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Original paper

Low-dose paediatric cardiac and thoracic computed tomography with prospective triggering: Is it possible at any heart rate?

Bouchra Habib Geryes[a,*], Raphael Calmon[a], Victoria Donciu[a], Diala Khraiche[b], Karine Warin-Fresse[c], Damien Bonnet[d,e], Nathalie Boddaert[f], Francesca Raimondi[g]

[a] Hôpital Universitaire Necker Enfants Malades, Service de Radiologie pédiatrique, 149, rue de Sèvres, 75743 Paris Cedex 15, France
[b] Hôpital Universitaire Necker Enfants Malades, Unité Médico-Chirurgicale de Cardiologie Congénitale et Pédiatrique, 149, rue de Sèvres, 75743 Paris Cedex 15, France
[c] Imagerie Cardiovasculaire, Centre Hospitalier Universitaire de Nantes, Blv Jacques Monod, 44093 Nantes, France
[d] Unité Médico-Chirurgicale de Cardiologie Congénitale et Pédiatrique, Centre de référence Malformations Cardiaques Congénitales Complexes – M3C, 149, rue de Sèvres, 75743 Paris Cedex 15, France
[e] Université Paris Descartes, Sorbonne Paris Cité, France
[f] Hôpital Universitaire Necker Enfants Malades, Service de Radiologie pédiatrique, 149, rue de Sèvres, 75743 Paris Cedex 15, France
[g] Hôpital Universitaire Necker Enfants Malades, Service de Radiologie pédiatrique, Unité Médico-Chirurgicale de Cardiologie Congénitale et Pédiatrique, 149, rue de Sèvres, 75743 Paris Cedex 15, France

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ABSTRACT

Objective: To demonstrate that the use of step-and-shoot (SAS) mode in paediatric cardiac CT angiography (CCTA) is possible at heart rates (HR) greater than 65 bpm, allowing low-dose acquisition with single-source 64-slices CT.

Methods: We retrospectively included 125 paediatric patients (0–6 years). CCTA was performed with SAS at diastolic phase in 31 patients (group D, HR $<$ 65 bpm), at systolic phase in 45 patients (group S, HR $\geq$ 65 bpm) and with non-gated mode in 49 patients (group NG). Effective dose (ED) and image quality using a 3-grade scoring scale (1, excellent; 2, moderate; 3, insufficient) of group S were compared with group D for coronary examinations and group NG for entire thorax vascular anatomy.

Results: For coronary indications, median ED was 0.6 mSv in group D versus 0.9 mSv in group S ($p < 0.01$). For whole thorax indications, median ED was 2.7 mSv in group NG versus 1.1 mSv in group S ($p < 0.001$). The mean image quality score was (1.4 $\pm$ 0.6) points in group D, (1.4 $\pm$ 0.7) in group S for coronary indications ($p = 0.9$), (1.3 $\pm$ 0.6) in group S for whole thorax indications and (2.0 $\pm$ 0.0) in group NG ($p < 0.001$).

Conclusion: SAS mode is feasible in children with HR greater than 65 bpm allowing low-dose CCTA. It provided comparable image quality in systole, compared to diastole. SAS at the systolic phase provided better image quality with less radiation dose compared to non-gated scans for whole thorax examinations.

1. Introduction

Sequential prospective acquisition, also known as step-and-shoot (SAS) mode, is currently used to limit radiation dose in cardiac computed tomography angiography (CCTA). The prospective-ECG gating technology has shown promising results in dose reduction, compared to the traditional retrospective acquisition, for heart rates (HR) up to 65 bpm, offering comparable imaging quality and diagnostic value [1–6]. It uses prospectively triggered axial SAS scans in which X-rays are turned on only during the required heart phase and turned off completely at all other times. In paediatric patients with stable HR lower than 65 bpm, prospective mode with mid-diastole reconstruction provides high-quality images with 70% less radiation compared to retrospective acquisition [7,8]. However, diastolic reconstruction is susceptible to motion artifacts when HR is greater than 65 bpm [9,10]. For higher HR, end-systolic reconstruction windows have been successfully used to optimise image quality (typically at 40% of R-R interval) in adult patients on dual-source CT [11–14]. However, to our

Abbreviations: ASIR, Adaptive Statistical Iterative Reconstruction; BPM, Beats per Minute; BSA, Body Surface Area; CCTA, Cardiac Computed Tomography Angiography; CTDIvol, Computed Tomography Dose Index to the volume; DLP, Dose Length Product; ECG, Electrocardiogram; ED, Effective Dose; Group D, image reconstruction at mid-diastole; Group S, image reconstruction at end-systole; Group NG, not gated scan acquisition; HR, Heart Rate; IQR, Interquartile Range; SAS, Step-And-Shoot; SD, Standard Deviation; SSDE, Size-Specific Dose Estimates

* Corresponding author.
E-mail address: bouchra.habib-geryes@aphp.fr (B. Habib Geryes).

