



Optimizing image quality and minimizing radiation dose in pediatric abdominal multiphase contrast-enhanced computed tomography: a study on CARE kV and CARE Dose 4D

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Background: Multiphase contrast-enhanced computed tomography (CECT) is a commonly used modality in pediatric computed tomography (CT) scans. However, the purposes and focus of each phase, such as CT angiography (CTA), and parenchymal phase, are different. In routine practice, the same scanning parameters are used for all phases, resulting in unnecessary radiation exposure for children. Accurately and rapidly adjusting the scanning parameters for each phase of CECT is challenging in clinical settings. This retrospective cross-sectional study was designed to investigate the feasibility of using both CARE kV and CARE Dose 4D to reduce the radiation dose while maintaining diagnostic quality in multiphase CECT scans of children.

Methods: Overall, 57 children (33 males and 24 females) who underwent multiphase abdominal CECT in Xinjiang Hospital of Beijing Children's Hospital with an average age of 6.52 ± 4.30 years (range, 0.1–15 years), were enrolled. The tube voltage was automatically modulated using CARE kV. The tube current was automatically modulated using CARE Dose 4D. Different dose saving optimization indices (DI) were used for the three phases: a DI value of 3 was used for the unenhanced CT phase, a DI value of 12 was used for the CTA phase, and a DI value of 7 was used for the parenchymal phase. The tube voltage and volume CT dose index ($CTDI_{vol}$) were recorded for each phase. Two reviewers subjectively evaluated the overall image quality and noise level of the three phases using a 5-point Likert scale (1–2 points: unqualified, 3 points: qualified, 4 points: better, 5 points: best). The CT and noise values of the descending aorta, liver, and back muscle were measured objectively. The voltage distribution and the image quality and $CTDI_{vol}$ in each phase were compared.

Results: The most selected tube voltage in the unenhanced CT, CTA, and parenchymal phases was 100 kV (49/57, 85.96%), 70 kV (36/57, 63.16%), and 80 kV (32/57, 56.14%), respectively. The differences between the three phases were statistically significant ($P < 0.001$). The $CTDI_{vol}$ values of the three phases were 3.99 ± 1.99 , 2.02 ± 1.71 , and 3.18 ± 2.10 mGy, respectively, with a significant difference between the three phases ($P < 0.001$). The $CTDI_{vol}$ decreased linearly as the DI value increased. All images met the diagnostic

requirements. The overall quality scores for the three phases were 4.24 ± 0.42 , 4.41 ± 0.49 , and 4.50 ± 0.45 , respectively, with no significant linear relationship with the change in the DI.

Conclusions: The combined use of CARE Dose 4D and CARE kV could effectively reduce the radiation dose in children during multiphase abdominal CECT without compromising the diagnostic image quality.

Keywords: Multi-phase contrast-enhanced computed tomography (multi-phase contrast-enhanced CT); radiography; abdomen; pediatric; radiation dose

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Introduction

Computed tomography (CT) has become a widely used clinical examination method because of its fast-scanning speed and wide scanning field (1-3). However, in pediatric clinics, children's sensitivity to ionizing radiation is significantly higher than that of adults (4), making it important to follow the principle of as low as reasonably achievable (ALARA) when performing CT examinations (5). Recently, the use of CARE Dose 4D, iterative reconstruction, and various postprocessing technologies (6-9) has helped reduce the radiation dose during CT, particularly in children. For example, the use of 70-kV voltage has reduced the radiation dose by approximately 50% in CT angiography (CTA) examinations for children (10). The variable scanning parameters used in different phases of contrast-enhanced CT (CECT) in children are chosen based on the different requirements for image quality and image noise tolerance in each scan phase (11-13). CTA focuses on observing the vascular structure with high contrast, which can withstand more image noise and allow for low voltage and low radiation dose for scanning. Meanwhile, the parenchymal phase requires a higher radiation dose to ensure good image quality, which could distinguish structures. Using the same scanning parameters for each phase of multiphase CECT would inevitably increase the unnecessary radiation dose. Therefore, finding a way to quickly set the appropriate scanning parameters for different phases of pediatric abdominal CECT scans in order to reduce the radiation dose while maintaining image quality is an urgent problem to be solved in children's clinics.

