Angiographic evaluation of the coronary artery anatomy in patients with hypoplastic left heart syndrome

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Abstract

OBJECTIVES: Evaluation of coronary anatomy in survivors of staged palliation for hypoplastic left heart syndrome might be capable of identifying anomalies and morphologic changes of the coronary arteries that may have implications for outcome.

METHODS: We reviewed coronary angiograms obtained by native aortic root injection of 84 patients (mitral atresia/aortic atresia, n = 39; mitral stenosis/aortic stenosis, n = 25; mitral stenosis/aortic atresia (MS/AA), n = 13 and mitral atresia/aortic stenosis, n = 7). Epicardial course, anomalies, coronary dominance and native ascending aorta dimensions were analysed.

RESULTS: Right dominance was present in 51%, left in 37% and balanced type in 12%. Dominance was unrelated to anatomic subtypes (P = 0.16). Ventriculocoronary connections (VCCs) were found in 15 (18%) and tortuosity was seen in 28 (33%) patients. Both occurred more often with MS/AA (tortuosity: 12 of 13 patients, P < 0.001; VCCs: 6 of 13 patients, P = 0.001). Collaterals to extra-cardiac vessels were visualized in 41 (49%) patients. Native ascending aorta dimensions were smaller with aortic atresia [40 (18–107) vs. 127 (32–328) mm2/m2, P < 0.001]. In 18 patients with a relatively large native aorta [106 (36–328) vs. 44 (18–248) mm2/m2, P < 0.001] retention of contrast in the aortic root identified areas of low blood flow.

CONCLUSIONS: Left coronary dominance was more prevalent compared with the normal population. The impact of observed anomalies is unclear. Most VCCs are small and probably have no impact on coronary perfusion. Native ascending aorta dimensions were larger in patients with aortic stenosis. Larger aortic roots may predispose to thrombus formation and effective anticoagulation might be considered.

Keywords: Coronary angiography • Coronary artery anomalies • Native aortic root • Ventriculocoronary connections

INTRODUCTION

Coronary artery anatomy is well studied for congenital heart defects where unusual coronary artery patterns have implications for surgery, e.g. with transposition of the great arteries or tetralogy of Fallot [1, 2]. Coronary artery anatomy in hypoplastic left heart syndrome (HLHS) was predominantly assessed in post-mortem analysis and focused on coronary anomalies and morphological changes [3–6]. The impact of the coronary circulation on the outcome of HLHS patients is unclear. Besides a recent study evaluating the relevance of ventriculocoronary connections (VCCs), as a potential risk factor for increased mortality after the Norwood procedure noticed in HLHS patients with mitral stenosis and aortic atresia (MS/AA), clinical studies from the current era focusing on the coronary system are lacking [7–9]. The evaluation of the coronary anatomy in surviving patients undergoing staged palliation goes beyond the demonstration of the essential coronary artery anatomy and, by providing dynamic images, might identify anomalies and morphological changes that may impact the patient’s outcome. Therefore, coronary angiography obtained by selective aortic root injection is part of our work-up during routine cardiac catheterization. To the best of our knowledge, this is the first angiographic study systematically evaluating coronary artery anatomy and the native ascending aorta in a large cohort of HLHS patients who successfully underwent staged palliation.

METHODS

Study population

A total of 193 HLHS patients received a Norwood operation as the first step of surgical palliation between 1 January 1996 and 28 February 2010. Operative technique and perioperative care have previously been described in detail elsewhere [10]. The transected pulmonary artery was connected side-by-side with the diminutive ascending aorta, which was incised longitudinally
along the inner curvature from the distal aortic arch deep into the aortic root. The aortic arch and the ascending aorta were patch augmented and connected with the circumference of the transected pulmonary artery to construct the neo-aorta. A modified Blalock-Taussig Shunt (BT-Shunt) between the distal innominate artery and the patch reconstructed pulmonary bifurcation provided pulmonary blood flow in all patients.

