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The value of low-dose prospective ECG-gated dual-source CT angiography in the diagnosis of coarctation of the aorta in infants and children

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AIM: To investigate the value of prospective electrocardiogram (ECG)-gated dual-source computed tomography (DSCT) in the diagnosis of coarctation of the aorta (CoA).

MATERIALS AND METHODS: Seventeen patients clinically suspected of having CoA underwent prospective ECG-gated DSCT angiography and transthoracic echocardiography (TTE). Surgery was performed in all patients. The diagnostic accuracy of DSCT angiography and TTE was compared with the surgical findings as the reference standard. Image quality was evaluated using a five-point scale. Effective radiation dose was calculated from the dose–length product (DLP).

RESULTS: CoA was diagnosed in 17 patients by DSCT angiography and in 16 patients by TTE. A total of 46 separate cardiovascular abnormalities were confirmed by surgical findings. The diagnostic accuracy of DSCT angiography and TTE was 96.32% and 97.06%, respectively. There was no significant difference in the diagnostic accuracy between DSCT angiography and TTE ($\chi^2 = 0$, $p > 0.05$). The mean score of image quality was 4.2 ± 0.8. The mean effective dose was 0.69 ± 0.09 mSv.

CONCLUSION: Prospective ECG-gated DSCT with a low radiation dose is a valuable technique in the diagnosis of CoA in infants and children.

Introduction

First described by Morgagni in 1760, coarctation of the aorta (CoA) accounts for 5–7% of all congenital heart diseases.[1] CoA is defined as a narrowing of the aorta usually at the aortic isthmus, between the left subclavian artery and the ductus arteriosus.[2] Simple aortic coarctation refers to an isolated anomaly without other cardiovascular abnormalities. Complex aortic coarctation presents with other congenital cardiovascular abnormalities, such as ventricular septal defect, atrial septal defect, or patent ductus arteriosus (PDA).[3] Coarctation is known to be associated with several conditions, 22–42% patients have bicuspid aortic valves and 10% of patients have cerebral aneurysms.[4] Persistent systemic hypertension is shown in most patients with CoA and will probably develop into heart failure. If untreated, the mean survival for the patients is 32 years as a consequence of congestive heart failure, endocarditis, aortic rupture, or cerebrovascular haemorrhage.[3] Therefore,

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detection and repair in early childhood is very important for the prognosis of patients with CoA.

Conventional cardiac angiography (CCA) is regarded as the reference standard for complete diagnosis of CoA; however, its invasive nature limits its widespread application. Transthoracic echocardiography (TTE) is a first-choice assessment method for its simplicity and availability, but it is limited by its acoustic window, operator dependence, and inability to depict extracardiac vascular structures.[5]

Rapid developments in multidetector computed tomography (CT) have made it an important alternative tool in the assessment of CoA.[1,2,4,6–9] The use of electrocardiogram (ECG)-gating during CT reduces motion and pulsation artefacts, when evaluating extracardiac vascular abnormalities.[10]

Retrospective ECG-gated CT is associated with a high radiation dose because of the low pitch and overlapping data acquisition technique. Effective radiation doses between 2 and 7 mSv have been published, using low tube voltage and current modulation.[11] A prospective ECG-triggered sequential CT or "step-and-shoot" (SAS) mode is now available to decrease radiation dose in adult cardiac CTA and paediatric patients with congenital heart disease; this technique can reduce the effective radiation dose to 1–3 mSv in adults.[12]

The purpose of the present study was to investigate the clinical value of prospective ECG-gated dual-source CT (DSCT) in the diagnosis of CoA in infants and children. The evaluation criteria were image quality, diagnostic accuracy, and radiation dose.

Materials and methods

Patients

The study was approved by our institutional review board. Informed consent was obtained from the parents of all patients. From March 2010 to January 2011, 20 paediatric patients with suspected CoA referred to Shandong Medical Imaging Research Institute (Jinan, China) for CT examinations were enrolled in this prospective study. Exclusion criteria were nephropathy ($n = 1$) or hypersensitivity to iodinated contrast media ($n = 2$). Prospective ECG-gated DSCT angiography was performed on 17 patients (age range 1 month to 6 years) after routine TTE examinations. Surgery was performed in all patients.

