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ORIGINAL ARTICLE

Role of gated cardiac computed tomographic angiography in the evaluation of postsurgical complications after stage I Norwood procedure and its implications on management: a comparative study with two-dimensional echocardiography

Rida Salman[1] · Snehal R. More[2] · Marcos P. Ferreira Botelho[1] · Pamela M. Ketwaroo[1] · Prakash M. Masand[1] · Silvana Molossi[3] · Siddharth P. Jadhav[1]

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Abstract

Background The Norwood procedure is the first part of a three-stage surgical palliation for patients with functionally single ventricle anatomy. Complications after the stage I operation are not uncommon. Transthoracic echocardiography (TTE) is traditionally the mainstay for evaluation.

Objective The purpose of our study is to compare gated cardiac computed tomographic angiography (CCTA) with TTE when evaluating for postoperative complications after stage I Norwood procedure and to describe management implications.

Materials and methods A retrospective chart review of all patients over a 4-year period who underwent nonelective urgent CCTA for suspected complications related to stage I Norwood procedure was performed. Elective CCTA studies before stage II palliation were excluded. Patient demographics, CCTA and TTE findings, as well as interventions performed, were recorded.

Results Thirty-four patients were included. The mean age at CCTA was 63 days (range: 4–210 days). All patients had a recent TTE with a mean time interval between TTE and CCTA of 2 days. CCTA detected 56 abnormalities in 30 patients, with 23 directly related to postsurgical complications, including shunt-related complications (10/23, 43%), Damus-Kaye-Stansel anastomotic narrowing (2/23, 9%) and neo-aortic arch/branch vessel abnormalities (11/23, 48%). These complications were managed as follows: surgery (9, 39%), catheter-based intervention (7, 30%), medical (4, 17%) and no change in management (3, 13%). TTE did not detect 8/23 (35%) findings found on CCTA, of which 75% were either managed with surgery (4/8, 50%) or catheter-based intervention (2/8, 25%).

Conclusion CCTA plays an important role in detecting surgical complications after stage I Norwood procedure and demonstrates additional findings that have direct management implications.

Keywords Catheter angiography · Children · Computed tomographic angiography · Congenital heart disease · Echocardiography · Heart · Hypoplastic left heart syndrome · Norwood procedure

✉ Siddharth P. Jadhav
spjadhav@texaschildrens.org

1 Edward B. Singleton Department of Radiology, Texas Children's Hospital, Baylor College of Medicine, 6701 Fannin St., Suite 470, Houston, TX 77030, USA

2 Virtual Radiologic Corporation, Eden Prairie, MN, USA

3 The Lillie Frank Abercrombie Section of Cardiology, Baylor College of Medicine, Houston, TX, USA

Introduction

Hypoplastic left heart syndrome (HLHS), as defined by the Congenital Heart Surgery Nomenclature and Database Committee, is a spectrum of cardiac malformations with different degrees of left heart-aorta complex underdevelopment, consisting of aortic and/or mitral valve atresia, stenosis or hypoplasia with marked hypoplasia or absence of the left ventricle, and hypoplasia of the ascending aorta and aortic arch [1]. HLHS affects approximately 11.6 in 100,000 live births [2]. Effective management of newborns with HLHS includes a staged surgical palliation or orthotopic heart transplantation [3].

Staged surgical palliation was first described by Norwood in 1983 [4] as a three-stage procedure. Stage I includes creation of a functional monoatrium, a neo-aorta by side-to-side anastomosis of the main pulmonary artery and ascending aorta, and fashioning an alternative pulmonary blood supply using a Blalock-Taussig-Thomas (BTT) or Sano shunt. Stage II or bidirectional Glenn consists of connecting the pulmonary arteries to the superior vena cava. This is followed by stage III or Fontan operation, which includes connecting the pulmonary arteries to the inferior vena cava.