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knowledge, prospective acquisition has not been evaluated for systolic reconstruction at high HRs in paediatric patients on single-source 64-slices CT which are still clinically widely used compared to the more expensive newer generation CT.

The objective of this study was to demonstrate that the use of SAS mode in paediatric CCTA can be feasible in paediatric patients with HR greater than 65 bpm using single-source 64-row CT equipment. Therefore, we compared prospective CCTA radiation dose and image quality at end-systole in paediatric patients (0–6 years) with high HRs (≥65 bpm) to those at mid-diastole in patients with low HRs (< 65 bpm) using a single-source 64-slices CT. We also compared the SAS mode at systolic phase to the non-gated scan mode for examination of the entire thorax and vascular anatomy.

2. Materials and methods

2.1. Study population

Between January 2014 and May 2016, we retrospectively included 125 consecutive paediatric patients (0–6 years old) who underwent CT examinations for cardiac indications. All patients were enrolled for the diagnostic work up of congenital heart disease. Examinations were performed for various indications, with overall 45% of CT for coronary examinations (transposition of great vessels, anomaly origin of coronary arteries and malposition of great vessels) and 55% for study of the thoracic vascular anatomy (aortic coarctation, anomaly of pulmonary veins, Tetralogy of Fallot, pulmonary atresia, pre and post-surgical complex congenital heart disease).

Patient characteristics (age, sex, weight, height, type of congenital heart disease) were collected from our central database. Mean heart rate and contrast administration during scan were noted. Mean ± standard deviation patient age was (3.9 ± 1.9) years, 64% were males. The mean ± standard deviation patient Body Surface Area (BSA) [21] was (0.1 ± 0.02) m^2. All patients who underwent CCTA for coronary arteries examinations were beta-blocked using oral administration of propranolol an hour before exam to avoid arrhythmia. Patients were monitored in day hospital. The mean ± standard deviation propranolol dose was (3.2 ± 1.8) g.

2.2. CT imaging protocols

CT examinations were performed using a 64-row multidetector CT scanner (LightSpeed VCT, GE Healthcare, Milwaukee, WI). The scan length was defined according to clinical indication: limited to the heart for coronary indications or extended to the whole thorax for the vascular anatomy studies. During CT acquisitions, contrast (Xenetix® 300 mg/ml, 2 ml/kg) was injected at a flow rate determined by body size and intravenous access size (1.5 ml/s up to 2 ml/s) followed by a saline flush using a power injector. All scans were performed in free-breathing. Image reconstruction was performed with a slice thickness of 0.625 mm, an increment of 0.625 mm, and the STANDARD reconstruction kernel. Iterative reconstruction was used with 60% ASIR.

ECG-gated scans were performed in SAS mode at a single phase (75%) in diastole for a HR < 65 bpm and a single phase (40%) in systole for HR ≥ 65 bpm. In patients with HR < 65 bpm, reconstructions were performed at mid-diastole (group D) and in patients with HR ≥ 65 bpm, reconstructions were performed at end-systole (group S). SAS scans were done with detector collimation of 64 × 0.625 mm, a gantry rotation time of 350 ms. 80 kV tube voltage and 200 mA tube current were used. The temporal padding was 0 ms for patients with regular HR, otherwise 100 ms were added to the beam-on time.

Non-gated scans for the examination of the whole thorax were performed with detector collimation of 64 × 0.625 mm, a gantry rotation time of 400 ms. A 0.984 pitch factor, 80 kV tube voltage and modulated mA tube current between 100 and 230 mA with a noise index of 25 Hounsfield Unit were used.

These protocols were optimised and regularly evaluated in terms of radiation dose and image quality. The optimisation process involved the local paediatric radiologist specialised in cardiology, the local medical physicist and the CT vendor application specialist in order to provide diagnostic image quality with the lower patient dose as possible.

2.3. Effective radiation dose evaluation

The ED was estimated by the DLP method using the total DLP values collected from the dose manager software (Radiation Dose Monitor® from Medsquare) for each examination using the following formula:

$$ED\,(\mathrm{mSv}) = k\,(\mathrm{mSv}\times\mathrm{mGy}^{-1}\times\mathrm{cm}^{-1}) \times DLP\,(\mathrm{mGy}\times\mathrm{cm})$$

where k is a body region, age and kV –specific dose conversion factor. We chose to use the published conversion factors by Deak [15], which are derived as a function of the International Commission on Radiological Protection Recommendations n°103. To calculate ED from the DLP conversion factors, one must reference the same phantom size. We use the paediatric 80 kV chest conversion factors reported by Deak [15] for a 32 cm body phantom. A k-factor of 0.0823, 0.0525, 0.0344 and 0.0248 mSv/mGy/cm was used respectively for new-borns, 1-, 5-, and 10-year-old children. A piecewise cubic Hermite interpolation was used to estimate k-factor values for intermediate ages [8].

