Low Dose and Low Contrast Medium Coronary CT Angiography Using Dual-Layer Spectral Detector CT
Low keV versus Low kVp

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Summary
The aim of the present study was to investigate the performance of low keV mono-energetic reconstructions in spectral coronary computed tomography angiography (CCTA) using spectral detector CT (SDCT) with reduced contrast media and radiation dose.

Sixty patients were randomly assigned to Groups A and B (both \( n = 30 \)) to undergo CCTA on a dual-layer SDCT with tube voltage 120 kVp and 100 kVp (average tube current: 108.5 and 73.8 mAs, respectively), with contrast media volume of 36 mL used in both groups. The mono-energetic 40-80 keV and conventional 120 kVp images in Group A and conventional 100 kVp images in Group B were reconstructed. Quantitative and qualitative image quality (IQ) were evaluated in the aortic root and distal segments of the coronary arteries.

The patient characteristics were not significantly different between the two groups (all \( P > 0.47 \)), nor was the effective radiation dose (1.5 ± 0.3 and 1.4 ± 0.3 mSv, \( P = 0.20 \)). The quantitative IQ in aorta and coronary arteries of mono-energetic 40-60 keV was superior to conventional 120 kVp and 100 kVp images (all \( P < 0.05 \)). The noise in spectral images was lower compared to conventional images (all \( P < 0.01 \)). The subjective IQ score of 40-50 keV images was not significantly different from that of 100 kVp images (\( P > 0.8 \)).

The mono-energetic 40-50 keV reconstructions from spectral CCTA using SDCT provide improved IQ compared to conventional techniques while facilitating reduced radiation dose and contrast media.

(Key words: Dual energy computed tomography, Mono-energetic reconstruction, Image quality, Spectral coronary CT angiography, Radiation dose)

Coronary CT angiography (CCTA) is the modality of choice for excluding coronary artery disease (CAD) in patients with low to intermediate risk. Nonetheless, one of the limitations is that CCTA using conventional single-energy can only provide morphological assessment.

Cardiac dual-energy CT (DECT) is becoming an active area of research for its potential to enable a 'one-stop' shop for anatomical and functional evaluation of CAD patients, because of improved tissue differentiation and reduction in artifacts. However, the radiation dose for CCTA using a traditional DECT is around 4-13 mSv, which continues to be cause of concern for its use in cardiac applications. Traditional DECT, using two polychromatic tube energy settings, (i.e. high and low peak tube voltage, such as 140/80 kVp) may inherently impose a higher radiation dose requirement than a typical low kVp scanning technique.

The newly introduced dual-layer spectral detector CT (SDCT) allows us to simultaneously acquire energy-sensitive projection data (using 120 kVp or 140 kVp) after material decomposition and generate a variety of spectral reconstructions. We conducted this study with the hypothesis that low keV mono-energetic reconstructions can maintain or improve the coronary image quality (IQ) of CCTA with low contrast media and radiation doses comparable to conventional scans performed at low tube energy (100 kVp).

Methods
This study was approved by the Institutional Com-
mittee of Ethics of Peking Union Medical College for clinical research of human subjects. Informed consent was received from all patients.

**Study population:** All symptomatic patients with suspected CAD referred for CCTA from April to June 2017 were initially enrolled in the study. Patients with one or more of the following conditions were excluded: BMI < 20 kg/m² or > 25 kg/m², pregnant or nursing women, allergic to iodinated contrast media, renal insufficiency (estimated glomerular filtration rate < 60 mL/minute/1.73 m² or serum creatinine level ≥ 120 mmol/L), history of coronary artery bypass grafting, unable to follow breath holding instructions, arrhythmia during scanning, or persistent arrhythmia with heart rate variability higher than 5 beats per minute (bpm). Finally, 60 patients were enrolled and randomly assigned to the 120 kVp spectral group (Group A, n = 30) and 100 kVp tube voltage conventional group (Group B, n = 30).

