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Effect of low tube voltage and low iodine concentration abdominal CT on image quality and radiation dose in children: preliminary study

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Abstract

Purpose To evaluate the image quality of a double-low protocol (low tube voltage and low iodine concentration) for abdominal CT in children.

Materials and methods The double-low protocol was compared to the conventional protocol in pediatric patients weighing less than 40 kg from May 2016 to December 2016. Double-low protocol (Group A, $n=18$): tube voltage, 70 kVp; and iodine concentration,: 250 mgI/mL versus Conventional protocol (Group B, $n=13$): tube voltage, 80–100 kVp; and iodine concentration, 350 mgI/mL. Mean attenuation, noise, signal-to-noise ratio (SNR), and contrast-to-noise ratio (CNR) were compared between the two groups. Image contrast, noise, beam-hardening artifacts, and overall image quality were subjectively scored. Reader performance for correctly differentiating two groups by visual assessment was evaluated. Radiation dose and total iodine load were recorded.

Results The mean attenuations of the portal vein and liver and the mean image noise in Group A were higher than in Group B ($p=0.04$, 0.03, 0.004, respectively). The mean SNR and CNR of the main portal vein and liver were lower in Group A without any statistically significant difference. There were no statistically significant differences between the two groups in qualitative analysis (image contrast, image noise, and overall image quality) with substantial agreement between the reviewers (weighted kappa values; 0.59–0.76). Significantly diminished radiation dose and iodine load were observed in Group A compared with Group B (25.0%, 36.8% reduction; $p=0.007$, 0.006, respectively).

Conclusion The double-low protocol was feasible for pediatric abdominal CT and reduced both radiation dose and iodine load, while maintaining image quality.

Keywords Children · Computed tomography · Low tube voltage · Iodine concentration · Dose reduction

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Introduction

With the increasing usage of computed tomography (CT) imaging with pediatric patients, interest in radiation dose reduction is also increasing [1, 2]. Nowadays, the "as low as reasonably achievable" ALARA concept and the *Image Gently* campaign are widely accepted for dose reduction in pediatric patients [2, 3]. Some scan parameters of CT have a direct influence on radiation dose, such as beam energy (kVp), tube current (mA), rotation time, section thickness, pitch, and dose reduction techniques. Radiation dose is approximately proportional to the square of the percentage change in kVp [2, 3]. Decreasing kVp reduces radiation dose and increases the attenuation of iodinated contrast media (CM) [3–5]. The adverse effects of intravenous, iodinated CM are divided into physiologic and allergic-like reactions,

with their severity divided into mild, moderate, and severe. Increasing concentration of iodine and the volume of CM can increase the risk of physiologic reactions [5–7]. Several studies have suggested that reducing the dose of CM could be a prevention strategy for the adverse effects of CM [8–10]. Considering the advantages of lower kVp and lower burden of CM, it seems ideal to use lower kVp with lower volume or lower concentration CM in CT scanning. However, lowering kVp without increasing mAs may increase image noise and artifacts. As CT technology advances, it has become possible to apply iterative reconstructions (IR) that overcome image noise associated with low tube voltage compared to filtered back projection [11, 12].

Recently, a "double-low" protocol for CT combining the low tube voltage and lower CM burden (lower volume of CM or lower concentration of CM) has found numerous applications in clinical practice [13]. Although it is mainly applied to pulmonary and coronary CT angiography, several studies have also described its application to liver CT in adults [13]. A tube voltage of 70 kVp has been recently applied to clinical practice, with promising results regarding radiation dose reduction for pediatric CT. [14, 15]. Since 80–100 kVp, which is low kVp applied to adults, has already been applied to pediatric CT, we hypothesized that a double-low protocol using 70 kVp could be applied to pediatric abdominal CT. To our knowledge, this study is the first to apply 70 kVp and low-concentration CM in pediatric abdominal CT. The purpose of this study was to evaluate the image quality of a low tube voltage and low iodine concentration protocol for abdominal CT in children weighing less than 40 kg.

