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Corresponding author:
S. W. Gould; Email: sharon.gould@nemours.org

Efficacy and safety of coronary computed tomography angiography in diagnosing coronary lesions in children

Sharon W. Gould[1], M. Patricia Harty[1], Mark Cartoski[2], Vijay Krishnan[3], Nicole Givler[1], John Ostrowski[2] and Takeshi Tsuda[2]

[1]Radiology Department, Nemours Children's Health Delaware Valley, Wilmington, DE, USA; [2]Nemours Cardiac Center, Nemours Children's Health Delaware Valley, Wilmington, DE, USA and [3]Department of Diagnostic Radiology and Nuclear Medicine, University of Maryland, Baltimore, MD, USA

Abstract

Introduction: Identification of paediatric coronary artery abnormalities is challenging. We studied whether coronary artery CT angiography can be performed safely and reliably in children. *Materials:* Retrospective analysis of consecutive coronary CT angiography scans was performed for image quality and estimated radiation dose. Both factors were assessed for correlation with electrocardiographic-gating technique that was protocoled on a case-by-case basis, radiation exposure parameters, image noise artefact parameters, heart rate, and heart rate variability. *Results:* Sixty scans were evaluated, of which 96.5% were diagnostic for main left and right coronaries and 91.3% were considered diagnostic for complete coronary arteries. Subjective image quality correlated significantly with lower heart rate, increasing patient age, and higher signal-to-noise ratio. Estimated radiation dose only correlated significantly with choice of electrocardiographic-gating technique with median doses as follows: 2.42 mSv for electrocardiographic-gating triggered high-pitch spiral technique, 5.37 mSv for prospectively triggered axial sequential technique, 3.92 mSv for retrospectively gated technique, and 5.64 mSv for studies which required multiple runs. Two scans were excluded for injection failure and one for protocol outside the study scope. Five non-diagnostic cases were attributed to breathing motion, scanning prior to peak contrast enhancement, or scan acquisition during the incorrect portion of the R-R interval. *Conclusions:* Diagnostic-quality coronary CT angiography can be performed reliably with a low estimated radiation exposure by tailoring each scan protocol to the patient's body habitus and heart rate. We propose coronary CT angiography is a safe and effective diagnostic modality for coronary artery abnormalities in children.

Paediatric coronary artery abnormalities are rare and may present with unexpected, life-threatening events. Identification of at-risk patients is essential.[1–3] Echocardiography provides baseline anatomical information but is subject to intrinsic pitfalls including operator dependence and limited windows in older children.[3–5] Cardiac MRI avoids ionising radiation but requires prolonged sedation and may have limited spatial resolution. Cardiac catheterisation is the gold standard but is invasive and cannot evaluate tissues outside the arterial lumen. CT angiography is superior to echocardiography for coronary artery anatomy, even in neonates, and has become widely utilised in adults due to its excellent spatial resolution and non-invasive technique.[6] However, paediatric coronary abnormalities in children differ from those in adults and CT scans require radiation.[1,4] The efficacy, safety, and appropriate clinical indications for coronary CT angiography in children are not well established. We present analysis of our experience during the establishment of a paediatric coronary CT angiography programme at our tertiary-care children's hospital.

Materials and methods

Patients

Retrospective review of coronary CT angiography examinations from April 2016 to April 2019 was performed following approval by the Nemours Children's Health Institutional Review Board. Patient demographics including age, gender, body surface area, and clinical indications for the scans were recorded.

Patient preparation

Patient preparation decisions were made prospectively based on clinical diagnosis, patient cooperation, and safe use of heart rate control. Employment of monitoring, sedation, or general anaesthesia by cardiac anaesthesiology was recorded. Heart rate control was attempted with pre-procedural oral β-blockade, propranolol, atenolol, or metoprolol as prescribed by the individual cardiologist based on their preference and when not contraindicated for outpatients from ages 2 years to 18 years with resting heart rates over 70 bpm. On-site intravenous heart rate control was provided by cardiac anaesthesiology for sedated and anaesthetised patients of all ages.

Scanning

Cases were performed on a single-source 64-slice scanner (GE VCT, General Electric, Chicago, USA) (n = 2, prospective axial sequential technique only) or on a dual-source scanner (Siemens Flash, Siemens Healthcare, Fordheim, Germany) (n = 58). Scanning protocol options on the latter included a high-pitch, electrocardiogram-triggered spiral scan, a prospectively gated axial sequential acquisition, or a retrospectively gated technique with data acquisition throughout the entire cardiac cycle. Protocol was chosen case-by-case as follows: the high-pitch spiral technique was utilised when heart rate variability was no more than 5 bpm because a stable heart rate is needed for the scanner to trigger the acquisition during the desired portion of a single cardiac cycle.[7–10] The prospective axial sequential technique was chosen for patients with heart rate variability of 5–10 bpm and who could breath-hold for the longer scan acquired over multiple beats.[9,11,12] The retrospective technique was reserved for assessment of the entire coronary vasculature throughout multiple cardiac cycles, maximising the opportunity to find images without motion artefact even in patients with variable heart rates.[8,13] To minimise suboptimal scanning, we practice breath holds with the patient at least twice before scanning, including during the test bolus injection to observe patient reaction to the sensation of the contrast and whether breath-holding reduces sinus arrhythmia.[7] With experience, we learned to select gating protocols based on patient heart rate and heart rate variability during practice breath-holding to maximise study outcome. The scanning phase was end-systole, 35–50% of the R-R interval, in patients with a heart rate greater than 70 bpm and end-diastole, 65–80% of the R-R interval, in those with a heart rate less than or equal to 70 bpm to image during the quiescent interval.[14–17] Initially manufacturer suggested tube voltage, current, and dose modulation exposure parameters were utilised. With additional training and experience, aggressive dose reduction and patient-specific exposure parameters were applied. "Other" cases were scanned with more than one run due to complex anatomy or circulation.

