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Original Article

Evaluating Low-kV Dual-source CT Angiography by High-pitch Spiral Acquisition and Iterative Reconstruction in Pediatric Congenital Heart Disease Patients

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We retrospectively evaluated the qualities of pediatric cardiovascular dual-source computed tomography (DSCT) images reconstructed by sinogram-affirmed iterative reconstruction (SAFIRE) and filtered back projection (FBP). We analyzed the cases of 287 congenital heart disease (CHD) patients < 5 years old, referred to our department in August 2013-March 2015. We divided them into two groups according to tube voltage (70 kVp, n = 147; 80 kVp, n = 140). All images were acquired by a CARE kV system and reconstructed by FBP and SAFIRE. The attenuation, noise, and signal-to-noise ratio (SNR) at each region of the heart and great vessels were measured. The volume CT dose index and dose-length product values were recorded. Compared to FBP, reconstruction by SAFIRE showed that the attenuation volume was significantly lower by 0.4% except for the ascending aorta ($p < 0.05$), the noise value was lower by about 20% ($p < 0.05$), and the SNR was higher by approx. 25% ($p < 0.05$). The radiation dose in the 70 kVp group was significantly lower than that in the 80 kVp group. No significant differences in SNR were observed between the patient groups. DSCT image acquisition with SAFIRE using the CARE kV system results in low image noise and radiation dose in pediatric patients with CHD.

Key words: congenital heart disease, iterative reconstruction, low-kV, computed tomography, pediatric

Because of the recent advances in computed tomography (CT), cardiovascular CT is widely used to evaluate congenital heart diseases (CHDs) [1-3]. However, the radiation exposure during the CT imaging remains a major limitation of this modality [4], and since children and neonates have a higher lifetime risk of malignancy than adults and are especially sensitive to radiation exposure [5-6], efforts to reduce the radiation dose provided by CT are important. However, low-dose imaging techniques can result in high image noise and low image quality due to beam-hardening artifacts [7-8]. The iterative reconstruction techniques that are now available, improve image quality by decreasing image noise even at low radiation doses [9-10]. Although iterative reconstruction techniques have been applied in the imaging of adults, there are a few appropriate imaging protocols using iterative reconstruction for CT in children, especially in the pediatric cardiovascular field [9]. We conducted the present study to

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comparatively evaluate the qualities of cardiovascular CT images reconstructed by sinogram-affirmed iterative reconstruction (SAFIRE) and filtered back projection (FBP) in terms of noise reduction.

Patients and Methods

Our institutional review board approved the retrospective evaluation of cardiovascular CT data. The need for informed consent was waived. We screened the imaging data of 338 consecutive patients under 5 years old who were referred to our department between August 2013 and March 2015 for known or suspected CHD. All imaging studies were performed using a dual-source 128-slice CT system (Somatom® Definition Flash; Siemens Healthcare, Forchheim, Germany). The exclusion criteria were as follows: tube voltage at 100 kVp; intensive body-motion artifacts; contrast medium leakage; and missing imaging data. After the exclusion of 51 patients, 287 patients were enrolled in this study (Fig. 1).

All images were acquired at automatically selected tube voltages using the CARE kV system (Siemens Healthcare), which proposes optimized kV and mA settings according to the intended type of investigation. Additionally, automated tube current modulation (CARE Dose 4D, Siemens Healthcare) was activated, and the imaging was performed in the high-pitch spiral mode. We divided the patients into 2 groups according to the tube voltage used for image acquisition: the 70 kVp (n = 147) and 80 kVp (n = 140) groups. Age, sex, and body weight before scanning were recorded for every patient. All patients were imaged during free breathing. Short-term sedation was achieved by an intravenous administration of secobarbital sodium at a dosage determined based on the body weight and clinical condition of the patient. Notably, 271 patients were examined by non-electrocardiogram (ECG)-gated CT, and the other 16 patients underwent ECG-gated CT. The following standard settings were used: collimation, 64 × 0.6 mm; gantry rotation speed, 0.28 sec; pitch factor, 3.2. Iodinated contrast medium (Iopamiron 300, Bayer, Osaka, Japan) was injected at a rate of 0.4-1.3 ml/sec, with the injection volume adjusted according to the patient's body weight (2 ml/kg). Data acquisition was triggered 2-4 sec after injection. The images were reconstructed using the FBP algorithm and using the SAFIRE algorithm. Transverse images were reconstructed at a 0.6-mm slice thickness, with a 0.3-mm increment and a matrix size of 512 × 512.

