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*Original Article*

# Photon-Counting Detector CT: Potential for 75% Reduction in Contrast Medium Amount: A Phantom Study

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**This study aimed to evaluate the potential reduction in contrast medium utilization using photon-counting detector computed tomography (PCD-CT). One PCD-CT scan (CT1) and three conventional (non-PCD-CT) CT scans (CT2-CT4) were performed using a multi-energy CT phantom that contained eight rods with different iodine concentrations (0.2, 0.5, 1, 2, 5, 10, 15, and 20 mg/ml). The CT values of the seven groups (CT1 for 40, 50, 60, and 70 keV; and CT2-4) were measured. Noise and contrast-to-noise ratio (CNR) were assessed for the eight rods at various iodine concentrations. CT2 and CT1 (40 keV) respectively required 20 mg/ml and 5 mg/ml of iodine, indicating that a comparable contrast effect could be obtained with approximately one-fourth of the contrast medium amount. The standard deviation values increased at lower energy levels irrespective of the iodine concentration. The CNR exhibited a decreasing trend with lower iodine concentrations, while it remained relatively stable across all iodine levels (40-70 keV). This study demonstrated that virtual monochromatic 40 keV images offer a similar contrast effect with a reduced contrast medium amount when compared to conventional CT systems at 120 kV.**

**Key words:** photon-counting detector CT, energy integrating detector CT, computed tomography, contrast medium amount, reduction

Although computed tomography (CT) is extensively used in clinical settings and provides diagnostic benefits, it has two major disadvantages: radiation exposure and the need for an iodine contrast medium [1].

Recent advancements in CT technology, such as software enhancements like the iterative reconstruction method and hardware improvements like dual-energy CT, have made it possible to decrease radiation exposure and contrast medium usage [2]. The photon-counting detector CT (PCD-CT), a novel CT technology based on a different principle from that of conventional CT, has become available in clinical settings. PCD-CT measures the energy carried by each incident X-ray photon and the total number of photons. Therefore, multiple energies can be measured simultaneously, thus allowing for the continuous collection of spectral data. This, in turn, would make it possible to further reduce the amount of contrast medium and radiation exposure.

Although several factors influence the contrast effect

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in CT images [3], we focused on the relationship between iodine concentration and tube voltage. We hypothesized that by adjusting these two factors in PCD-CT, we could quantitatively verify the relationship between voltage and contrast (the CT value of iodine) and determine the actual changes in CT values at different voltage levels in PCD-CT, thereby elucidating the theoretical percentage reduction of the contrast agent while ensuring sufficient diagnostic contrast in PCD-CT. This is because PCD-CT can generate virtual monochromatic images at lower energy levels at any time, which increases the contrast effect. However, research on reducing contrast medium usage with PCD-CT compared to conventional CT systems has been limited. Thus, this study aimed to evaluate the potential to reduce contrast medium usage with PCD-CT.

## Materials and Methods

***CT.*** This study was performed at our institution using PCD-CT (CT1) (NAEOTOM Alpha, Siemens Healthineers, Forchheim, Germany) and three conventional CT scans (CT2-CT4): CT2 (Aquilion Precision, Canon Medical Systems, Otawara, Japan), CT3 (Aquilion ONE Vision, Canon Medical Systems), and CT4 (Discovery CT 750HD, GE Healthcare, Chicago, IL, USA).

***Phantom experiment.*** Eight rods with different iodine levels (0.2, 0.5, 1, 2, 5, 10, 15, and 20 mg/ml) were inserted into a multi-energy CT phantom (Sun Nuclear Corporation, Melbourne, FL, USA) (Fig. 1A, B). The CT values of the eight rods were then measured using CT1-4. Imaging was performed 10 times by each CT system. For CT1, images with virtual monochromatic tube voltages of 40, 50, 60, and 70 keV were also obtained. The imaging conditions for CT1-4 are listed in Table 1. The slice thickness of CT4 differed from that of CT1-3 owing to equipment limitations. In CT2-4, the tube voltage was set to 120 kV because the monochromatic X-ray energy equivalent to 120 kV was approximately 65 or 70 keV [4].