CT protocol

All patients were examined on a DSCT machine (Somatom Definition, Siemens Healthcare, Forchheim, Germany). Sedation was achieved with oral administration of chloral hydrate under the supervision of a paediatrician, and all patients were free-breathing.

Iodinated contrast medium (Schering Ultravist, Iopromide, 350 mg iodine/ml, Berlin, Germany) was injected via peripheral veins in the elbow or back of the hand with a dual-head power injector (Stellant; Medrad, Indianola, PA, USA). The volume of contrast medium was 2 ml/kg. The contrast medium was followed by a saline bolus, half the volume of the total contrast medium injected. Saline was injected to reduce artefacts caused by undiluted intravascular contrast medium. The time from injection to data acquisition (scan delay) was set at 25 s. The injection rate was calculated at total injected volume/30 s (delay time + 5 s). For example, a 6 kg baby with peripheral access would be injected with 12 ml contrast medium and 6 ml saline at 0.6 ml/s.

DSCT parameters were set as follows: 0.33 s gantry rotation time, $2 \times 32 \times 0.6$ mm detector collimation, a slice collimation $2 \times 64 \times 0.6$ mm by z-flying focal spot technique, 80 kV tube voltage, tube current adapted to body weight (40–59 mAs/rotation for patients <5 kg body weight, 60–79 mAs/rotation for patients 5–10 kg body weight, 80–120 mAs/rotation for patients >10 kg body weight). Current modulation (CARE Dose 4D, Siemens AG) was not used. An ECG-gated sequential prospective scan mode was used, centred on 40% of the R–R interval of cardiac cycle. The duration of CT data acquisition ranged from 4.3 to 9.1 s.

DSCT data post-processing and analysis

Transverse images were reconstructed with 0.75 mm section thickness and 0.5 mm intervals using a medium smooth-tissue convolution kernel (B26f). Reconstruction was performed from 32 to 48% of the R–R interval with a "padding" technique (additional 8% exposure time just before and after the optimal phase in the cardiac cycle) and in 2% increments, and the optimal reconstruction phase was determined from eight phases at 2% intervals. Image data were transferred to an external workstation (Multiple Modality Workplace, Siemens Healthcare, Forchheim, Germany). Multiplanar reformation (MPR), maximum intensity projection (MIP), and volume rendering (VR) were used for image interpretation.

Two trained cardiac radiologists interpreted the image quality independently blinded to the results of TTE and surgical findings. Consensus agreement was achieved between the two observers if disagreement existed. Overall image quality was evaluated using a five-point scoring system (5 = excellent; 4 = good; 3 = fair; 2 = insufficient for complete evaluation; 1 = not interpretable).[13] Grades 3–5 were considered sufficient for complete diagnosis.

TTE

All patients underwent two-dimensional TTE and Doppler flow ultrasound from the parasternal, apical, subxiphoid, and suprasternal approaches using a SONOS 7500 ultrasound system (Philips Medical System, Bothell, WA, USA). The examinations were performed by an experienced echocardiographic technician, and the data were evaluated by a trained paediatrician.

Radiation dose estimations

The volume CT dose index (CTDIvol) and dose–length product (DLP) were recorded and the effective radiation dose (mSv) was estimated from the DLP (mGy·cm) multiplied by 2.5 to adapt results to a 16–cm phantom (the DLP for the body surface area was given for a 32–cm phantom on the scanner protocol and the conversion factor of 2.5 is scanner specific for paediatric examinations at 80 kV[10]). The corrected DLP value was then multiplied by the infant-specific conversion coefficients given for a 16–cm phantom: 0.039 mSv/[mGy·cm] for children up to 4 months, 0.026 mSv/[mGy·cm] between 4 months and 1 year of age, and 0.018 mSv/[mGy·cm] between 1 year and 6 years of age.[14,15]

Statistics

The results from surgery were taken as the reference standard. The sensitivity, specificity, positive predictive value, and negative predictive value for the separate cardiovascular abnormalities were calculated. Results were expressed as means ± standard deviations for quantitative variables and as frequencies or percentages for categorical variables. Interobserver agreement for grading image quality was assessed by using kappa statistics ($\kappa > 0.81$, excellent agreement; $\kappa = 0.61–0.80$, good agreement). Comparative analysis of the diagnostic accuracy between DSCT angiography and TTE was obtained using the non-parametric chi-square test. $P < 0.05$ was considered statistically significant.