For follow-up, native aortic root and coronary angiography was attempted in all HLHS patients undergoing staged palliation, either during routine diagnostic cardiac catheterization prior to Hemifontan operation or before or after Fontan completion. We enrolled 84 patients (44% of the original cohort), who underwent native aortic root and coronary angiography at one of the routine follow-up catheterizations within the same period. Patients were assigned to distinct anatomic subgroups (mitral and aortic atresia, MA/AA; mitral atresia and aortic stenosis, MA/AS; MS/AA and mitral and aortic stenosis, MS/AS) based on the echocardiography performed prior to the Norwood operation [10, 11]. Informed consent for the anonymized data analysis was obtained and the local research ethics committee approved the study protocol.

Cardiac catheterization and angiographic analysis

Cardiac catheterization was performed prior to Hemifontan operation or either before or after Fontan completion, respectively. After haemodynamic evaluation, cine angiograms including a selective injection into the native aortic root in standard anterior–posterior and lateral projections or in right and left anterior oblique projections were obtained. Depending on the catheter’s route, we used a 5F Berman angiographic balloon catheter, a 4F multi-purpose catheter or a right or left coronary Judkins catheter. All angiograms were analysed for the presence of the right (RCA) and the left coronary artery (LCA), for the separation of the LCA into the circumflex (CX) and the left anterior descending artery (LAD) and for the presence of LAD diagonal and septal branches. The origin of the sinus node artery (SNA) was determined. The coronary artery system was classified as right dominant if the RCA or as left dominant if the CX gave rise to the posterior descending artery, respectively. In the case of a balanced coronary system, the RCA supplied the posterior descending coronary and the CX gave rise to a posterolateral artery with an occasional additional parallel posterior descending branch.

Coronary arteries were classified as tortuous if tortuosity was visible for the entire cardiac cycle. VCCs were diagnosed if flow of contrast medium between a coronary artery branch and a ventricular cavity was visualized. The number of VCCs in the individual patient and the supplying epicardial coronary artery branch were determined. Collaterals between the coronary arteries and extra-cardiac vessels were present if contrast medium passed into non-cardiac vessels. Native aortic root angiograms were reviewed for the presence of thrombus formation and retention of contrast medium in the aortic root indicating an area of low blood flow. Diameter and length of the native ascending aorta were measured in at least two of the recorded projections. To evaluate native ascending aorta dimensions, a cross-sectional index was calculated by dividing the cross-sectional area of the native ascending aorta with the patient’s body surface area. The native ascending aorta length was indexed by division with the patient’s body surface area. Neonatal echocardiography was evaluated for the presence of VCCs in the original cohort of 193 patients.

Statistical analysis

Continuous variables are expressed as median and range; categorical data as count and percentages. We employed chi-square or Fisher’s exact test for categorical data. Continuous variables were compared with the Mann–Whitney U-test or with the Kruskal–Wallace test in case of more than two independent groups. Survival was estimated with the Kaplan–Meier method. All statistical analyses were performed with the statistical software package SPSS 17.0 (SPSS Inc., Chicago, IL, USA). A P < 0.05 was considered statistically significant. The Bonferroni method was applied for alpha adjustment if post hoc test were calculated.

RESULTS

Patient’s characteristics

Of the original cohort of 193 patients, 84 underwent native aortic root and coronary angiography, the sample being representative in terms of the underlying anatomic subtype (MA/AA: \( n = 39 \) of 88, MS/AS: \( n = 25 \) of 47, MS/AA: \( n = 13 \) of 46 and MA/AS: \( n = 7 \) of 12, \( P = 0.063 \)). Angiography was performed prior to Hemifontan operation in 24 (29%) and before or after completion of the Fontan circulation in 47 (56%) and 13 (15%) patients, respectively. The median age at catheterization was 1.8 (0.1–9.9) years (\( P = 0.47 \)). At the end of the study, the estimated survival was 94% with one early death after Hemifontan operation, two inter-stage deaths before Fontan operation and two late deaths after Fontan completion. The median follow-up was 7.7 (0.4–14.0) years.