**CCTA protocol:** All images were acquired on a dual-layer SDCT (IQon, Philips Healthcare, Cleveland, OH, USA). The tube voltage was set at 120 kVp for Group A and 100 kVp for Group B. The Dose Right Index, which achieves a targeted noise level in the images by adjusting the mAs for a selected kVp and patient size (automatically determined from the surveyp/viewtopogram), was set to 15 for both groups. All CCTA exams were performed using the prospective ECG-triggering axial scan mode with detector collimation 64 × 0.625 mm, gantry rotation time of 0.27 seconds, and the triggering window at 78% (for heart rate < 70 bpm) or 45% R-R interval (for heart rate ≥ 70 bpm) without padding. The acquisition ranged from the carina to the level of the diaphragm.

The contrast media (370 mgI/mL) was administered via a 20 G trocar in an antecubital vein by a dual-syringe power injector (DUAL SHOT GX, Nemoto-Kyorindo, Tokyo). Contrast media (36 mL) followed by 30 mL of saline chaser were injected at a flow rate of 3 mL/second. The bolus tracking technique was used with a region-of-interest (ROI) placed in the descending aorta for monitoring the contrast arrival and data acquisition triggered 6 seconds after a threshold of 90 HU was reached.

The data was reconstructed using 0.8 mm slice thickness, 0.4 mm increment, CB kernel, 512 × 512 matrix, and 180-200 mm field of view adjusted for individual patients. Images in Group A were reconstructed using a spectral reconstruction algorithm (Spectral Recon Level 3) with these datasets being spectral based images (SBI) that stored the decomposition pair of photoelectric and Compton scattering effect which were used to generate monoenergetic spectral images. Images in Group B were reconstructed using a hybrid iterative reconstructive algorithm (iDose® Level 3, Philips Healthcare). All reconstructions were transferred to a commercial spectral workstation for image analysis (IntelliSpace Portal Version 6.5, Philips Healthcare).

The resulting tube current time product, volume CT dose index (CTDIvol), and dose length product (DLP) were recorded from the CT console. The effective dose was calculated by multiplying DLP and a conversion coefficient k for chest (k = 0.014).

**Quantitative image evaluation:** The quantitative IQ evaluation was performed by an experienced cardiovascular radiologist. In Group A, the mono-energetic 40, 50, 60, 70, 80 keV spectral images as well as conventional 120 kVp images were used. In Group B, only conventional 100 kVp images were used. A circular ROI was carefully placed in the aortic root and distal segments of the left anterior descending artery (LAD), left circumflex (LCX) artery, and right coronary artery (RCA). All ROIs were placed in homogeneous areas and the sizes were selected to be as large as possible without touching the vessel wall or surrounding tissues. The ROIs were placed in the distal segments of the LAD, LCX, and RCA to test whether sufficient opacification was achieved with reduced blood flow greater than in proximal segments. To maintain the reliability of the measurement in the distal segments, the location of these ROIs was selected in the arteries whose diameter was larger than 2.0 mm. The mean attenuation of all ROIs and the noise (standard deviation [SD] of the ROI in aortic root) were recorded. The signal-to-noise ratio (SNR) was calculated by dividing the mean attenuation in the arteries by the noise. To measure the contrast-to-noise ratio (CNR), additional ROIs were placed in periarterial soft tissue.

The formulae for calculating SNR and CNR were as follows:

\[
\text{SNR} = \frac{\text{CT attenuation}}{\text{Noise}} \\
\text{CNR} = \frac{\left(\text{CT attenuation}_{\text{arteries}} - \text{CT}_{\text{soft tissue}}\right)}{\text{Noise}_{\text{aortic root}}} 
\]

**Qualitative image assessment:** The qualitative IQ was assessed independently by two experienced cardiovascular radiologists. The images were reviewed on transverse view, curved multi-planar reformation (CMPR), and maximum intensity projection. The readers were blinded to the patient characteristics, history, and scanning and reconstruction techniques. According to our preliminary evaluation, the attenuation in coronary arteries at a monoenergetic level higher than 90 keV was insufficient to depict the coronary arteries and lesions. Therefore, 40, 50, 60, 70 and 80 keV mono-energetic images in addition to conventional 120 kVp images were scored for Group A, and all conventional images in Group B. The initial window width and window level baseline of the CCTA images were 750 HU and 900 HU, respectively. The exact window width and window level adjustment were adjusted by the investigator, who then qualitatively assessed the image quality. A disagreement between the two readers was resolved by consulting a third experienced cardiovascular radiologist.