Non-ionic, low-osmolar iodinated contrast was utilised for all cases. Contrast dosage ranged from 1.5 to 3.0 mL/kg based on length of vascular opacification needed and injection rate. Multiphase injections were performed utilising a dual head injector (Medrad, Inc., Warrendale, Pennsylvania USA) with an initial pure contrast phase followed by a mixed contrast and saline, and finally, a saline flush. Injection timing was based on timing boluses with calculation of peak distal thoracic aortic enhancement (DynEva Software, Siemens Healthcare, Fordheim, Germany) to allow for coronary filling. An empiric delay of 6–8 s was added that was shorter for higher heart rates and high-pitch scan technique, and longer for slower heart rates and axial sequential or retrospective gating technique to extend vascular opacification for the longer techniques.

Radiation dose estimation

The estimated radiation exposure per slice volume and dose-length product data were collected for each case from the scanner. Estimated effective dose also was calculated based on conversion factors reported by Hill et al. in 2017, which take into account patient age and radiation sensitivity of exposed tissues.[18] In addition, for the sake of comparison to prior coronary CT angiography studies, estimation of the effective dose in milliSieverts also was performed utilising earlier reported conversion factors for CT scanning of the chest in children.[19,20] As previously described, the dose-length product was multiplied by an additional factor of two for patients under 14 years of age to account for the dose-length product data reported by the scanner being based on adult data with the larger, 32 cm field of view.

Image analysis

Qualitative assessment consisted of independent review of each case by two board-certified radiologists (S.G. and M.H.) and one imaging fellowship-trained cardiologist (M.C.). A 4-point Likert scale was utilised for scoring coronary artery visualisation: one = non-diagnostic, two = motion artefact present but diagnostic, three = mild artefact with very good visualisation, and four = excellent with no motion artefact (Fig. 1).

Quantitative assessment consisted of determination of image noise, contrast-to-noise ratio and aortic signal-to-noise ratio, as described by Barrera et al.[17] Regions of interest were placed in air outside the patient or in the trachea, in the interventricular septum, and in the aortic root. Image noise equalled the standard deviation of the attenuation of the region of interest in air. The contrast-to-noise ratio was calculated the aortic root mean attenuation minus the interventricular septal mean attenuation, with the difference divided by the image noise. The signal-to-noise ratio was calculated as the mean attenuation value of the aortic root divided by noise.

Image data post-processing

Data post-processing included utilisation of iterative reconstruction for noise reduction (Sinogram Affirmed Iterative Reconstruction [SAFIRE], Siemens Healthcare, Fordhiem, Germany). Additional multiplanar, curved plane reformatting, and 3D volume rendering were performed on independent workstations using commercially available platforms (TeraRecon, Foster City, California USA or AW, GE, Chicago, Illinois USA) for additional evaluation of spatial relationships and vascular analysis.

Descriptive statistics

Variables were shown as either median [range] or mean ± standard deviation. Simple and multivariable regression analyses of multiple variables regarding image quality and radiation dose were performed. Comparison of variables in more than two groups was done via 1-way analysis of variance. A p-value of less than 0.05 was considered statistically significant. Interobserver reliability, or the degree of reproducibility of study quality assessment between observers, also was examined with Cronbach's alpha and Intraclass Correlation Coefficients calculated.

Results

Sixty consecutive coronary CT angiography studies were performed during the study period, including 37 males and 22 females with 1

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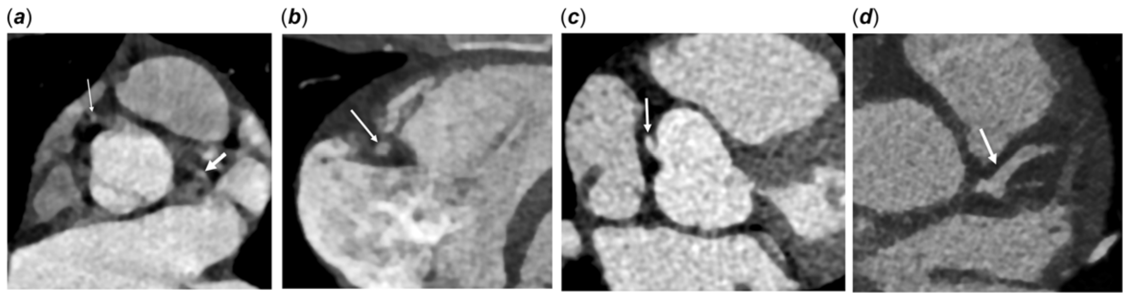