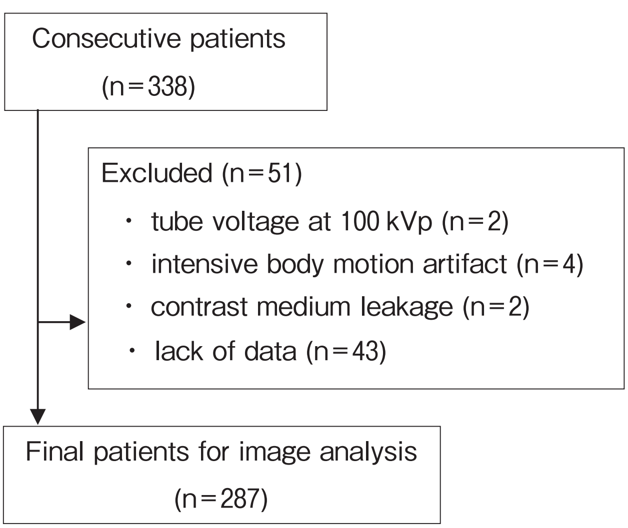

Fig. 1 Flowchart for patient enrollment.

The images were anonymized and transferred to an external workstation (Synapse Vincent, Fujifilm Medical Systems, Tokyo, Japan) for further analysis. For the evaluation of objective image quality, attenuation was measured at the ascending and descending aorta, the main, right, and left pulmonary arteries, and the ventricles in 0.6-mm thick axial images Fig. 2. Each region of interest (ROI) was placed such that the area of coverage was maximized. The quantitative image quality parameters included the image noise and the signal-to-noise ratio (SNR). Image noise was determined by the standard deviation (SD) of Hounsfield units (HU) within six ROIs placed at corresponding positions on transverse sections. The SNR was calculated as the ratio of the attenuation value to the noise.

The volume CT dose index (CTDIvol) and dose-length product (DLP) during imaging were recorded. The estimated effective dose (ED) was derived as the product of the DLP and the conversion coefficient k: ED = DLP × k where k is the conversion coefficient for children: 0.039 mSv/mGy.cm for infants up to 4 months of age; 0.026 mSv/mGy.cm for children between 4 months and 1 year old; and 0.018 mSv/mGy.cm for children between 1 and 5 years old) [11].

The statistical analyses were performed using SPSS software ver. 23.0 (SPSS, Chicago, IL, USA). Quantitative variables are expressed as mean ± SD. Quantitative variables were compared using the

