tsang: That’s right.

Dr Griselli: First of all is anatomic reason. Not all morphological left hypoplastic heart syndrome are approachable by using no tissue. In a previous study by Dr Ichino, from the same institution, done a few years ago, showed at least 15%-20% of patients were not operable without using any patch. Second, it is very much a surgeon-dependent technique. So it’s a very difficult operation without patch. Using a homograft patch seems more reproducible, adaptable to all morphologies we encountered, and seems both easy to teach and to learn as well.

Dr Tsang: But my understanding is that with native tissue-to-native tissue arch reconstruction, as somebody mentioned, there is a risk of compromising the left-sided pulmonary vasculature. Did you come across that? Was that the reason you stopped?

Dr Griselli: No. There was no reason to stop that. The reason was that technique was more difficult and not adaptable to every patient.

Dr C. Pizarro (Wilmington, Delaware, USA): A technical issue. How do you insert the distal end of the conduit into the main pulmonary artery? Do you close that primarily and then make an anastomosis there? Do you use a patch of pulmonary homograft or a patch of pericardium? And could the issues be related to the technique?

I know that your group had described taking the conduit over the right and over the left side, trying to find a better position. Do you think that by changing the approach you’re sort of revisiting a learning curve?

Dr Griselli: Different techniques have been tried. One technique was closing primarily the defect in the central pulmonary arteries and then putting the conduit in different position. Another technique has been tethering the distal end of the conduit in a way to cover the defect in the central pulmonary arteries. The other technique that has been used is, basically, before the operation, put a graft in a little sort of PTFE tissue, inserting it, and then with that tissue, patch the defect in the central pulmonary artery, particularly when we use the conduit on the left side.

So we tried different techniques. I mean this seems not to help in terms of central pulmonary arteries. But in general terms, we try all of the technique, like is also bovine pericardium to close primarily. Several times we close, as Dr Spray showed yesterday, direct closure particularly in large pulmonary arteries. So different techniques have been tried.