Coronary artery anatomy

Results of native aortic root and coronary angiography are displayed in Table 1. The LCA and RCA were identified in all patients. The CX was absent in one and severely underdeveloped in two other cases. In one patient, the CX originated from the RCA. The distribution of coronary dominance was not different between anatomic subgroups (\( P = 0.16 \)). Angiograms of patients with right and left dominance are shown in Fig. 1a and b. Blood supply of the sinus node was neither related to anatomic subgroups (\( P = 0.70 \)) nor to the type of coronary dominance (\( P = 0.063 \)).

Coronary tortuosity

Tortuosity of the coronary arteries mainly affected the LAD and was more frequently found with MS/AA compared with MA/AA or MS/AS (\( P = 0.002 \), (Fig. 1b). Right coronary dominance was more common together with tortuosity (\( P = 0.031 \)).
patients who survived until Hemifontan operation (VCCs detected by echocardiography was different neither from MS/AA, VCCs were seen in 7 of 14 patients. The frequency of

\[ P = 0.002 \]

operation (fluography identified and did not undergo coronary angiography, neonatal echocardiography is usually present in only 10%. The remaining 12% of our patients were classified as balanced type compared with those with aortic atresia (13 patients with AS vs. 5 patients with AA, \( P = 0.001 \)). One of the patients in whom contrast retention was detected experienced myocardial infarction and cerebral stroke 7 years after the examination, and thrombus formation was detected within the aortic root.

**DISCUSSION**

**Coronary artery anatomy**

According to previous findings of Baffa and colleagues, the epicardial course of the coronary arteries and the separation into the main branches in HLHS patients were basically equivalent to normal hearts [3]. Coronary dominance was distributed differently compared with the normal population. Right dominance is usually present in \( \sim 70\% \) but was only seen in 51% of our HLHS patients. Instead left dominance, accounting for 37% of our cohort, normally occurs in only 10%. The remaining 12% of our patients were classified as balanced type compared with 20% in the normal population [12]. The higher prevalence of left coronary dominance was previously observed in post-mortem analyses [3, 5, 6]. With respect to the underlying anatomic subtypes, Sauer and colleagues described a significantly higher

**Ventriculocoronary connections**

VCCs were displayed in 15 (18%) patients (Table 2, Fig. 2, Supplementary Video 1). Thirteen patients with VCCs had aortic atresia and MS/AA accounted for 6 of these 13 patients. Compared with the remainder, VCCs were more common with left anterior descending; RCA, right coronary artery; CX, circumflex artery; LCA, left coronary artery; VCCs, ventriculocoronary connections. Asc. ao., ascending aorta. P-values refer to global tests; footnotes indicate significant results of post hoc tests.

\*MS/AA > MA/AA, MS/AA > MS/AS, MA/AA > MA/AS, mitral atresia/aortic atresia; MS/AS, mitral stenosis/aortic stenosis; MS/AA, mitral stenosis/aortic atresia; MA/AS, mitral atresia/aortic stenosis; LAD, left anterior descending; RCA, right coronary artery; CX, circumflex artery; LCA, left coronary artery; VCCs, ventriculocoronary connections. Asc. ao., ascending aorta.

Native aortic root angiography did not show stenosis or thrombus formation in any patient. The measurements of the native ascending aorta are displayed in Table 3. Native ascending aorta dimensions showed variations between anatomic subgroups (Fig. 3) and they were significantly smaller in the presence of aortic atresia compared with patients with aortic stenosis [40 (18–107) vs. 127 (32–328) mm²/m², \( P < 0.001 \)]. In 18 (21%) patients with relatively large native ascending aorta [106 (36–328) vs. 44 (18–248) mm²/m², \( P < 0.001 \)] retention of contrast medium in the aortic root identified areas of low blood flow (Fig. 4). Contrast retention was more frequently found in patients with aortic stenosis, who had larger native ascending aorta dimensions compared with those with aortic atresia (13 patients with AS vs. 5 patients with AA, \( P = 0.001 \)). One of the patients in whom contrast retention was detected experienced myocardial infarction and cerebral stroke 7 years after the examination, and thrombus formation was detected within the aortic root.