Materials and methods

This study was approved by the institutional review board of our institution.

Patients

We retrospectively reviewed the clinical data and imaging findings of pediatric patients weighing less than 40 kg who underwent abdomino-pelvic computed tomography (A-P CT) for various indications between May 2016 and December 2016 in our institution. Inclusion criteria were abdominal and pelvic CT scans of patients weighing less than 40 kg which were performed in our institution during the study periods. Exclusion criteria were the following: (1) motion or respiration artifacts that interfered with image analysis; (2) arm down artifacts which can affect qualitative image analysis. The routine protocol of pediatric A-P CT of our institution includes only portal venous phase images. Since September 2016, our institution has adopted a double-low protocol (low tube voltage; 70 kVp) with lower concentration of CM (250 mgI/mL) for pediatric A-P CT. The patients who underwent A-P CT scans with the double-low protocol from September to November 2016 were classified as Group A. The patients who underwent conventional A-P CT scans in our institution from May to August 2016 were included as a control group (Group B).

CT protocols

All patients underwent A-P CT using a 128-channel MDCT (SOMATOM Definition Flash, Siemens AG, Forchheim, Germany). All CT scans were reconstructed using a sinogram-affirmed iterative reconstruction (SAFIRE, Siemens Healthcare, Forchheim, Germany) algorithm with a medium-sooth convolution kernel (I30f), medium strength of level 3.

Patients were sedated with an oral sedative (chloral hydrate). Iodinated CM was injected using a power injector (Envision CT; Medrad, Pittsburgh, PA) in the amount of 1.7 mL/kg, followed by normal saline flush for 30 s, with an injection rate of 3.0–4.0 mL/s. Portal venous phase scan was initiated 90 s after the start of contrast medium injection. The total amount of CM was determined according to the child's body weight, and thus the amount of contrast medium varied.

The protocol used for Group A consisted of fixed tube potential of 70 kVp; reference tube current of 700 mAs; iodinated CM at a concentration of 250 mgI/mL (Iopamidol, Pamiray 250; Dongkook Pharmaceutical, Seoul, Korea). The standard protocol, using the automatic tube voltage selection and automatic tube current modulation, was as follows: reference tube voltage of 80–100 kV, reference tube current of 150 mAs, and iodinated CM at a concentration of 350 mgI/mL (Iobitridol, Xenetix 350; Guerbet, Aulnay-sous-Bois, France). The other CT scan parameters are noted in Table 1.

Radiation dose and iodine uptake

The CT dose index volume ($CTDI_{vol}$, mGy) and dose-length products (DLPs, mGy.cm) were recorded for each CT scan. The effective dose (ED, mSv) was calculated by the following equation: $ED = DLP \times K$ (tissue-weighting factors for abdomen; variable according to kVP and age [16]). Since the tissue-weighting factors of 70 kVp are not known, the tissue-weighting factors of 80 kVp were used for the 70 kVp applied group. The amount of total iodine intake in each patient was calculated using the following equation: body weight (kg) × 1.7 mL/kg × iodine concentration (mgI/mL; 250 for Group A, 350 for Group B).

Table 1 CT scanning parameters and contrast medium of each protocol

CT parameters	Double-low protocol	Standard protocol
Contrast medium	Iopamidol 250 mgI/mL	Iobitridol 350 mgI/mL
Tube voltage (kVp)	70	80–100
Reference tube current–time product (mAs)	700	150
Table pitch (s)	0.6	1.5
Detector configuration	128 × 0.6 mm	
Gantry rotation time (s)	0.28	
Slice thickness/interval (mm)	3/2	
Scan timing	Portal phase (90 s after initiation of contrast medium administration)	
Reconstruction kernel	SAFIRE, medium-smooth convolution kernel (I30f), medium strength of level 3	