Since the 1980s, advancement in surgical techniques has produced more promising results; however, complications remain. In clinical practice, transthoracic echocardiography (TTE) is commonly the first imaging evaluation of possible complications related to a stage I Norwood procedure [5]. Gated cardiac computed tomographic angiography (CCTA) and cardiac magnetic resonance imaging (MRI) play a role in preoperative planning and cardiac anatomy assessment before a Glenn procedure. Krupickova et al. [6] showed in their cohort of 27 patients (10 after a Norwood stage I) that CCTA for detection of great vessel stenosis or hypoplasia can replace cardiac catheterization before a Glenn operation with fewer complications and less radiation when no intervention is needed. Muthurangu et al. [7] showed that cardiac MRI can be used to determine the ventricular and valvar function and vascular anatomy in infants with HLHS and to identify any revisions or additional valvar surgery. However, there is not much data regarding the role of urgent nonelective CCTA in detecting complications directly related to a stage I Norwood procedure and its effects on management. The purpose of this study is to compare CCTA with TTE in the evaluation of possible complications after a stage I Norwood procedure and describe management implications.

Materials and methods

Data collection

Thirty-four children with HLHS underwent urgent nonelective CCTA for suspected complications related to a stage I Norwood procedure between 2016 to 2019 at a large standalone children's hospital. Patients were identified through a search of the picture archiving and communication system (PACS). Elective presurgical CCTAs before stage II were excluded. A retrospective chart review of the clinical data was performed including patient demographics (gender, age), date and indication for CCTA, TTE date and results, cardiac catheter angiography date and results, management of complications following CCTA (medical, surgical or catheter-mediated management), eventual patient outcome in relation to the primary indication, and findings of CCTA.

Cardiac computed tomography angiography

CCTA examinations were performed either on a 320-row multidetector CT (MDCT) scanner (Aquilion ONE; Canon Medical Systems, Tochigi, Japan) or a 192×2-slice dual-source CT (DSCT) system (Somatom Force; Siemens Medical Solutions, Forchheim, Germany). On the MDCT, volumetric scans were performed with target mode prospective echocardiogram (ECG) gating and the target for the center of the acquisition window was set at 40% of the R-R interval. On the DSCT, an ECG-triggered scan was executed with turbo flash mode and the start of acquisition was synchronized to 20% of the R-R interval. In both scanners when coronary artery evaluation was also needed, helical scan with retrospective ECG gating was used. Tube voltage was set at 80 kV and mA was based on patient size. Patients were scanned with a single first-pass arterial contrast-enhancement technique, as determined by a bolus-tracking technique. The nonionic contrast agent Iohexol 300 mg I/mL (Omnipaque 300; GE Healthcare, Princeton, NJ) was injected through a 22-gauge catheter with a dual-syringe injector at a dose of 2–2.5 mL/kg. The injection rate was 1.5–3 mL/s depending on patient size. We do not prefer injection through a 24-gauge catheter in children due to the low rate of injection (1 mL/s) resulting in inadequate vascular opacification. None of the included patients was specifically intubated for CCTA. All exams were performed with free breathing and without additional sedation. Premedication was not used to reduce heart rate. Data were reconstructed with an iterative reconstruction algorithm (AIDR [adaptive iterative dose reduction], Toshiba [Canon] Medical Systems, or ADMIRE [advanced modeled iterative reconstruction], Siemens Medical Solutions) in 0.5-mm-thick slices. With the 320-slice scanner, the best motion-free cardiac phase was selected from the raw data when needed by the attending radiologist using ImageXact software (Canon Medical Systems), which allows half-scan reconstruction of data for a selected slice across the entire spectrum of cardiac phases spanned by the rotation time.

The CCTA findings were classified into seven categories, including complications related to BTT or Sano shunt; Damus-Kaye-Stansel (DKS) anastomosis; aortic arch reconstruction and its main branches; pulmonary arteries; pulmonary veins, coronary arteries and airways.

We compared CCTA results with TTE and presurgical cardiac catheter angiography findings when available. Management decisions and immediate postsurgical outcomes were recorded.

The volume CT dose index ($CTDI_{vol}$) and dose length product (DLP) displayed on the CT console were recorded and were obtained for a 32-cm phantom. Given all the factors that go into computing an effective dose, we used an average conversion factor of 0.09 mSv/mGy·cm [8].

