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Physiology-Adapted Cardiac CT Angiography during Veno-Arterial ECMO in Neonatal and Pediatric Postoperative Congenital Heart Disease: Feasibility and Clinical Impact

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Abstract

Background

Cardiac computed tomographic angiography (CCTA) provides high-resolution anatomical assessment in cases of congenital heart disease (CHD). This is crucial in patients supported by veno-arterial extracorporeal membrane oxygenation (VA-ECMO), since the fundamental alteration of systemic hemodynamics and contrast transit kinetics makes conventional CT acquisition strategies unreliable. We evaluated the feasibility, diagnostic yield, and clinical impact of a structured CCTA protocol adapted to ECMO-dependent physiology in postoperative neonatal and pediatric CHD patients.

Methods

This retrospective, single-center cohort study (2013–2022) included all consecutive postoperative neonatal and pediatric patients with CHD who underwent clinically indicated CCTA while supported by VA-ECMO subsequent to cardiac surgery. Contrast administration route and scan timing were individualized according to ECMO circuit flow characteristics and clinical indication.

Results

Twenty-six CCTA examinations were performed in 25 patients ranging in age from 3 days to 14.8 years (median age 133 days; median weight 5.1 kg). Contrast was administered via the arterial ECMO limb in 15 cases and intravenously with controlled ECMO flow modulation in 11. In 18 of the 26 examinations (69%) the examination revealed a pathology. CCTA provided anatomical information beyond echocardiography in 22 of 26 cases (85%) and directly informed a surgical or catheter-based intervention in 14 cases (54%), with procedural confirmation in all. No transport-related or CT-related adverse events occurred.

Conclusion

When acquisition protocols are adapted to ECMO-dependent hemodynamics, CCTA is feasible and diagnostically consequential in neonatal and pediatric patients supported by VA-ECMO after congenital cardiac surgery. A physiology-guided strategy enables consistent vascular enhancement and frequently identifies clinically actionable findings not detected by echocardiography which can directly inform therapeutic decision-making in this critically ill population.

Introduction

Cardiac computed tomographic angiography (CCTA) has become an established component of multimodality imaging in congenital heart disease (CHD) that provides high spatial resolution, rapid acquisition, and detailed three-dimensional (3D) anatomical reconstruction.[1–3] In postoperative patients, CCTA complements echocardiography by enabling a detailed evaluation of surgical anastomoses, extracardiac conduits, pulmonary vasculature, and coronary arteries in cases characterized by restricted acoustic windows and/or complex surgical anatomy.[4–5] Current imaging guidelines recommend CT when echocardiographic assessment is incomplete or inconclusive.[18,19]

Despite advances in surgical management, a subset of neonates and children require VA-ECMO for postoperative circulatory support. In this critically ill population, persistent hemodynamic instability may reflect residual structural lesions, coronary compromise, cannula-related obstruction, or vascular thrombosis, all of which require precision anatomical localization before re-intervention can be planned. However, echocardiographic assessment in ECMO-supported patients is limited by postoperative anatomical distortion, mechanical ventilation, and cannula positioning. Cardiac catheterization is technically demanding and has potential procedural risks in hemodynamically unstable infants on extracorporeal support.[6]

The VA-ECMO physiological milieu makes conventional CT acquisition strategies unreliable. This is because the arterial return from the extracorporeal circuit may dominate systemic perfusion, native cardiac output is often markedly reduced, and the intravenously administered contrast may be partially diverted into the circuit before reaching the target vessels.[8–10] These hemodynamic alterations typically produce heterogeneous vascular enhancement that undermines diagnostic image quality when standard bolus-timing strategies are applied.

Although CT during ECMO has been described in adult and pediatric populations, most reports consist of small heterogeneous series or isolated cases without standardized acquisition strategies or systematic descriptions of physiology-adapted protocols.[7,11–15] Few studies have dealt with CCTA protocols tailored to ECMO-dependent hemodynamics in postoperative neonatal and pediatric CHD patients. The current study was designed to (1) describe a structured CCTA acquisition strategy that accounts for ECMO-driven alterations in contrast transit and vascular enhancement, and (2) evaluate its diagnostic yield and clinical impact in this high-risk population.

Methods

Study design and population

This retrospective, single-center cohort study included all consecutive postoperative neonatal and pediatric patients with CHD who underwent clinically indicated CCTA while supported by VA-ECMO subsequent to cardiac surgery between January 2013 and December 2022 at a tertiary pediatric cardiac center. This study was approved by the institutional review board of our center; the requirement for informed consent was waived given the retrospective design.

All the CCTA examinations were clinically indicated emergency procedures when multidisciplinary team discussions concluded that transthoracic or transesophageal echocardiography required further anatomical clarification. Parental consent for the clinical imaging procedure was obtained in accordance with institutional policy.