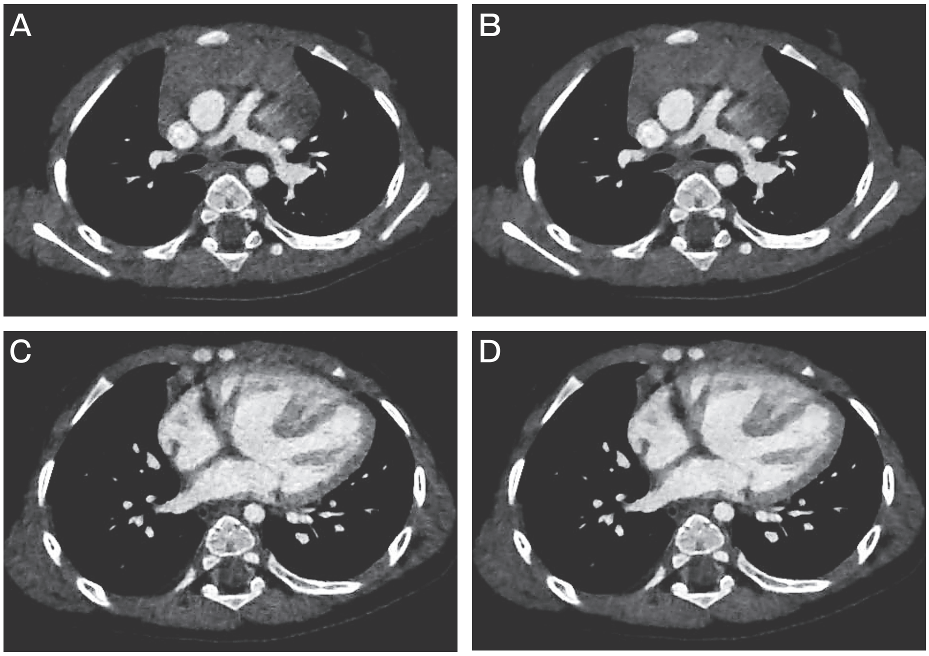

Fig. 2 Axial images reconstructed by FBP (A, C) and SAFIRE (B, D) from 8-month-old boy with double outlet right ventricle.

unpaired t-test for intergroup comparisons and Student's t-test for intra-individual comparisons. All p-values are two-sided, with values <0.05 considered significant.

Results

Patient characteristics. The final diagnoses of all 287 patients with CHD are presented in Table 1, and the patient characteristics in both groups are summarized in Table 2. The mean ages in the 70 kVp and 80 kVp groups were 15.3 ± 17.4 months and 24.4 ± 17.5 months, and the corresponding body weights were 6.5 ± 3.6 kg and 9.2 ± 3.5 kg, respectively. These 2 patient characteristics differed significantly ($p<0.001$) between the 2 groups.

Evaluation of image quality. Diagnostic images were acquired during all examinations. Significant differences ($p<0.001$) in attenuation were observed between the FBP and SAFIRE groups at every region except the ascending aorta (Table 3). Significant differences ($p<0.001$) were also observed in image noise and the SNR between the 2 groups at every region. The differences in the attenuation value and noise reduction and the increase in the SNR were calculated as %decrease or %increase, respectively, using the SAFIRE algorithm (Table 3).

We then compared the images reconstructed by SAFIRE between the 70 kVp and 80 kVp groups (Table 4). The attenuation values in the 70 kVp group were significantly higher than those in the 80 kVp group. The

Table 1 The 287 pediatric patients' congenital heart disease diagnoses

Diagnosis	n
Hypoplastic left heart syndrome	54
Double outlet right ventricle	40
Pulmonary atresia	30
Tetralogy of Fallot	30
Single ventricle	22
Coarctation of the aorta	18
Tricuspid atresia	13
Transposition of the great arteries	12
Persistent truncus arteriosus	12
Other diseases	56

Table 2 Patient characteristics

	70 kVp (n = 147)	80 kVp (n = 140)	p-value
Male : Female, n	93 : 54	74 : 66	
Age, Months	15.3 ± 17.4	24.4 ± 17.5	<0.001
Body weight, kg	6.5 ± 3.6	9.2 ± 3.5	<0.001

Table 3 The attenuation value, noise and SNR in various anatomic regions of interest reconstructed by FBP and SAFIRE