Results

The male to female ratio was 1:1. The mean age at the time of the CCTA was 63 days (range: 4–210 days). Thirty-four patients had echocardiography followed by CCTA; 18 patients underwent presurgical cardiac catheter angiography. The mean time between TTE and CCTA was 2 days (range: 0–9 days). The mean time between CCTA and cardiac catheter angiography was 15 days (range: 0–60 days). CCTA was ordered based on patients' symptoms and signs, ECG and laboratory findings including hypoxia, low cardiac output, blood pressure gradient, ST segment changes and elevated troponin, as well as TTE findings such as increased velocity across the shunt, aortic arch narrowing, gradient at the level of the aorta, the pulmonary veins or arteries and intracardiac thrombus. Overall, the main clinical indication was acute onset of hypoxemia.

Eighteen CCTA exams were performed on the MDCT scanner: 17 with prospective target mode ECG gating and 1 with retrospective ECG gating. Sixteen CCTA exams were performed on the DSCT: 15 with turbo flash mode and 1 with retrospective ECG gating. The heart rate ranged between 97 and 159 beats per min with an average of 134 beats per min. The range of tube-current levels was 127–534 mAs with an average of 180 mAs.

The mean $CTDI_{vol}$ was 4.74 mGy (range: 0.46–11.2 mGy) and the mean DLP was 17.06 mGy·cm (range: 5.9–75 mGy·cm). The mean effective dose was 1.65 mSv (range: 0.53–4.24 mSv) on MDCT and 1.41 mSv (range: 0.54–6.75 mSv) on DSCT. In one case, the exam was repeated on DSCT for optimal vascular opacification in order to answer the clinical question. Another reason for having broad dose range is performing some studies with retrospective gating for coronary artery evaluation.

CCTA detected 56 complications in 30 patients, with 23 directly related to postsurgical complications. Postsurgical complications included shunt stenosis (*n*=9; 3 not detected by TTE, 4 confirmed by cardiac catheter angiography, 1 believed to be not hemodynamically significant), shunt leak (*n*=1; not detected by TTE), DKS anastomotic narrowing (*n*=2; 1 not detected by TTE, 1 confirmed by cardiac catheter angiography), aortic arch or major branch vessel stenosis (*n*=11; 3 not detected by TTE, 4 confirmed on cardiac catheter angiography) (Fig. 1). These findings were managed as follows: catheter-based intervention (*n*=7), surgical (*n*=9), medical (*n*=4), no change in management (*n*=3). TTE did not detect 8 of the 23 findings found on CCTA (Table 1; Figs. 2, 3 and 4). These complications were managed as follows: catheter-based (*n*=2), surgical (*n*=4), no immediate intervention needed (*n*=2).

Twenty-two and 12 children had a BTT or Sano shunt placement, respectively. We found 10 shunt-related complications, including 2 patients with a BTT shunt stenosis (Fig. 5), 1 patient with a BTT shunt leak (3/22, 13.6%) and 7 patients with a Sano shunt stenosis (7/12, 58.3%) (Fig. 6). More shunt interventions were needed with a Sano shunt (3/12, 25%, vs. 3/22, 14%, with a BTT shunt).

There were 33 complications unrelated to surgery, which included pulmonary artery stenosis (*n*=18; 11 not detected by TTE, 7 confirmed on cardiac catheter angiography with 1 considered not significant), pulmonary vein stenosis (*n*=7; 3 not detected by TTE, 3 confirmed on cardiac catheter angiography and 1 not confirmed on cardiac catheter angiography), and coronary stenosis (*n*=4; 2 not detected by TTE, 2 confirmed on cardiac catheter angiography, 2 did not undergo cardiac catheter angiography), as well as airway complications such as bronchial narrowing (*n*=4; expectedly not seen by TTE). Note that TTE and cardiac catheter angiography subsets mentioned for each CCTA finding are not related to the same patients since not all patients were evaluated with cardiac catheter angiography.

