Abstract

OBJECTIVES: Branch pulmonary artery (BPA) size is one of the factors that influence the efficacy of the Fontan circulation. Central pulmonary artery stenosis and small left pulmonary artery (LPA) are well-known problems following Norwood palliation for hypoplastic left heart syndrome (HLHS). We investigated anatomical and technical factors that may stand behind these problems.

METHODS: A total of 47 consecutive patients were included in the study. All had complete magnetic resonance imaging (MRI) study pre-second-stage palliation. Measurements were taken using a first-pass 3D angiography technique after intravenous injection of an extravascular contrast agent. Factors investigated included the following: size and site of the pulmonary artery bifurcation stump in relation to the Damus–Kaye–Stansel (DKS) anastomosis, interaortic distance/ratio (neoaorta to descending aorta distance/antero-posterior dimension of the chest) (IAD/IAR), distance from the under surface of the arch and the size of native aorta and pulmonary artery. IAD/IAR were compared between two different arch reconstruction techniques.

RESULTS: Stenosis occurred either centrally, at the origin of the BPA, or more distally, in the mid-LPA (posterior to DKS). There was a significant lower incidence of central BPA stenosis when the pulmonary artery stump was placed in the mid-position compared with right/left position (26 vs 67%; \( P = 0.011 \)). A more bulky pulmonary artery stump was also found in those patients with central BPA stenosis (186 vs 137 mm²/m²; \( P = 0.047 \)). The mid-LPA consistently showed antero-posterior compression (mean cranio-caudal diameter 3.82 mm vs mean antero-posterior diameter 3.07 mm, \( P < 0.001 \)). Indexed mid-LPA area was only correlated with IAD/IAR (\( r = 0.49 \) and 0.51, \( P < 0.001 \)). No correlation was shown with the distance to the under surface of the arch (\( r = 0.14, P = 0.37 \)), again confirming antero-posterior compression of the LPA rather than cranio-caudal. In multivariable analysis, the only predictor of indexed mid-LPA area was the IAR (\( P < 0.001 \)). There was no significant difference in the IAD or IAR between the two arch reconstruction techniques (mean IAD 15.5 vs 13.5 mm (\( P = 0.14 \)); [mean IAR 0.17 vs 0.19 (\( P = 0.21 \))].

CONCLUSIONS: Of all studied factors, IAR and the size and position of the pulmonary artery bifurcation plays the main role in LPA growth and central BPA stenosis.

Keywords: Congenital • Hypoplastic left heart syndrome • Pulmonary artery • Norwood

INTRODUCTION

As a palliation for hypoplastic left heart syndrome (HLH), the final goal of the Norwood procedure is to reach the Fontan circulation. The size of the branch pulmonary arteries (BPAs) significantly influences the efficiency of the Fontan circulation [1, 2]. Both central BPA stenosis and small left pulmonary artery (LPA) are known problems with the classical Norwood and its Sano modification [3, 4]. Although this problem is documented since early reports, there is very little research into the factors influencing such problems [5].

The development of the BPA involves the interplay of anatomical, functional and technical factors. Bellsham-Revell et al. recently reported on ventricular and vascular adaptation following the Norwood procedure, but failed to correlate the development of the LPA to any functional (total cardiac output or shunt narrowing).
or anatomical factors (ventricular dilatation or proximal aortic area) [6].

Currently, magnetic resonance imaging (MRI) is our investigation of choice in preparation for second- and third-stage palliation in the Norwood pathway. MRI has proved to be non-inferior to angiography as a diagnostic tool in single ventricle palliation [7–9]. In addition, MRI provides valuable anatomical data difficult to obtain with standard diagnostic angiography. In this report, we used pre-second-stage MRI data, to uncover the anatomical and technical factors that result in BPA complications following the first stage of the Norwood palliation.