CARE kV can select the optimal pre-examination voltage for patients based on their individual size, density, and clinical needs. When combined with CARE Dose 4D, it can adjust the current to reasonable levels based on the scout view, ultimately minimizing radiation exposure

and improving scan technique while preserving diagnostic accuracy. This is critical in safeguarding the health of pediatric patients (14-17). However, the application of CARE kV in pediatric care has not been extensively researched (10,18). Given that abdominal CECT is an important tool for assessing tumors and other diseases, particularly in children (19), and that it is performed frequently, optimizing the application of CARE kV can increase its clinical utilization in pediatric multiphase abdominal CECT.

CARE kV and CARE Dose 4D can be used separately to adjust scanning voltage (14-18) and reduce radiation dose (6-10), which has been confirmed in multiple previous studies. However, there is an expectation whether the combined implementation of CARE kV and CARE Dose 4D may yield improved outcomes in clinical practice. Therefore, this study aimed to investigate the impact of the conjoined application of CARE kV and CARE Dose 4D on voltage selection, image quality, and radiation dose in pediatric patients who are subjected to abdominal CECT, incorporating the three stages of unenhanced CT, CTA, and parenchymal CT with different dose saving optimization index (DI) value. Furthermore, the objective is to assess the practicability of utilizing CARE kV in pediatric patients undergoing abdominal CECT and to optimize the selection of scanning parameters for the purpose of achieving an optimal balance between radiation dose and image quality. We present this article in accordance with the STROBE reporting checklist (available at <https://qims.amegroups.com/article/view/10.21037/qims-23-1181/rc>).

Methods

General information

This retrospective cross-sectional study was conducted in

accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Ethics Committee of Beijing Children's Hospital (No. 2022-E-164-Y). The study protocols were performed following the approved guidelines and regulations of our hospital and informed consent forms were signed by the parents of pediatric patients. Fifty-seven children who underwent multiphase abdominal CECT were retrospectively and continuously enrolled from June 1, 2022 to August 3, 2022. The inclusion criteria were as follows: (I) patients underwent multiphase abdominal CECT from June 1, 2022 to August 3, 2022; (II) patients were under 18 years of age. The exclusion criteria were as follows: clinical documents or imaging data were not completed.

CT imaging methodology

All data were acquired using a 64-row CT detector (SOMATOM Definition Edge VA48A, Siemens Healthcare, Forchheim, Germany). CARE kV was used to automatically adjust the scanning voltage, with a basic reference tube voltage of 120 kV and an adjustment range of 70–120 kV. CARE Dose 4D was used to automatically adjust the scanning current, with a basic reference tube current of 110 mAs and an adjustment range of 28–270 mAs. All examinations were performed in three scanning phases: unenhanced CT, CTA, and parenchymal. Each phase used a different DI for CARE kV to adjust the scanning voltage (13,16). Based on previous studies (13,16), the DI value was 3, 12, and 7 for the unenhanced scan phase, CTA phase, and parenchymal phase, respectively. Regarding the image reconstruction, a 3-mm-thick iterative reconstruction (sinogram affirmed iterative reconstruction, level 3) image was used. After acquiring the unenhanced CT images, an iodinated contrast medium (320 mgI/mL iodixanol) was administered using a high-pressure injector (Accutron CT-D, Medtron, Germany). The contrast medium dosage was calculated based on the body weight of each child (400–600 mgI/kg). The flow rate was adjusted based on a fixed injection time of 18 s, and the contrast-enhanced scan started 20 s after the administration of contrast injection for the CTA and 60 s after the administration of contrast injection for the parenchymal phase, during the CECT examination, no adverse events occurred due to the injection of contrast medium. During the scan, the children were positioned supine with their arms raised above their heads and allowed to breathe freely without holding their breath. If the children could not cooperate, oral sedatives were administered to keep them still during the scan.