**Collateral blood flow to extra-cardiac vessels**

Collaterals between the coronary arteries and extra-cardiac vessels were visualized in 41 (49%). The age at catheterization was significantly higher in patients who had collateral blood flow to extra-cardiac vessels [(2.2 (0.5–9.9) vs. 1.2 (0.1–8.5) years, \( P = 0.002 \)]].

**The native ascending aorta**

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DISCUSSION

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**Table 1:** Results of native ascending aorta and coronary angiography

<table>
<thead>
<tr>
<th></th>
<th>MA/AA (n = 39)</th>
<th>MS/AS (n = 25)</th>
<th>MS/AA (n = 13)</th>
<th>MA/AS (n = 7)</th>
<th>Total (n = 84)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAD diagonal branches</td>
<td>39 (100%)</td>
<td>25 (100%)</td>
<td>13 (100%)</td>
<td>7 (100%)</td>
<td>84 (100%)</td>
<td>1.00</td>
</tr>
<tr>
<td>LAD septal branches</td>
<td>28 (72%)</td>
<td>16 (64%)</td>
<td>11 (85%)</td>
<td>7 (100%)</td>
<td>62 (74%)</td>
<td>0.37</td>
</tr>
<tr>
<td>Circumflex artery</td>
<td>39 (100%)</td>
<td>24 (96%)</td>
<td>13 (100%)</td>
<td>7 (100%)</td>
<td>83 (99%)</td>
<td>0.54</td>
</tr>
<tr>
<td>Coronary dominance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.163</td>
</tr>
<tr>
<td>Right</td>
<td>18 (49%)</td>
<td>14 (56%)</td>
<td>10 (85%)</td>
<td>1 (14%)</td>
<td>43 (51%)</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>16 (41%)</td>
<td>9 (36%)</td>
<td>2 (15%)</td>
<td>4 (57%)</td>
<td>31 (37%)</td>
<td></td>
</tr>
<tr>
<td>Balanced</td>
<td>5 (13%)</td>
<td>2 (8%)</td>
<td>1 (8%)</td>
<td>2 (29%)</td>
<td>10 (12%)</td>
<td></td>
</tr>
<tr>
<td>Origin sinus node artery</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.70</td>
</tr>
<tr>
<td>RCA</td>
<td>12 (31%)</td>
<td>10 (40%)</td>
<td>6 (46%)</td>
<td>2 (29%)</td>
<td>30 (36%)</td>
<td></td>
</tr>
<tr>
<td>CX</td>
<td>22 (56%)</td>
<td>10 (40%)</td>
<td>7 (54%)</td>
<td>4 (57%)</td>
<td>43 (51%)</td>
<td></td>
</tr>
<tr>
<td>LCA</td>
<td>0 (0%)</td>
<td>1 (4%)</td>
<td>0 (0%)</td>
<td>1 (14%)</td>
<td>2 (2%)</td>
<td></td>
</tr>
<tr>
<td>unknown</td>
<td>5 (13%)</td>
<td>4 (16%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>9 (11%)</td>
<td></td>
</tr>
<tr>
<td>Coronary tortuosity*</td>
<td>11 (29%)</td>
<td>6 (24%)</td>
<td>10 (77%)</td>
<td>1 (14%)</td>
<td>28 (33%)</td>
<td>0.005</td>
</tr>
<tr>
<td>LAD</td>
<td>9 (23%)</td>
<td>6 (24%)</td>
<td>10 (77%)</td>
<td>1 (14%)</td>
<td>26 (31%)</td>
<td></td>
</tr>
<tr>
<td>CX</td>
<td>4 (10%)</td>
<td>0 (0%)</td>
<td>2 (15%)</td>
<td>0 (0%)</td>
<td>6 (7%)</td>
<td></td>
</tr>
<tr>
<td>RCA</td>
<td>1 (3%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>1 (1%)</td>
<td></td>
</tr>
<tr>
<td>VCCs</td>
<td>7 (18%)</td>
<td>2 (8%)</td>
<td>6 (46%)</td>
<td>0 (0%)</td>
<td>15 (18%)</td>
<td>0.026</td>
</tr>
<tr>
<td>Collateral arteries</td>
<td>24 (62%)</td>
<td>10 (40%)</td>
<td>5 (38%)</td>
<td>2 (29%)</td>
<td>41 (49%)</td>
<td>0.17</td>
</tr>
</tbody>
</table>

MA/AA, mitral atresia/aortic atresia; MS/AS, mitral stenosis/aortic stenosis; MS/AA, mitral stenosis/aortic atresia; MA/AS, mitral atresia/aortic stenosis; LAD, left anterior descending; RCA, right coronary artery; CX, circumflex artery; LCA, left coronary artery; VCCs, ventriculocoronary connections. Asc. ao., ascending aorta.