Figure 1. Examples of grades of image quality using axial 0.6 mm thick images with noise reduction applied. (***a***) Grade 1 – non-diagnostic. Technique: prospectively gated high-pitch spiral acquisition. The proximal right coronary artery (thin arrow) and proximal left circumflex artery (thick arrow) appear blurry with poorly defined contours. (***b***) Grade 2 – motion artefact present, but diagnostic. Technique: prospectively gated high-pitch spiral acquisition. The mid-right coronary artery (white arrow) is slightly blurred by motion artefact, but the margins of the vessel are readily distinguished. (***c***) Grade 3 – mild artefact with very good vessel visibility. Technique: retrospective gating. The proximal right coronary artery (white arrow) is well seen, even if the margins are not completely sharp. (***d***) Grade 4 – excellent vessel definition with no artefact. Technique: prospectively gated high-pitch spiral acquisition. The proximal left anterior descending artery (white arrow) is sharply defined.

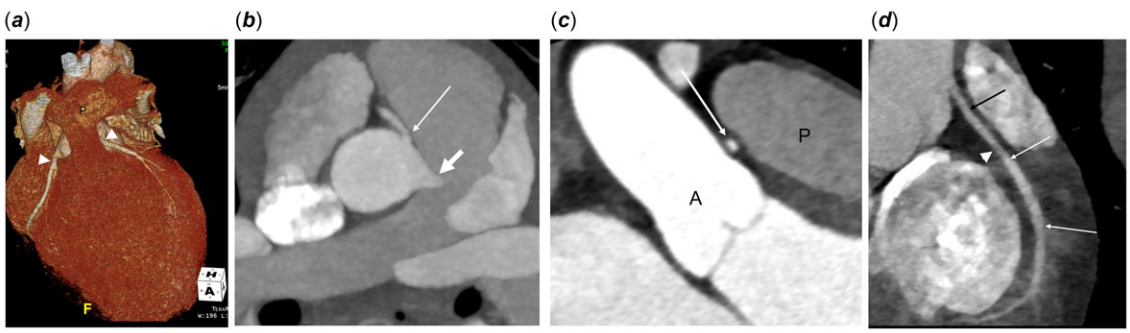

Figure 2. (***a***) A 17-year-old male with d-transposition of the great arteries status post Jatene arterial switch operation with LeCompte manoeuvre. A 3D virtual rendering viewed from anteriorly, slightly to the left, and from above shows the relationship of the coronaries (white arrowheads) to the pulmonary artery (P). The overall score for this study was 3.04. (***b***) A 13-year-old male with syncope and an anomalous origin of the right coronary artery noted on echocardiogram. An axial oblique maximum intensity projection image shows the normal left main coronary artery origin (short arrow) and the oblique take off of the right coronary artery (thin arrow). The overall score for this study was 3.19. (***c***) A 12-year-old male with Ehlers-Danlos syndrome and early fatigue during exercise, anomalous origin of the right coronary artery by echocardiogram. A reformatted image perpendicular to the lumen of the proximal right coronary artery shows an elliptic shape of the vessel (arrow) between the aortic root (A) and the pulmonary artery (P). The overall study score was 3.62. (***d***) A 16-year-old male with a history of Kawasaki disease. A curved plane reformatted maximum intensity projection image through the right coronary artery shows a normal calibre of the proximal artery (black arrow) and a region of relative dilatation between the white arrows. There is a subtle stenosis (arrowhead) just proximal to the region of dilatation. This patient will require close follow up. The overall score for this study was 2.38.

male included twice. The median age was 12 years old (0.5 to 30 years). Indications included: coronary artery reimplantation (Jatene arterial switch operation for transposition of the great arteries) (n = 11) (Fig. 2a), suspected anomalous aortic origin of the coronary artery (n = 21) (Fig. 2b and Fig. 2c), Kawasaki disease follow up (n = 5) (Fig. 2d), and others (history of coronary artery aneurysm/fistula/flap, other CHD, other suspected coronary abnormality on echocardiogram, primordial dwarfism, hypercholesterolaemia, Williams syndrome) (n = 20).

Excluded cases, complications, and non-diagnostic cases

Three cases were excluded from this study; two for failed injections, including the first attempt for the male patient included twice, and one due to use of a non-coronary specific protocol. Extravasation of contrast is uncommon and has been shown to occur in 0.7% of power injections for CT angiography in children.[21] One adolescent male patient experienced vagal symptoms during intravenous access following administration of the oral β-blocker. He was given a fluid bolus prior to the CT and was normotensive throughout the scan with no further difficulty. There were no other complications. Five low-scoring cases were the result of breathing motion (two scans), early scanning prior to peak contrast enhancement (2 scans), and scan acquisition outside the target region of the R-R interval (one scan). Scanning prior to peak contrast was likely due to incorrect calculation of the empiric delay needed for coronary opacification. Scan acquisition outside the target region of the R-R interval was human error in scan planning. Four of the five patients with suboptimal imaging were asymptomatic and had clinical and electrocardiogram follow up with no further CT imaging or catheterisation. The fifth patient underwent cardiac catheterisation 1 week after the CT for pre-operative planning for complex CHD. The CT scan correctly identified all major cardiac and great vessel structural abnormalities, although the coronary arteries were not ideally evaluated. No coronary artery abnormalities were reported from the subsequent angiogram.