Qualitative image quality evaluation

All images were transferred to the imaging workstation (Multi-Modality Workplace; Siemens Healthcare) and anonymized to conceal all patient and scanning data. One radiologist with 12 years of experience (9 years of adult radiology experience and 3 years of pediatric radiology experience) and another with 16 years of pediatric radiology work experience independently conducted subjective scoring. The default reconstruction window width of all images was set to 400, with a window level of 40. However, the window width and level were adjusted according to the radiologists' requirements. Furthermore, the multiplanar reconstruction tool provided by the workstation was used to examine the images.

In terms of qualitative image quality, according to similar study (13), we used a 5-point Likert scale for two evaluations: (I) overall image quality and (II) subjective image noise. The evaluation criteria for the overall image quality were as follows: very good (5 points), good but with slightly unclear tissue edges (4 points), sufficient for diagnosis despite slightly fuzzy tissue edges (3 points), unable to diagnose because of indistinct tissue edges (2 points), and tissue edges completely indistinguishable (1 point). The criteria for the image noise were as follows: rare noise in the image (5 points), low amount of noise in the image (4 points), moderate noise that does not hinder diagnosis (3 points), excessive noise that impedes diagnosis (2 points), and severe noise that prevents structure identification (1 point).

Quantitative image quality measurement

Following the qualitative image evaluation, the two radiologists quantitatively evaluated the image and measured the image noise. The layer of the liver hilum was selected for the measurement image, and a circular region of interest (ROI) was selected, which comprised approximately 1/4 of the area of the descending aorta at the same level. The three ROIs were placed in the center of the descending aorta, the uniform part of the right lobe of the liver, and the uniform part of the right vertical spine muscle individually; thereafter, the CT value and standard deviation were measured. The standard deviation was used to represent the objective noise of the tissue. Furthermore, we measured three ROIs on the adjacent upper and lower slices simultaneously, and the average value of the three slices was recorded.

Table 1 Patient characteristics

Characteristics	Values
Male:female, n	33:24
Ages (years), mean \pm SD (range)	6.52 \pm 4.30 (0.1–15.0)
Body weight (kg), mean \pm SD (range)	23.13 \pm 11.81 (4.0–59.0)
Body height (cm), mean \pm SD (range)	115.6 \pm 30.04 (53.0–162.0)
Body mass index (kg/m ²), mean \pm SD (range)	16.10 \pm 2.50 (9.7–26.2)
Neuroblastoma	5
Wilm's tumour	4
Hepatoblastoma	4
Lymphoma	4
Angio lymphoma	1
Malformation of urinary	24
Abdominal pain	15

SD, standard deviation.

Radiation dose

The volume CT dose index (CTDI_{vol}) and the dose length product (DLP) were recorded for the three scan phases. The effective dose (ED) was calculated using the following formula: ED = k \times DLP, where k is the conversion factor. According to the ICRP103 recommendation (20), the k range for children depends on the scanning voltage and their age and falls between 0.0246 and 0.0935.

Statistical analysis

The subjective score and objective noise measurement values were expressed as mean \pm standard deviation. For normally distributed data, analysis of variance was used for comparison between groups, followed by the Bonferroni correction test to determine differences. The data that did not follow a normal distribution were compared using the Friedman test. The kappa test was used to determine the consistency of the subjective scores of the two radiologists. All statistical analyses were performed using SPSS (version 17.0; IBM Corp., Armonk, NY, USA), and differences with $P < 0.05$ (two-sided) were considered statistically significant.

Results

Patient characteristics

A total of 57 children (33 males and 24 females) with an average age of 6.52 \pm 4.30 years (age range, 0.1–15 years), and body mass index of 16.10 \pm 2.50 kg/m² were selected retrospectively and continuously from June 1, 2022 to August 3, 2022. Among them, 17 cases were suspected of tumor lesions, 1 case of lymphangioma, 24 cases were suspected of urinary system abnormalities, and 15 cases of abdominal pain (Table 1).

Voltage distribution results and radiation dose

Voltage distribution results showed that the most selected voltage mode was 100, 70, and 80 kV in unenhanced CT, CTA, and the parenchymal phase, respectively (Table 2). There were significant statistical variances observed in the voltage selection across different phases (Friedman =85.31; $P < 0.001$). Statistics showed that CTDI_{vol} decreased by 49.37% and 20.30%; DLP decreased by 56.21% and 22.70%; and ED decreased by 65.80% and 37.66% when DI =12 and DI =7, respectively, compared with those when DI =3. The decrease in CTDI_{vol}, DLP, and ED with the increase in the DI index was statistically significant (Table 3, Figure 1).