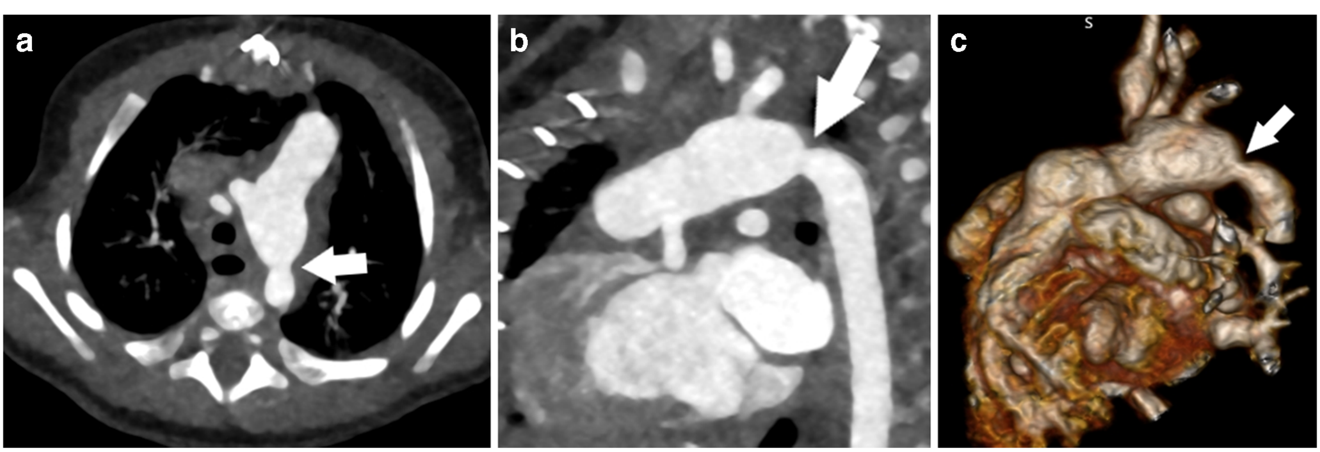

Fig. 1 A 7-week-old girl with aortic isthmic stenosis. **a**–**c** Axial (**a**), sagittal (**b**) and three-dimensional rendered (**c**) cardiac CT angiography images demonstrate discrete moderate narrowing of the isthmus (*arrows*). The patient underwent balloon angioplasty by catheter angiography

Table 1 Management of complications with discrepant findings on cardiac computed tomographic angiography (CCTA) compared to transthoracic echocardiography (TTE)

Complication category	CCTA finding	TTE finding	Management
BTT/Sano shunt	Contained hemorrhage/anastomotic leak of the BTT shunt (Fig. 2).	Echodensity seen along the right side of the atrial septum with extension into the left atrium, suspicious for thrombus. Continuous flow seen in the shunt, leak not detected.	Repeat median sternotomy for control of disrupted shunt.
	Mild to moderate narrowing at distal Sano anastomosis.	Patent Sano shunt. Stenosis not detected.	Stent angioplasty of the distal Sano conduit.
	Mild narrowing at distal Sano anastomosis.	Patent Sano conduit with peak flow velocities between 3.0 and 4.0 m/s, similar to previous TTE. Distal conduit and branch pulmonary arteries not well seen.	Catheter angiography: Stenosis not hemodynamically significant. Elective Glenn scheduled with medical management.
	Moderate stenosis of the BTT shunt near its pulmonary anastomosis and severe LPA stenosis.	Stenosis not detected.	Glenn 3 days after CCTA.
DKS anastomosis	DKS anastomosis extremely small in caliber measuring 1 mm in diameter (Fig. 3).	DKS anastomosis patent, measures 3.4 mm.	DKS revision, BTT takedown and Sano placement.
Neo-aortic arch/branch vessel	Moderate focal narrowing of the brachiocephalic trunk near its origin (Fig. 4).	Nothing mentioned in the report. Not seen.	Surgical augmentation with autologous pericardial patch.
	Complete occlusion of the origin of the left subclavian artery.	Not seen during aortic arch evaluation on the initial TTE.	No intervention.
	Mild concentric narrowing of the neo-aortic isthmus in addition to a small eccentric posterior ledge.	Unobstructed aortic arch with diastolic flow reversal in the context of a BTT shunt. Peak velocity of 2.2 m/s across the descending thoracic aorta. Normal abdominal aorta pulsatility with expected diastolic flow reversal.	Angioplasty of coarctation.