Quantitative image analysis

Quantitative analysis of axial portal venous phase images was performed by a board-certified radiologist (S.K.Y with 8 years of experience) who was blinded to the clinical findings and the CT parameters. CT images were displayed at a Picture Archiving and Communication System workstation with soft tissue window settings (width, 400 HU; level, 20 HU). The mean CT attenuation of the portal vein, liver parenchyma, paraspinal muscle, and subcutaneous fat of the anterior abdominal wall were measured by manually placing the round regions of interest (ROI) in each organ (Fig. 1) [17]. All measurements were performed at the main portal vein level. The ROI was drawn as large as possible within the main portal vein. The size of the ROI varied and depended on the size of the main portal vein (mean 11.2 ± 5.9, range 3.4–26.7 mm^2). The size and shape of each ROI were maintained constant as far as possible in one patient. The attenuation of the portal vein was obtained at the main portal vein with a single ROI. The attenuation of the liver was recorded as the mean of the four ROIs derived from the anterior and posterior segments of the right lobe and the medial and lateral segments of the left lobe of the liver, taking care to avoid the inhomogeneous area and vessels. The attenuation of the paraspinal muscle was recorded as the mean of the ROIs measured on both sides, taking care to avoid the fat and blood vessels. The standard deviation of the subcutaneous fat in the anterior abdominal wall (SDn) was used as image noise. The contrast-to-noise ratio (CNR) and the signal-to-noise ratio (SNR) were calculated using the following equations: CNR = (ROIo–ROIm)/SDn; ROIo = attenuation of the organ, ROIm = attenuation of the paraspinal muscle, SNR = ROIo/SDn.

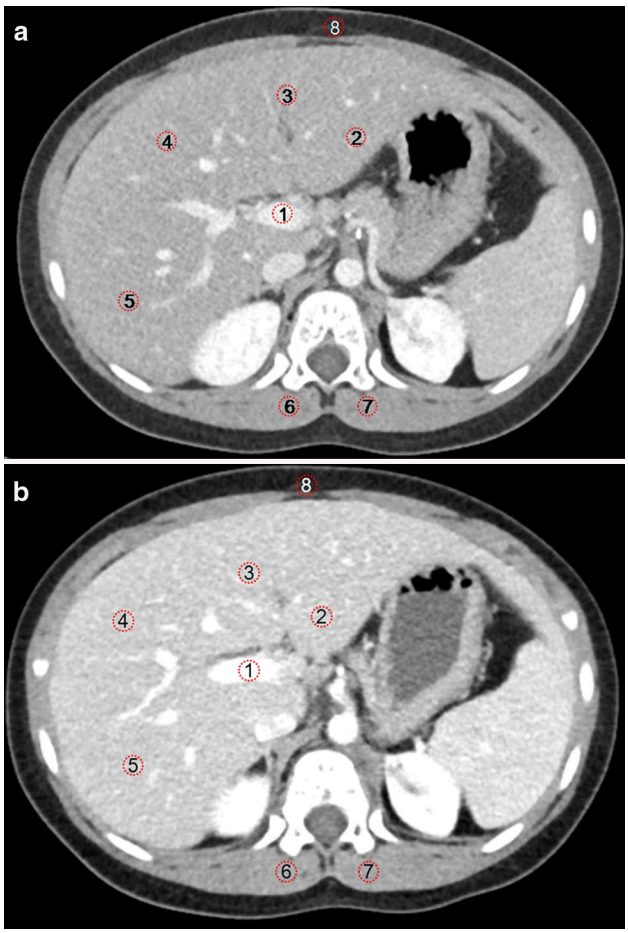

Fig. 1 Axial contrast-enhanced portal phase computed tomography (CT) images obtained at different times through different protocols in the same patient (8-year-old girl who underwent a serial follow-up CT after resection of a neuroblastoma). **a** Standard protocol (80 kVP, 350 mgI/mL) and **b** double-low protocol (70 kVP, 250 mgI/mL) 3 months later show manually drawn regions of interest (ROIs) on the main portal vein (ROI 1), liver (ROIs 2–5), paraspinal muscles (ROIs 6–7), and subcutaneous fat of the anterior abdominal wall (ROI 8)

Qualitative image analysis

CT images were reviewed independently by two board-certified pediatric radiologists (Y.H.C and S.K.Y. with 13

and 8 years of experience, respectively) who were blinded to the clinical findings and the CT parameters. The readers graded image contrast, image noise, and overall image quality, using a 5-point scoring system for qualitative comparisons. Before starting a subjective analysis, the scale of assessment for each item of the qualitative analysis was defined by consensus between the two reviewers.

