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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.