BTT Blalock-Taussig-Thomas, *DKS* Damus-Kaye-Stansel, *LPA* left pulmonary artery

Of 30 patients with abnormalities on CCTA, 26 (87%) went on to a successful stage II palliation and 4 patients (13%) died before the stage II operation from factors not directly related to postsurgical complications.

Between 2016 and 2019, there were 104 Norwood operations. Hence, 33% (34/104) of these patients underwent CCTA to evaluate for postoperative complications. No patients were referred for cardiac MRI.

Discussion

The role and accuracy of CCTA in patients with HLHS after a stage I Norwood procedure but before a stage II Glenn procedure are well established in the literature [4, 9]. However, its role in detecting potential postoperative complications in the urgent nonelective setting and subsequent impact on management have not been described. A study by Goo [10] included a

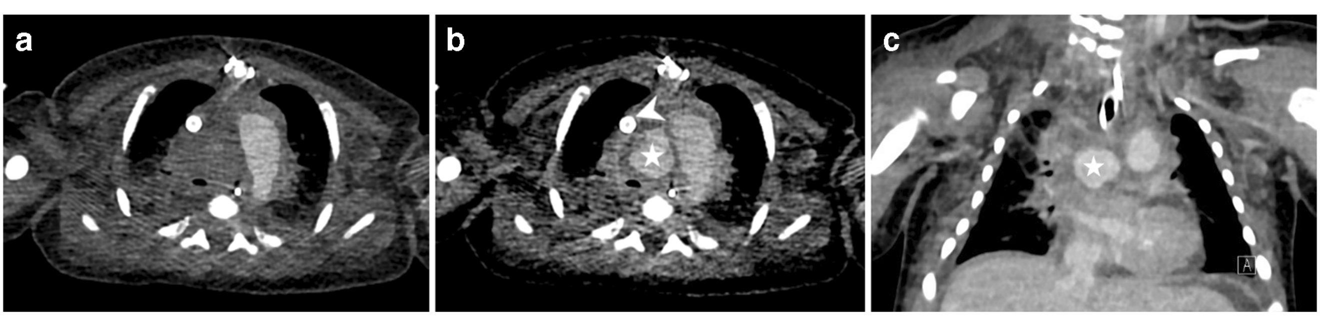

Fig. 2 A 1-month-old boy on extracorporeal membrane oxygenation (ECMO) with Blalock-Taussig-Thomas (BTT) shunt leak. **a–c** Axial cardiac CT angiography images with early (**a**) and delayed (**b**) phases and coronal maximum intensity projection in delayed phase (**c**). There is poor visualization of the BTT shunt itself, possibly related to contrast timing in the setting of complex ECMO hemodynamics. Note the pooling of contrast with smooth margins (*stars*) not corresponding to an anatomical structure and posteromedial to the ECMO cannula (*arrowhead*) corresponding to the contained hemorrhage/anastomotic leak. The patient underwent repeat median sternotomy for control of the disrupted shunt