Seven groups were evaluated: CT1 at 40, 50, 60, and 70 keV; and CT2-4.

The measurements were independently conducted by each of our co-authors using a console. The region of interest (ROI) for the measurements was 2 cm in diameter.

We also simultaneously assessed the noise level at

Table 1 Summary of imaging conditions of computed tomography scans CT1-4

| | CT1 | CT2 | CT3 | CT4 |
|---|---|---|---|---|
| Tube voltage | 140 kV | 120 kV | 120 kV | 120 kV |
| Tube current | 129 mAs | 205 mAs | 125 mAs | 365 mAs |
| CTDI vol | 14.8 mGy | 14.8 mGy | 15.1 mGy | 14.8 mGy |
| Rotation time | 0.5 s | 0.5 s | 0.5 s | 0.5 s |
| Slice thickness | 2.0 mm | 2.0 mm | 2.0 mm | 2.5 mm |

CT1 (NAEOTOM Alpha; Siemens Healthineers), CT2 (Aquilion Precision; Canon Medical Systems), CT3 (Aquilion ONE Vision; Canon Medical Systems), and CT4 (Discovery CT 750HD, GE Healthcare).

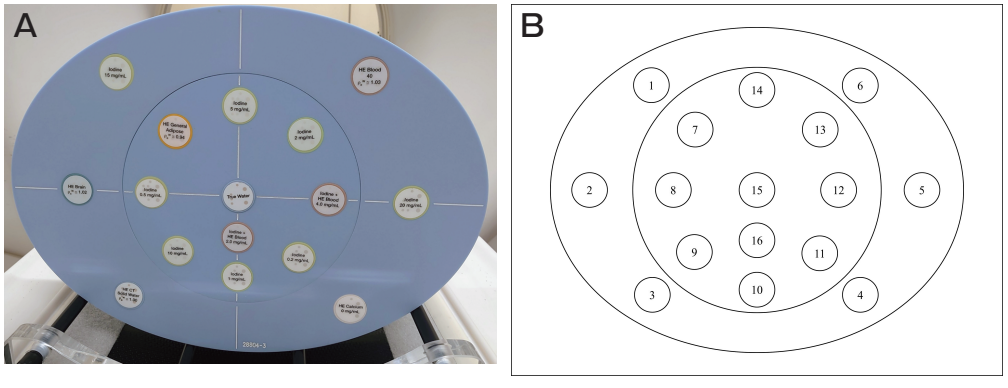


Fig. 1 Image (A) and layout (B) of the multi-energy CT phantom. The study included various substances and materials, such as: (1) iodine 15 mg/ml, (2) high-equivalency (HE) brain, (3) HE CT solid water, (4) calcium, (5) iodine 20 mg/ml, (6) HE blood, (7) HE general adipose, (8) iodine 0.5 mg/ml, (9) iodine 10 mg/ml, (10) iodine 1 mg/ml, (11) iodine 0.2 mg/ml, (12) iodine+HE blood, (13) iodine 2 mg/ml, (14) iodine 5 mg/ml, (15) true water, and (16) iodine+HE blood.

each CT measurement. We set up ROIs next to each phantom to obtain background CT values and standard deviation (SD) values. A total of 40 SD values were obtained at each iodine level. Thus, 320 SD values were obtained for CT1 at 40 keV for the eight iodine concentrations.

CNR, calculated as ROI phantom−ROI background/SD background, was also obtained to evaluate noise.

***Statistical analysis.*** Scatter plots of CT values as a function of iodine concentration and their fitted regression lines were constructed for all of the imaging conditions studied.

We examined whether the slope of the approximate line for CT1 at 40 keV differed significantly from the slopes of the approximate lines for the other conditions. In the linear regression analysis, CT values were used as the response variable, while iodine concentration, imaging conditions, and their interaction terms served as explanatory variables.