*MS/AA > MA/AA, MS/AA > MS/AS, P < 0.05.

**CONGENITAL**
prevalence of left dominance with MA/AA compared with regular right coronary dominance in hearts with MS/AA [5]. Baffa et al. [3] found left dominance in 80% of patients with MA/AA compared with 60% and 45% in patients with MS/AA and MS/AS, respectively. Our results do not confirm these previous findings, as the anatomic subtype was not significantly related to the type of coronary artery dominance.

The pathomechanism for the increased prevalence of LCA dominance in HLHS patients is unknown, but a higher rate of left dominance has also been observed with other systemic outflow tract anomalies like aortic stenosis and bicuspid aortic valves [12–15]. The influence of coronary dominance on myocardial perfusion, especially for the right ventricle is unknown and further studies evaluating myocardial perfusion in HLHS are needed.

The SNA originates from the RCA in 66% and from the LCA in 34% of the normal population and correlates with coronary dominance [16]. In our patients, origin from the RCA was only found in 40%, whereas in 60% of the cases the SNA was supplied by the LCA, mainly by the CX. We did not find a significant relationship between anatomic subgroups and origin of the SNA, but the higher prevalence of left coronary dominance in our patients might explain the relatively frequent origin of the SNA from the LCA.

**Ventriculocoronary connections**

VCCs communicating with the residual left ventricular cavity were displayed in 15 (18%) patients. This frequency is comparable with a recent study, where VCCs have been diagnosed by echocardiography in 15% of unselected HLHS patients undergoing staged palliation and have exclusively been found in the subgroup of patients with MS/AA [9]. This agrees with previous post-mortem studies and our results, where VCCs have predominantly been observed with MS/AA as well [3, 4]. The presence of VCCs in seven of our patients classified as MA/AA might be explained by residual antegrade flow into the left ventricle during foetal cardiac development before the mitral valve finally became atretic.

VCCs in HLHS are thought to be remnants of persisting embryological communications between the coronary arteries and the ventricular cavity, comparable with those seen in patients with pulmonary atresia and intact ventricular septum [17].
However, significant differences of the histopathological structure and smaller size of these communications have been shown in HLHS autopsies compared with patients with pulmonary atresia and intact ventricular septum. Especially coronary artery stenosis or interruption, which is common with the latter entity, is extremely rare with HLHS. Therefore, severe interference with the coronary perfusion is less likely [3, 4, 9, 18]. In addition, the right ventricle in pulmonary atresia with intact ventricular septum provides poorly oxygenated blood to the coronary circulation, which is assumed to be the second major cause for the impairment of ventricular function.