2.4. Image quality analysis

The reconstructed images were analysed by two independent paediatric radiologists with at least 5 years of experience in cardiovascular imaging.

For coronary CT scans, image quality was evaluated using a three-point scale [16]: score 1 corresponded to excellent image quality (no motion or stair-step artifacts), score 2 indicated moderate image quality (moderate motion artifacts and stair-step artifacts or blurring), and score 3 indicated insufficient image quality (distinct motion artifacts and stair-step artifacts). Images with a score of 1 or 2 were considered to be acceptable for diagnosis.

For whole thorax cardiac CT scans, image quality was still evaluated using a three-point scale based on European guidelines on quality criteria for computed tomography [17]: 1 = excellent, 2 = moderate, 3 = insufficient image quality.

Scoring was performed using a window adapted for the mediastinum on 2-D axial, reformatted, and thick-slab maximal intensity projection images.

2.5. Statistical analysis

Patient age is expressed as mean ± standard deviation (SD), whereas DLP and ED are expressed as median ± interquartile range (IQR). Categorical variables are expressed as percentages. Differences in continuous variables were assessed using, Wilcoxon rank-sum test analysis of variance as appropriate. The Kruskal-Wallis H test was used to compare variances of image-quality scores between groups D vs S and S vs NG for coronary and whole thorax examinations respectively. A p-value ≤ 0.05 was considered statistically significant. Cohen's Kappa coefficients were calculated for inter-reader agreement for qualitative items.

K-agreement was defined as following: < 0 less than chance agreement, 0.01–0.20 slight agreement, 0.21–0.40 fair agreement, 0.41–0.60 moderate agreement, 0.61–0.80 substantial agreement, 0.81–0.99 almost perfect agreement.

Table 1
Patient characteristics (n = number of patients).

Patients included (n = 125)	Mean Heart Rate ± SD (bpm)	Mean Age ± SD (years)	Indications
Group D (n = 31)	67 ± 4	5.2 ± 0.8	100% Coronary examinations
Group S (n = 45)	91 ± 22	3.1 ± 1.9	56% Coronary, 44% Whole thorax examinations
Group NG (n = 49)	Non gated	1.6 ± 1.8	100% Whole thorax examinations
P value Group D-S	0.00004	0.0008	
P value Group NG-S	NA	0.1129	

Group D image reconstruction at mid-diastole (heart rate < 65 bpm), Group S image reconstruction at end-systole (heart rate ≥ 65 bpm), Group NG not gated scan acquisition.

3. Results

3.1. Patients

One hundred twenty-five consecutive paediatric patients (0–6 years old) who underwent CT examinations for cardiac indications were included. Patient characteristics are summarized in Table 1. Mean patient age was (5.2 ± 0.8), (3.1 ± 1.9) and (1.6 ± 1.8) years for groups D, S and NG, respectively (p value D-S < 0.001 and p value NG-S > 0.05). Mean heart rate was (67 ± 4) and (91 ± 22) bpm for groups D and S, respectively (p value < 0.001). For coronary examinations, 31 scans were included in group D and 25 scans were included in group S. For whole thorax examinations, 49 and 20 scans were included in groups NG and S, respectively.

3.2. Radiation exposure

CTDIvol, DLP and ED values for all groups are shown in Table 2.

We analysed separately the scan examinations centred on the heart for coronary diagnosis and the scan examination of the whole thorax. For coronary indications, CTDIvol and DLP were (1.3 ± 1.1) mGy and (15 ± 11) mGy × cm in group D versus (2.4 ± 1.1) mGy and (26 ± 11) mGy × cm in group S (p < 0.05 for CTDIvol and p > 0.05 for DLP). Median ED for group S was 33% higher than median ED for group D ((0.9 ± 0.4) versus (0.6 ± 0.3) mSv, p < 0.01). For the whole thorax indications, CTDIvol and DLP were (2.8 ± 1.1) mGy and (49 ± 27) mGy × cm in the group NG versus (1.6 ± 1.1) mGy and (22 ± 8) mGy × cm in the group S (p < 0.001 for CTDI vol and for DLP). Median ED for group NG was 60% higher than median ED for group S ((2.7 ± 1.0) versus (1.1 ± 0.6) mSv, p < 0.001).

3.3. Image quality

Detailed scoring data of the image quality evaluation are reported in Tables 3 and 4 for coronary and whole thorax examinations respectively. The inter-reader agreement for image quality analysis for 125 patients was very good (k = 0.79 for Group D, k = 0.87 for group S for coronary indications, k = 0.89 for group S for whole thorax indications and k = 1 for group NG). The mean image quality score was (1.4 ± 0.6) points in group D, (1.4 ± 0.7) points in group S for coronary indications (p value = 0.9), (1.3 ± 0.6) points in group S for whole thorax indications and (2.0 ± 0.0) points in group NG (p value < 0.001).