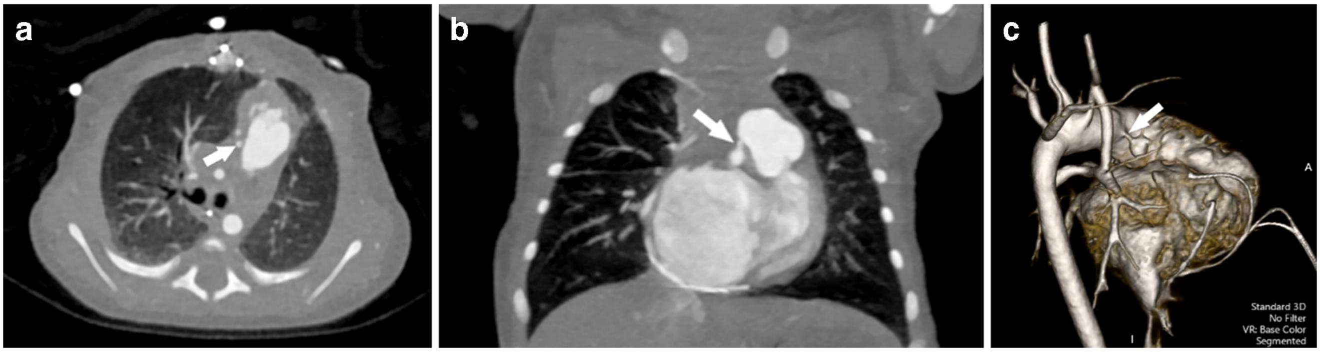

Fig. 3 A 2-month-old boy with Damus-Kaye-Stansel (DKS) anastomosis narrowing. **a–c** Axial (**a**), coronal (**b**) and three-dimensional rendered (**c**) cardiac CT angiography images show extremely diminutive DKS anastomosis (*arrows*) measuring only 1 mm in diameter. Note that the preoperative diameter of the hypoplastic native ascending aorta was 2 mm. The patient underwent DKS revision, Blalock-Taussig-Thomas shunt takedown and Sano placement

small cohort of 14 patients with 3 sequential CCTAs performed before Norwood, early and late after the procedure, studying the serial changes of cardiac morphology and function after the Norwood surgery.

In our study, CCTA demonstrated additional postoperative complications that were missed by TTE. Complications directly related to the surgery were not detected in 8 patients by TTE and 75% of those went on to surgical or catheter-mediated interventions before an eventual successful Glenn procedure, except 1 patient who had an emergent Glenn procedure based on CCTA findings (Table 1).

In our cohort, more shunt interventions were needed for Sano shunt complications. Our results are similar to those published in a prior study of 103 patients by Fischbach et al. [11], who showed a higher rate of shunt interventions in patients with a Sano shunt; 30% vs. 6% with a BTT shunt. We had 5 interstage deaths in this cohort (3/12 with a Sano shunt and 2/22 with a BTT shunt).

In addition, CCTA was superior to TTE and cardiac catheter angiography in detecting aortic arch and major branch vessel stenosis. One case of subclavian artery stenosis and another case of carotid artery stenosis were not specifically evaluated on cardiac catheter angiography although they were detected on CCTA.

CCTA also detected four complications related to coronary arteries including thrombosis or fistulae. However, it missed an unsuspected left main coronary artery stenosis in one patient who underwent cardiac catheter angiography 2 days after the CCTA, requiring catheter-based recanalization of the left main coronary artery. The coronary artery stenosis in this case was missed because the study was not tailored for coronary artery evaluation. This was the only case in our cohort where cardiac catheter angiography by itself changed management.

Bronchial narrowing was incidentally found in 4 of our patients (11.7%). As expected, TTE and cardiac catheter angiography did not evaluate these. Airway abnormalities seen on CCTA may affect clinical management and have implications for cardiovascular anesthesia during future interventions/surgery.

We compared CCTA and TTE describing detection of complications related to stage I Norwood procedure in an urgent nonelective setting, as well as the impact of those complications on management. There are several limitations of