ECMO configuration

The VA-ECMO was configured to have venous drainage from the right atrium or superior vena cava and arterial return to the aortic arch, as a function of the surgical configuration and institutional ECMO best practices.[16] Extracorporeal support was delivered via the Medos system (Xenios AG, Heilbronn, Germany). The contrast administration routes and circuit configurations for arterial and venous injection are illustrated schematically in Fig. 1.

CT acquisition protocol

All examinations were performed on a 256-slice CT scanner (GE Revolution, GE Healthcare) using ECG-gated acquisition, consistent with established practice for congenital cardiac CT.[1–3] Pediatric radiation dose-optimization strategies were applied in accordance with established principles of radiation minimization in congenital imaging.[20] Transport and image acquisition were carried out by a dedicated multidisciplinary team comprising a pediatric cardiologist, a pediatric radiologist, and a pediatric intensivist. The ECMO circuit tubing configuration and circuit length were verified before transport to ensure safe passage through the scanner gantry. Continuous hemodynamic monitoring was maintained throughout acquisition. A representative setup is shown in Fig. 2.

Physiology-adapted contrast administration

Arterial ECMO limb injection

When coronary insufficiency or myocardial dysfunction was suspected, the contrast was injected into the arterial ECMO limb proximal to the intra-aortic cannula (Fig. 1). Because arterial opacification during VA-ECMO is circuit-dependent rather than cardiac output-dependent, scan delay was calculated from the ECMO flow rate, tubing diameter, and injection-to-aorta distance (*Supplementary Methods S1*). Injection rates of 4–5 mL/s were used to achieve dense opacification of the ascending aorta and coronary arteries while limiting total contrast volume.

Intravenous injection with controlled ECMO flow modulation

When evaluation of extracardiac vascular structures was required, the contrast was administered intravenously at 2–3 mL/s. To mitigate contrast diversion into the ECMO circuit, the pump flow was transiently reduced during image acquisition, a strategy consistent with previously described approaches to improving vascular enhancement during extracorporeal support.[9,10] In certain low-weight patients, a saline bridge between circuit limbs was temporarily opened to maintain circuit priming while functionally isolating the patient from the circuit during the contrast injection (Fig. 1). Flow reduction was limited to less than 90 seconds, with immediate restoration of baseline flow following acquisition.

Results

Patient characteristics

Between January 2013 and December 2022, 4920 patients were admitted to the pediatric cardiac intensive care unit, of whom 131 required VA-ECMO support. Survival to ECMO decannulation was 65%, and survival to hospital discharge was 48%. Among these patients, 25 postoperative CHD patients underwent clinically indicated CCTA while on VA-ECMO, comprising 26 examinations in total.

The cohort was composed of 17 male and 8 female patients (5 neonates, 14 infants, and 6 children ranging in age from 3 days to 14.8 years). The median age was 133 days, the median weight was 5.1 kg, and the median ECMO support duration was 8 days. The demographic and clinical characteristics are detailed in Table 1. The contrast was administered via the arterial ECMO limb in 15 examinations and intravenously in 11; one patient underwent both approaches on separate occasions.

Table 1
Clinical characteristics, CCTA findings, and outcomes of 26 CCTA examinations in 25 patients

Case	Age (days)	Sex	Weight (kg)	Cardiac diagnosis	Index surgery	ECMO POD	CCTA POD	CCTA finding	Subsequent intervention	Intervention POD	ECMO duration (days)
1	239	M	7.8	TAPVD, status post correction	TAPVD repair	0	9	Restrictive left atrial membrane	Surgery	10	5
2	361	M	5.9	Pulmonary vein stenosis	Potts Shunt	0	1	Pulmonary vein stenosis	Surgery	1	12
3	137	M	6.3	Taussig-Bing anomaly, interrupted aortic arch, single coronary artery	Repair of re-coarctation	0	6	No new finding (single coronary artery)	Surgery	7	7
4	33	F	3.6	HLHS, status post Norwood	Norwood-Sano	1	5	Stenosis of Damus-Kaye-Stansel anastomosis	None	—	8
5	362	M	2.7	Hypoplastic heart, Situs, ambiguous, right-sidedness	Glenn procedure	1	6	Narrowing of the mid portion of the SVC	Surgery	9	27
6	1537	M	11.5	Crisscross heart, single right-dominant coronary artery	Glenn procedure	0	13	Discrete narrowing of the left main coronary artery	Catheterization	15	39
7	38	M	3.3	Doubly committed VSD, severe coarctation	Yasui operation with conduit to PA	0	2	LAD compressed by conduit	Surgery	2	9
8	13	F	3.5	HLHS	Norwood-Sano	0	7	Narrow proximal LPA, small pseudoaneurysm	Surgery	—	10
9	43	M	5.2	HLHS	Norwood-Sano	3	7	Suspected RCA narrowing due to external compression by the venous cannula	Catheterization	8	16
10	20	F	3.5	Pulmonary atresia with intact ventricular septum	BTT Shunt	0	7	Small pulmonary circulation	None	—	11
11	42	M	4.4	TGA	ASO	0	1	Left coronary artery stenosis	Catheterization	2	8
12	124	F	4.72	TOF, double aortic arch, left arch atresia	Complete repair	0	1	Post-repair TOF and double arch with mild isthmic coarctation	Catheterization	13	4
13	1177	M	10.8	DILV, TGA, PA	Fontan	0	0	Marked narrowing of the LPA origin	Catheterization	1	1
14	16	M	3.1	DORV, MGA, hypoplastic arch, VSD	ASO, VSD closure, neo-aortic reconstruction	0	0	ASO with poor opacification of the left coronary arteries	Surgery	10	10