Image quality evaluation

Table 4 shows the qualitative and quantitative results of image quality. The results indicated that all images met the diagnostic requirements through qualitative evaluation. The overall quality score for CTA (DI =12) was the highest and that for unenhanced CT (DI =3) was the lowest. No significant correlation was observed between the quality score and DI value (Figure 2). The image noise score for CTA was the lowest (3.35 \pm 0.49) and that for unenhanced CT was the highest (3.93 \pm 0.39). The image noise score decreased with an increase in the DI value; the kappa value of the two observers was 0.83 ($P < 0.001$). The overall qualitative image score in CTA was the highest at 4.50 \pm 0.45, indicating that arteries, especially small arterial blood vessels, can be displayed better, a good image quality was guaranteed while reducing the radiation dose (Figure 3).

Table 2 Changes in voltage selection under different dose optimization indices of CARE kV

Tube voltage (kV)	Unenhanced CT (DI =3)	CTA (DI =12)	Parenchymal phase (DI =7)	F value	P value
70	0 (0.00)	36 (63.16)	2 (3.51)	85.31	<0.001
80	4 (7.02)	14 (24.56)	32 (56.14)		
100	49 (85.96)	5 (8.77)	19 (33.33)		
120	4 (7.02)	2 (3.51)	4 (7.02)		

Data are presented as n (%). CT, computer tomography; DI, dose saving optimization index; CTA, CT angiography.

Table 3 Changes in radiation dose for different dose optimization indices after the combined use of CARE Dose 4D and CARE kV

Radiation dose	Unenhanced CT (DI =3)	CTA (DI =12)	Parenchymal phase (DI =7)	F value	P value
CTDI _{vol} (mGy)	3.99±1.99 [†]	2.02±1.71 ^{†§}	3.18±2.10 [§]	14.93	<0.001
DLP (mGy·cm)	164.14±90.05 ^{†‡}	65.31±56.87 ^{†§}	115.29±92.25 ^{†§}	19.34	<0.001
ED (mSv)	4.62±3.31	1.58±1.08	2.88±1.56	12.35	<0.001

Data are presented as mean ± SD. [†], there was a statistical difference between unenhanced CT and CTA; [‡], there was a statistical difference between unenhanced CT and parenchymal phase; [§], there was a statistical difference between CTA and parenchymal phase. CT, computer tomography; DI, dose saving optimization index; CTA, CT angiography; CTDI_{vol}, volume CT dose index; DLP, the dose length product; ED, effective dose; SD, standard deviation.

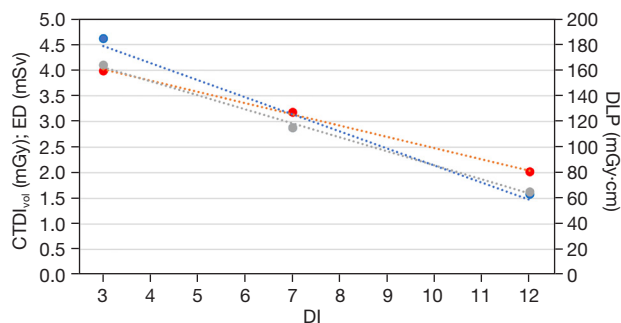


Figure 1 Changes in radiation dose of the CTDI_{vol} (red dot), the DLP (blue dot) and the ED (gray dot) at different DI values. Dotted lines are fitting lines. CTDI_{vol}, volume CT dose index; CT, computer tomography; ED, effective dose; DLP, dose length product; DI, dose saving optimization index.

The objective noise for unenhanced CT (DI =3) was the lowest and that for CTA (DI =12) was the highest, with a statistical difference (P=0.010). The image noise for CTA (DI =12) was 57.72–73.73% higher than that for unenhanced CT (DI =3) and that for the parenchymal phase (DI =7) was 14.57–21.39% higher than that for unenhanced CT. The noise value increased with an increase in the DI value of all tissues (Figure 4).