Results

Prospective ECG-gated DSCT angiography was performed without complications in 17 patients. The patient demographics can be seen in Table 1. Using surgical findings as the reference standard, all 17 patients were diagnosed with CoA, among them simple CoA (Fig 1) in three patients and complex CoA in 14 patients with PDA ($n = 7$, Figs 2 and 4), atrial septal defect ($n = 4$, Figs 3 and 4), ventricular septal defect ($n = 9$, Figs 3 and 4), bicuspid aortic valve ($n = 3$), hypoplasia of the aortic arch ($n = 3$), abnormal origin of the coronary artery ($n = 2$, Fig 5), transposition of the great arteries ($n = 1$, Fig 4), and bronchus artery dilation ($n = 1$). Dilation of the internal mammary arteries and intercostal arteries was found in three cases (Fig 3).

A total of 46 separate cardiovascular anomalies were proven by surgical results. Table 2 demonstrates the details on the separate cardiovascular abnormalities. The diagnostic accuracy of DSCT angiography and TTE was 96.32% (131/136) and 97.06% (132/136) separately. There was no significant difference in the diagnostic accuracy between DSCT angiography and TTE ($\chi^2 = 0$, $p > 0.05$). The sensitivity, specificity, positive predictive value, and negative predictive value were all 100% when combined DSCT angiography with TTE (Table 3).

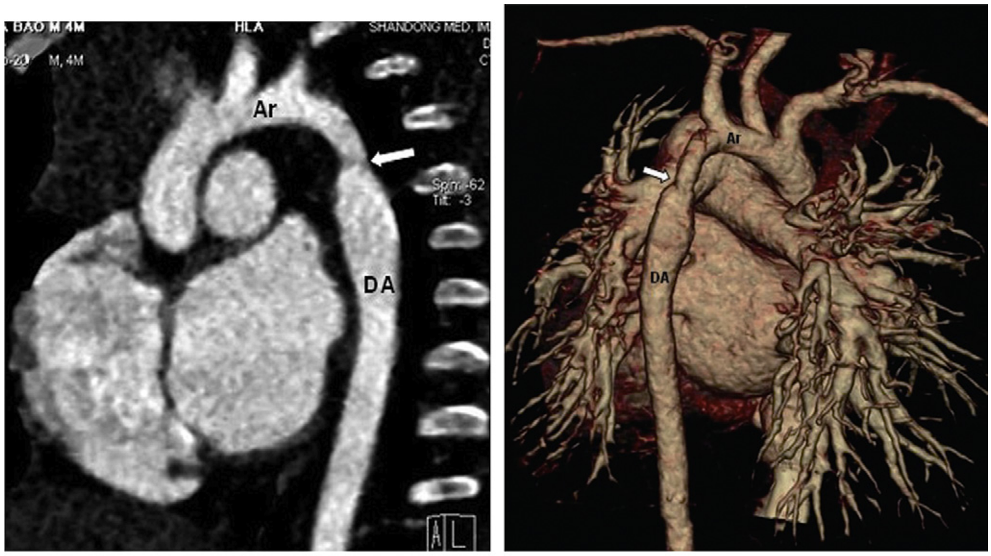
Prospective ECG-gated DSCT angiography diagnosed all 17 patients with CoA. TTE misdiagnosed one patient with an interrupted aortic arch. All findings were confirmed at surgery. For diagnosis of associated complications, TTE failed to identify an abnormal origin of the coronary arteries in two patients and hypoplasia of the aortic arch in one patient. DSCT failed to identify one case of a small atrial septal defect and misdiagnosed an atrial septal defect as normal. Three cases of bicuspid aortic valves were not identified using DSCT because only the end-systolic data were reconstructed.

Image quality assessment

Diagnostic CT images (images graded 3 or more) were obtained in all patients. The mean image quality score was 4.2 ± 0.8, and distributed as score 3 ($n = 4$, 24%), score 4 ($n = 6$, 35%), and score 5 ($n = 7$, 41%). The agreement on the

Table 1
Demographics of the 17 patients and their radiation dose in prospective electrocardiogram (ECG)-gated dual-source computed tomography (DSCT) angiography.