	FBP (n = 287)	SAFIRE (n = 287)	*p*-value	%decrease or increase[1]
Attenuation, HU				
Ascending aorta	453.2 ± 126.3	453.7 ± 125.4	0.505	0.1
Descending aorta	461.5 ± 135.7	460.0 ± 135.6	<0.001	0.3
Main pulmonary artery	424.1 ± 141.0	422.0 ± 139.7	<0.001	0.5
Right pulmonary artery	430.4 ± 186.9	428.1 ± 184.5	<0.001	0.5
Left pulmonary artery	437.2 ± 197.8	434.1 ± 194.1	<0.001	0.7
Ventricle	442.0 ± 123.0	440.3 ± 122.2	<0.001	0.4
Noise, HU:				
Ascending aorta	31.3 ± 10.1	25.2 ± 8.1	<0.001	19.5
Descending aorta	31.4 ± 8.1	24.7 ± 6.6	<0.001	21.3
Main pulmonary artery	38.4 ± 38.8	32.8 ± 39.1	<0.001	14.6
Right pulmonary artery	39.1 ± 58.4	33.5 ± 60.0	<0.001	14.3
Left pulmonary artery	36.7 ± 48.8	30.7 ± 49.4	<0.001	16.3
Ventricle	32.8 ± 9.1	26.4 ± 7.7	<0.001	19.5
SNR:				
Ascending aorta	15.2 ± 4.4	18.9 ± 5.5	<0.001	24.3
Descending aorta	15.2 ± 4.9	19.4 ± 6.5	<0.001	27.6
Main pulmonary artery	13.7 ± 5.3	17.0 ± 7.0	<0.001	24
Right pulmonary artery	13.9 ± 5.2	17.4 ± 6.8	<0.001	25.2
Left pulmonary artery	14.3 ± 5.3	18.2 ± 7.2	<0.001	27.2
Ventricle	13.9 ± 3.7	17.2 ± 4.7	<0.001	23.7

SNR, signal-to-noise ratio; FBP, filtered back projection; SAFIRE, sinogram-affirmed iterative reconstruction,
[1]|FBP - SAFIRE| /FBP× 100%.

Table 4 The attenuation value, noise and SNR values in the 70 kVp and 80 kVp groups reconstructed by SAFIRE

	70 kVp (n = 147)	80 kVp (n = 140)	*p*-value
Attenuation, HU			
Ascending aorta	510.4 ± 131.7	394.2 ± 84.7	<0.001
Descending aorta	520.3 ± 143.7	396.9 ± 91.2	<0.001
Main pulmonary artery	468.5 ± 137.1	374.2 ± 126.0	<0.001
Right pulmonary artery	485.9 ± 208.8	367.5 ± 130.5	<0.001
Left pulmonary artery	487.0 ± 180.6	378.8 ± 193.1	<0.001
Ventricle	496.8 ± 127.5	381.0 ± 82.3	<0.001
Noise, HU:			
Ascending aorta	28.5 ± 7.5	21.9 ± 7.4	<0.001
Descending aorta	28.1 ± 6.4	21.2 ± 4.8	<0.001
Main pulmonary artery	34.3 ± 41.9	31.3 ± 36.2	0.535
Right pulmonary artery	37.0 ± 67.1	30.0 ± 51.6	0.32
Left pulmonary artery	32.9 ± 43.3	28.5 ± 55.2	0.449
Ventricle	30.5 ± 7.6	22.1 ± 5.1	<0.001
SNR:			
Ascending aorta	18.6 ± 5.3	19.3 ± 5.8	0.286
Descending aorta	19.2 ± 6.3	19.7 ± 6.6	0.518
Main pulmonary artery	17.3 ± 6.8	16.8 ± 7.4	0.588
Right pulmonary artery	17.4 ± 6.9	17.4 ± 6.8	0.961
Left pulmonary artery	18.3 ± 6.9	18.2 ± 7.6	0.869
Ventricle	16.8 ± 4.6	17.8 ± 4.7	0.062

Table 5 Radiation dose measurements

	Total (n = 287)	70 kVp (n = 147)	80 kVp (n = 140)	*p*-value
CTDI, mGy	0.84 ± 0.31	0.57 ± 0.15	1.13 ± 0.13	<0.001
DLP, mGy × cm	21.55 ± 9.98	13.81 ± 4.82	29.67 ± 7.12	<0.001
ED, mSv	1.48 ± 0.57	1.04 ± 0.31	1.94 ± 0.39	<0.001

CTDI, computed tomography dose index; DLP, dose-length product; ED, effective dose.

noise values in the 70 kVp group were also significantly higher except for the main, right and left pulmonary arteries. No significant differences in SNR were observed between the 2 groups (Table 4).