Enhancement of organs such as the liver, spleen, and pancreas was scored on a 5-point scale (score 1, very poor; 2, suboptimal; 3, acceptable; 4, above average; and 5, excellent). Enhancement of vessels, especially of the main portal vein, was scored on a 5-point scale (score 1, very poor; 2, suboptimal; 3, acceptable; 4, above average; and 5, excellent). Graininess in the image, which represented image noise, was scored on a 5-point scale (score 1, unacceptable noise; 2, above-average noise; 3, average noise on an acceptable image; 4, less-than-average noise; 5, minimum or no image noise). Overall image quality was evaluated on a 5-point scale (score 1, unacceptable diagnostic image quality; 2, sub-diagnostic; 3, average; 4, better than average; 5, excellent). The CT scans included in this study were performed for various indications. Because most scans were acquired for follow up after underlying disease treatment, it is difficult to evaluate directly lesion's conspicuity or diagnostic accuracy. Therefore, we decided to evaluate "reader performance" by assessing whether the reviewers correctly distinguished between group A and group B by visual evaluation. To evaluate reader performance, i.e., correctly differentiating the two groups by visual assessment, the two readers reviewed the CT images in random order and subjectively determined which protocol had been used.

Statistical analysis

Data were analyzed using IBM SPSS Statistics for Windows (Version 21.0., IBM Corp., Armonk, NY). A p value of < 0.05 was considered to be statistically significant. The mean and standard deviation were calculated for quantitative data. The Mann–Whitney U test was used to compare quantitative data: quantitative image analysis, radiation dose, and iodine uptake calculation between Groups A and B. Sex ratios were compared using Pearson Chi-squared test. The Mann–Whitney U test was used to compare qualitative image analysis scores between Groups A and B. Cohen's kappa statistics were used to assess the degree of interobserver agreement for qualitative analysis using MedCalc (version 17.2, Mariakerke, Belgium). The weighted kappa value was interpreted as follows: 0.81–1.00, excellent agreement; 0.61–0.80, substantial agreement; 0.41–0.60, moderate agreement; 0.21–0.40, fair agreement; < 0.20, poor agreement.

Results

Patients

The characteristics of the patients are presented in Table 2. There were no significant differences in sex, age, weight, height, and BMI between Groups A and B. Patients usually underwent CT for follow-up after treatment of underlying disease, including neuroblastoma ($n=9$), ganglioneuroblastoma ($n=3$), lymphoma ($n=5$), leukemia ($n=3$), sarcoma ($n=8$), Wilms tumor ($n=3$), other various intra-abdominal tumor ($n=6$), aganglionosis ($n=2$), postoperative complication evaluation ($n=2$), colitis($n=2$), acute pancreatitis ($n=1$) meckel's diverticulitis ($n=1$), systemic lupus erythematosus ($n=1$), chronic granulomatous disease ($n=1$), ventriculoperitoneal shunt ($n=1$), and azotemia ($n=1$).

Radiation dose and iodine uptake

Radiation dose reduction was estimated by mean $CTDI_{vol}$, mean DLP, and mean ED. The mean $CTDI_{vol}$, DLP, and ED of Group A were statistically lower than that of Group B, respectively (Table 3) The mean $CTDI_{vol}$, DLP, and ED of Group A were reduced by 25.0, 29.8, and 29.4%, respectively, compared to group B. There was no significant difference in volume of CM between the two groups (Group A vs. B; 32.6 ± 13.8 mL vs. 36.4 ± 19.9 mL, $p=0.44$). The mean iodine intake of Group A was statistically significantly lower than that of Group B ($p=0.006$). Compared with group B, the iodine intake of Group A was decreased by 36.8%.