Patient number	Gender	Age (months)	Weight (kg)	Heart rate (beats/min)	Volume CT dose index (mGy)	Dose–length product (mGy cm)	Effective dose (mSv)
1	M	3	6	145	0.72	7	0.683
2	M	1	3.5	134	1.05	9	0.878
3	M	4	4	140	0.93	10	0.650
4	M	6	5.5	120	1.13	10	0.650
5	M	15	10	133	0.83	11	0.495
6	F	10	7.5	134	0.83	11	0.715
7	F	8	6	117	0.97	12	0.780
8	M	6	7	139	0.97	12	0.780
9	M	5	6	120	0.97	12	0.780
10	M	20	9	118	1.03	14	0.630
11	F	12	8	133	0.97	14	0.630
12	M	14	7	128	0.97	14	0.630
13	F	18	10	106	0.97	14	0.630
14	F	24	10	113	0.97	14	0.630
15	M	36	13	125	1.16	16	0.720
16	M	40	13	103	1.32	16	0.720
17	M	72	25	91	1.32	16	0.720
Average	—	17.29 ± 19.94	8.85 ± 4.98	123.47 ± 14.55	1.01 ± 0.16	12.47 ± 2.60	0.69 ± 0.09



(a) (b)

Figure 1 A 4-month-old male infant with simple CoA. Prospective ECG-gated DSCT angiography was performed at 80 kV and 60 mAs/rotation (effective radiation dose 0.65 mSv). MPR image (a) and VR image (b) show narrowing of the aortic isthmus (arrow). Ar, aortic arch; DA, descending aorta.

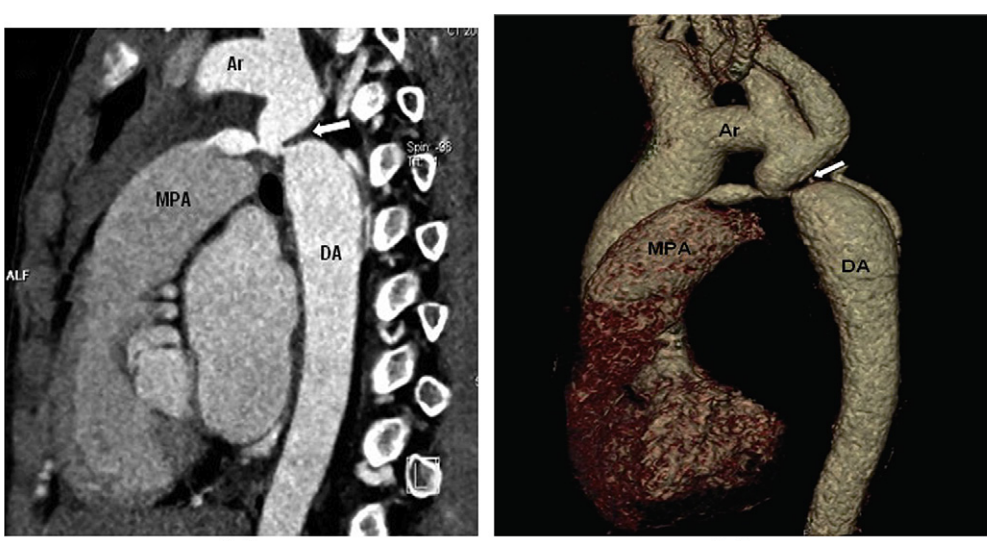
overall image quality scoring between the two observers was excellent ($\kappa = 0.82$).

Radiation dose estimation

The mean CTDIvol was 1.01 $\pm$ 0.16 mGy (range 0.72–1.32 mGy). The mean DLP was 12.47 $\pm$ 2.60 mGy·cm (range 7–16 mGy·cm), resulting in a mean estimated effective dose of 0.69 $\pm$ 0.09 mSv (range 0.5–0.88 mSv). Radiation dose for each patient is given in Table 1.

Discussion

The purpose of this study was to investigate the clinical value of prospective ECG-gated dual-source CT (DSCT) in the diagnosis of CoA in infants and children. The results of the present study indicate that ECG-gated prospective DSCT can provide low dose, diagnostic image quality data for infants and children with this congenital heart defect. However, there are a host of associated anatomical anomalies that are difficult to diagnose with certainty,



(a) (b)

Figure 2 CoA with PDA in a 6-year-old male child. Prospective ECG-gated DSCT angiography was performed at 80 kV and 120 mAs/rotation (effective radiation dose, 0.72 mSv). MPR image (a) and VR image (b) show CoA (arrow) and PDA. MPA, main pulmonary artery; Ar, aortic arch; DA, descending aorta.