Abbreviations: ASO, arterial switch operation; CCTA, cardiac computed tomographic angiography; CoA, coarctation of the aorta; DILV, double-inlet left ventric ventricle; ECMO, extracorporeal membrane oxygenation; HLHS, hypoplastic left heart syndrome; IAA, interrupted aortic arch; LAD, left anterior descending ar artery; LPA, left pulmonary artery; MGA, malposed great arteries; MPA, main pulmonary artery; NA, not available in the source table; PA, pulmonary atresia; P arteriosus; POD, postoperative day; RCA, right coronary artery; SVC, superior vena cava; TAPVD/TAPVR, total anomalous pulmonary venous drainage/return; great arteries; TOF, tetralogy of Fallot; VSD, ventricular septal defect. Dash indicates not recorded or not applicable in the source table.

Case	Age (days)	Sex	Weight (kg)	Cardiac diagnosis	Index surgery	ECMO POD	CCTA POD	CCTA finding	Subsequent intervention	Intervention POD	ECMO duration (days)
15	166	M	5.7	Mitral regurgitation	MVR	0	17	Patent coronary arteries	None	—	27
16	3201	M	25	Interrupted aortic arch, VSD, subaortic stenosis	Ross procedure; IAA repair	0	7	ASO with subvalvar MPA narrowing	Surgery	11	6
17	59	M	3.3	TGA, interrupted aortic arch, DORV, single coronary origin	ASO, coronary repair	2	6	Normal coronaries	None	—	7
18	858	F	NA	HLH, TGA, CoA	Fenestrated Fontan	3	6	LAD appears narrowed on venous injection, thrombi	Surgery	9	7
19	1320	F	16	HLHS	Heart transplant	12	12	Mild RCA narrowing	None	—	8
20	1020	M	NA	NA	Fontan	1	7	No pathological findings	None	—	8
21	120	F	4	TGA, aberrant LCA	ASO	1	1	No pathological findings	None	—	6
22	129	M	5.3	TGA	ASO	0	1	LAD thrombus	Surgery	1	10
23	3	M	4	TAPVR	TAPVR repair, PDA division	0	2	Pulmonary vein stenosis	None	—	5
24	16	M	5	DORV, MGA, hypoplastic arch	NA	0	7	Subvalvar MPA stenosis	None	—	11
25	5360	F	40	HLHS	Heart Transplant	0	2	Mild LPA stenosis	None	—	4
26	120	M	5	TGA	ASO	0	0	Normal coronaries	None	—	6

Abbreviations: ASO, arterial switch operation; CCTA, cardiac computed tomographic angiography; CoA, coarctation of the aorta; DILV, double-inlet left ventric ventricle; ECMO, extracorporeal membrane oxygenation; HLHS, hypoplastic left heart syndrome; IAA, interrupted aortic arch; LAD, left anterior descending ar artery; LPA, left pulmonary artery; MGA, malposed great arteries; MPA, main pulmonary artery; NA, not available in the source table; PA, pulmonary atresia; P arteriosus; POD, postoperative day; RCA, right coronary artery; SVC, superior vena cava; TAPVD/TAPVR, total anomalous pulmonary venous drainage/return; great arteries; TOF, tetralogy of Fallot; VSD, ventricular septal defect. Dash indicates not recorded or not applicable in the source table.