Sathanadam et al. performed a detailed echocardiographic evaluation of VCCs in HLHS patients. They noted a dominant retrograde systolic and an antegrade diastolic flow pattern in the epicardial coronary artery connected to the VCC [9]. A bidirectional flow pattern was not observed in our angiograms. Blood flow was visible during diastole only and directed into the left ventricular cavity. All VCCs were relatively small and systolic flow from the ventricle into the epicardial coronary arteries might be too little to be detected by angiography. Dilatation of the coronary artery branches draining into the VCCs was not seen in our cohort. The left ventricular end-diastolic pressure is usually elevated making a diastolic runoff and an impairment of coronary perfusion unlikely. This is different with coronary artery fistulas connected to a low pressure cavity in otherwise normal cardiac anatomy. They can cause relevant flow resulting in ectasia of the supplying coronary artery branch. A regression of VCCs has been described and supports the impression that VCCs do not alter myocardial perfusion unless they are very large [19, 20]. However, some authors argued that VCCs might be responsible for poorer survival after the Norwood operation noted in patients with MS/AA [7, 8]. In a previous study, we also found less survival in patients with MS/AA until the second surgical stage [10]. Inevitably, these patients never underwent coronary angiography. However, the frequency of detected VCCs during neonatal echocardiography in non-survivors with MS/AA was not different from patients with MS/AA who successfully underwent Norwood operation. Except one patient who received cardiac transplantation for severely impaired right ventricular function after the Hemifontan operation, all remaining patients with VCCs detected during angiography were doing well at the end of the follow-up period and most of them already underwent Fontan completion. This supports the results of Sathanadam et al. [9] who did not observe increased mortality in the presence of VCCs. It remains unclear why survival after the Norwood operation is compromised especially in patients with MS/AA. Eventually, subendocardial ischaemia due to the high diastolic left ventricular pressure predisposes one to arrhythmias and sudden death. In addition, right ventricular function

### Table 2: Overview of patients with VCCs

<table>
<thead>
<tr>
<th>Patient</th>
<th>Anatomy</th>
<th>Time of angiography</th>
<th>Number and side of VCCs</th>
<th>Follow up</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MA/AA</td>
<td>After Norwood</td>
<td>1 CX</td>
<td>Fontan</td>
</tr>
<tr>
<td>2</td>
<td>MS/AA</td>
<td>After Norwood</td>
<td>4 LAD and 1 CX</td>
<td>Fontan</td>
</tr>
<tr>
<td>3</td>
<td>MA/AA</td>
<td>After Norwood</td>
<td>2 LAD</td>
<td>Fontan</td>
</tr>
<tr>
<td>4</td>
<td>MA/AA</td>
<td>After Hemifontan</td>
<td>1 LAD and multiple CX</td>
<td>Fontan</td>
</tr>
<tr>
<td>5</td>
<td>MA/AA</td>
<td>After Norwood</td>
<td>1 CX</td>
<td>Transplant</td>
</tr>
<tr>
<td>6</td>
<td>MS/AA</td>
<td>After Fontan</td>
<td>1 LAD</td>
<td>Fontan</td>
</tr>
<tr>
<td>7</td>
<td>MA/AA</td>
<td>After Hemifontan</td>
<td>1 LAD and 2 CX</td>
<td>Fontan</td>
</tr>
<tr>
<td>8</td>
<td>MS/AA</td>
<td>After Hemifontan</td>
<td>1 CX</td>
<td>Fontan</td>
</tr>
<tr>
<td>9</td>
<td>MS/AA</td>
<td>After Norwood</td>
<td>1 CX</td>
<td>Fontan</td>
</tr>
<tr>
<td>10</td>
<td>MS/AS</td>
<td>After Hemifontan</td>
<td>2 CX</td>
<td>Fontan</td>
</tr>
<tr>
<td>11</td>
<td>MS/AS</td>
<td>After Hemifontan</td>
<td>1 LAD</td>
<td>Fontan</td>
</tr>
<tr>
<td>12</td>
<td>MA/AA</td>
<td>After Hemifontan</td>
<td>1 LAD, 1 CX and 1 RCA</td>
<td>Fontan</td>
</tr>
<tr>
<td>13</td>
<td>MS/AA</td>
<td>After Hemifontan</td>
<td>1 CX</td>
<td>Fontan pending</td>
</tr>
<tr>
<td>14</td>
<td>MA/AA</td>
<td>After Hemifontan</td>
<td>1 CX</td>
<td>Fontan pending</td>
</tr>
<tr>
<td>15</td>
<td>MS/AA</td>
<td>After Fontan</td>
<td>1 LAD</td>
<td>Fontan</td>
</tr>
</tbody>
</table>

VCCs, ventriculocoronary connections; MA/AA, mitral atresia/aortic atresia; MS/AS, mitral stenosis/aortic stenosis; MS/AA, mitral stenosis/aortic atresia; MA/AS, mitral atresia/aortic stenosis; LAD, left anterior descending; CX, circumflex artery; RCA, right coronary artery.