Table 2
Median ± IQR for CTDIvol (mGy), DLP (mGy × cm) and ED (mSv) by patient group.

Group	CTDIvol (mGy)	DLP (mGy × cm)	ED (mSv)
D – Coronary indications	1.3 ± 1.1	15 ± 11	0.6 ± 0.3
S – Coronary indications	2.4 ± 1.1	26 ± 11	0.9 ± 0.4
S – Whole thorax indications	1.6 ± 1.1	22 ± 8	1.1 ± 0.6
NG – Whole thorax indications	2.8 ± 1.1	49 ± 27	2.7 ± 1.0
p value D-S Coronary indications	0.022	0.13	0.0013
p value NG-S Whole thorax indications	< 0.001	< 0.001	< 0.001

Group D image reconstruction at mid-diastole (heart rate < 65 bpm), Group S image reconstruction at end-systole (heart rate ≥ 65 bpm), Group NG not gated scan acquisition.

Table 3
Assessment of image quality by patient group for the two readers (n = number of patients) for coronary CT scans. Image quality is evaluated using a 3-grade scoring scale.

Image quality Score	Reader	Group D (n = 31)	Group S (n = 25)
1	1	21 (68%)	18 (71%)
	2	18 (58%)	15 (58%)
2	1	8 (26%)	4 (16%)
	2	10 (32%)	7 (29%)
3	1	2 (6%)	3 (13%)
	2	3 (10%)	3 (13%)
k value		0.79	0.87

Group D image reconstruction at mid-diastole (heart rate < 65 bpm), Group S image reconstruction at end-systole (heart rate ≥ 65 bpm), k value is the kappa value of the inter-reader agreement test for each group.

Table 4
Assessment of image quality by patient group for the two readers (n = number of patients) for whole thorax cardiac CT. Image quality is evaluated using a 3-grade scoring scale.

Image quality Score	Reader	Group S (n = 20)	Group NG (n = 49)
1	1	15 (75%)	0 (0%)
	2	14 (70%)	0 (0%)
2	1	4 (20%)	49 (100%)
	2	5 (25%)	49 (100%)
3	1	1 (5%)	0 (0%)
	2	1 (5%)	0 (0%)
k value		0, 89	1

Group S image reconstruction at end-systole (heart rate ≥ 65 bpm), Group NG not gated scan acquisition, k value is the kappa value of the inter-reader agreement test for each group.

4. Discussion

Husmann et al. suggested in 2007 that image reconstruction algorithms at CT coronary angiography should be adapted to the patient HR [18]. Furthermore, the use of SAS mode in CCTA in young children on single-source 64-slices CT has been limited for a long time to HR < 65 bpm. Since the development of high-pitch and dual-source CT technologies, many reports [11–14,19] proposed to extend SAS mode to higher HR. None of them to our knowledge was based on paediatrics and single-source 64-slices CT. The use of high technology scans is still limited all over the world for economical reasons. In France, only 3% of

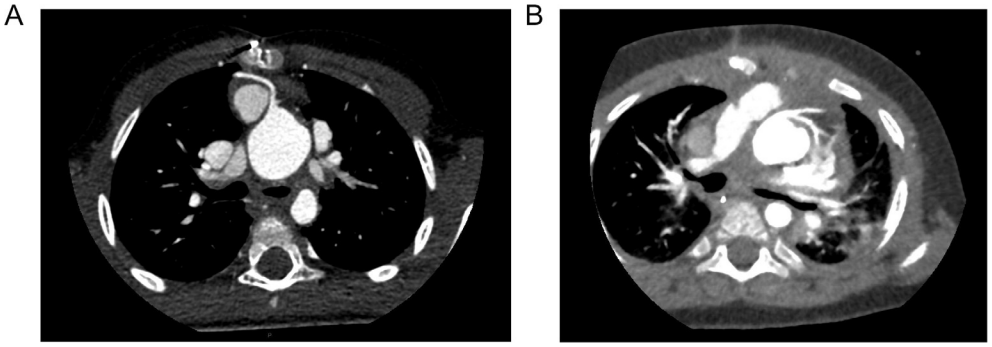

Fig. 1. Comparisons of SAS acquisition at diastolic phase (A) vs systolic phase (B). A: Axial view of the ostium of right coronary artery in 5 years old boy after arterial switch operation (C 282/W 789). Acquisition was made at 75% of cardiac cycle, DLP was 21.60 mGy × cm, CTDIvol was 5.37 mGy. Mean heart rate during acquisition was 65 bpm.