Diagnostic findings

Pathology was identified in 18 of the 26 examinations (69%). The CCTA provided anatomical information not revealed by echocardiography in 22 of the 26 examinations (85%); in the remaining 4, the CCTA confirmed the absence of the suspected structural pathology, which itself guided clinical decision-making. The CCTA directly informed interventions in 14 of the 26 examinations (54%; 10 surgical and 4 catheter-based), with procedural confirmation of the CT diagnosis in all cases. Of the 14 patients who underwent intervention based on the CCTA, 9 were subsequently weaned from the VA-ECMO (7 after surgery and 2 after catheterization). A further 7 patients were weaned from the ECMO without intervention, of whom 6 survived to discharge. Echocardiography (transthoracic or transesophageal) had failed to pinpoint any of the pathologies prior to CCTA referral.

Arterial ECMO limb injection

Of the 15 examinations using arterial ECMO limb contrast injection, coronary pathology was identified in 8 cases: left coronary artery stenosis (n = 4), right coronary artery stenosis (n = 1), cannula-related left anterior descending artery compression (n = 1), cannula-related right coronary artery compression (n = 1), and coronary ostial stenosis (n = 1). All 8 patients underwent subsequent intervention (5 surgical, 3 catheter-based), confirming the CCTA diagnosis in each case. The remaining 7 arterial examinations showed no significant coronary pathology.

Intravenous injection with controlled ECMO flow modulation

Of the 11 examinations using intravenous contrast administration, pathology was identified in 10 cases: pulmonary artery stenosis (n = 4), pulmonary vein stenosis (n = 2), restrictive left atrial membrane (n = 1), superior vena cava stenosis (n = 1), aortic stenosis (n = 1), and pericardial thrombosis (n = 1); one examination showed no significant extracardiac vascular pathology. Six of the 10 patients with identified pathology subsequently underwent an intervention. Representative imaging findings from each acquisition strategy are illustrated in Figs. 3–6.

Safety

No transport-related or CT-related adverse events occurred. Transient hemodynamic changes observed during ECMO flow reduction resolved promptly after restoration of the baseline flow in all cases.

Discussion

Overall, these findings show that CCTA can be performed safely and has high diagnostic yield in neonatal and pediatric patients supported by VA-ECMO after congenital cardiac surgery, provided that acquisition protocols are explicitly adapted to the altered hemodynamics imposed by extracorporeal circulation. In this cohort, a physiology-guided strategy enabled consistent vascular enhancement across a range of patient ages, weights and underlying diagnoses, provided anatomical information unavailable via echocardiography in 85% of the examinations, identified diagnostic pathology in 69%, and directly informed interventions in 54%.

The diagnostic yield observed here; namely, diagnostic pathology in 69% of the examinations, additional anatomical information unavailable via echocardiography in 85%, and direct procedural impact in 54%, testifies to the limitations of echocardiography in this setting in identifying critical clinical indications. CCTA was ordered when anatomical uncertainty persisted despite echocardiographic assessment; in most examinations, it resolved clinically relevant uncertainties without transport-related or CT-related adverse events. These findings thus support an acquisition strategy designed around circuit physiology rather than native cardiac output.

The two acquisition strategies addressed different physiological constraints. Coronary evaluation is particularly challenging in postoperative neonates on ECMO: the acoustic windows are frequently inadequate[17] and the clinical consequences of unrecognized coronary pathology are severe. Direct injection into the arterial ECMO limb made the timing independent of the native cardiac output by delivering the contrast to the ascending aorta through the circuit, and calculating the delay from the circuit flow rate, tubing geometry, and dead-space volume. This strategy achieved reliable coronary opacification and enabled the identification of both intrinsic stenosis and extrinsic cannula-related compression in all eight affected patients, each of whom were subsequently sent for intervention with procedural confirmation. For extracardiac assessment, a transient reduction of the ECMO flow permitted sufficient native cardiac transit to opacify pulmonary and systemic the venous structures; in the youngest and low-weight patients, the temporary opening of the saline bridge directed the contrast bolus entirely through the native circulation. The extracardiac pathologies identified by this approach, which included pulmonary artery and vein stenoses, systemic venous obstruction, restrictive atrial anatomy, and pericardial thrombosis, each correspond to a potentially correctable cause of ongoing ECMO dependence, and six of these patients proceeded to intervention.

The transport of ECMO-supported patients for CT imaging has logistical and clinical risks, and requires institutional preparation. In this series, strict multidisciplinary coordination, pre-transport circuit verification, and continuous hemodynamic monitoring enabled imaging without adverse events. This again underscores that the safety of CCTA in this population depends on the organizational framework supporting its implementation as much as on the imaging protocol itself.

Previous reports of CT imaging during ECMO have mainly described heterogeneous adult cohorts or isolated pediatric cases without structured acquisition strategies.[7,11–15] To the best of our knowledge, the present series is one of the largest systematically described cohorts of postoperative neonatal and pediatric CHD patients undergoing physiology-adapted CCTA on VA-ECMO support, and potentially the first to describe a structured protocol that explicitly takes circuit flow into account in timing calculations and contrast route selection. The findings thus support the selective use of CCTA as a diagnostic adjunct when echocardiography is inconclusive and precise anatomical definition is required before intervention.