The IQ was scored using the 4-point Likert scale on a modified 18-segment classification system of the coronary artery proposed by the Guidelines of the Society of Cardiovascular Computed Tomography. A detailed description of the scoring standard is presented in Table I. Segments with a score of 1 were considered non-diagnostic. Segments with stents, diameter < 2 mm, or without sufficient opacification after an occlusion in a proximal segment were excluded from analysis.

**Stenosis analysis:** The prevalence of coronary artery plaques was assessed based on a per-vessel and per-patient level. On a per-lesion basis, the total lesions, luminal stenosis, and plaque classification were analyzed. Mild-moderate and severe stenosis were identified as <
Patient demographics: The patient characteristics are shown in Table II. The average ages of the patients in Groups A and B were 62.6 ± 9.4 and 61.6 ± 13.1 years, with gender sex ratios of 17/13 and 19/11 (male/female), BMIs of 23.1 ± 1.5 and 23.0 ± 1.3 kg/m², and average heart rates of 61.9 ± 8.1 and 62.6 ± 11.7 bpm, respectively. There were no significant differences in these patient characteristics between the two groups (all P ≥ 0.74). Likewise, the CTDIvol (8.6 ± 1.7 mGy and 8.0 ± 1.2 mGy; P = 0.09), DLP (104.8 ± 21.0 mGy*cm and 99.3 ± 22.0 mGy*cm; P = 0.2) and effective radiation dose (1.5 ± 0.3 mSv and 1.4 ± 0.3 mSv; P = 0.2) were not significantly different between Groups A and B. There were significant differences among the attenuation of the conventional 100 kVp, 120 kVp, and mono-energetic images (P < 0.001, Figure 1). The attenuation in the aortic root was significantly higher in 40-60 keV mono-energetic images than in all conventional images (all P < 0.05), while not significantly different between 70 keV and 100 kVp images (P = 0.64) or between conventional 120 kVp and 100 kVp images (P = 0.33). On the other hand, the attenuation was significantly lower in 80 keV mono-energetic images (P < 0.001) compared to 100 kVp images. Similarly, the attenuation in the LAD and LCX was significantly higher in 40 keV images (both P < 0.001), similar in 50 keV (P = 0.16 and 0.08, respectively) and 60 keV (P = 0.52 and 0.90, respectively), but lower in 70-80 keV and 120 kVp conventional images than the 100 kVp images (all P < 0.05). The attenuation in RCA was significantly higher in 40 keV images (P < 0.001), with no significant difference in 50 keV images (P = 0.99), but significantly lower in 60-80 keV and 120 kVp images (all P < 0.05) than in 100 kVp images in Group B. The noise in the aortic root was significantly higher in Group B than that in all images in Group A (all P < 0.001, Figure 2).

The SNR and CNR were significantly different between Groups A and B (Figures 3 and 4). They were sig-
Table III. Quantitative Image Quality Evaluation