medical centers are using high technology CT (40 high technology scans over 1322 scans in 2016), the 97% still have a single source 64-slices CT (General Agency of Health Equipment and Products source). Therefore, we considered of utmost clinical importance to demonstrate that SAS mode is feasible also on single-source 64-slices CT at HR greater than 65 bpm. Indeed, the possibility to extend the use of SAS mode in young children as a systematic way to perform CCTA changes the perspective about the use of radiation in children. It allows to perform CCTA with protocols with dose as low as possible. Unfortunately, in small children < 4 years of age the effectiveness of oral beta blockers is quite low and often the use of intravenous beta blockers is not possible for practical organisation of radiology departments or for specific medical contraindications. So CCTA on single-source 64-slices CT was for a long time performed with high dose protocols with retrospective reconstructions or cancelled for very high HR.

In this study, we demonstrated that CCTA with SAS mode is feasible in children with HR greater than 65 bpm with a good image quality (Figs. 1–4). As showed in Figs. 1–4, SAS acquisition was possible in infants (Fig. 1, 7 months of age, 168 bpm) and children (Fig. 23 months of age, 120 bpm) with a very good image quality at high heart rate. Coronary arteries were very well visualised and analysed for diagnosis without significant step artifacts (Fig. 3). Radiation dose in group S for coronary examinations was 33% higher in comparison to group D ((0.9 ± 0.4) mSv in group S versus (0.6 ± 0.3) mSv in group D, $p < 0.01$) (Table 2). However, radiation dose in group S is still lower then effective dose from the retrospective mode (3.8 mSv for 0–4 years patients) as shown in Habib-Geryes et al. [7]. Iterative reconstruction algorithm was used for all examinations. The use of these methods allows about 40% radiation dose reduction while image quality is maintained compared to conventional reconstruction methods [7,22]. Comparison of our results with published radiation dose data for paediatric prospective cardiac CT is difficult mainly due to inconsistent grouping of patients and differences in the scanner technology. Median ED obtained by Ghoshhajra et al. [8] for coronary CCTA was 2.3 mSv for 0–6 years patients (25 patients), 6.8 mSv for 0–18 years with 64-slice multidetector scanner (43 patients), 2.9 mSv for 0–18 years with 64-slice dual source scanner (16 patients) and 1.0 mSv for 0–18 years with 128-slice dual source scanner (36 patients), whereas in the present study, the median ED was 0.6 for diastolic mode and 0.9 mSv for systolic mode in coronary CCTA with 64-slice multidetector scanner.

We also demonstrated that CCTA with SAS mode is also feasible when the exam is indicated to study the detailed anatomy of thoracic vessels, in particular for distal pulmonary arteries, pulmonary veins (Fig. 2) and thoracic aorta (Fig. 4). Step artifacts were not significant in the majority of patients (95%, Table 4) as showed in Fig. 4. In this case the use of SAS mode in comparison to non-gated acquisition allows a better and more detailed image quality with lower dose ((1.1 ± 0.6) mSv in group S for whole thorax examinations versus