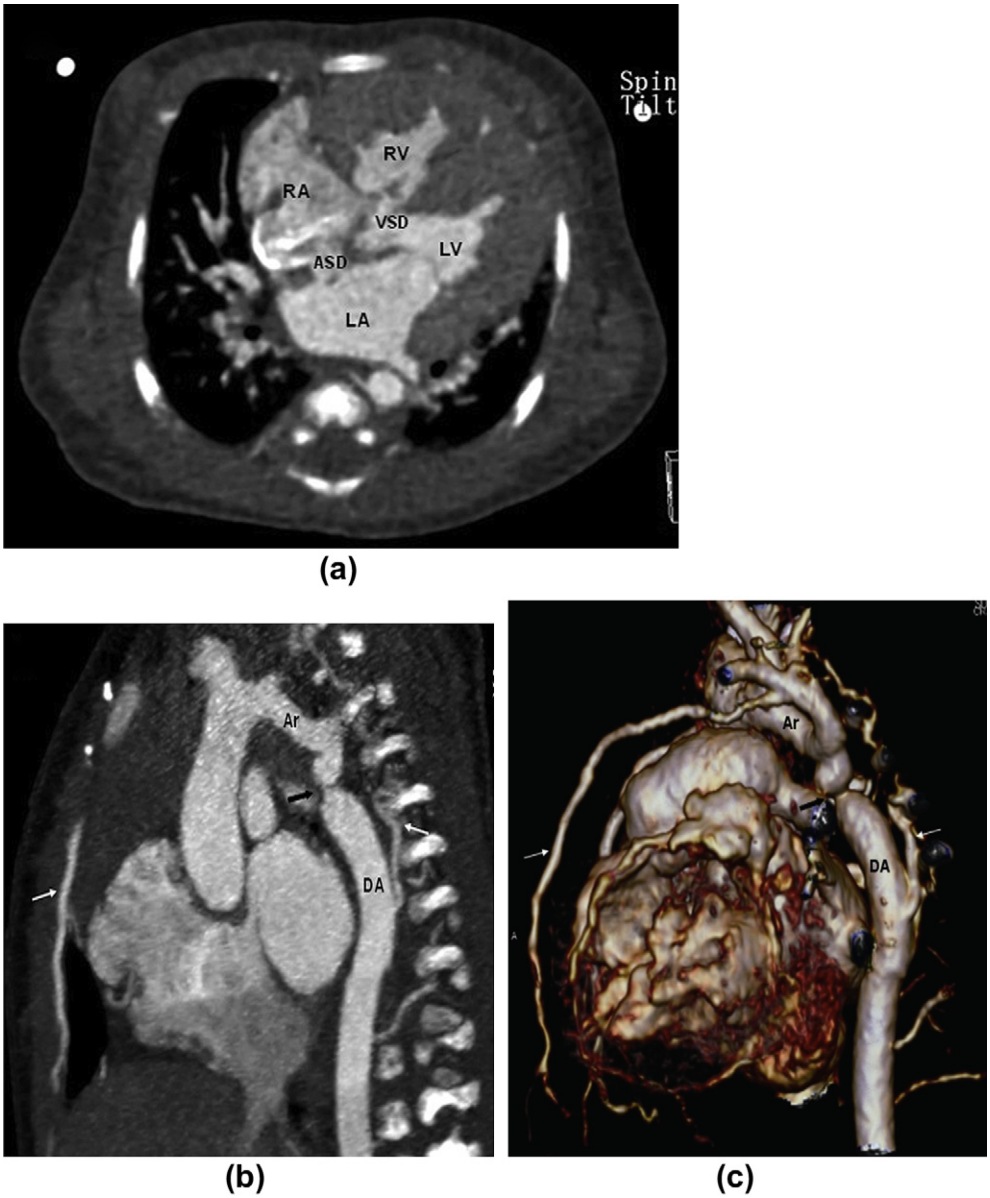


Figure 3 A 3-month-old male infant with complex CoA. Prospective ECG-gated DSCT angiography was performed at 80 kV and 60 mAs/rotation (effective radiation dose, 0.68 mSv). MPR image (a) shows atrial septal defect and ventricular septal defect. Thick-section MIP (b) and VR image (c) show CoA (black arrow) and dilation of the internal mammary arteries and intercostal arteries (white arrow). RA, right atrium; LA, left atrium; RV, right ventricle; LV, left ventricle; Ar, aortic arch; DA, descending aorta.