METHODS

After ethical and institutional approval was obtained (St Thomas’ Hospital Research Ethics Committee [London, England] 08/H0810/058), the department database (Heartsuite XP 3.9.14, Systeria, Glasgow, UK) was used to identify patients diagnosed with HLHS (defined as any combination of mitral stenosis or atresia with aortic stenosis or atresia) who had Stage I Norwood operation between January 2006 and December 2011. All data were collected retrospectively and only those with complete pre-second-stage (hemi-Fontan) MRI dataset were included. Those who went through initial hybrid procedure or more complex variants of HLHS were excluded from the study.

All our patients had a classical Norwood operation with systemic-to-pulmonary artery shunt constructed between the innominate artery and the right pulmonary artery (RPA). Two techniques were used to reconstruct the aortic arch (by two different surgeons). Both techniques involved a Damus–Kaye–Stansel (DKS) anastomosis between the native aorta and pulmonary artery and the use of pulmonary homograft patch for arch reconstruction. The difference lies in the way the arch is reconstructed. The first technique involves resection of the isthmus with subsequent end-to-end anastomosis. In the second technique, after incising the arch and descending aorta, only the coarctation intimal ridge is enucleated followed by augmentation of the arch vertical dimension by suturing the anterior and posterior edges of the incised aorta. Both techniques were used throughout the study period and still are currently used.

The stump of the pulmonary artery carrying the BPA confluence was closed in all cases using a pulmonary homograft patch. The size and shape of the patch was decided by the surgeon at the time of the operation to achieve the best possible geometry of the stump. Although tacking sutures are not used, positioning and siting of the shunt heavily defines the eventual position of the confluence and vice versa. The decision of stump positioning is left to the surgeon to what felt to offer the best lay of the BPAs.

In regard to MRI imaging, all scans were performed on a Philips 1.5-Tesla Achieva scanner (Philips Healthcare, Best, Netherlands). The extracardiac vasculature was imaged using a first-pass 3D angiography technique after intravenous injection of an extravascular contrast agent [either gadopentetate dimeglumine (Magnevist, Berlex Laboratories, Wayne, NJ, USA) or gadoterate meglumine (Dotarem, Guerbet, Villepinte, France)], 0.1 mmol/kg body weight. Imaging parameters included 200–320 mm field of view, 1.2–1.7 mm isotropic voxel size, acceleration factor (SENSE acquisition) 2, flip angle 40°, breath-hold time 20–30 s (minimum of 2 phases acquired).

Figure 1: Measurement of interaortic distance (blue dotted lines) and chest antero-posterior diameter (orange longer dotted lines).

The following measurements were taken:

(i) Native aorta and pulmonary artery cross-sectional area measured just below the DKS anastomosis.
(ii) Interaortic distance (IAD) defined as the shortest distance between the neoaorta and the descending aorta in the region that contains the LPA.
(iii) Interaortic ratio (IAR) defined as the IAD divided by the chest antero-posterior distance (Fig. 1).
(iv) Antero-posterior and cranio-caudal diameters of mid-LPA (defined by the interaortic region of LPA at its narrowest point).
(v) Cross-sectional area of the distal LPA and RPA measured before their first branch.
(vi) Cross-sectional area of the mid-LPA at its narrowest point.
(vii) Cross-sectional area of the pulmonary artery confluence/stump.
(viii) Distance between mid-LPA and the undersurface of the aortic arch.

Also the following data were retrieved:

(i) Presence of proximal BPA kink or significant stenosis (defined as a reduction of more than 30% of the branch diameter).
(ii) The position of the pulmonary artery confluence in relation to the DKS.
(iii) Presence of aortic arch obstruction.

All areas were indexed to body surface area recorded at the time of the MRI. Data considering arch reconstruction technique were collected retrospectively from operative report and patients were divided into two groups according to the surgical technique. Group A included patients who had resection of the isthmus while Group B had coarctation shelf enucleation only.

Statistical analysis

Bivariate correlation was used to ascertain relationships between measured factors and mid-LPA size. In addition, χ² analysis was used.
to determine relationships between categorical variables. Independent t-tests were used to determine differences between surgical techniques and for differences in confluence size. Paired t-test was used to identify difference between BPA sizes. Additionally, multivariable stepwise multivariable regression was used to determine the factors determining mid-LPA size. Only those variables that were clinically important or identified by univariate analysis were added. In addition, stepwise addition of variables was used with exclusion of variables not improving model fit.