Limitations

This study has several limitations. The sample size was small (25 patients, 26 examinations), reflecting the rarity of the clinical scenario which precludes formal statistical comparison between acquisition strategies or subgroup analyses. The retrospective, single-center design introduced selection bias and limits generalizability. Image quality was not evaluated using a standardized quantitative scoring system. The observational design did not allow outcomes such as ECMO weaning or survival to be attributed to the CCTA findings specifically, since other clinical factors contributed to management decisions. Finally, the multidisciplinary expertise and institutional infrastructure needed to implement this protocol safely may not be universally available.

Conclusion

CCTA can be performed safely in neonatal and pediatric patients supported by VA-ECMO subsequent to congenital cardiac surgery when acquisition protocols are tailored to the hemodynamic constraints imposed by extracorporeal circulation. The physiology-guided strategy described here provided reliable anatomical assessment, identified diagnostic pathology in 69% of the examinations, yielded additional anatomical information unavailable via echocardiography in 85%, and directly informed the therapeutic intervention in 54%. Prospective multicenter studies are needed to validate this approach and define its role in the management of postoperative ECMO-supported patients.

Declarations

Funding declaration

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Author Contribution

Y.S. and S.T.-Y. conceived and designed the study.Y.S., A.S., J.M.J., O.G., D.M., E.H., T.T., R.K.L., O.V., M.S., A.V. and S.T.-Y. contributed to data acquisition, clinical interpretation and study supervision.Y.S., A.S. and S.T.-Y. analyzed and interpreted the data and drafted the manuscript.J.M.J. and O.G. contributed radiological interpretation and imaging protocol expertise.D.M., E.H., A.V., T.T., R.K.L., O.V. and M.S. contributed clinical, surgical and intensive care interpretation.Y.S., A.S. and S.T.-Y. prepared the figures and tables. All authors critically reviewed the manuscript, approved the final version, and agree to be accountable for all aspects of the work.

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Data Availability

The data supporting the findings of this study are not publicly available due to patient confidentiality and the retrospective clinical nature of the dataset. De-identified data may be made available from the corresponding author upon reasonable request and subject to institutional approval.