The regression coefficient equaled the slope of the interaction term, indicating that the statistically significant interaction terms were equivalent and the slopes of the two imaging conditions differed significantly.

Given that six comparisons were performed, a $p$-value of less than 0.0083 (derived by dividing 0.05 by 6) was considered statistically significant to account for the multiple tests conducted.

## Results

The relationship between the energy level and CT values at each rod (0.2, 0.5, 1, 2, 5, 10, 15, and 20 mg/ml) of the CT phantom in the PCD-CT (CT1) is shown in Fig. 2. The figure indicates that low-energy settings resulted in higher CT values (in Hounsfield units (HU)) at each iodine concentration.

A total of 40 CT values were obtained for each iodine level (imaging was performed 10 times and measured by each of our co-authors), thus yielding 320 CT values for CT1 at 40 keV for the eight different iodine concentrations. The average CT values for iodine levels of 1, 5, and 20 mg/ml at CT1-4 are shown in Table 2.

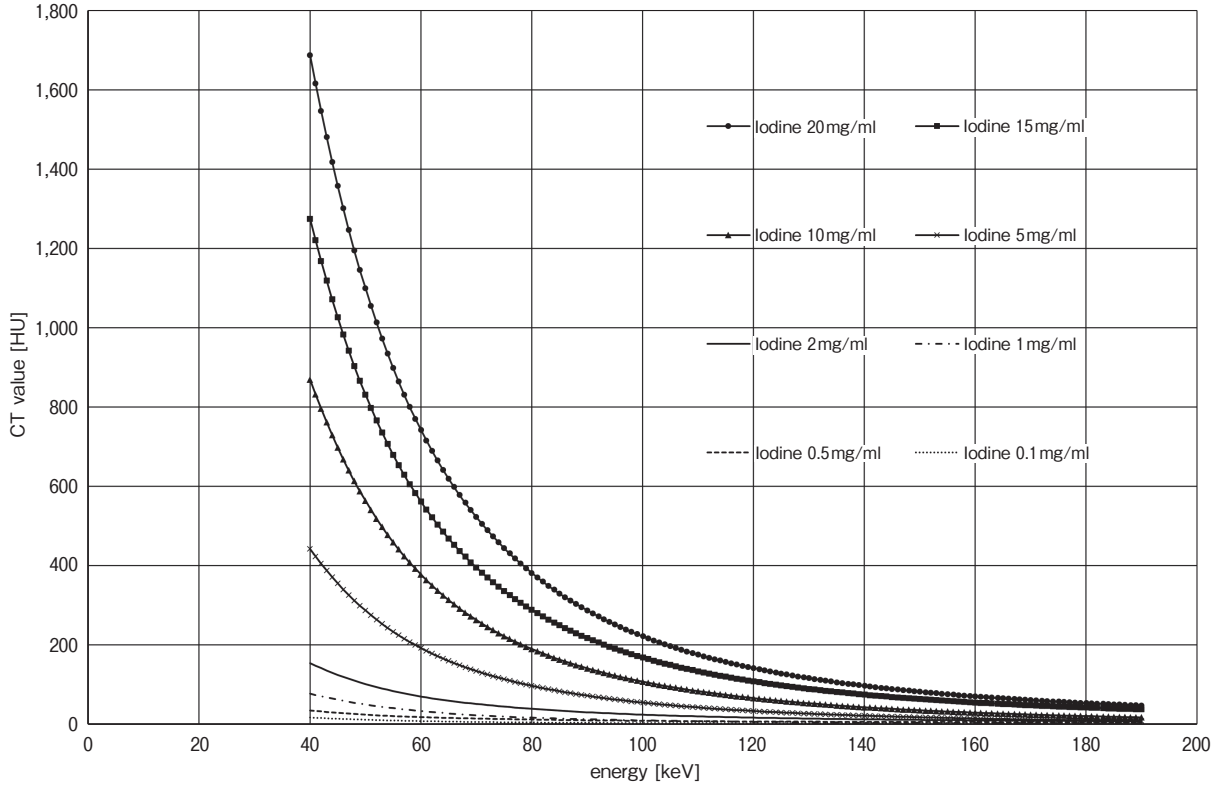


**Fig. 2** Relationship between the energy level and computed tomography (CT) values at each rod. The graphs demonstrate that lower energy levels result in higher CT values (in Hounsfield units (HU)) at each iodine concentration.