|                   | Group A |                |                |                |                | Group B |
|-------------------|---------|----------------|----------------|----------------|----------------|---------|
|                   | 120 kV  | 40 keV         | 50 keV         | 60 keV         | 70 keV         | 80 keV  |
| Attenuation       |         |                |                |                |                |         |
| Aortic root       | 345.3 ± 54.3 | 1100.2 ± 200.0  | 721.9 ± 127.2  | 494.7 ± 84.6  | 358.8 ± 59.1  | 273.3 ± 42.9 |
| LAD distal        | 172.0 ± 35.7 | 399.6 ± 112.1  | 272.0 ± 69.2  | 197.0 ± 45.5  | 153.0 ± 31.8  | 124.9 ± 25.6 |
| RCA distal        | 210.0 ± 58.2 | 484.8 ± 178.3  | 347.7 ± 107.2 | 254.6 ± 69.1  | 196.3 ± 51.6  | 160.7 ± 41.0 |
| LCX distal        | 190.9 ± 51.1 | 485.4 ± 161.6  | 327.3 ± 103.2 | 234.3 ± 69.8  | 178.1 ± 50.5  | 144.3 ± 40.2 |
| Noise             | 24.2 ± 2.7 | 23.9 ± 4.2      | 20.0 ± 2.3     | 18.1 ± 1.8     | 17.5 ± 1.8     | 17.2 ± 1.9     |
| SNR               | 14.5 ± 3.0 | 46.8 ± 9.1      | 36.4 ± 6.4     | 27.5 ± 5.0     | 20.8 ± 4.1     | 16.1 ± 3.1     |
| CNR               | 18.7 ± 3.4 | 54.1 ± 9.9      | 43.2 ± 6.8     | 33.9 ± 5.3     | 26.6 ± 4.5     | 21.6 ± 3.5     |
|                   |         |                |                |                |                | 9.0 ± 1.3     |
|                   | 11.7 ± 2.0 | 25.0 ± 7.6      | 20.9 ± 4.9     | 17.2 ± 3.1     | 14.8 ± 2.6     | 12.9 ± 2.3     |
|                   | 14.5 ± 6.4 | 28.4 ± 9.4      | 24.7 ± 6.3     | 20.6 ± 4.0     | 17.5 ± 3.4     | 15.0 ± 2.4     |
|                   | 12.1 ± 2.5 | 27.4 ± 7.8      | 23.0 ± 5.6     | 18.6 ± 4.7     | 15.6 ± 3.6     | 13.9 ± 2.8     |

Group A: mono-energetic 40-80 keV spectral images and conventional 120 kV images; Group B: conventional 100 kVp. LAD indicates left anterior descending artery; RCA, right coronary artery; and LCX left circumflex.

Figure 1. Attenuation. The boxplot of the attenuation in aortic root (A), LAD (B), RCA (C) and LCX (D) for the mono-energetic 40-80 keV spectral images (mono40-mono80), conventional 120 kV images (120 conv) in Group A and conventional 100 kV images in Group B (100 conv).

significantly higher in mono-energetic 40-70 keV spectral images (all \( P < 0.001 \)) in the aortic root, while not significantly different in 80 keV and 120 kV images compared with that of 100 kVp images in Group B (all \( P > 0.22 \)). The SNR and CNR in the LAD and LCX were significantly higher in 40-60 keV images compared to 100 kVp...
Figure 2. Noise (Aorta). The image noise in aortic root for the mono-energetic 40-80 keV spectral images (mono40-mono80), conventional 120 kVp images (120 conv) in Group A and conventional 100 kVp images in Group B (100 conv).

Figure 3. Signal-to-Noise Ratio (SNR). The boxplot of SNR in aortic root (A), LAD (B), RCA (C) and LCX (D) for the mono-energetic 40-80 keV spectral images (mono40-mono80), conventional 120 kVp images (120 conv) in Group A and conventional 100 kVp images in Group B (100 conv).
images of Group B (all $P < 0.05$), while in the RCA, they were significantly higher in 40-50 keV images (all $P < 0.001$). No significant difference was found in 70-80 keV and 120 kVp images compared to 100 kVp images (all $P \geq 0.26$) for the SNR and CNR (all $P \geq 0.26$).