All measurements are presented as range and mean ± standard deviation. The level of statistical significance was set at \( P = 0.05 \).

## RESULTS

Forty-seven consecutive patients were included in the study. The measurement of mid-LPA was not possible in 4 patients (2 had the confluence positioned to the left of the DKS with the mid-LPA outside the interaortic area and in 2 patients, the mid-LPA measurement was not possible due to quality of images). All other measurements were possible in all 47 patients. Measurements are summarized in Table 1.

### Pulmonary artery anatomy

Indexed distal LPA cross-sectional area was significantly smaller than distal RPA (57 ± 23.3 vs 111.2 ± 44.3 \( \text{mm}^2/\text{m}^2; \ P < 0.001 \)). Compression of the mid-LPA in the interaortic area was evident with indexed mid-LPA smaller than distal LPA (38 ± 20.8 vs 57 ± 23.3 \( \text{mm}^2/\text{m}^2; \ P < 0.001 \)).

There was no correlation between the size of the mid-LPA and the size of the native pulmonary artery (\( r = 0.255, \ P = 0.10 \)), their combined size (\( r = 0.3, \ P = 0.63 \)) or the size of the pulmonary artery confluence stump (\( r = 0.3, \ P = 0.06 \)).

There was an evident antero-posterior compression of the mid-LPA with resulting in an overall oval shape with a crano-caudal diameter significantly larger than the antero-posterior diameter (3.91 ± 1.35 vs 3.07 ± 0.97 mm; \( P < 0.001 \)). This was further confirmed by positive correlation between the mid-LPA cross-sectional area and IAD and IAR (\( r = 0.49, \ P = 0.001 \) and \( r = 0.51, \ P < 0.001 \), respectively). IAD and IAR were only significantly correlated with the size of native pulmonary artery (\( r = 0.46, \ P = 0.001 \) and \( r = 0.36, \ P = 0.013 \), respectively).

The mid-LPA was closely related to the undersurface of the aortic arch with a mean distance of 2.1 ± 1.14 mm (range of 1–6.5 mm); however, there was no correlation between the mid-LPA area and the distance from the undersurface of the aortic arch.

In multivariable analysis, the only predictor of indexed LPA area was IAR (\( P < 0.001 \)).

### Proximal stenosis

Sixteen patients had significant kink/stenosis of their BPA origin (8 RPA and 8 LPA origin stenosis/kink). Patients were not dichotomized according to bulk. Cross-sectional maximum area of the confluence was compared between groups displaying stenosis. A more bulky stump was found in those patients with central BPA stenosis (186 vs 137 \( \text{mm}^2/\text{m}^2; \ P = 0.047 \)). When analysing the position of the pulmonary artery confluence/stump, 10 patients had confluence on the right side of the neoaorta, 2 to the left and 35 patients had their confluence in mid-position behind the neoaorta. Analysis has shown that there was a significant lower incidence of central BPA kink/stenosis when bifurcation is in mid-position compared with right/left position (26 vs 67%; \( P = 0.011 \) (Figs. 2–4). When the confluence was on the right or left, the resulting kink/stenosis was found to be ipsilateral in all cases. When the confluence was central, while the kink/stenosis is less overall, it occurred more commonly on the left (\( n = 6 \)) versus right (\( n = 2 \)).