Average CT values for the eight different iodine levels were used to create the approximate straight lines (iodine concentration vs. CT value) in Fig. 3. Seven groups of straight lines were generated, including CT1 at 40, 50, 60, and 70 keV, as well as CT2-4:

CT1 (40 keV), $y = 84.973 \times -0.6946$
CT1 (50 keV), $y = 55.35 \times -0.5876$
CT1 (60 keV), $y = 37.342 \times -0.5536$
CT1 (70 keV), $y = 26.237 \times -0.4438$
CT2, $y = 19.617 \times -0.6472$
CT3, $y = 21.267 \times +5.2804$
CT4, $y = 21.336 \times +5.1756$.

Based on the lowest graph slope of CT2, the slope ratio of CT1 for 40 keV is four times stronger.

As presented in Table 3, CT1 at 40 keV exhibited a significantly steeper slope compared with all other conditions ($p < 0.001$ for all comparisons).

To achieve a contrast effect with a CT value of 400 HU, CT2 requires an iodine concentration of approximately 20 mg/ml, whereas the reconstruction of CT1 images (40 keV) requires < 5 mg/ml of iodine. This indicates that a comparable contrast effect can be obtained with approximately one-fourth the amount of contrast agent. The slope of the approximate straight line suggests that CT1 images (70 keV) may reduce the iodine dose by 19-26% compared with other CT systems, as the conventional CT's 120 kV is considered equivalent to virtual monochromatic X-rays at 70 keV [4].

Table 4 and Fig. 4 display the average SD values (HU) of CT1 (40, 50, 60, and 70 keV). The SD values increased at lower energy levels, irrespective of the iodine concentration.

Table 5 and Fig. 5 display the CNR of CT1 (40, 50, 60, and 70 keV). The CNR tended to decrease at lower

Table 2 Average CT values for 1 mg/ml, 5 mg/ml, and 20 mg/ml of iodine in CT1-4

| | Iodine | | |
|---|---|---|---|
| | 1 mg/ml | 5 mg/ml | 20 mg/ml |
| CT1 40 keV | | | |
| Average CT value (HU) | 78.9 | 442.0 | 1,690.0 |
| SD | 3.39 | 3.28 | 5.49 |
| 95%CI | 77.8–79.9 | 441.0–443.0 | 1,680.0–1,690.0 |
| CT1 50 keV | | | |
| Average CT value (HU) | 50.9 | 287.0 | 1,100.0 |
| SD | 2.14 | 2.05 | 3.68 |
| 95%CI | 50.2–51.6 | 286.0–287.0 | 1,100.0–1,100.0 |
| CT1 60 keV | | | |
| Average CT value (HU) | 33.7 | 192.0 | 742.0 |
| SD | 1.32 | 1.26 | 2.50 |
| 95%CI | 33.3–34.1 | 192.0–192.0 | 741.0–743.0 |
| CT1 70 keV | | | |
| Average CT value (HU) | 23.0 | 134.0 | 522.0 |
| SD | 0.62 | 0.74 | 1.53 |
| 95%CI | 22.8–23.2 | 134.0–134.0 | 521.0–522.0 |
| CT2 | | | |
| Average CT value (HU) | 17.0 | 101.0 | 387.0 |
| SD | 1.37 | 1.21 | 1.22 |
| 95%CI | 16.6–17.5 | 101.0–102.0 | 386.0–387.0 |
| CT3 | | | |
| Average CT value (HU) | 24.5 | 118.0 | 426.0 |
| SD | 1.45 | 1.59 | 2.23 |
| 95%CI | 24.1–25.0 | 117.0–118.0 | 425.0–426.0 |
| CT4 | | | |
| Average CT value (HU) | 25.2 | 114.0 | 425.0 |
| SD | 0.88 | 0.99 | 5.12 |
| 95%CI | 24.9–25.5 | 114.0–115.0 | 423.0–426.0 |

SD, standard deviation; CI, confidence intervals; HU, Hounsfield units.