![Figure 2: Native aortic root angiography in the posterior-anterior view in a patient with MS/AA. Right dominance and multiple ventriculocoronary connections between the ILAD and CX artery and the residual left ventricular cavity.](image-url)
Collateral arteries

Communications between the coronary arteries and extracardiac vessels such as mediastinal and pulmonary vessels were commonly seen in our patients. These collaterals are likely to result from adhesions in the pericardial space after extensive surgery. These collaterals were more frequently found in older children undergoing catheterization before or after Fontan completion. Although the exact mechanism for the formation of these collaterals is unknown, the later presentation might be explained by the longer time interval to previous surgery, which might be necessary for the collaterals to develop. In addition, the chronic exposure to cyanosis may support the development of such collateral vessels. None of the detected collaterals had actually haemodynamic relevance, but later development of coronary steal must be considered.

The native ascending aorta

The native ascending aorta is the source of coronary blood flow after the Norwood operation. Impaired coronary perfusion due to pre-coronary stenosis was one of the most frequent causes of death in a post-mortem study conducted during an early era of Norwood palliation [23]. In our cohort, selective aortic root injection revealed no stenosis of the native ascending aorta in any patient. The size of the native aorta was significantly different between anatomic subgroups at birth and at the time of cardiac catheterization. In particular, ascending aorta dimensions with aortic atresia were significantly smaller compared with patients with residual antegrade flow.

A larger native aortic root may lead to reduced flow velocities and bear a risk for thrombus formation causing coronary obstruction or systemic embolism [24, 25]. During selective aortic root injection, we observed retention of contrast medium in the aortic root, indicating a low-flow area, in approximately one-fifth of the patients. The native ascending aorta dimensions of these patients were significantly larger than in the remaining cohort. Retention of contrast medium was more frequently found in patients with aortic stenosis, who had larger native ascending aorta dimensions. Besides the actual size, the amount of residual flow across the native aortic valve and the function of the residual left ventricle may also influence regional low flow in the aortic root. Contrast retention, reflecting stasis in a large native ascending aorta, might not be seen in the presence of higher residual antegrade flow, whereas impaired function of the left

Table 3: Dimensions of the native ascending aorta

<table>
<thead>
<tr>
<th>Anatomy</th>
<th>MA/AA (n = 39)</th>
<th>MS/AS (n = 25)</th>
<th>MS/AA (n = 13)</th>
<th>MA/AS (n = 7)</th>
<th>Total (n = 84)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)*</td>
<td>4.8 (3.2–7.9)</td>
<td>7.9 (3.5–12.8)</td>
<td>4.8 (2.8–7.2)</td>
<td>7.9 (4.3–19.5)</td>
<td>5.5 (2.8–19.5)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Asc. Ao. index (mm²/m²)*</td>
<td>38 (18–98)</td>
<td>127 (32–248)</td>
<td>45 (18–107)</td>
<td>89 (38–328)</td>
<td>51 (18–328)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Indexed length (mm/m²)†</td>
<td>40 (19–82)</td>
<td>43 (24–108)</td>
<td>53 (27–74)</td>
<td>47 (23–78)</td>
<td>42 (19–108)</td>
<td>0.31</td>
</tr>
</tbody>
</table>


*P-values refer to global tests; footnotes indicate significant results of post hoc tests.
†MA/AA <MS/AS; MA/AA <MA/AS; MA/AA <MS/AS.
‡MA/AA <MS/AS; MA/AA <MA/AS; MA/AS <MS/AS.

Coronary tortuosity

Tortuosity of the coronary arteries was more common with MS/AA as well and previously described in other studies evaluating autopsy specimens [3–5]. In a study by Sauer et al., histology revealed tortuous coronary arteries with increased media thickness in cases with MS/AA compared with normal-appearing coronary arteries with MA/AA. In some of their cases the wall thickness compared with the luminal size was increased and resulted in luminal narrowing [5]. These alterations are most likely related to the increased intra-ventricular pressure during foetal cardiac development leading to secondary vascular changes. Because the LAD is almost exclusively affected and a right dominant coronary artery system was significantly more common in our patients with tortuous coronary arteries, it seems unlikely that these changes have any effect on myocardial perfusion of the right ventricle.

might be impaired due to interference with the hypertrophied left ventricular remnant [21, 22].