and in the present study it was useful to combine image data from the two compared imaging methods: TTE and DSCT.

TTE is usually adopted for the initial assessment of children with CoA because of its availability, safety, and capacity to provide haemodynamic parameters using Doppler flow studies.[5] TTE combined with Doppler flow imaging has the advantage of enabling the diagnosis of intracardiac deformities, and in the present study, TTE was able to identify an atrial septal defect not found in the DSCT images. However, TTE is not robust for evaluating extracardiac structures and failed to diagnose four patients with such complications accurately in the present study.

CT offers high-resolution data that covers both intracardiac and extracardiac structures. The data can also be post-processed in a variety of ways (two-dimensional (2D), three-dimensional (3D) volume-rendered, MRP, etc.) making it extremely flexible for visualization and surgical planning. The location, relative size and extent of the stenosis, the relationship of the coarctation to the great vessels, and the collateral vessel formation are better displayed with MPR, VR, and MIP images than with axial images.[2,8] Axial images are sufficient for assessing intracardiac deformities, and three-dimensional VR images can show the great vessels in different directions and angles; however, the intracardiac structures are poorly depicted.[16]

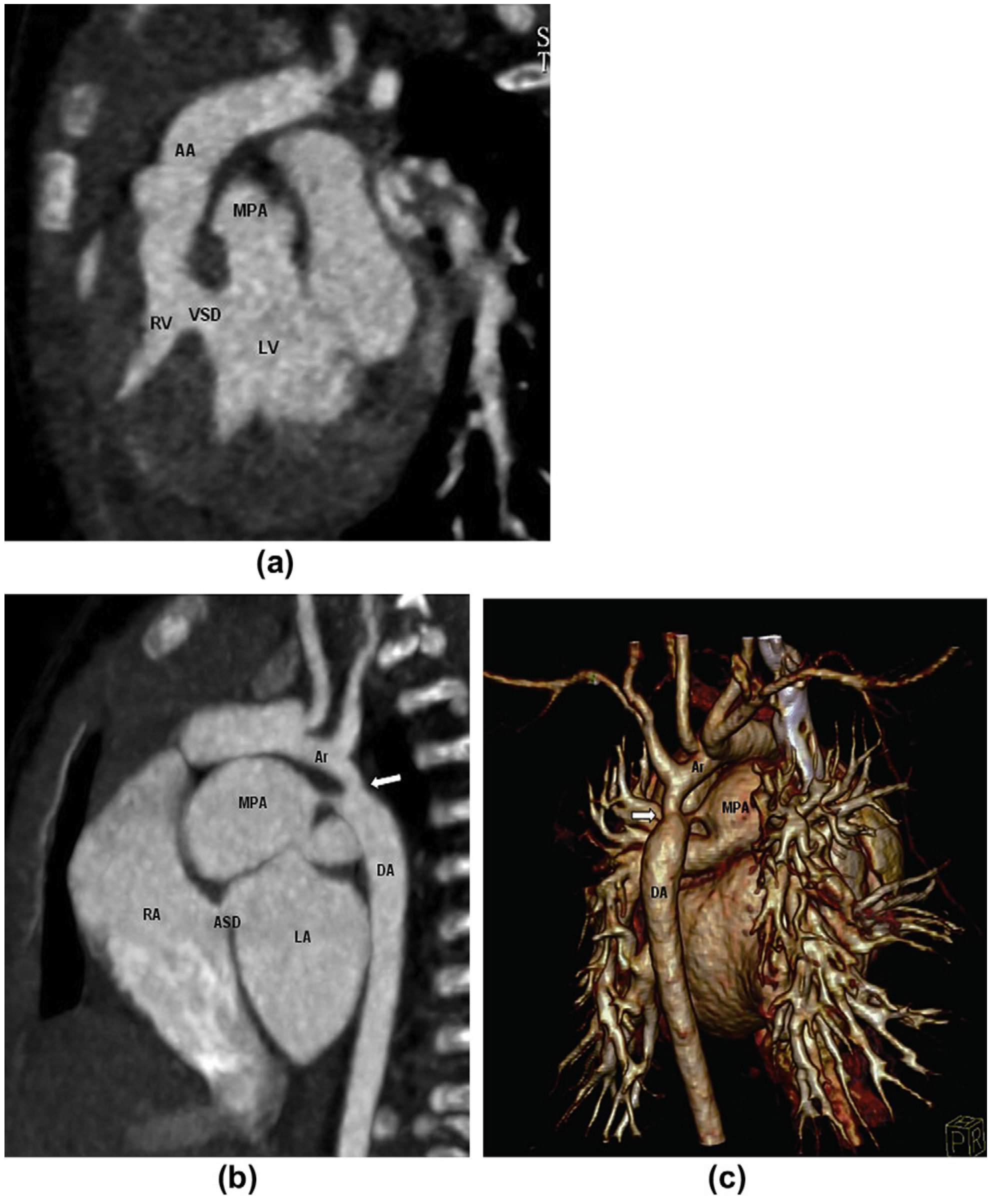


Figure 4 A 5-month-old male infant with complex CoA. Prospective ECG-gated DSCT angiography was performed at 80 kV and 70 mAs/rotation (effective radiation dose, 0.78 mSv). MPR image (a) shows transposition of the great arteries and ventricular septal defect. Thick-section