### Surgical technique

Thirty-one patients had resection of the isthmus (Group A) while 16 patients had shelf enucleation (Group B). There was no

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### Table 1: Summarized measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Mean</th>
<th>SD</th>
<th>Max</th>
<th>Min</th>
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<tr>
<td>MLPA (mm²)</td>
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<td>20.78</td>
<td>88.89</td>
<td>11.54</td>
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<td>iMLPA (mm²)</td>
<td>3.81</td>
<td>1.35</td>
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<td>1.50</td>
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<tr>
<td>AP (mm)</td>
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<td>0.97</td>
<td>5.50</td>
<td>1.5</td>
</tr>
<tr>
<td>iDLPA (mm²)</td>
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<td>23.34</td>
<td>120.69</td>
<td>21.21</td>
</tr>
<tr>
<td>iRPA (mm²)</td>
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<td>28.00</td>
</tr>
<tr>
<td>iAo (mm²)</td>
<td>67.23</td>
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<td>14.81</td>
</tr>
<tr>
<td>iPA (mm²)</td>
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<td>201.21</td>
<td>1384.00</td>
<td>192.00</td>
</tr>
<tr>
<td>iStump (mm²)</td>
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<td>108.00</td>
<td>12.00</td>
</tr>
<tr>
<td>IAD Group A (mm)</td>
<td>15.58</td>
<td>4.57</td>
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<td>9</td>
</tr>
<tr>
<td>IAD Group B (mm)</td>
<td>13.56</td>
<td>2.99</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>Chest AP (mm)</td>
<td>80.96</td>
<td>7.07</td>
<td>103</td>
<td>68</td>
</tr>
</tbody>
</table>

MLPA: mid-left pulmonary artery; iMLPA: indexed mid-left pulmonary artery area; CC: cranio-caudal diameter; AP: antero-posterior diameter; iDLPA: indexed distal left pulmonary artery area; iRPA: indexed distal right pulmonary artery area; iAo: indexed aortic area; iPA: indexed pulmonary artery area; iStump: indexed stump area; IAD: interaortic distance; SD: standard deviation.

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**Figure 2:** MRI gadolinium-enhanced image showing the pulmonary artery confluence and stump positioned to the left of the DKS with LPA origin kinking (arrow). NA: neoaorta; S: stump; R: right pulmonary artery; L: left pulmonary artery; DA: descending aorta; LPA: left pulmonary artery; DKS: Damus–Kaye–Stansel.
the diameter of the LPA and that of the reconstructed aorta [5]. Furthermore, they showed extreme proximity of the LPA to the undersurface of the arch, again seen in our study, in which we showed a mean distance of only 2 mm from LPA to the undersurface of the arch. However, different from the aforementioned study, our study goes further by demonstrating that the geometry of this compression is in the antero-posterior direction. From our data, it appears that this is caused by a bulky reconstruction, resulting in a small IAD in comparison with the overall chest size. Some authors have commented that a diminutive native aorta can affect the development of the mid portion of the LPA as a result of a bulky neoaortic reconstruction [10]. Our results have denied any correlation between the size of the native aorta and the size of LPA. Same result was found when the native pulmonary artery (neoaortic) area was correlated to the area of the mid-LPA. This reaffirms the importance of the IAD achieved (indexed to chest size) as the main variable affecting the mid-LPA growth.

The second factor by which the IAD was tested against is the surgical technique. Two technical factors could, theoretically, affect the development of the mid-LPA. The first is the height of the arch and the second is the size of the patch used and subsequently the size of the arch. Here we have compared two surgical techniques. Theoretically, the drawback of the first technique, where the coarctation segment is completely resected, is the decrease in the arch height. On the other hand, the decreased height can increase the curve of the arch, and theoretically increase the IAD. The second technique, where only the shelf is resected and plasty of the arch is carried out by suturing the incised anterior and posterior edges, would theoretically decrease the IAD with less reduction in the height of the arch. When our results were reviewed, the MRI data showed no significant difference between both techniques considering IAD, IAR and mid-LPA development (although there were only 16 patients in the second group and perhaps a larger study may be able to demonstrate a difference). This effect of arch reconstruction technique on LPA growth has been previously studied by Griselli et al. from Birmingham, UK. They found that resection of the coarctation segment is associated with higher rate of pulmonary artery reintervention. However, this result is likely to be more related to their own technique where no patch was used in arch reconstruction [11].