Estimation of radiation dose. The radiation dose for imaging at 70 kVp was significantly lower compared to that for imaging at 80 kVp ($p < 0.001$; Table 5). The effective radiation doses in the 70 kVp and 80 kVp groups were 1.04 ± 0.31 mSv and 1.94 ± 0.39 mSv, respectively.

Discussion

Cardiovascular CT is an important method for the evaluation of CHD, especially for ensuring accurate spatial resolution [12]. Because of its high temporal resolution, high-pitch spiral mode dual-source computed tomography (DSCT) is very useful for the accurate diagnosis of anomalies in infants and children with complex CHD [1]. However, the radiation exposure associated with cardiovascular CT is an issue, especially in children and neonates [13]. Decreasing the tube voltage is an effective method for reducing the radiation dose [14]. However, a reduction in the radiation dose leads to issues such as beam-hardening artifacts and image noise [15].

Although FBP is a simple and rapid reconstruction method for CT images, it tends to result in poor image quality at low radiation doses. In contrast, iterative reconstruction techniques can be used to improve the quality of low-dose CT images. Several types of iterative reconstruction algorithms have been reported [7, 16, 17]. In the present study, we compared cardiovascular CT images reconstructed using the SAFIRE and FBP algorithms, and the comparison revealed significant differences in the noise and SNR between the 2 methods. Reconstruction by SAFIRE resulted in a reduction in image noise and an increase in the SNR by approx. 20% and 25%, respectively, which demonstrates the usefulness of SAFIRE in clinical diagnoses. Despite a tendency similar to that observed in the present study, Zheng *et al.* [11] reported no significant differences between these 2 reconstruction methods. This discrepancy between the 2 studies is due to the larger sample size in the present study.

We observed significant differences in attenuation values between the images reconstructed by FBP and those reconstructed by SAFIRE at all regions except the ascending aorta. This is due to the low-pass filter used for image noise reduction in iterative reconstruction. However, the filter use appeared to have no effect on diagnosis, because the differences in attenuation were slight and not apparent to the naked eye.

In our patient series, the mean body weights in the 70 kVp and 80 kVp groups were 6.5 kg and 9.2 kg, respectively. The CARE kV system automatically determines the optimal tube voltage and current according to the radiolucency of the scout view. Although the tube voltage is not determined solely by the patient's body weight, the present data might serve as a guide for determining the optimal tube voltage.

Although the mean ED for image acquisition at 70 kVp (1.04 mSv) was significantly lower compared to that at 80 kVp (1.94 mSv), the images acquired at 70 kVp did not appear to be inferior compared to those acquired at 80 kVp upon visual inspection. Moreover, no significant differences in the SNR were observed between the 2 groups.

Rompel *et al.* [18] assessed the image quality and radiation dose in second and third-generation DSCT and evaluated the effects of advanced modeled iterative reconstruction (ADMIRE: Siemens Healthcare), a new iterative reconstruction technique. They examined 42 children and reported mean effective radiation doses of 0.36 mSv and 0.62 mSv for imaging at 70 kVp and 80 kVp, respectively. These values are higher compared to those obtained in the present study, which might be because the Rompel study's subjects were younger (< 3 years old) compared to those of our study. Moreover, ADMIRE might be a more effective algorithm than

SAFIRE for reducing the radiation dose.

There are some limitations to our study, with the first being its retrospective nature. Second, all our subjects presented with CHD, which includes several types of diseases; this variety makes it challenging to investigate the same disease in a large number of children. Third, ECG-gated CT examinations were included. However, we feel that the nonECG-gated CT images were equivalent to the ECG-gated CT images because of the high heart rate of children and the high temporal resolution of high-pitch spiral CT.

In conclusion, DSCT images acquired at low kV using the SAFIRE algorithm exhibited low noise and a high SNR, and the radiation doses for image acquisition were relatively low. This method might be effective in children with CHD who must undergo repetitive CT examinations.

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