Scan technique and electrocardiographic gating

A high-pitch electrocardiographic-triggered spiral technique (3.4) was used in 26 (51%) cases (median 12.5 years, range 3–18 years). A prospectively electrocardiographic-triggered axial sequential technique was used in 20 cases (median 10 years, range 0.5–30 years), and retrospective electrocardiographic-gating was used in 7

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Table 1. Regression analyses.

	Image quality simple regression		Estimated radiation dose simple regression	
Variables	Regression coefficient	P-value	Regression coefficient	P-value
Age	0.0249	0.0494	0.1271	0.1078
BSA*	0.0072	0.1923	0.0534	0.109
Mean HR**	−0.0232	0.0001	0.0335	0.3036
HR variability	−0.0097	0.0844	0.0121	0.6859
Estimated dose	0.0194	0.3732	N/A[a]	N/A[a]
***CTDIvol	0.0199	0.1036	N/A[b]	N/A[b]
Image noise	-9^{e-04}	0.9442	−0.1015	0.2045
Aorta SNR****	0.0146	0.0047	−0.0115	0.7277
CNR*****	0.0014	0.5184	−0.0178	0.191

*BSA=body surface area.
**HR=heart rate.
***CTDIvol=CT dose index per volume.
****SNR=signal-to-noise ratio.
*****CNR=aortic contrast-to-noise ratio.
[a]Estimated dose is the value to which the variables are being correlated.
[b]The CT dose index per volume is used to calculate the estimated dose and is proportional to that value.

cases (median 8 years, range 4–17 years), with 4 cases using 2 runs with a combination of techniques (median 14 years, range 9 to 17 years).

Image outcomes by heart rate control or sedation/general anaesthesia

Younger patients tended to have higher heart rates, but there was significant overlap with heart rates from 65 to 95 bpm in patients under 2 years and from 49 to 95 bpm in patients older than 2 years. Heart rate variability also overlapped with ranges from 4 to 11 bpm in patients under 2 years and from 0 to 58 bpm in older patients. Heart rate control was provided in 38 cases (64.9%); 8 received only pre-procedural oral β-blockers, 14 received intra-procedural intravenous therapy (either esmolol or dexmedetomidine hydrochloride), and 15 received both. Heart-rate-controlled patients and -uncontrolled patients had similar median heart rates: 68 bpm and 67 bpm, respectively. Thirty-four patients (49%) had no pre-medication. Of the 23 patients who received sedation, 10 received general anaesthesia. The median age of patients receiving sedation or anaesthesia was 8 years (range 0.5–17 years) compared to 14 years (range 6 to 30 years) for non-sedated patients.

Image quality scoring

Image quality scores based on the 0.6 mm images rated 52 of 57 studies (91.3%) as diagnostic quality or better (score greater than or equal to two) for evaluation of the complete coronary arteries. Five studies (8.7%) received scores of less than two or inadequate. (Segmental scores are shown in Supplemental Fig S1.) For evaluation of the main left and right coronary arteries, 96.5% of studies were of diagnostic quality.

Increasing age, increasing aortic signal-to-noise ratio, and decreasing mean heart rate correlated significantly with improved image quality (Table 1). Body surface area, estimated dose, estimated radiation exposure per slice volume, and heart rate variability tended to affect study quality but did not reach statistical significance. In the multivariable analysis, only mean heart rate, estimated radiation exposure per slice volume, and aortic signal-to-noise ratio had a statistically significant effect on perceived image quality (Supplemental Table S1). Image quality scores were similar across gating techniques with considerable overlap, although there were too few retrospectively gated studies to assess statistical significance (Table 2). Image quality scores also were similar for cases performed with or without sedation/anaesthesia (p-value 0.372) or heart rate control (p-value 0.133, Supplemental Table S2). When image quality scores are examined by coronary segment, proximal scores tended to be higher than distal segment scores (Supplemental Table S3).

Radiation dose scoring

We found some correlation between age, body surface area, heart rate, heart rate variability, image noise, aortic signal-to-noise ratio, and contrast-to-noise ratio with radiation dose, but none reached statistical significance (Table 1). In contrast, scanning protocol had a pronounced effect on radiation dose (Table 2). Median dose was lowest for the electrocardiographic-triggered high-pitch technique, and highest for the "Other" group due to the multiple runs utilised in this group, although overlap is noted among all groups. Notably, the prospectively gated cases had a higher median dose than retrospectively gated cases.

While higher heart rate and variability were associated with higher doses, the effect did not reach statistical significance (Table 1). The mean heart rate for controlled and uncontrolled groups was comparable, but we did not record pre-control heart rates and cannot assess the effectiveness of heart rate control therapy. No significant differences were found in estimated dose between the sedated, anaesthetised, monitored, and unmonitored groups although the cohorts for each group were small (not shown).

Observer reliability scoring

We analysed interobserver reliability. Overall internal consistency was good to very good (0.736-0.893) with moderate to good interrater reliability for all coronary segments except the mid-left

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Table 2. CT technique analysis.