Different techniques are being used for arch reconstruction. Itatani et al. [12] had beautifully illustrated seven different techniques where they studied the effect of arch reconstruction on the single ventricle workload. It would be valuable to determine the IAD achieved in these cases. Unfortunately, most of the techniques address the problem of arch reobstruction with less interest in effect of the reconstructed aorta on LPA development. Ultimately, only prospective study, utilizing the different techniques and measuring the patch size in order to improve the IAD, will be able to demonstrate if BPA outcomes can be improved while maintaining arch patency.

The third finding from our study was that proximal BPA kinking is related to the size and position of the pulmonary artery stump with stenosis occurring if there is a bulky stump and if the confluence is placed to either side of the DKS (Figs. 2–4). After transecting the PA in order to achieve the DKS anastomosis, the surgeon has to decide where to position the stump and whether to close it directly or to augment it with a patch. Our findings suggest that resisting the temptation to position the stump to the right or the left of the neoaorta will keep the natural angle of the BPA origins, and avoid any kinking. Dragging the pulmonary artery confluence to the right for more proximal insertion of the modified BT shunt.

**DISCUSSION**

Our results have shown a definite discrepancy between the sizes of BPAs in favour of the RPA. This matches the global agreement that Norwood procedure is associated with less development of the LPA. Our data showed both proximal kinking of the LPA and mid-LPA compression.

The first finding from our study is that the size of the arch reconstruction appears to affect the degree of mid-LPA compression. Similar to our findings, using an MRI-based reconstruction in 16 HLHS patients, Dasi et al. showed a negative correlation between...
or to the left to avoid stretching of the LPA, results in more liability for kinking and origin stenosis (Figs. 2 and 3). This finding is not unique to the classical Norwood, as the surgeon performing the Sano modification, with a right ventricle to pulmonary artery (RV-PA) conduit, will note that placing the conduit to the stump of the pulmonary artery drags the stump to either the right or left side of the neoaorta. Reports of pulmonary artery development following RV-PA conduit have high incidence of central hypoplasia and origin stenosis that is more with left-sided RV-PA conduits. Those reports match our results with classical Norwood when the stump/confluence is dragged to either the right or left side [13–15]. In fact, angiography images included in some of these reports resemble to a great extent our MRI results [13,16].

When it comes to the size of the stump, our data have shown correlation between the size of the stump and the incidence of branch origin kink/stenosis. In all our cases, the pulmonary artery stump was closed by a homograft patch. The concept behind that is to avoid distortion of the central pulmonary artery with better flow in the LPA. However, a large stump is difficult to place behind its original site, and may cause kinking of the origin of either branch, especially with a large neoaorta or a narrow IAD. Pruetz et al. from Birmingham (UK), previously compared two groups of patients where the stump was closed directly or with a patch and they found no difference in the need for BPA intervention [16].

Again those results are centre and technique-dependent (from a centre preferring the Sano modification) and the answer to the question whether to close the stump directly or to add a patch is left to surgeon's judgement and the size of the available native tissue. Our data support surgical techniques resulting in a smaller stump (e.g. direct closure or small patch).

Finally, there are some limitations to this study that include the retrospective nature of the study, being a single-centre study and no prospective data on the size of the patch used for arch reconstruction. On the other hand, this study confirms findings of other investigators, and adds useful new insights into the anatomical and technical factors contributing to the development of BPs. We used geometrical and anatomical data rather than crude indicators as pulmonary artery reintervention, which may vary according to institutional practices. In addition, this study has shed light on the possible relation between IAD and development of mid-LPA, which should pave the way for further studies to analyse the different existing techniques using the parameter identified. This can give rise to technique modifications and technological innovations that may help address this limitation of the Norwood procedure. Comparison of the effect of our arch reconstruction techniques on the development of future arch obstruction is beyond the scope of our study. However, it is worth mentioning that none of our studied patients had arch reintervention.

CONCLUSION

Results have shown that correct size and positioning of the pulmonary artery stump can improve development of central BPs. Ideal arch reconstruction remains an area that needs further investigation. An ideal arch should have no obstruction, and offer enough space for LPA development.

Conflict of interest: none declared.

REFERENCES