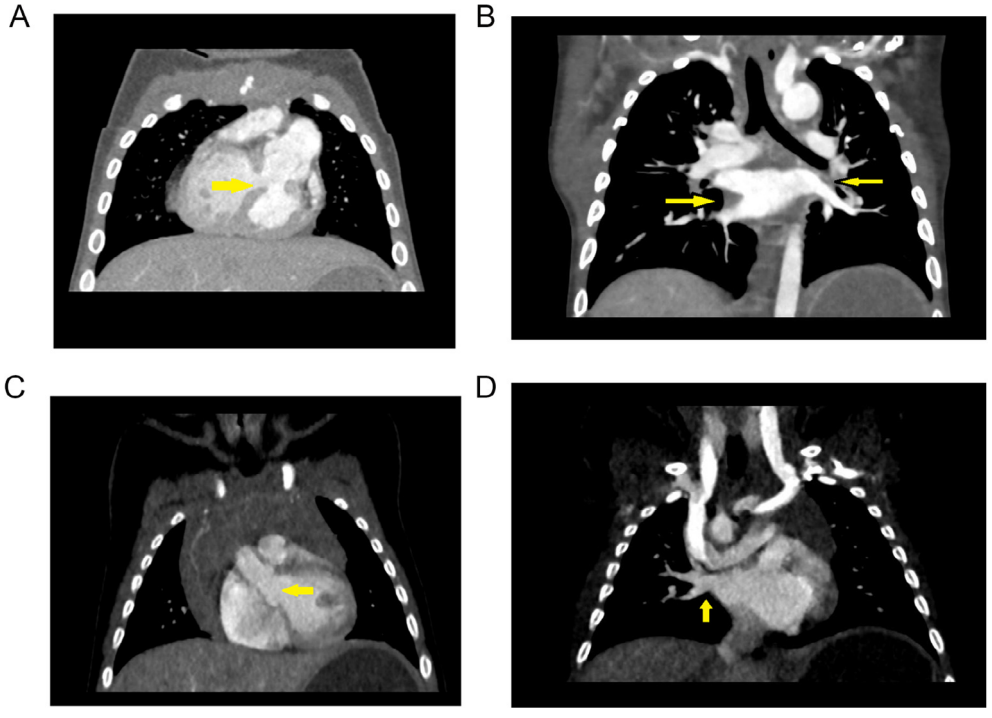

Fig. 2. Comparison of SAS acquisition at systolic phase (A and B) vs non-gated acquisition (C and D) for whole thorax indications CCTA. A: Coronal view of whole thorax of a 7 months old boy showing a large interventricular septal defect (C 141/W 678). Acquisition was made at 40% of cardiac cycle, DLP was 12.96 mGy × cm, CTDIvol was 5.28 mGy. Mean heart rate during acquisition was 120 bpm. B: Coronal view of the same patients, showing pulmonary veins of excellent image quality. C: Coronal view of whole thorax of a 3 months old boy showing left ventricular outflow tract (C 234/W 624). Acquisition was non-gated, DLP was 23.59 mGy × cm, CTDIvol was 4.18 mGy. D: Coronal view of the same patients, showing pulmonary veins of moderate image quality.

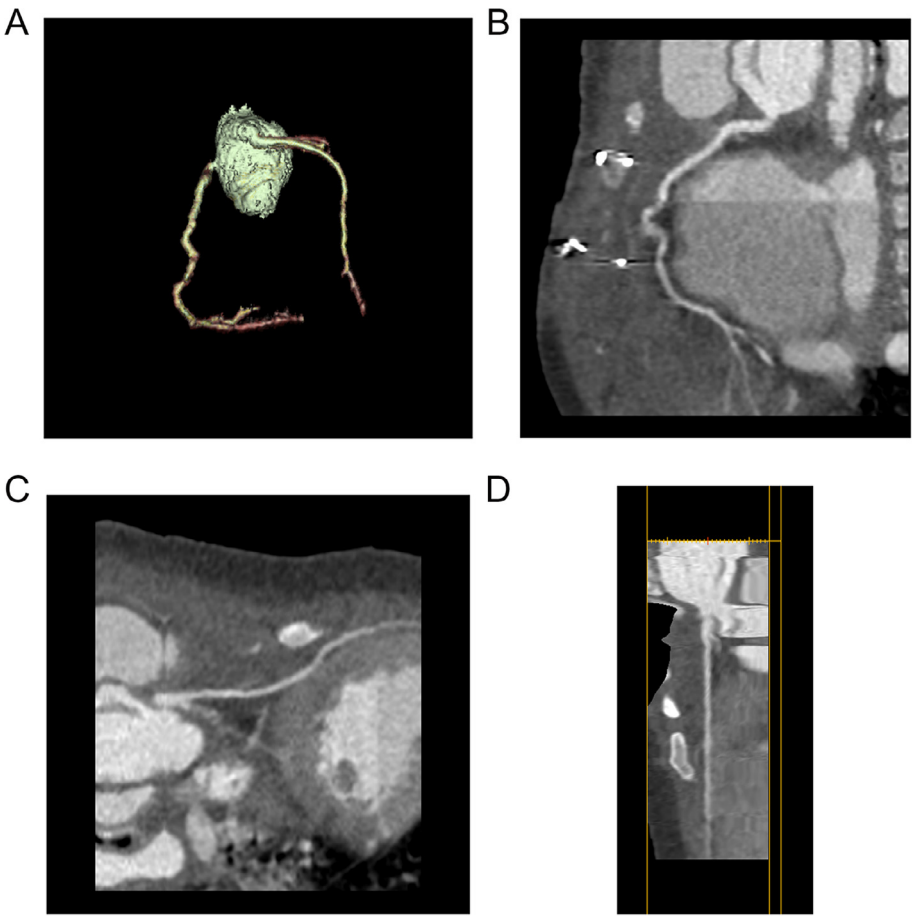

Fig. 3. Volume rendering and curved planar reformatted views of coronary tree of patient of Fig. 1B. A: Volume rendering of coronary tree. B: Curved planar reformatted view of right coronary artery. Stairstep artifact is present that not affects coronary analysis. C and D: Curved planar reformatted view of anterior descending left coronary artery. No stairstep artifacts are visible.

(2.7 ± 1) mSv in group NG, $p < 0.01$) (Table 2, Fig. 2). The national diagnostic reference levels in our country [20] for standard thorax scans in paediatrics are defined as 3 mGy and 30 mGy × cm, and 4 mGy and 65 mGy × cm for CTDIvol and DLP in 1 year and 5 years patients respectively. The values in this study for detailed whole thorax indications in S mode (CTDIvol and DLP were (1.6 ± 1.1) mGy and (22 ± 8) mGy × cm in the group S) were sensibly lower than the diagnostic reference levels for standard thorax scans.