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Figures

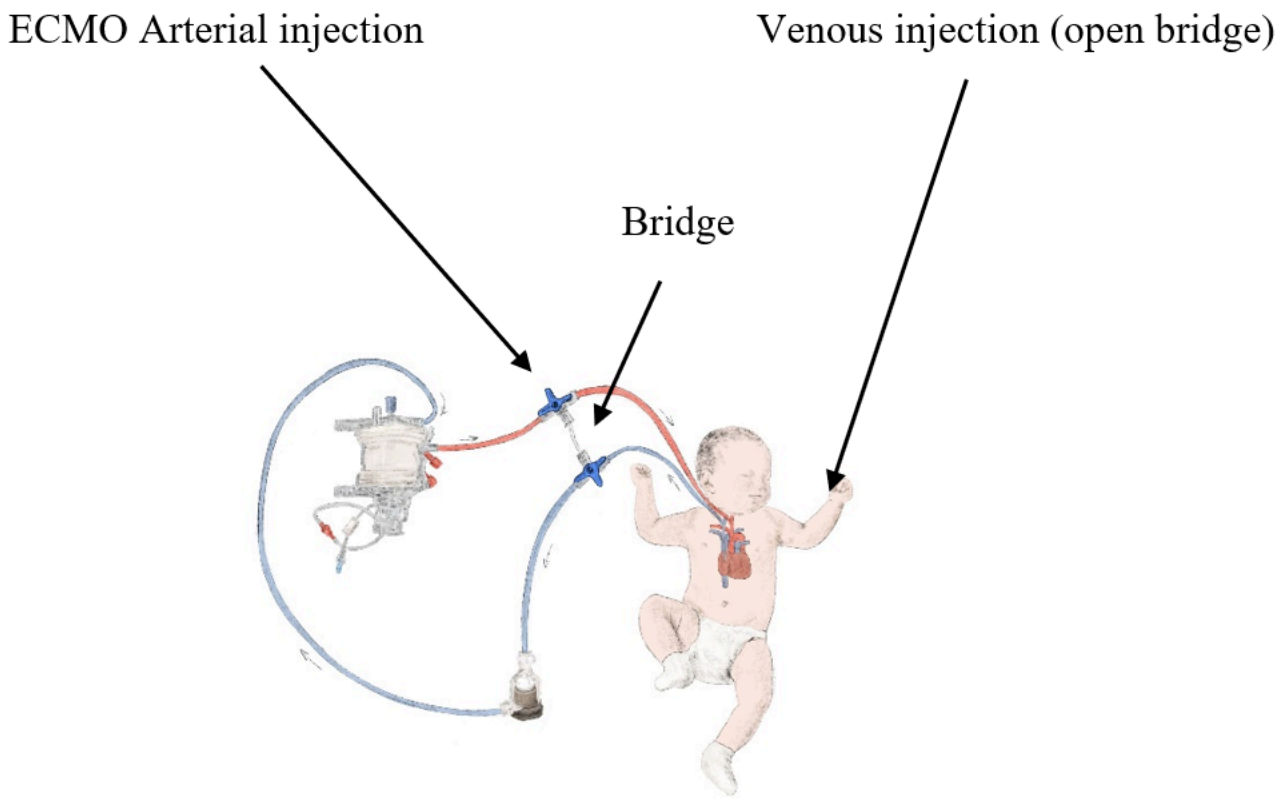


Figure 1

Schematic of a neonatal veno-arterial extracorporeal membrane oxygenation (VA-ECMO) circuit illustrating the two contrast administration strategies used for cardiac CT angiography: direct injection into the arterial ECMO limb (left) and intravenous injection via a temporarily opened saline bridge (right).

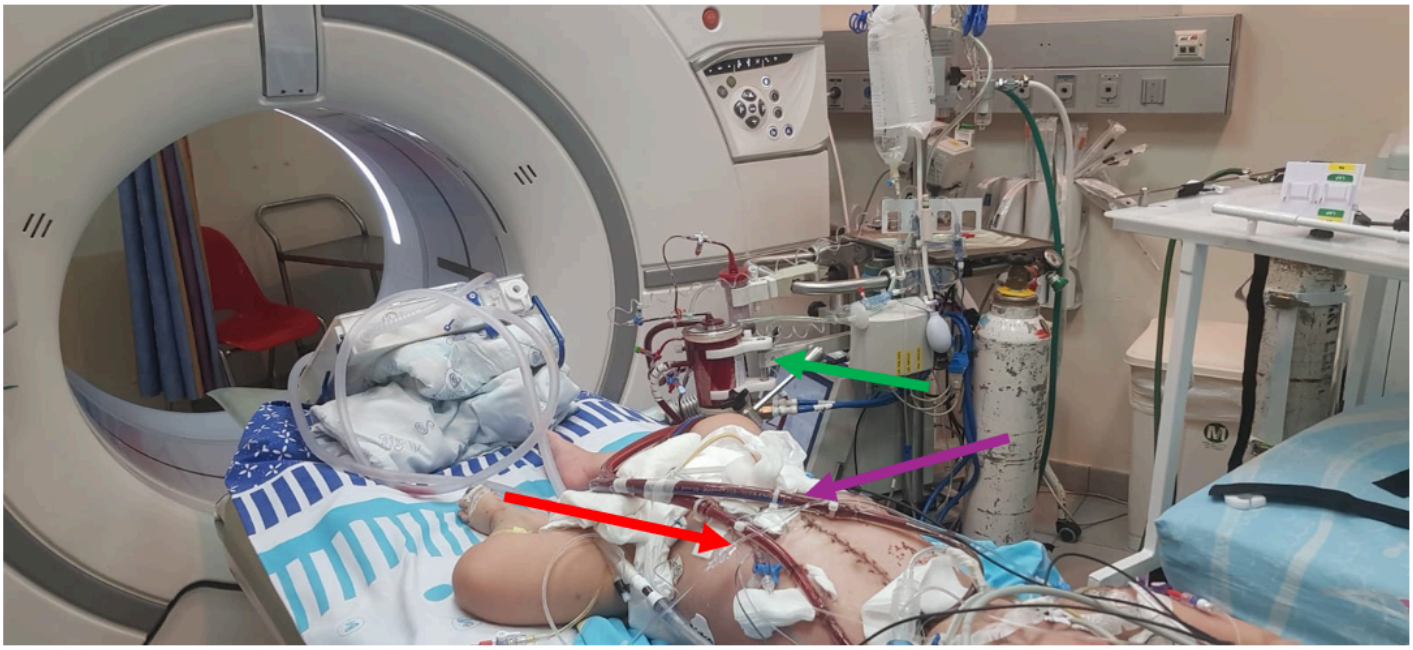


Figure 2

An infant supported by VA-ECMO positioned for cardiac CT acquisition. Red arrow: arterial return tubing; blue arrow: venous drainage tubing; green arrow: ECMO oxygenator.