Quantitative image analysis

The CT number, image noise, SNR, and CNR for the two groups are summarized in Table 4. The CT number of liver in Group A were higher than in Group B ($p=0.02$). The mean image noise of Group A was higher than that of Group B, and the difference was not significant ($p=0.42$). The mean SNR and CNR of the main portal vein and liver in Group A were higher than in Group B, and the difference was not significant (all $p > 0.05$).

Table 2 The characteristics of the patients in the two groups

	Group A ($n=24$)	Group B ($n=25$)	p
Sex (M/F)	12/12	18/7	0.11
Age (years)	5.7 ± 3.6	5.4 ± 3.2	0.72
Weight (kg)	18.2 ± 8.5	20.6 ± 11.5	0.41
Height (cm)	104.3 ± 23.8	107.8 ± 22.8	0.59
BMI (kg/m^2)	15.9 ± 2.0	16.5 ± 2.3	0.32

BMI, body mass index

Table 3 Radiation dose and iodine intake in the two groups

	Group A	Group B	Reduction (%)	*p*
$CTDI_{vol}$ (mGy)	1.2 ± 0.3	1.6 ± 0.5	25.0	0.007
DLP (mGycm)	43.7 ± 20.1	62.3 ± 30.2	29.8	0.015
ED (mSv)	1.2 ± 0.4	1.7 ± 0.4	29.4	< 0.001
Iodine intake (mg I)	7757.1 ± 3636.8	12280.8 ± 6843.6	36.8	0.006

Table 4 Results of the quantitative analysis

	Group A	Group B	*p*
CT number (mean ± SD)			
Portal vein	229.8 ± 57.4	219.7 ± 38.1	0.46
Liver	144.7 ± 22.3	131.4 ± 18.8	0.02
Paraspinal muscle	75.6 ± 16.6	75.0 ± 6.0	0.86
Image noise	9.3 ± 3.0	8.6 ± 2.6	0.42
SNR (mean ± SD)			
Portal vein	27.7 ± 12.1	27.7 ± 9.1	0.99
Liver	17.6 ± 7.7	16.4 ± 4.5	0.50
Paraspinal muscle	9.5 ± 5.8	9.4 ± 2.7	0.92
CNR (mean ± SD)			
Portal vein	18.4 ± 7.7	18.3 ± 7.0	0.96
Liver	8.0 ± 3.7	6.9 ± 2.4	0.23

Table 5 Results of the qualitative image analysis

	Group A	Group B	*p* Value	*k* Value
Enhancement of vessel				
Reader 1	3.6 ± 0.5	3.7 ± 0.3	0.67	0.76
Reader 2	3.5 ± 0.5	3.8 ± 0.3	0.23	
Enhancement of organ				
Reader 1	3.5 ± 0.5	3.7 ± 0.4	0.38	0.75
Reader 2	3.6 ± 0.5	3.6 ± 0.4	0.91	
Image noise				
Reader 1	3.3 ± 0.5	3.6 ± 0.4	0.30	0.59
Reader 2	3.6 ± 0.5	3.5 ± 0.5	0.67	
Overall image quality				
Reader 1	3.5 ± 0.5	3.8 ± 0.5	0.30	0.61
Reader 2	3.5 ± 0.5	3.6 ± 0.4	0.57	

Qualitative analysis

The results of qualitative analysis by the two readers are presented in Table 5. Image contrast (enhancement of vessels and organs), image noise, and overall image quality were not significantly different between the two groups (all $p > 0.05$). The interobserver agreement was substantial; weighted kappa values ranged from 0.59 to 0.76. Sensitivity and specificity for correct differentiation between the two groups by visual assessment of reader 1 were 38.8% and 46.1% and of reader 2 were 33.3% and 61.5%. Overall