Techniques	ECG* high-pitch spiral (n = 26)	Prospective axial sequential (n = 20)	Retrospective (n = 7)	Others** (n = 4)
Mean SAS*** ± SD****	2.93 ± 0.572	2.88 ± 0.473	2.75 ± 0.558	2.31 ± 0.727
Median SAS [min, max]	3.07 [1.43, 3.76]	2.95 [1.86, 3.50]	2.81 [1.71, 3.48]	2.14 [1.62, 3.33]
Median CTDIvol^ (mGy^^) [min,max]	2.005 [0.79, 6.66]	6.265 [0.95, 30.09]	5.96 [2.37, 7.39]	4.77 [1.26, 7.17]
Median DLP^^^ (mGy^^-cm) [min, max]	46.5 [23, 144]	105.5 [20, 539]	105 [37, 150]	152.5 [47, 267]
Median estimated dose with newer conversion factors [min, max]	2.42 mSv# [0.50, 5.33]	5.37 mSv# [1.41, 17.75]	3.92 mSv# [2.41, 6.83]	5.64 mSv# [3.06, 9.88]
Median estimated dose with older conversion factors [min, max]	1.74 mSv# [0.650, 5.18]	3.61 mSv# [1.12, 18.2]	2.63 mSv# [1.56, 4.42]	3.97 mSv# [2.00, 9.60]
Mean SAS*** ± SD****	2.93 ± 0.572	2.88 ± 0.473	2.75 ± 0.558	2.31 ± 0.727
Median SAS [min, max]	3.07 [1.43, 3.76]	2.95 [1.86, 3.50]	2.81 [1.71, 3.48]	2.14 [1.62, 3.33]
Median estimated dose [min, max]	1.74 mSv# [0.650, 5.18]	3.61 mSv# [1.12, 18.2]	2.63 mSv# [1.56, 4.42]	3.97 mSv# [2.00, 9.60]

*ECG=electrocardiogram.
**Others=Cases where multiple runs were required utilising one or more techniques.
***SAS=study average score.
****SD=standard deviation.
^CTDIvol=CT dose index-volume.
^^mGy=milliGray, 10 mGy=1 rad.
^^^DLP=Dose-length product, or CTDIvol multiplied by the length of the scan.
#mSv=milliSieverts, 1 mSv=0.1 rem1 mSv=0.1 rem.

anterior descending artery, where interobserver reliability was poor (Supplemental Table S2).

Discussion

Accurate diagnosis is essential in children with potential coronary abnormalities and screening or surveillance methods must be safe.[1–5,7,8,19] Multi-slice CT has advantages over both MRI and heart catheterisation for imaging of paediatric coronary arteries.[2,4,22–24] Careful attention to scanning parameters, radiation dose, and case selection is mandated according to the As Low As Reasonably Achievable principle due to the higher radiation sensitivity of children.[7,8,13,24]

We have shown coronary CT angiography can be performed reliably and safely across a wide range of patient ages and heart rates by tailoring the exam to each patient.

Image quality was considered diagnostic in 91.3% of cases for overall coronary evaluation and 96.5% for imaging of the proximal coronaries. The most significant factors affecting our perceived image quality were patient age, heart rate, and aortic signal-to-noise ratio with radiation exposure per slice having a significant effect in the multivariable analysis. Based on these findings, steps that may improve image quality include adding more frequent heart rate control and aggressive bolus timing optimisation. Appropriate scanning exposure technique also is critical to avoid excessive image noise – balance exists between radiation dose reduction and imaging optimisation. Additionally, either utilisation of retrospective gating or prospective axial sequential imaging with a wider acquisition window might improve image quality for those cases where mid- to distal-coronary evaluation is paramount, such as in Kawasaki disease. We had an insufficient number of cases performed with this technique for statistical analysis. Retrospective technique provides imaging in multiple cardiac phases and is useful in patients with variable heart rates or if evaluation throughout the cardiac cycle is required.[8,13,25] Use of retrospective gating should be carefully considered because the only factor that correlated significantly with estimated radiation dose in our study was electrocardiogram-gating technique.

Multiple gating techniques for electrocardiogram-triggered multi-slice CT have previously been shown to be effective in imaging the coronary arteries in children.[9,11,12,17,24,26–29] We found overlap among gating techniques regarding overall image quality, suggesting that choosing the gating technique according to patient parameters was successful. We did not have a sufficient cohort with all gating techniques to establish significance. Image quality for evaluation of distal-coronary arteries was not as good as for proximal vessels. Because prospective adaptive and retrospective techniques allow imaging of the vessels in a selected range of cardiac cycle phases, these higher dose techniques may be warranted for improved vessel visualisation when evaluation of the coronaries beyond the proximal segments is needed. We did not attempt to confirm the effectiveness of this strategy as we assigned higher and more variable heart rate patients to the higher dose techniques, which would obscure any difference among techniques.

Patient age had a significant effect on image quality similar to prior studies.[30–32] Younger children are more likely to have a higher heart rate, which adversely affects image quality.[4,9,11,17,26,33] Image quality is better at lower heart rates likely due to a longer quiescent interval as well as slower coronary arterial motion, decreasing artefact.[11,33–36] In our study, the potential effect of heart rate control on study quality was likely obscured by the similarity of heart rates in the controlled and uncontrolled groups despite the younger age of the heart-rate-controlled cohort. Smaller vessel sizes for younger patients also likely contributed to lower image quality in the younger age group.