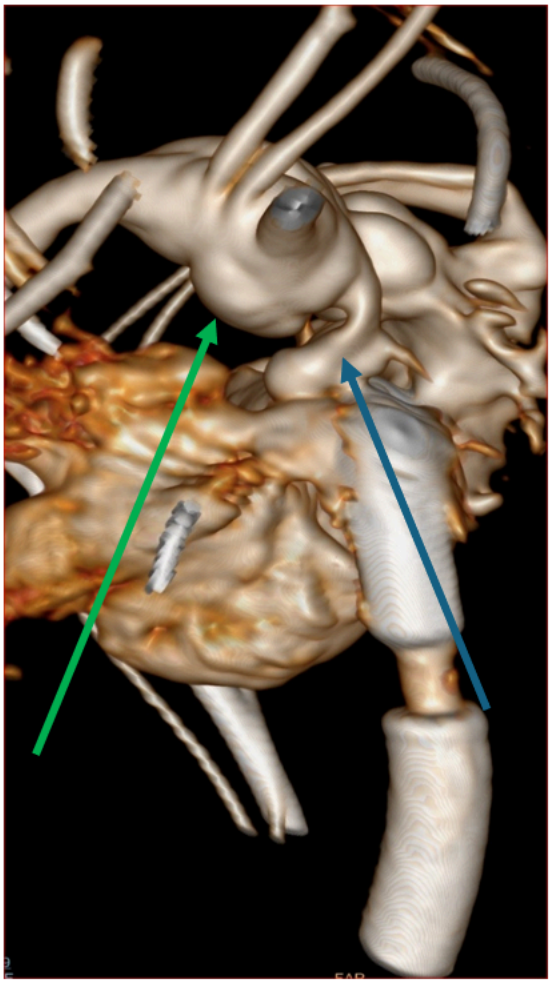


Figure 3

Patient 4, HLH, Norwood Sano Green arrow indicates the neo-aorta, blue arrow indicates the narrowing of the Stansel anastomosis.

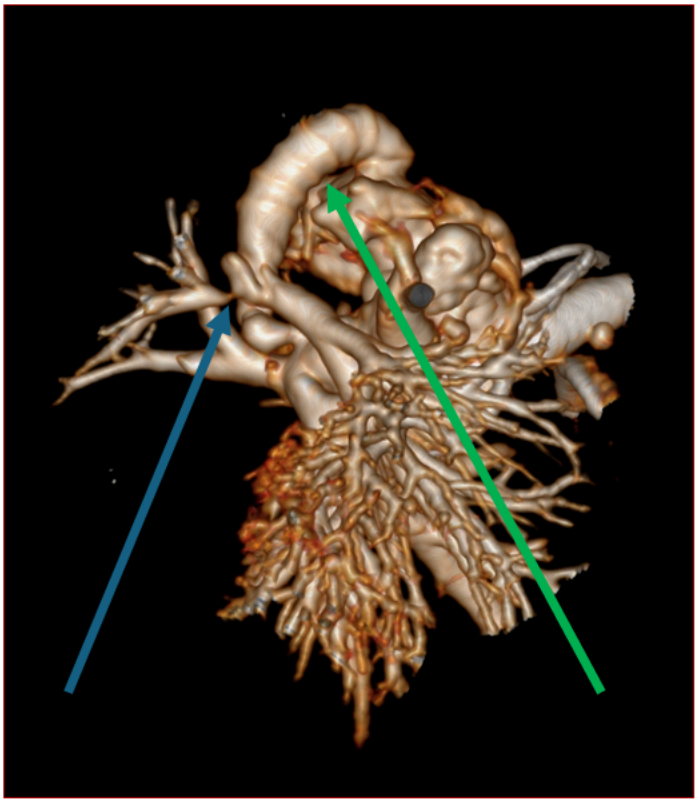
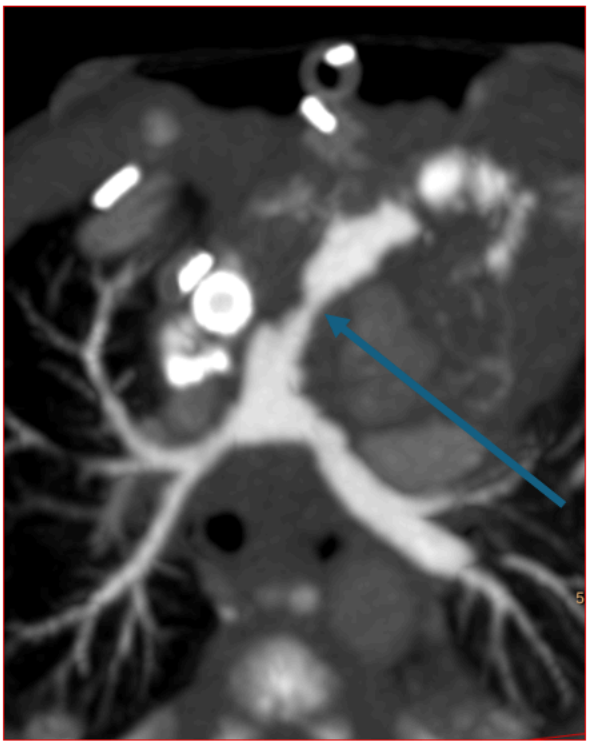