Figure 3: Native ascending aorta index according to the underlying anatomic subtype. Native ascending aorta dimensions were significantly smaller in patients with MA/AA compared with MS/AS and MA/AS and significantly smaller with MS/AA compared with MS/AS.
ventricular remnant might promote stasis due to less antegrade flow. The critical size of the native aortic root associated with an increased risk for thrombus formation cannot be determined from our data. Effective anticoagulation using warfarin might be considered in this subset of patients to prevent coronary obstruction or systemic embolism.

The length of the native ascending aorta depends on the surgical technique applied. In our cohort, it was measured with a median of 21 mm for all patients. While no comparable data exist, we try to keep the length of the native ascending aorta small in order to minimize energy loss for coronary perfusion.

LIMITATIONS

Until the end of the study period only 44% of our HLHS patients who received a Norwood operation already underwent coronary angiography. Although coronary angiography was attempted in all patients, it was only performed during routine diagnostic cardiac catheterization and, therefore, virtually all patients who did not survive until the Hemifontan operation could not be considered for analysis. In addition, coronary angiography was performed at different time points during staged surgical palliation and took place prior to Fontan completion in the majority of patients. This is explained by technical difficulties to access the native aorta via the femoral vein in relatively small patients, where we tried to avoid arterial puncture for retrograde catheterization if otherwise not needed for routine diagnostic or interventions. Therefore, anatomic variations and anomalies of the coronary arteries, including VCCs, which might occur more often in patients not surviving the most critical period between the Norwood and Hemifontan operation, may be underrepresented. However, the frequency of VCCs detected during neonatal echocardiography in non-survivors was not different from that in surviving patients. The later timing may have also resulted in an underestimation of the original size of the VCCs as a regression of these communications has previously been observed [20]. Detailed evaluation of the VCCs by echocardiography was not feasible in the setting of the present study.

CONCLUSIONS

The epicardial course of the coronary arteries and the separation into the main branches were basically similar to normal hearts in the majority of our patients. Left coronary dominance was more common with HLHS than in the normal population, but a relation to the underlying anatomic subtype was not detected. VCCs and tortuosity of the coronary arteries are more frequently found with MS/AA. VCCs were usually small and did not cause relevant diastolic run-off. They were never associated with coronary stenosis or interruption, which could impair myocardial perfusion. Therefore, the presence of VCCs might not be the main reason for the increased mortality rate after the Norwood operation observed in patients with MS/AA. A potential risk for thrombus formation in the native aortic root might exist for patients with a dilated native aortic root. Anticoagulation might be especially considered in this subset of patients to prevent coronary obstruction or systemic embolism.

SUPPLEMENTARY MATERIAL

Supplementary material (Video 1) is available at EJCTS online.

Conflict of interest: none declared.

REFERENCES

Exciting view on coronary arteries in children with hypoplastic left heart syndrome: finding new answers helps asking better questions

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Successful treatment of neonates with hypoplastic left heart syndrome (HLHS) is a recent major achievement [1]. A little over two decades ago, there were still no treatment options for these patients. Upon the spontaneous closure of the ductus arteriosus in these neonates, they died under compassionate care within the first weeks of life. Nevertheless, during this pre-therapeutic area, early serial postmortem examinations revealed the high rate of coronary anomalies in HLHS [2, 3].

Multiple ventriculocoronary arterial connections and thick-walled and kinking coronary arteries were observed, especially in those infants with patent left ventricular inflow and obstructed left outflow [3].

Over the past two decades, we have continuously progressed in our ability to treat these patients pre-, peri- and postoperatively. We have learned that the success is deeply rooted in novel surgical techniques in conjunction with excellent intensive care therapy, particularly regarding the principle of a well-balanced relationship between pulmonary and systemic flow.

Thanks to staged Norwood operations nowadays, most children with HLHS achieve palliation to Hemi-Fontan and modified...