Heart rate variability had a negative effect on image quality but did not reach statistical significance possibly because we prescribed different protocols based on variability, similar to the approaches described by Han et al. and Le Roy et al.[9,31] As previously shown, we found that signal-to-noise ratio did affect image quality.[32,37]

In our study, estimated radiation dose was only significantly affected by selection of gating technique. The Society for Cardiac Computed Tomography guidelines for radiation dose optimisation recommend selection of lower dose techniques for patients with stable heart rates when possible.[8,17,24,27] A ß-blockade can be utilised to decrease heart rate and variability so a lower-dose protocol can be utilised effectively.[4,7–9,36] Very young or neurologically impaired patients may require sedation or anaesthesia to minimise motion and prevent a non-diagnostic study.[8–10,17] Radiation dose reduction also involves using the lowest exposure parameters that will generate diagnostic images.[11,13,26,29,38,39] Our aggressive application of dose reduction techniques succeeded with a wide range of patient ages and clinical indications as shown by the lack of correlation of electrocardiographic-triggering technique with image quality.

Our estimated effective doses with cardiac CT conversion factors are reported in Table 2.[18] For the sake of comparison to prior studies, estimated doses also are reported with an older set of conversion factors used in previous studies.[19,20] The higher estimated doses with the newer, more accurate conversion factors highlight the importance of dose reduction strategies. These doses are still considerably lower than those associated with scanning techniques in adults. Our prospectively gated axial sequential technique cases had a higher median dose than our retrospectively gated cases, opposite to what we expected as the retrospective technique usually requires a longer exposure time. This was likely due to use of manufacturer-recommended settings with a subset of prospective axial sequential cases performed prior to implementation of aggressive dose control that included reduced tube current outside the desired phases of the cardiac cycle with retrospective gating. In the group with multiple imaging runs, estimated doses were highest, underscoring the need to avoid more than one scan if possible.

Using the chest conversion factors, our median estimated dose for the electrocardiographic-triggered high-pitch spiral technique of 1.74 milliSieverts is similar to that reported by Barrera et al. (1.82 milliSieverts with similar patient age ranges).[17] Our median estimated dose for the prospective axial sequential studies of 3.61 milliSieverts is higher than that reported previously by Pache et al. (0.32 milliSieverts) and Huang et al. (1.6 milliSieverts), although their patient cohorts were much younger.[11,12] For our retrospective gating studies, we had a median estimated dose of 2.63 milliSieverts, similar to that reported by Li et al., but higher than that reported by Ben Saad et al.[26,27] Of note, our patient cohort was older than the patients in both of those reports.

The estimated radiation exposure per slice volume and estimated dose both had a positive relationship with image quality with the exposure per slice volume reaching statistical significance in the multivariable analysis. Higher radiation dose is usually associated with improved image quality due to decreased noise; however, noise reduction algorithms, such as iterative reconstruction, can significantly improve image quality with reduced doses.[29,39]

Sedation or anaesthesia tended to reduce radiation dose, possibly due to decreased motion or decreased heart rate variability permitting selection of a dose-conserving technique, but the relationship did not reach statistical significance. Because sedation and anaesthesia add additional risk, these interventions are indicated only when needed for patients unable to cooperate for the scan and when the likelihood of a non-diagnostic study due to motion is too high.[4,8] A lower heart rate did show a slight tendency to be associated with a lower dose, but this relationship did not reach statistical significance. It is possible that a relationship between heart rate and radiation dose may have been obscured by the higher doses associated with the small number of prospectively gated adaptive cases performed early in the programme, as this technique would have been chosen for slower, less variable heart rates.

Our interobserver reliability was reasonably good except for the mid-left anterior descending artery, likely reflecting variability in motion in this segment.

Study limitations

Because this study was retrospective, a variety of techniques were utilised. This somewhat limited our ability to assess our techniques because they evolved as we implemented more advanced protocols and dose-reduction techniques. We also did not randomise the choice of electrocardiographic-gating technique, the administration of heart rate control measures, or the administration of sedation or anaesthesia. Our cohort was small, limiting the power of the study. Our patient cohort included a wide variety of patient ages, heights, weights, and coexisting medical conditions, all of which can affect study quality and radiation exposure. These varied patients also required a variety of sedation, anaesthesia, and heart rate control protocols.

We likely underrated image quality due to inherent image noise with such thin slices (0.6 mm). We chose to use the thinner slices for optimal resolution given the small size of the coronary arteries in paediatric patients.

Areas of future study include the efficacy and safety of heart rate control intervention and scanning parameters to further lower radiation dose. Regarding patient outcomes, the optimal timing of surveillance imaging for post-operative coronaries, known anomalies, and other coronary abnormalities should be evaluated as well as the frequency of surveillance imaging.