Figure 4

Patient 8. Hypoplastic left heart syndrome after Norwood stage I with Sano modification. Blue arrow indicates stenosis at the origin of the left pulmonary artery (Gore-Tex graft); green arrow indicates the Sano conduit.

5A



5B

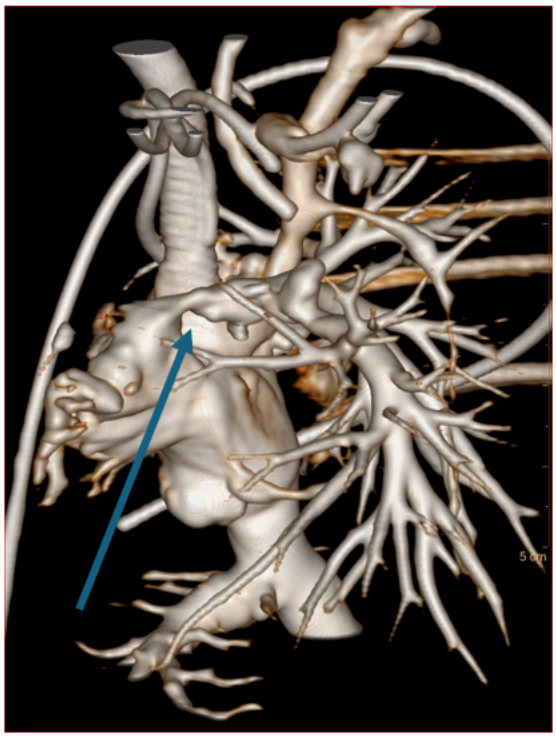


Figure 5

Main pulmonary artery stenosis in a patient with a double outlet right ventricle, malposed great arteries, and a hypoplastic aortic arch (Patient 24). Blue arrows indicate the site of stenosis. 5A: Axial multiplanar reconstruction. 5B: Sagittal plane with volume rendering.

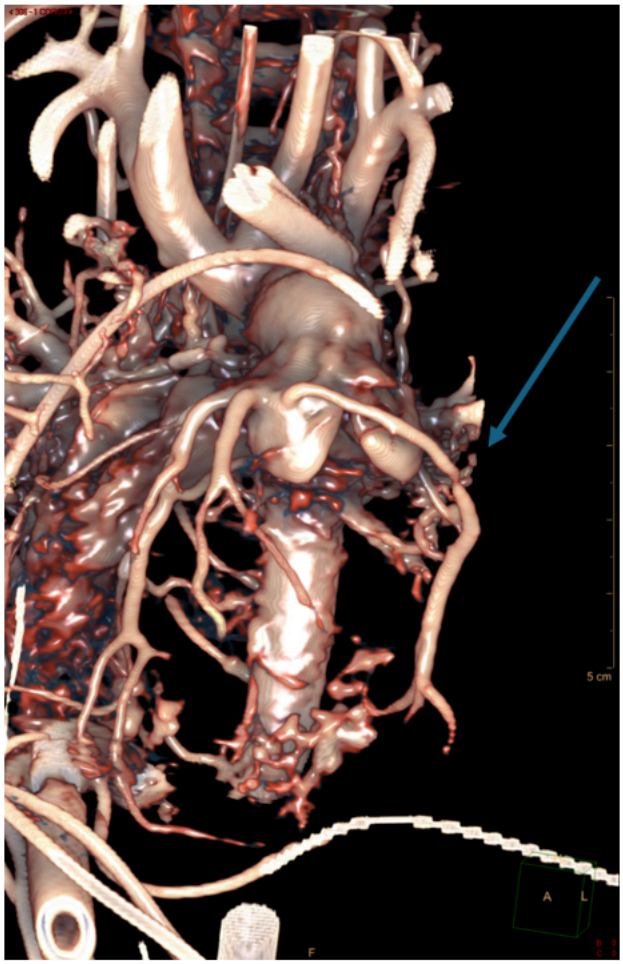


Figure 6

Patient 6 with a crisscross heart and a single right-dominant coronary artery subsequent to the Glenn procedure. The blue arrow points to the discrete narrowing of the left main coronary artery.

Supplementary Files

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- SupplementaryMethodsS1.docx