We suggest that the SAS CT acquisition mode can be proposed for cardiac and thoracic studies when vascular anatomy examination is needed.

5. Limitations

The main limitation is the small number of patients in each group, which is inherent to study with paediatric populations. Our study was retrospective so we were not able to have the same number of patients in each group. Another limitation is the use of conversion factors derived from the literature [15] to calculate the effective dose from DLP values as Deak et al. [15] performed their Monte Carlo simulations on a different system (Somatom Sensation 64 CT scanner, Siemens Healthcare). Moreover, dose comparison in this study was based on CTDIvol and DLP dose indices. These indices are automatically collected from the DICOM structured report by the dose management system. CTDIvol and DLP are sensitive to changes in scan parameters, but are

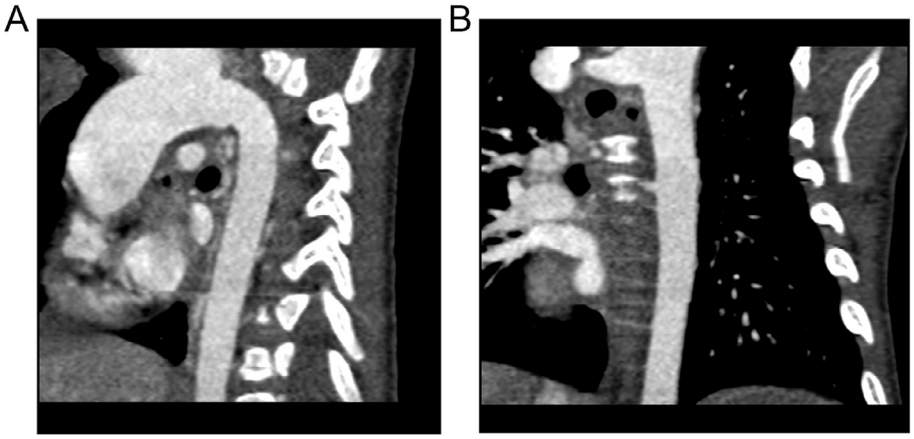

Fig. 4. A and B: Curved planar reformatted view of thoracic aorta in patient of Fig. 2A. No stairstep artifacts are visible.

independent of patient size since CTDIvol is determined for either a 16 cm or a 32 cm diameter polymethyl methacrylate cylindrical reference phantom. In further studies, the Size-Specific Dose Estimates (SSDE) [23] calculation from CTDIvol and factors associated with patient size is recommended. Another limitation is about our assessment of image quality. Analysis was subjective since quantitative analysis was inappropriate due to the manual scan acquisition after contrast injection in children. Moreover, we carefully analysed several methodologies to give an appropriate image quality evaluation but it was difficult to find a metric adapted to our population that is purely paediatric and with really different cardiac anomalies and so CT scan indications. Metrics vary across indication, so we judged as the most important issue whether the examination was diagnostic or not. We hope that future studies in paediatric population will provide more data about appropriate image quality analysis methods for congenital heart diseases.

6. Conclusion

CCTA in paediatrics with SAS mode is feasible even if HR is greater than 65 bpm allowing low dose prospective acquisition and good image quality. Moreover, the SAS at the systolic phase provides better image quality with less radiation dose compared to non-gated scans for the whole thorax CCTA.

Disclosure paragraph

The authors have no conflicts of interest.

References

[1] Podberesky DJ, Angel E, Yoshizumi TT, Toncheva G, Salisbury S, Alsip C, et al. Radiation dose estimation for prospective and retrospective ECG-gated cardiac CT angiography in infants and small children using a 320 MDCT Volume scanner. AJR 2012;199:1129–35.

[2] Sun Z, Ng KH. Prospective versus retrospective ECG-gated multislice CT coronary angiography: a systematic review of radiation dose and diagnostic accuracy. Eur J Radiol 2012;81. e94-e100.

[3] Hirai N, Horiguchi J, Fujioka C, Kiguchi M, Yamamoto H, Matsuura N, Kitagawa T, Teragawa H, Kohno N, Ito K. Prospective versus retrospective ECG-gated 64-detector coronary CT angiography: assessment of image quality, stenosis, and radiation dose. Radiology 2008;248(2):424–30.

[4] Shuman WP, Branch KR, May JM, Mitsumori LM, Lockhart DW, Dubinsky TJ, et al. Prospective versus retrospective ECG gating for 64-detector CT of the coronary arteries: comparison of image quality and patient radiation dose. Radiology 2008;248(2):431–7.