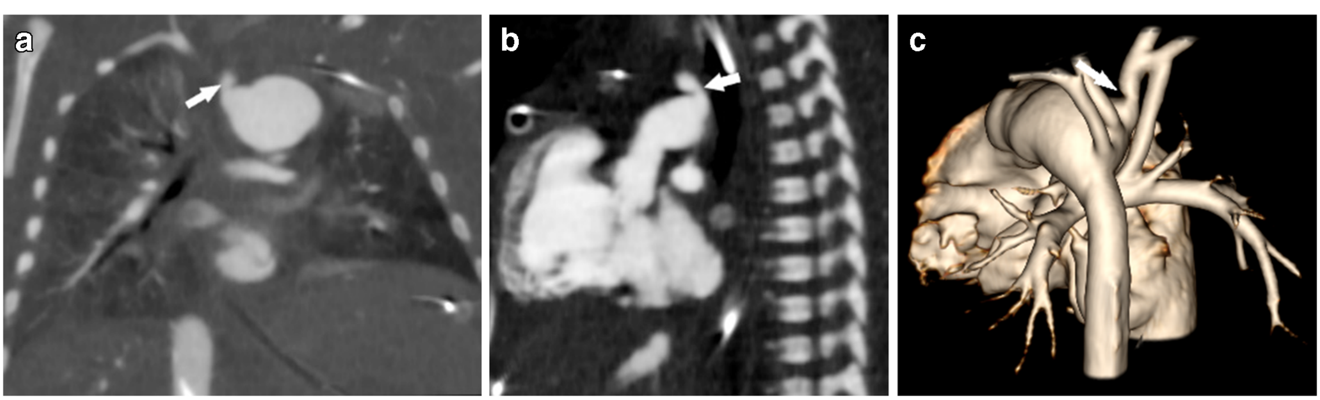

Fig. 4 A 1-month-old girl with brachiocephalic trunk narrowing. **a–c** Coronal (**a**), sagittal (**b**) and three-dimensional rendered (**c**) cardiac CT angiography images show moderate focal narrowing of the brachiocephalic trunk near its origin (*arrows*) as a result of acute anterior angulation with normal caliber distal to this narrowing. The patient underwent surgical augmentation with autologous pericardial patch

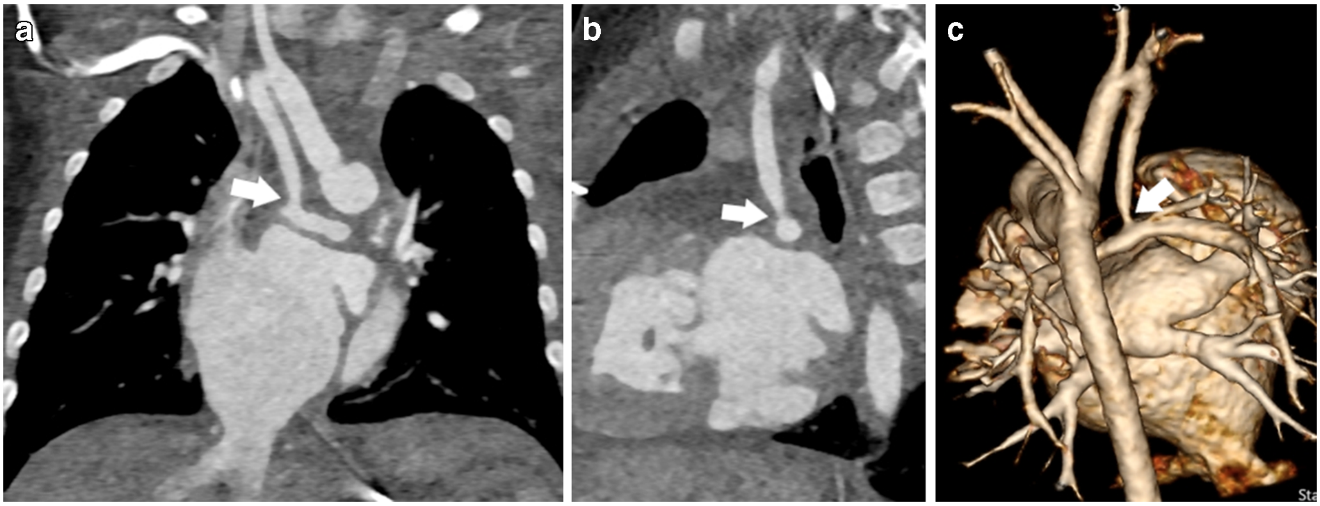

Fig. 5 A 2-month-old girl with Blalock-Taussig-Thomas (BTT) shunt stenosis. **a–c** Coronal (**a**), sagittal (**b**) and three-dimensional rendered (**c**) cardiac CT angiography images show moderate stenosis of the BTT shunt at its pulmonary anastomosis (*arrows*). The patient was clinically unstable and underwent urgent Glenn procedure