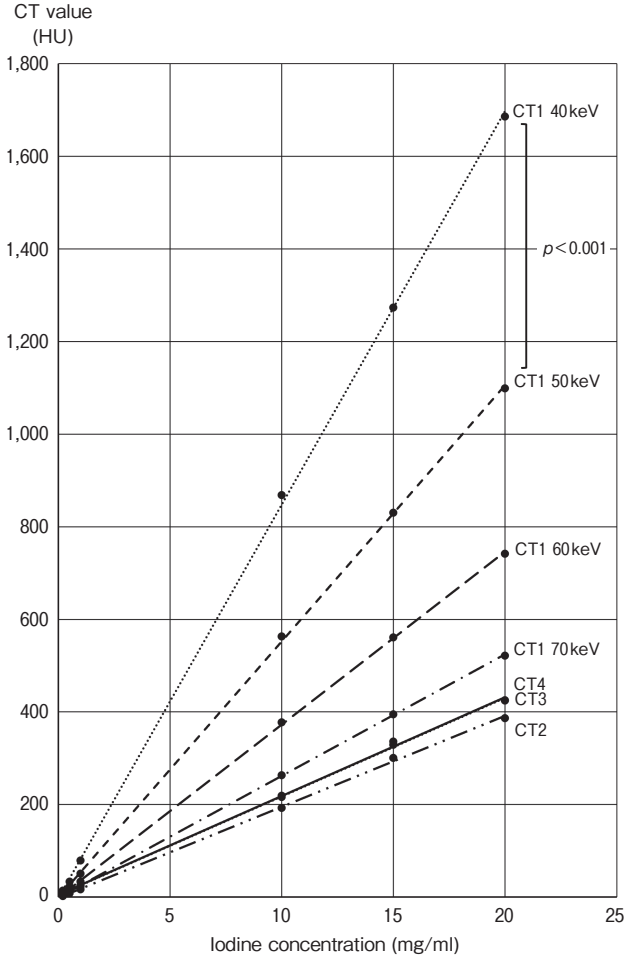


**Fig. 3** Relationship between iodine concentration and CT values (HU) for each CT system of CT1 (40, 50, 60, and 70 keV) and CT2-4. The graphs show an approximately straight line for the relationship between iodine concentration and CT values (HU) for each CT system, including CT1 (40, 50, 60, and 70 keV) and CT2-4. To obtain a contrast effect with a CT value of 400 HU, CT2 requires an iodine concentration that is approximately equal to 20 mg/ml, while CT1 40 keV image requires <5 mg/ml. This indicates that a comparable contrast effect can be achieved with approximately one-fourth the amount of contrast agent (CT1 (NAEOTOM Alpha; Siemens Healthineers), CT2 (Aquilion Precision; Canon Medical Systems), CT3 (Aquilion ONE Vision; Canon Medical Systems), and CT4 (Discovery CT 750HD, GE Healthcare)).

iodine concentrations but remained relatively stable across almost all iodine levels (40-70 keV).

## Discussion

This study demonstrated that the virtual monochromatic CT images (40 keV) provided a comparable contrast effect with only one-fourth of the amount of contrast medium used in a conventional CT system at 120 kV. The availability of iterative reconstruction methods and dual-energy CT has led to various efforts to reduce the use of contrast medium [5]. PCD-CT (*i.e.*, multi-energy CT) can advance these efforts.