Low-dose coronary CT angiography can be performed in children with known or suspected pre-clinical coronary artery abnormalities safely and reliably. Our findings reinforce those of Barrera et al. regarding the reliability of high-pitch electrocardiographic-triggered spiral scanning.[17] Our varied case cohort supports the findings of Han et al. and Le Roy et al., demonstrating exam safety and quality remain high when utilising varied protocols tailored to patient physiology.[9,31] Some patients may also benefit from aggressive heart rate control, sedation or anaesthesia to lower heart rate, reduce variability, and potentially permit utilisation of lower dose technique. Careful, patient-specific selection of electrocardiographic-gating and scanning technique, patient preparation, and exposure parameters can provide successful coronary imaging in a wide range of patient sizes, ages, and heart rates. More studies are warranted to establish standard clinical guidelines for coronary CT angiography in obtaining reliable diagnostic image quality with minimum radiation exposure in infants and children with coronary anomalies.

Supplementary material. The supplementary material for this article can be found at https://dx.doi.org/10.1017/S1047951123003438.

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References

1. Tsuda T. Preclinical coronary artery anomalies and silent myocardial ischemia in children: how can we identify the potentially life-threatening conditions? J Pediatr Cardiol Cardiac Surg 2017; 1: 49–60.
2. Tsujii N, Tsuda E, Kanazaki S, Kurosaki K. Measurements of coronary artery aneurysms due to Kawasaki disease by dual-source computed tomography (DSCT). Pediatr Cardiol 2016; 37: 442–447.
3. Sailing LJ, Raptis DA, Parekh K, Rockefeller TA, Sheybani EF, Bhalla S. Abnormalities of the coronary arteries in children: looking beyond the origins. Radiographics 2017; 37: 1665–1678.
4. Han BK, Rigsby CK, Hlavacek A, et al. Computed tomography imaging in patients with congenital heart disease part 1: rationale and utility. An expert consensus document of the society of cardiovascular computed tomography (SCCT) endorsed by the society of pediatric radiology (SPR) and the North American society of cardiac imaging (NASCI). J Cardiovasc Comput Tomogr 2015; 9: 475–492.
5. van Stijn D, Planken RN, Groenink M, Streekstra GJ, Kuijpers TW, Kuipers IM. Coronary artery assessment in Kawasaki disease with dual-source CT angiography to uncover vascular pathology. Eur Radiol 2020; 30: 432–441.
6. Odawara Y, Kawamura N, Yamasaki Y, Hashimoto J, Ishikawa S, Honda H. Evaluation of coronary artery variations using dual-source coronary computed tomography angiography in neonates with transposition of the great arteries. Jpn J Radiol 2019; 37: 308–314.
7. Abbara S, Blanke P, Maroules CD, et al. SCCT guidelines for the performance and acquisition of coronary computed tomographic angiography: a report of the scoiety of cardiovascular computed tomography guidelines committee endorsed by the North American society for cardiovascular imaging (NASCI). J Cardiovasc Comput Tomogr 2016; 10: 435–449.
8. Han BK, Rigsby CK, Leipsic J, et al. Computed tomogrpahy imaging in patients with congenital heart disease, part 2: technical recommendations. An expert consensus document of the society of cardiovascular computed tomography (SCCT) endorsed by the society of pedaitric radiology (SPR) and the North American society of cardiac imaging (NASCI). J Cardiovasc Comput Tomogr 2015; 9: 493–513.
9. Han BK, Lindberg J, Overman D, Schwartz RS, Grant K, Lesser JR. Safety and accuracy of dual-source coronary computed tomography angiography in the pediatric population. J Cardiovasc Comput Tomogr 2012; 6: 252–259.
10. Malone LJ, Morin CE, Browne LP. Coronary computed tomography angiography in children. Pediatr Radiol 2022; 52: 2498–2509.
11. Pache G, Grohmann J, Bulla S, et al. Prospective electrocardiography-triggered CT angiography of the great thoracic vessels in infants and toddlers with congenital heart disease: feasibility and image quality. Eur J Radiol 2011; 80: e440–e445.
12. Huang MP, Liang CH, Zhao ZJ, et al. Evaluation of image quality and radiation dose at prospective ECG-triggered axial 256-slice multi-detector CT in infants with congential heart disease. Pediatr Radiol 2011; 41: 858–866.
13. Booij R, Dijkshoorn ML, van Straten M, et al. Cardiovascular imaging in pediatric patients using dual source CT. J Cardiovasc Comput Tomogr 2016; 10: 13–21.
14. Goetti R, Feuchtner G, Stolzmann P, et al. High-pitch dual-source CT coronary angiography: systolic data acquisition at high heart rates. Eur Radiol 2010; 20: 2565–2571.