this study. Due to its retrospective nature, a selection bias in performing CCTA could not be avoided. It is possible that other patients with suspected postoperative complications after stage I were never referred for CCTA and, therefore, the true sensitivity for TTE detection of urgent postoperative complications is not assessed by our study. Nevertheless, our results suggest CCTA has a complementary role for evaluation of complications after stage I palliation, impacting decision-making regarding re-intervention. The number of patients in this cohort is small. However, the focused nature of our HLHS cohort with urgent nonelective postsurgical CCTA made it difficult to have a large number of cases, even in a high-volume congenital heart disease surgical center. A future multi-institutional study would be needed to confirm our results. CCTA also has potential risks related to ionizing radiation, although some patients may have avoided or reduced duration of radiation related to diagnostic cardiac catheter angiography because of the CCTA. In this study, radiation dose of CCTA was reduced by state-of-the-art CT scanners, applying radiation dose-lowering techniques and indication-based protocol optimization. Understanding this particular subset of high-risk patients following a stage I Norwood might impact outcomes.

Conclusion

CCTA plays an important role in detecting complications after a stage I Norwood procedure, and detects additional findings compared to TTE, including those unrelated to surgery that may affect management. CCTA can be an effective, noninvasive, quick, low radiation alternative to cardiac catheter angiography for initial workup of these critically ill, high-risk patients. CCTA complements TTE and should be considered part of the imaging algorithm for suspected postoperative complications.

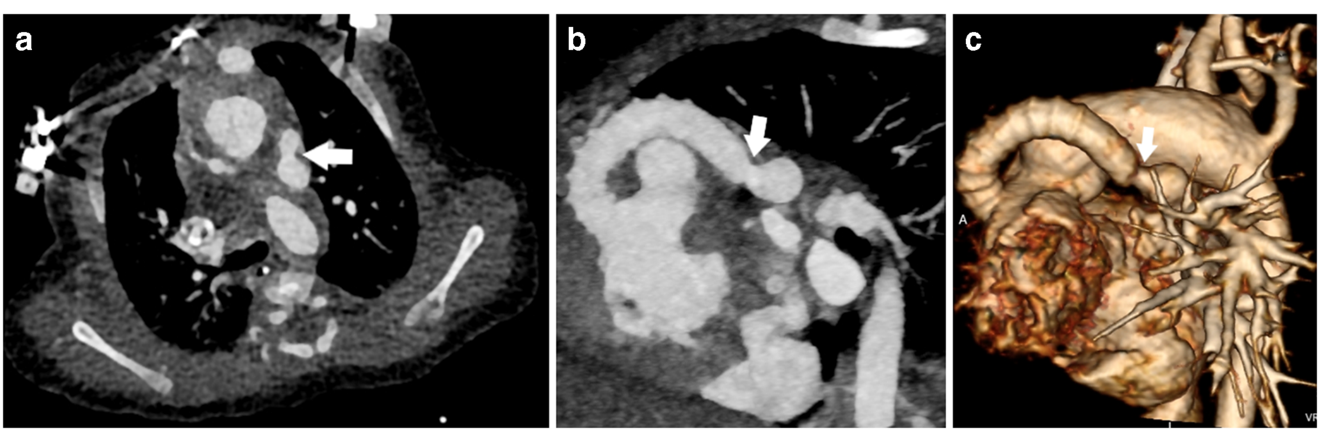

Fig. 6 A 7-week-old girl with Sano shunt stenosis. **a–c** Axial (**a**), sagittal (**b**) and three-dimensional rendered (**c**) cardiac CT angiography images show patent Sano shunt with moderate focal stenosis at its distal anastomosis with the main pulmonary artery (*arrows*). The patient remained hemodynamically stable and underwent elective Glenn procedure

Compliance with ethical standards

Conflicts of interest None

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