Contrast-induced nephropathy (CIN) is an acute kidney injury manifested by a greater than 0.5 mg/dl (or 25%) increase in serum creatinine within 72 h after intravascular administration of contrast medium [6]. Weisbord *et al.* reported that the use of >100 ml of contrast medium was associated with an increased risk of CIN in 421 patients with chronic kidney disease (odds ratio 3.3, 95% CI 1.0-11.5) [7]. The ESUR guidelines recommend using the lowest contrast dose necessary for diagnosis in patients at risk of CIN, such as those with chronic kidney disease, diabetes mellitus, or advanced age, as well as those prescribed with nonsteroidal anti-inflammatory drugs [8, 9].

Contrast enhancement in CT images is influenced

**Table 3** Comparison of the coefficient of the interaction terms in CT1 (50 keV, 60 keV, and 70 keV) and CT2-4 with that of CT1 40 keV

| Comparison of coefficient of interaction terms | Coefficient of the interaction term = Slope difference | *P*-value |
|---|---|---|
| CT1 50 keV | 29.62 (27.96 to 31.29) | <0.001 |
| CT1 60 keV | 47.63 (46.11 to 49.15) | <0.001 |
| CT1 70 keV | 58.74 (57.26 to 60.21) | <0.001 |
| CT3 | 63.71 (62.19 to 65.22) | <0.001 |
| CT4 | 63.64 (62.07 to 65.21) | <0.001 |
| CT2 | 65.36 (63.83 to 66.88) | <0.001 |

**Table 4** Average SD values (noise) for 1 mg/ml, 5 mg/ml, and 20 mg/ml of iodine in CT1

| SD | Iodine | | |
|---|---|---|---|
| | 1 mg/ml | 5 mg/ml | 20 mg/ml |
| CT1 40 keV | | | |
| Average SD value (HU) | 91.9 | 91.6 | 81.6 |
| CT1 50 keV | | | |
| Average SD value (HU) | 60.3 | 60.0 | 53.5 |
| CT1 60 keV | | | |
| Average SD value (HU) | 41.0 | 40.8 | 36.5 |
| CT1 70 keV | | | |
| Average SD value (HU) | 28.7 | 29.0 | 25.6 |

SD, standard deviation; HU, Hounsfield units.