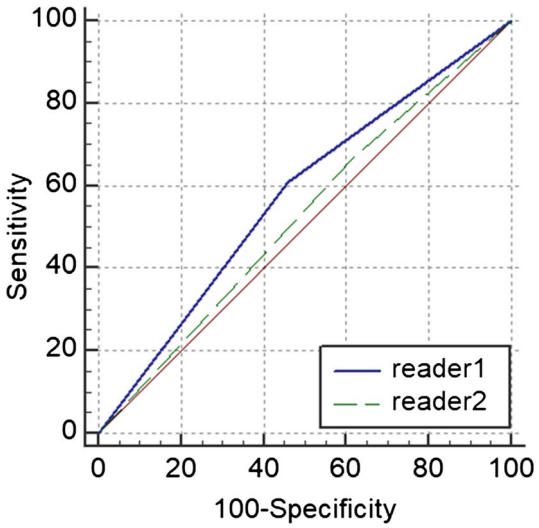

Fig. 2 Comparison of receiver operating characteristic curves for evaluating reader performance in differentiating the two groups by visual assessment

sensitivity and specificity of reader performance were 36.1% and 53.8%, respectively. The areas under the curve (AUC) of two readers were 0.5 (95% confidence interval, 0.38–0.75 and 0.33–0.70, respectively). Compared to the receiver operating characteristic curve, the AUCs of readers 1 and 2 did not show any statistically significant difference (Fig. 2, $p = 0.6$).

Discussion

In this study, the double-low abdominal CT protocol using 70 kVp and iodinated CM at a concentration of 250 mgI/mL reduced both radiation dose and iodine load in children weighing less than 40 kg, while maintaining image quality, with a 25.0% reduction in radiation dose and a 36.8% reduction in iodine load, compared to a control group that underwent CT with the standard protocol. The results of our study are similar to those of previous studies with adult patients [18–21]. There have been several studies [18–20] using a double-low protocol (combined low tube voltage (80–100 kVp) with less iodine burden) for adult patients. These studies showed that combination of double-low protocol with iterative reconstruction (e.g.,

adaptive statistical iterative reconstruction, hybrid IR) can reduced radiation dose (by approximately 28.8–50%) and iodine load (by approximately 20–40%) without degradation of image quality compared to a control group using 120 kVp. Various IR techniques are used in different scanners [22, 23]. SAFIRE is an IR technique that we used for our patients. Several studies have shown that when we use IR (SAFIRE) for low-dose protocols, it can reduce the image noise and increase CNR [24, 25].

Nakaura et al. [26] reported that even when not using IR for low tube voltage scanning, it is possible to reduce the contrast dose up to 40% and radiation dose up to 20% without compromising image quality of multiphase hepatic dynamic CT in adults. They used high tube current–time product for low tube voltage scanning. Inspired by the above-cited study, we used the high tube current–time product (automatic tube current modulation program with upper limits 700 mA) for the double-low protocol. In our study, 70 kVp scanning successfully reduced the radiation dose without degradation of image quality, even though the automated tube voltage and current modulation program with SAFIRE had been already used for optimization of radiation dose for pediatric patients.

Moreover, there were no significant differences in the results of the qualitative image analysis (image contrast, image noise, beam-hardening artifacts, and overall image quality) by the two readers. Besides, the two readers showed poor 'reader performance,' which suggests that they were unable to differentiate the two groups by visual assessment.

The CT numbers of the portal vein and liver in Group A (double-low protocol) were higher than those in Group B (standard protocol). This result was similar to those of other studies [18–21]. When we use low-concentration iodine CM, 70 kVp could generate a higher CT value than that could be generated with 80–100 kVp. Because the mean energy level of the X-ray at 70 kVp is closer to the K-edge of iodine (33 keV), the reduced voltage can improve attenuation of iodine compared to the standard protocol using 80–100 kVp [4, 5].