Discussion

Current research has emphasized a critical problem: how to reduce the radiation dose in children during CT. Reducing unnecessary scans or scanning procedures is the most effective measure (14). During the necessary scan procedure, the radiation dose could be reduced through automatic tube current modulation and iterative reconstruction technologies (21). Automatic tube current modulation technologies, such as CARE Dose 4D, can dynamically adjust the current intensity on the z-axis according to the size of the child to reduce the radiation dose compared with that during fixed-current CT. Combined with the iterative reconstruction algorithm, it can reduce the radiation dose, ensure or improve the image quality, and meet the diagnostic requirements (14,21,22).

Children's bodies are small and suitable for low-voltage scanning. A previous phantom experiment (22) highlighted that a small body size can avoid the hardening artifacts produced by low-voltage scanning and can benefit from the effects of low voltage to enhance the CT value of the contrast medium in order to increase the contrast-noise ratio of enhanced CT images and improve image quality (23,24). To observe the density and enhancement degree of different tissues, CECT examination generally requires

Table 4 Differences in image quality of different dose optimization indices after the combined use of CARE Dose 4D and CARE kV

Image quality	Unenhanced CT (DI =3)	CTA (DI =12)	Parenchymal phase (DI =7)	F value	P value
Overall image quality	4.24±0.42 [†]	4.50±0.45 [†]	4.41±0.49	27.78	0.010
Subjective image noise	3.93±0.39 [†]	3.35±0.49 [§]	3.81±0.42 [§]	5.09	<0.001
SD of aorta	5.75±1.53 ^{†‡}	9.99±7.69 [§]	6.98±1.99 [§]	27.98	<0.001
SD of liver	5.18±1.38 ^{†‡}	8.17±2.21 [§]	6.13±1.68 [§]	41.65	<0.001
SD of muscle	4.94±1.07 ^{†‡}	7.93±1.72 [§]	5.66±1.71 [§]	59.09	<0.001

Data are presented as mean ± SD. [†], there was a statistical difference between unenhanced CT and CTA; [‡], there was a statistical difference between unenhanced CT and parenchymal phase; [§], there was a statistical difference between CTA and parenchymal phase. CT, computer tomography; DI, dose saving optimization index; CTA, CT angiography; SD, standard deviation.

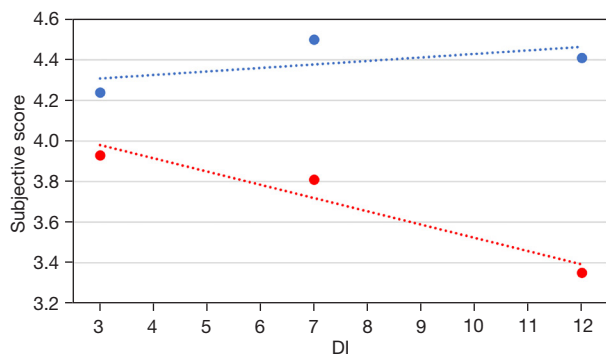


Figure 2 The subjective noise score (red dot) and the subjective score of the overall image quality (blue dot) change with the DI values. The dotted line is a fitting line, and the noise score decreases with an increase in DI. The overall image quality score does not significantly change under different DI values. DI, dose saving optimization index.

the unenhanced CT, CTA, and parenchymal phases. Unenhanced CT is used to observe high-density areas, such as those with bleeding, calcification or urinary stone (25), and to determine the scanning range for the subsequent phases. However, the density difference of each tissue in unenhanced CT is small, requiring a higher radiation dose to reduce image noise and maintain the contrast-noise ratio that meets the diagnostic requirements. CTA is mainly used to observe arteries and is suitable for using low-voltage scanning protocols to improve the CT value of the iodine contrast medium and increase the image contrast. In cases of high contrast, it can tolerate higher image noise to ensure the contrast-noise ratio of arteries. In the parenchymal phase, the contrast medium can also be used to increase the tissue contrast to determine the region of lesions. Because the contrast degree is lower than that in

CTA, the radiation dose should be higher than that in CTA; however, the required radiation dose is lower than that in unenhanced CT. Therefore, the voltage and radiation dose during contrast-enhanced scanning in children are different. To reduce the radiation dose more accurately, the scanning parameters should be set for each scanning phase.