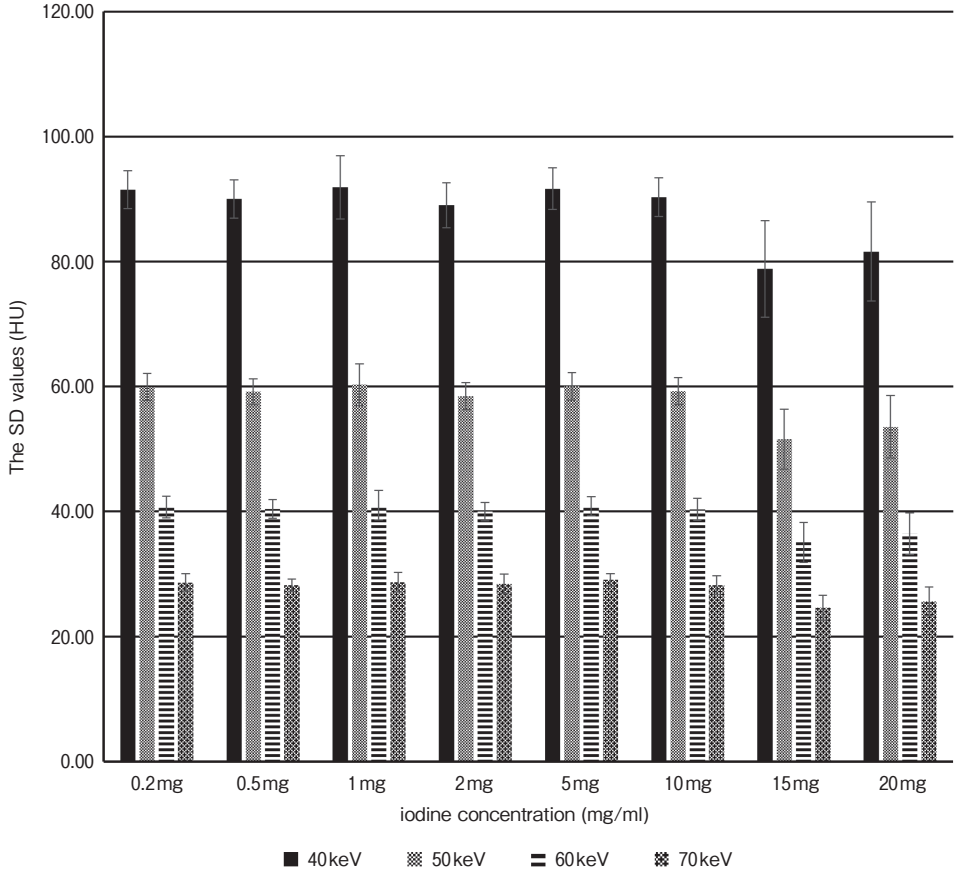


**Fig. 4** SD values (noise) from 40 keV to 70 keV for each studied iodine concentration in CT1. The SD values (noise) tended to increase at lower energy levels at each iodine level (SD, standard deviation).

**Table 5** CNR values for 1 mg/ml, 5 mg/ml, and 20 mg/ml of iodine in CT1

| CNR | Iodine | | |
|---|---|---|---|
| | 1 mg/ml | 5 mg/ml | 20 mg/ml |
| CT1 40 keV | 0.88 | 4.84 | 20.85 |
| CT1 50 keV | 0.89 | 4.82 | 20.71 |
| CT1 60 keV | 0.92 | 4.77 | 20.54 |
| CT1 70 keV | 0.96 | 4.72 | 20.59 |

CNR, contrast to noise ratio.

by various factors, such as contrast injection and scan parameters [3,10]. The contrast injection parameters include iodine dose, injection volume, injection rate, injection duration, and saline chaser. The scan parameter was the tube voltage (kV). Lower tube voltages are known to enhance the effect of iodine contrast medium; however, CT images obtained at low tube voltages have the disadvantage of reduced image quality (increased image noise and artifacts) owing to the insufficient number of X-rays necessary to produce the images [11]. Although the noise increased at lower tube voltages, the CNR exhibited only marginal changes in this study. This is attributed to the increase in contrast rather than an increase in noise. Thus, compared with energy integrating detector (EID)-CT, PCD-CT yields high-iodine contrast and high-CNR imaging outcomes by eliminating the effects of electrical noise from the measured data [12-14].

The widespread use of CT image reconstruction techniques such as iterative reconstruction (IR) are overcoming the disadvantages of low-voltage imaging. The use of IR in combination with low-tube-voltage imaging can reduce the image quality deterioration caused by the lack of X-rays [15].