Automatic tube current modulation (or automatic exposure control), automated tube potential selection, and iterative reconstruction (IR) are representative radiation dose reduction tools in CT scanners [27]. Tube current is the most common CT scan parameter that is adjusted to reduce radiation dose. The tube current and the radiation dose have a linear relationship. Tube potential also has a direct effect on radiation dose, but it is more complicated than tube current. Kim et al. [11], in a previous study of pediatric abdominal CT, reported that using the automated tube voltage and current modulation program with IR (SAFIRE) can reduce the radiation dose while maintaining image quality, compared to using only the tube current modulation program without IR.

Recently, as it has become possible with some CT scanners that can use 70 kVp, a few studies using a double-low protocol applying 70 kVp have been reported in cardiac CT [15, 28], pulmonary CT angiography [29], and cerebral CT angiography [30]. A common conclusion in these studies was that the double-low protocol using 70 kVp combined with IR leads to reduction of radiation dose and the dose of CM, while maintaining image quality. In a pediatric study, Nakagawa et al. [15] compared a 70 kVp protocol (70 kVp and 225 mgI/mL CM) with an 80 kVp protocol (80 kVp and 300 mgI/mL CM) in cardiac CT angiography of infants with congenital heart disease, and they reported that the 70 kVp protocol with IR reduced the radiation dose and maintained image quality. To our knowledge, this is the first study to adopt 70 kVp with IR for abdominal CT.

According to the literature review, high dose CM in adults as well as in children is a risk factor for CIN in the risk group, and CM should be used at the lowest volume possible to prevent CIN [31–33]. According to the survey of Society of Chairs of Radiology in Children's Hospitals member institutions [34], the most commonly used concentration of CM for pediatric A-P CT was 300–320 mgI/mL. In our study, we used iodinated CM at a concentration of 250 mgI/mL for pediatric A-P CT. Low concentration CM can be used to reduce the amount of iodine. Hence, the double-low protocol could be an alternative scan protocol for the risk group without alteration of CM volume and injection rate, which can affect the degree or timing of enhancement of the aorta and liver. Conversely, Martin et al. [35] reported that there was no significant difference in the incidence of CIN in children between low-osmolar CM (iobitridol 300) and iso-osmolar (iodixanol 270) despite a higher iodine load in the iobitridol group. This could be due to the fact that scanning was performed only in children with normal kidney function.

Pamiray 250 and Xenetix 350 are both nonionic monomer type low-osmolar CM. Although the viscosity of CM is not proportional to the iodine concentration of CM, Pamiray 250 has lower osmolarity (515 mOsm/kg H_2O vs. 915 mOsm/kg H_2O) and lower viscosity (3.3 mPa.s vs. 10 mPa.s at 37 °C) than Xenetix 350. The lower osmolarity and viscosity of Pamiray 250 might have advantages in neonates and small children who are susceptible to intravascular osmotic loads and have small vessels using smaller gage angiocatheters. As the viscosity of CM increases, the pressure related to injection of CM also increases, which can lead to rupture or injure vessels.

There are some limitations in this study. First, the reference tube current of the double-low protocol was higher in group A than in group B (700 mAs vs. 150 mAs) to overcome the image noise, which can affect image quality and diagnostic accuracy. Nevertheless, the double-low protocol provides radiation dose reduction without scarifying image quality. We expect to proceed with studies on proper tube

current regulation of the double-low protocol. Second, only the feasibility of low tube voltage with low-concentration CM was evaluated rather than its diagnostic performance. Reducing the reference tube current with the double-low protocol and evaluating its diagnostic performance may be used in potential follow-up studies. Third, this study included only children weighing less than 40 kg. If studies with overweight children or adolescents are carried out, they could be applicable to adult patients with low body mass.

Conclusion

The double-low protocol using a low tube voltage (70 kVp) and a low iodine concentration (250 mgI/mL) in abdominal CT was feasible for a pediatric population and reduced both radiation dose and iodine load, while maintaining image quality.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This study was approved by the institutional review board of our institution and was waived the requirement for informed consent.

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