In this study, each child was scanned in three phases and different DI values were used. Because the same scout view was used in all three phases, the changes in the voltage and radiation dose in the three phases were mainly affected by DI. The results showed that the DI value of unenhanced CT was 3, which was the lowest value in this study, furthermore, 100 kV was selected as the tube voltage in 85.96% of the cases (49/57), and the radiation dose was the highest in this phase. The CTDI_{vol} reached 3.99±1.99 mGy, and the obtained image had the lowest noise (5.75±1.53). The DI value of CTA was 12, which was the highest value among the three phases. Moreover, 70 kV was selected as the tube voltage in 63.16% of the cases (36/57), whereas 70 or 80 kV was selected as the tube voltage in 87.72% of the cases (50/57). The lower voltage ensures the contrast degree of the arteries. Although the radiation dose was significantly reduced (to only 50.63% of unenhanced CT) and the image noise increased to the highest value (9.99±7.69), the lower scan voltage improves the contrast of the arteries and ensures good image quality. However, if the DI value is set to 12 in other scanning phases, it will inevitably superimpose a high level of image noise on the image, which reduces the contrast, and the subjective score may be less than 3 points, making the image difficult to diagnose. Therefore, in the phase beyond CTA, excessive DI values should be employed with caution. In the parenchymal phase, DI was 7, and the radiation dose was 20.30% lower than that in unenhanced CT. Although the subjective and objective noise values were slightly higher than those in