Recently, some authors have reported the ability to

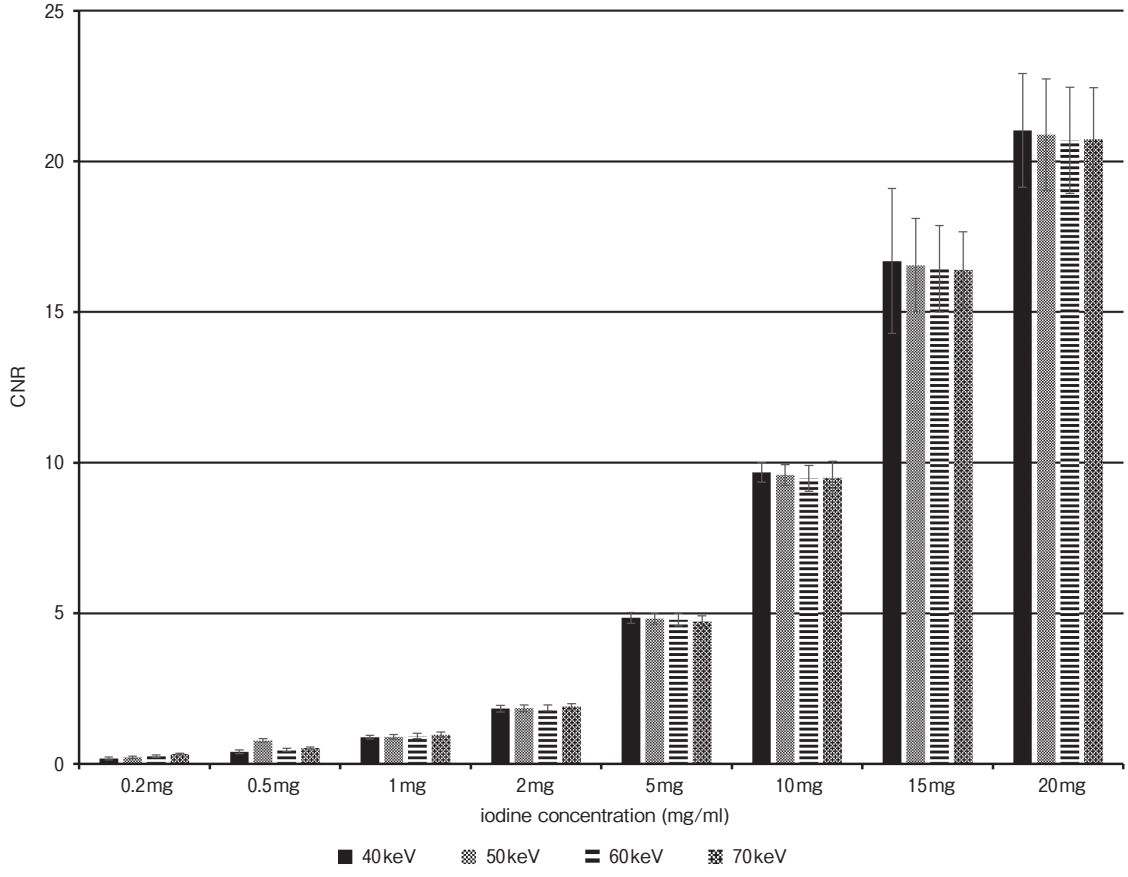


**Fig. 5** CNR values from 40 to 70 keV for all studied iodine concentrations in CT1. The CNR tended to decrease at lower iodine concentrations, but the CNR from 40 to 70 keV was almost the same at all iodine levels (CNR, contrast to noise ratio).

reduce contrast medium by using virtual monochromatic X-ray images with dual-energy CT [16]. These images were reconstructed based on dual-energy data and can represent any single-energy (effective energy, keV) CT image. In a study of 45 adults with renal dysfunction, Nagayama *et al.* reported a 50% reduction in contrast materials by using virtual monochromatic X-ray images (40-50 keV) without degradation of image quality [17]. It was reported that the use of 40 keV virtual monochromatic CT angiography (CTA) images generated similar enhancements in renal arteries to those recorded in conventional CTA with only 50% of the contrast dose [17]. Our PCD-CT results showed the potential for further reduction in the amount of contrast medium needed.

PCD-CT is a multi-energy technique, and any reduction in contrast can be easily counteracted by lowering the energy level in virtual monochromatic images. Unlike the case with conventional CT equipment, the tube voltage in PCD-CT can be changed to virtual monoenergetic after imaging, allowing for greater flexibility than with conventional equipment. Although the purpose of this study was to reduce the use of contrast medium, the marked improvement in the quality of CT images and the reduction in radiation exposure with PCD-CT would also be of great benefit to patients.

This experimental study was associated with some limitations. Considering that an excessive reduction in the volume of contrast medium may decrease diagnostic performance, further clinical evaluations on the effects of reducing contrast materials in PCD-CT are required. Another limitation is that the study was performed at a single center; future multicenter studies are required to validate the results.

In conclusion, this study demonstrated that virtual monochromatic 40 keV images provide a comparable

contrast effect with one-fourth of the amount of contrast medium used in conventional CT systems at 120 kV.

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