[5] Hsieh J, Londt J, Vass M, Li J, Tang X, Okerlund D. Step-and-shoot data acquisition and reconstruction for cardiac x-ray computed tomography. Med Phys 2006;33:4236–48.

[6] Dowe D. Prospectively gated computed tomographic angiography dramatically reduces radiation dose. Diagn Imaging 2006;28(suppl):S1–5.

[7] Habib Geryes B, Calmon R, Khraiche D, Boddaert N, Bonnet D, Raimondi F. Radiation dose reduction in paediatric coronary computed tomography: assessment of effective dose and image quality. Eur Radiol. 2016;26(7):2030–8.

[8] Ghoshhajra BB, Lee M, Engel L-C, Celeng C, Kaira MK, Bradi TJ, Hoffmann U, Westra SJ, Abbara S. Radiation dose reduction in pediatric cardiac computed tomography: experience from a tertiary medical center. Pediatric Cardiol 2014;35:171–9.

[9] Buechel RR, Husmann L, Herzog BA, Pazhenkottil AP, Nkoulou R, Ghadri JR, et al. Low-dose computed tomography coronary angiography with prospective electrocardiogram triggering feasibility in a large population. J Am Coll Cardiol 2011;57(3):332–6.

[10] Herzog BA, Husmann L, Burkhard N, Valenta I, Gaemperli O, Tatsugami F, et al. Low-dose CT coronary angiography using prospective ECGtriggering: impact of mean heart rate and heart rate variability on image quality. Acad radiol 2009;16(1):15–21.

[11] Bamberg F, Sommer WH, Schenzle JC, Becker CR, Nikolaou K, Reiser MF, et al. Systolic acquisition of coronary dual-source computed tomography angiography: feasibility in an unselected patient population. Eur radiol 2010;20(6):1331–6.

[12] Seifarth H, Wienbeck S, Pusken M, Juergens KU, Maintz D, Vahlhaus C, et al. Optimal systolic and diastolic reconstruction windows for coronary CT angiography using dual-source CT. AJR Am J Roentgenol 2007;189(6):1317–23.

[13] Sun G, Li M, Li L, Li GY, Zhang H, Peng ZH. Optimal systolic and diastolic reconstruction windows for coronary CT angiography using 320-detector rows dynamic volume CT. Clin Radiol 2011;66(7):614–20.

[14] Paul JF, Amato A, Rohnean A. Low-dose coronary-CT angiography using step and shoot at any heart rate: comparison of image quality at systole for high heart rate and diastole for low heart rate with a 128-slice dual-source machine. Int J Cardiovasc Imaging 2013;29:651–7.

[15] Deak PD, Smal Y, Kalender WA. Multisection CT protocols: sex- and age-specific conversion factors used to determine effective dose from dose-length product. Radiology 2010;257(1):158–66.

[16] Gu J, Shi HS, Han P, Yu J, Ma GN, Wu S. Image quality and radiation dose for prospectively triggered coronary CT angiography: 128-slice single-source CT versus first-generation 64-slice dual-source CT. Sci Rep 2016 Oct;18(6):34795.

[17] Bodelle B, Fischbach C, Booz C, Yel I, Frellesen C, Beeres M, et al. Free-breathing high-pitch 80 kVp dual-source computed tomography of the pediatric chest: image quality, presence of motion artifacts and radiation dose. Eur J Radiol. 2017 Apr;89:208–14.

[18] Husmann L, Leschka S, Desbiolles L. Coronary artery motion and cardiac phases: dependency on heart rate e implications for CT image reconstruction. Radiology 2007;245. 567e576.

[19] Booij R, Dijkshoorn ML, van Straten M, du Plessis FA, Budde RP, Moelker A, et al. Cardiovascular imaging in pediatric patients using dual source CT. J Cardiovasc Comput Tomogr 2016;10(13):21.

[20] JORF n°0012 du 14 janvier 2012 page 715 texte n° 22. Arrêté du 24 octobre 2011 relatif aux niveaux de référence diagnostiques en radiologie et en médecine nucléaire. NOR: ETSP1129093A.

[21] Du Bois D, Du Bois EF. A formula to estimate the approximate surface area if height and weight be known. Arch Intern Med 1916;17(6):863–71.

[22] Greffier Joël, Pereira Fabricio, Macri Francesco, Beregi Je-Paul, Larbi Ahmed. CT dose reduction using automatic exposure control and iterative reconstruction: a chest paediatric phantoms study. Phys Med 2016;32(4):582–9.

[23] Size-Specific Dose Estimates (SSDE) in Pediatric and Adult Body CT Examinations. Report of AAPM Task Group 204. 2011, ISBN: 978-1-936366-08-8. ISSN: 0271-7344. Published by American Association of Physicists in Medicine, One Physics Ellipse, College Park, MD 20740-3846.