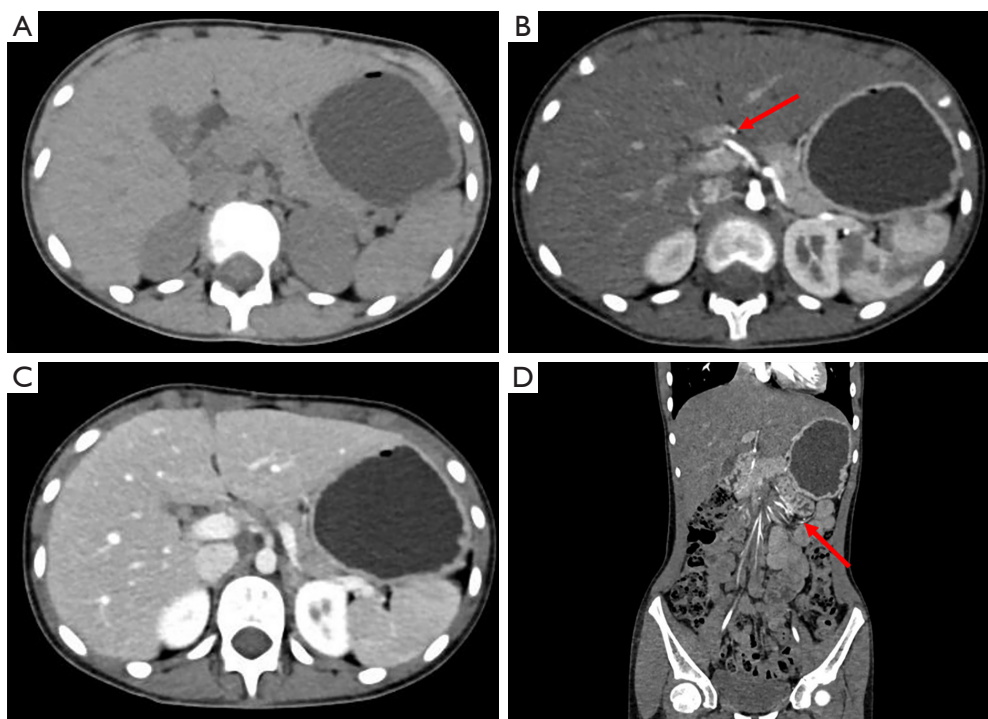


Figure 3 An 11-year-old girl presented with the complaint of abdominal pain since a month. (A) The unenhanced CT phase; DI is set to 3, tube voltage is automatic modulation to 100 kV, and $CTDI_{vol}$ is 3.72 mGy. (B) A CTA image; DI is set to 12, tube voltage is 70 kV, and $CTDI_{vol}$ is 1.39 mGy. (C) The parenchymal phase; DI is 7, tube voltage is 80 kV, and $CTDI_{vol}$ is 2.85 mGy. (D) A multiplanar reformation or reconstruction image of the CTA. The image noise in unenhanced CT is the lowest, and the image noise in CTA is the highest. Because the low voltage of 70 kV improves the contrast of iodine, small blood vessels can still be clearly displayed (as shown by the red arrows in B,D), meeting the diagnostic requirements. The radiation dose in the parenchymal phase is lower than that in the unenhanced CT phase; however, because 80 kV enhances iodine, the structure is clearly and adequately displayed, reducing the impact of high image noise on diagnosis. CT, computer tomography; DI, dose saving optimization index; $CTDI_{vol}$, volume CT dose index; CTA, CT angiography.

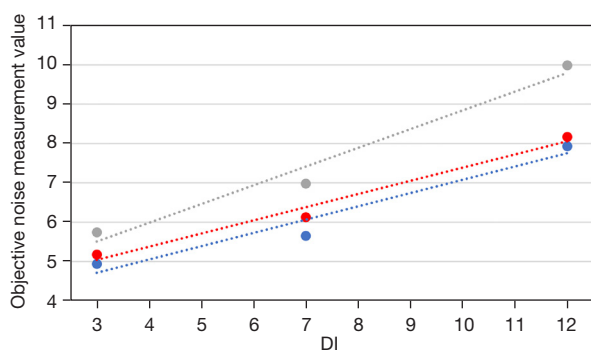


Figure 4 The change in the objective noise measurement value of the image with the DI values. The noise values of the aorta (gray), liver (red), and muscle (blue) increase with an increase in DI. The dotted line is the fitting line. DI, dose saving optimization index.

the unenhanced CT phase, in 89.47% of the cases (51/57), 80 or 100 kV was chosen, which was lower than that in the unenhanced CT phase. Thus, the contrast of the enhanced image was also improved, making the boundaries of the parenchymal organs clearer, and the subjective score remained higher than that in the unenhanced CT phase.

This study has some limitations. First, the sample size was small, the effect of diseases on the image quality was not considered in this experiment, such as severe artery stenosis, which may cause difficulties in diagnosis under low dose scan, on the other hand, the patients' age was not covering the newborn and not stratified, which will be included in a later experimental design. Second, using different scan tube voltage values will change the CT value

of tissues. Because of the variation in scanning voltage between CECT and unenhanced CT, the enhancement degree will be determined differently. However, given that the difference is mainly caused by the iodine ions in CECT, the effect is minor. Third, because the number of studies on children's CARE kV that can be used as references is limited (14,26), the DI setting, reference tube voltage, and reference tube current in this study may be unsuitable. In future research, a more detailed DI research protocol will be set up to determine the DI values, reference tube voltage, and reference tube current suitable for different scanning phases. Finally, we did not evaluate the potential impact of iterative reconstruction on image quality. In subsequent studies, we should select sinogram affirmed iterative reconstruction with different intensities (grade 1–5) and observe the effect difference.

Conclusions

The combination of CARE kV and CARE Dose 4D can reduce the radiation dose and scan voltage by properly adjusting the DI values of multiphase CECT while meeting the diagnostic requirements.

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Footnote

Reporting Checklist: The authors have completed the STROBE reporting checklist. Available at <https://qims.amegroups.com/article/view/10.21037/qims-23-1181/rc>

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at <https://qims.amegroups.com/article/view/10.21037/qims-23-1181/coif>). The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are

appropriately investigated and resolved. The study was conducted in accordance with the Declaration of Helsinki (as revised in 2013). The study was approved by the Ethics Committee of Beijing Children's Hospital (No. 2022-E-164-Y). Informed consent forms were signed by the parents of pediatric patients.

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