15. Zhang W, Bogale S, Golriz F, Krishnamurthy R. Relationship between heart rate and quiescent interval of the cardiac cycle in children using MRI. Pediatr Radiol 2017; 47: 1588–1593.
16. Le Roy J, Azais B, Zarqane H, et al. Selection of optimal cardiac phases for ECG-triggered coronary CT angiography in pediatrics. Phys Med 2021; 81: 155–161.
17. Barrera CA, Otero HJ, White AM, Saul D, Biko DM. Depiction of the native coronary arteries during ECG-triggered high-pitch dual-source coronary computed tomography in children: determinants of image quality. Clin Imaging 2018; 52: 240–245.
18. Hill KD, Frush DP, Han BK, et al. Radiation safety in children with congenital and acquired heart disease: a scientific position statement on multimodality dose optimization from the image gently alliance. JACC Cardiovasc Imaging 2017; 10: 797–818.
19. Thomas KE, Wang B. Age-specfic effective doses for pediatric MSCT examinations at a lrage children's hospital using DLP conversion coefficients: a simple estimation method. Pediatr Radiol 2008; 38: 645–656.
20. McCollough C, Edyvean S, Gould B, et al. The Measurement, Reporting, and Management of Radiation Dose in CT. AAPM Report 96. American Association of Physicists in Medicine, College Park, MD, 2008.
21. Barrera CA, White AM, Shepherd AM, et al. Contrast extravasation using power injectors for contrast-enhanced computed tomography in children: frequency and injury severity. Acad Radiol 2019; 26: 1668–1674.
22. Arnold R, Ley S, Ley-Zaporozhan J, et al. Visualization of coronary arteries in patients after childhood Kawasaki syndrome: value of multidetector CT and MR imaging in comparison to conventional coronary catheterization. Pediatr Radiol 2007; 37: 998–1006.
23. Albrecht MH, Varga-Szemes A, Schoepf UJ, et al. Diagnostic accuracy of noncontrast self-navigated free-breathing MR angiography versus CT angiography: a prospective syudy in pediatric patients with suspected anomalous coronary arteries. Acad Radiol 2019; 26: 1309–1317.
24. Meinel FG, Henzler T, Schoepf UJ, et al. UJ, etal, ECG-synchronized CT angiography in 324 consecutive pediatric patients: spectrum of indications and trends in radiation dose. Pediatr Cardiol 2015; 36: 569–578.
25. Krishnamurthy R, Masand PM, Jadhav SP, et al. Accuracy of computed tomography angiography and structured reporting of high-risk morphology in anomalous aortic origin of coronary artery: comparison with surgery. Pediatr. Radiol 2021; 51: 1299–1310.
26. Ben Saad M, Rohnean A, Sigal-Cinqualbre A, Adler G, Paul JF. Evaluation of image quality and radiation dose of thoracic and coronary dual-source CT in 110 infants with congenital heart disease. Pediatr Radiol 2009; 39: 668–676.
27. Li T, Zhao S, Lui J, et al. Feasibility of high-pitch spiral dual-source CT angiography in children with complex congential heart disease compared to retrospective-gated spiral acquisition. Clin Radiol 2017; 72: 864–870.
28. Nie P, Wang X, Cheng Z, Ji X, Duan Y, Chen J. Accuracy, image quality and radiation dose comparison of high-pitch spiral and sequential acquisition on 128-slice dual-source CT angiography in children with congential heart disease. Eur Radiol 2012; 22: 2057–2066.
29. Zheng M, Zhao H, Xu J, Wu Y, Li J. Image quality of ultra-low-dose dual-source CT angiography using high-pitch spiral acquisition and iterative reconstruction in young children with congenital heart disease. J Cardiovasc Comput Tomogr 2013; 7: 376–382.
30. Goo HW. Quititative evaluation of coronary artery visibility on CT angiography in Kawasaki disease: young vs. old children. Int J Cardiovasc Imaging 2021; 37: 1085–1092.
31. Le Roy J, Kovacsik H, Zarqane H, et al. Submilisievert multiphasic coronary computed tomography angiography for pediatric patients with congenital heart diseases. Circ Cardiovasc Imaging 2019; 12: e008348.
32. Yamasaki Y, Kawanami S, Kamitani T, et al. Patient-related factors influencing detectability of coronary arteries in 320-row CT angiography in infants with complex congential heart disease. Int J Cardiovasc Imaging 2018; 34: 1485–1491.
33. Bridoux A, Hutt A, Faivre JB, et al. Coronary artery visibility in free-breathing young children on non-gated chest CT: impact of temporal resolution. Pediatr Radiol 2015; 45: 1761–1770.
34. Wang Y, Vidan E, Bergman GW. Cardiac motion of coronary arteries: variability in the rest period and implications for coronary MR angiography. Radiology 1999; 213: 751–758.
35. Barrera CA, Otero HJ, White AM, Saul D, Biko DM. Image quality of ECG-triggered high-pitch, dual-source computed tomography angiography for cardiovascular assessment in children. Curr Probl Diagn Radiol 2020; 49: 23–28.
36. Watanabe H, Kamiyama H, Kato M, Komori A, Abe Y, Ayusawa M. Appropriate use of a beta-blocker in paediatric coronary CT angiography. Cardiol Young 2018; 28: 1148–1153.
37. Cademartiri F, Mollet NR, Lemos PA, et al. Higher intracoronary attenuation improves diagnostic accuracy in MDCT coronary angiography. AJR Am J Roentgenol 2006; 187: W430–W433.
38. Liu Y, Li J, Zhao H, et al. Image quality and radiation dose of dual-source CT cardiac angiograhpy usnig prospective ECG-triggering technique in pediatric patients with congenital heart disease. J Cardiothorac Surg 2016; 11: 47.
39. Layritz C, Schmid J, Achenbach S, et al. Accuracy of prospectively ECG-triggered very low-dose coronary dual-source CT angiography using iterative reconstruction for the detection of coronary artery stenosis: comparison with invasive catheterization. Eur Heart J Cardiovasc Imaging 2014; 15: 1238–1245.

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