MIP (b) shows atrial septal defect and PDA accompanied by CoA (arrow). VR image (c) shows narrowing of the aortic isthmus (arrow) and PDA. RV, right ventricle; LV, left ventricle; AA, ascending aorta; MPA, main pulmonary artery; RA, right atrium; LA, left atrium; Ar, aortic arch; DA, descending aorta.

A limitation of prospective ECG-gated DSCT angiography is that it cannot provide haemodynamic information such as the pressure gradient across the aortic stenosis, which is important for surgical planning.

The concern with CT imaging in paediatrics is the radiation exposure, and here the ECG-gated prospective CT mode has advantage over retrospective or non-gated CT[17,18] of limiting the exposure to a predefined window in the cardiac cycle. This significantly reduces the dose to the patient, but the disadvantage is that reconstruction of the data is then limited to the systolic phase of the cardiac cycle. Anomalies of the aortic valves, such as the unusual bicuspid aortic valve condition might go unnoticed in such a CT data set, as occurred in the present study with three patients. At our institute additional methods are employed when using DSCT to lower the dose as far as possible, and no compromise in image quality was necessary. An 80 kV tube voltage and an adapted tube current to body weight are routinely used.[19–22]

It is clear that all methods have advantages and disadvantages in imaging CoA, but using TTE and DSCT in combination gave 100% diagnostic accuracy of the CoA and associated anatomical complications. The alternative to DSCT could be cardiac magnetic resonance imaging (MRI) as it is non-invasive and non-ionizing and can provide both morphological and functional information. Cine MRI is

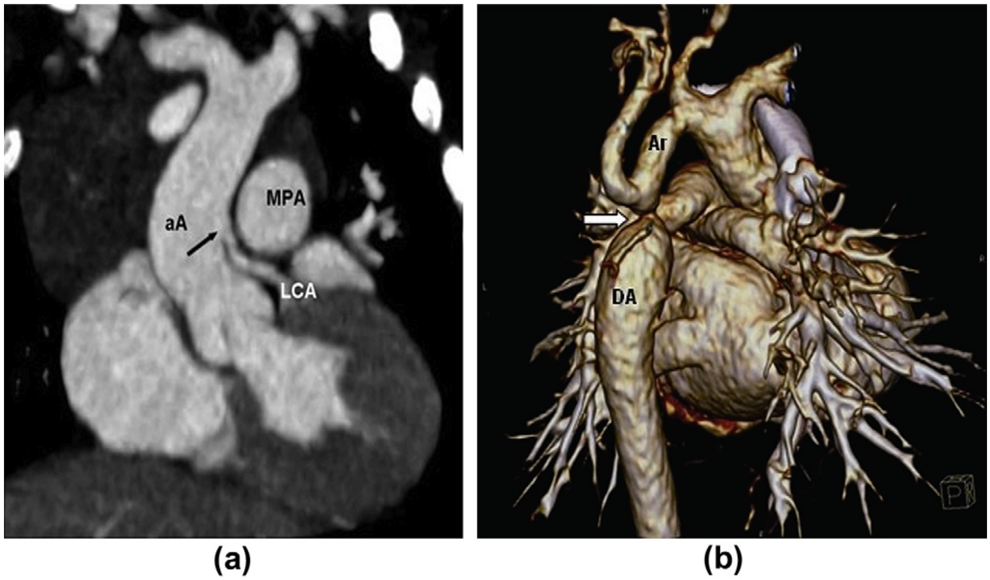


Figure 5 CoA with abnormal origin of coronary artery in a 6-month-old male infant. Prospective ECG-gated DSCT angiography was performed at 80 kV and 70 mAs/rotation (effective radiation dose, 0.78 mSv). Thick-section MIP image (a) shows the left coronary artery originating from a higher position above the left coronary sinus (arrow). VR image (b) demonstrates narrowing of the aortic isthmus (arrow). aA, ascending aorta; MPA, main pulmonary artery; LCA, left coronary artery; Ar, aortic arch; DA, descending aorta.

particularly valuable in the assessment of valvular and cardiac function, and the haemodynamic significance of CoA. However, the long acquisition time may necessitate long periods of sedation for small children; this is not desirable and may not be possible in some patients, thus limiting the application of MRI. If MRI is performed, the spatial resolution is also a limiting factor compared to CT or conventional cardiac angiography (CCA) and can limit clear visualization of the smaller cardiac structures and anomalies.

The alternative approach could be CCA, which can provide both haemodynamic and anatomical information in a single procedure, with high spatial resolution on the images. The major arguments not to use this method are the fact it is invasive and runs a 1% procedure-related mortality risk in neonates,[6] the long procedure time, possible need for sedation, relatively high doses of ionizing radiation,[13] and the limitations of the data post-processing.

Study limitations

The study was performed on a small population of paediatric patients who all had CoA confirmed at surgery. This adds a certain bias to the results and in a larger study patients with suspected but not confirmed CoA should be included if clinically possible. TTE was used as the comparison imaging method and future studies should also look at the diagnostic statistics for MRI and CT or CCA and CT.

In conclusion, prospective ECG-gated DSCT angiography can be used routinely in the evaluation of infants and children with CoA, providing adequate image quality, high diagnostic accuracy, and low radiation dose. Attention should be paid to the limitations in diagnosing certain associated anomalies using DSCT and indeed any other single method.

Table 2
Findings at prospective electrocardiogram (ECG)-gated dual-source computed tomography (DSCT) angiography and transthoracic echocardiography (TTE) compared to surgical results ($n = 17$).

Cardiovascular deformities	DSCT findings				TTE findings				Surgical results
	TP	FP	FN	TN	TP	FP	FN	TN	
Coarctation of aorta	17	0	0	0	16	0	1	0	17
Ventricular septal defect	9	0	0	8	9	0	0	8	9
Atrial septal defect	3	1	1	12	4	0	0	13	4
Patent ductus arteriosus	7	0	0	10	7	0	0	10	7
Bicuspid aortic valve	0	0	3	14	3	0	0	14	3
Hypoplasia of aortic arch	3	0	0	14	2	0	1	14	3
Abnormal origin of the coronary artery	2	0	0	15	0	0	2	15	2
Transposition of the great arteries	1	0	0	16	1	0	0	16	1
Total	42	1	4	89	42	0	4	90	46

TP, true-positive detection; FP, false-positive detection; FN, false-negative detection; TN, true-negative detection.

Table 3
Diagnostic performance of prospective electrocardiogram (ECG)-gated dual-source computed tomography (DSCT) angiography and transthoracic echocardiography (TTE).

Technique	Sensitivity	Specificity	PPV	NPV
DSCT	91.30%	98.89%	97.67%	95.70%
TTE	91.30%	100%	100%	95.74%
DSCT+TTE	100%	100%	100%	100%

PPV, positive predictive value; NPV, negative predictive value.

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