Qualitative image analysis: In the qualitative IQ assessment, 398 and 421 segments were scored in Groups A and B, respectively. There were 62, 7, 73 and 0 segments in Group A and 76, 4, 34 and 5 segments in Group B excluded because of congenital absence, stent, vessel caliber < 2 mm, and inadequate opacification due to proximal segment occlusion, respectively. The distribution of image scores on a segment based analysis is listed in Table IV. The image scores of 60-80 keV and 120 kVp images were significantly lower than those of 100 kVp images (all $P < 0.05$). However, the scores of 40-50 keV images showed no significant differences compared to that of 100 kVp images ($P = 1.0$ and 0.89 respectively, Figure 5). The kappa between the two readers was 0.94. Figure 6 shows representative cases.

Stenosis analysis: On a per-vessel and per-patient basis, the prevalence of coronary artery plaques was detected in 32/180 vessels (17.8%) and 21/60 patients (35.0%). There were a total of 38 plaques, with the plaque detection consistency being 100% among all the conventional images and 40-80 keV mono-energetic images. On per-lesion based analysis, the stenosis prevalence results of conventional images and 40-80 keV level images showed 81.6% (31/38) mild-moderate stenosis and 18.4% (7/38) severe stenosis, respectively. In addition, there were 52.6% (20/
Figure 5. Histogram of subjective image quality score. The mono-energetic 40-50 keV spectral images in Group A showed similar subjective image quality scores to conventional 100 kVp reconstructions of Group B, but with significantly more segments that were ranked 4 (excellent) compared to conventional 120 kVp reconstructions.

Figure 6. Case examples. The images of a 62-year-old female with BMI 22.7 kg/m² from Group A (A and B), and a 59-year-old female with BMI 22.66 kg/m² from Group B (C). The effective radiation dose was 1.19 mSv and 1.13 mSv, respectively. The volume rendered image (A1) at 50 keV depicts more small branches of coronary arteries than conventional 120 kVp VR image (B1). Also shown are the curved multi planar reformations of LAD using mono-energetic 40 (A2), 50 (A3), 60 (A4), 70 (A5) and 80 (A6) keV and conventional 120 kVp images (B2). The contrast-to-noise ratios of aortic root in these reconstructions were 67.16, 47.57, 36.05, 28.32, 23.68, and 24.10, respectively, compared to 32.92 of the 100 kVp images (C2).
38) calcified plaques, 18.4% (7/38) non-calcified plaques, and 28.9% (11/38) mixed plaques.

**Discussion**

In this study, we investigated the IQ of CCTA images obtained from a dual-layer SDCT using conventional 120 kVp, and mono-energetic spectral 40-80 keV reconstructions (Group A) and conventional 100 kVp reconstructions (Group B), with protocols for both groups set at the same low radiation dose level and a matched reduced contrast volume. The results demonstrated that the IQ of mono-energetic 40-50 keV spectral images in Group A was either equivalent or superior to conventional 100 kVp images in Group B.

The rapid improvements in CT technology make CCTA a preferred non-invasive imaging modality for excluding and diagnosing CAD in clinical practice with excellent sensitivity and negative predictive value. However, the use of traditional single-energy CCTA for evaluation of CAD has been limited to anatomical assessment. Since the degree of coronary stenosis and the presence of myocardial ischemia is not strongly correlated, additional benefits provided by DECT become important, namely the reduction of beam hardening and calcium blooming, and also better tissue differentiation and functional hemodynamic estimation. Nevertheless, a big concern for DECT cardiac studies continues to be the burden of relatively high radiation doses with ranges of 4-13 mSv being reported. Consequently, we investigated the feasibility of significantly reducing both the CCTA radiation dose and contrast media load under 120 kVp using the newly introduced dual-layer SDCT.

The dual-layer SDCT allows us to simultaneously acquire energy sensitive projection data using 120 kVp tube voltage. The capability of discrimination between high and low energy photons simultaneously from a single polychromatic 120 kVp beam makes it possible for these photons to be registered both spatially and temporally with minimum time-lag. By reducing the tube current under 120 kVp tube voltage, the radiation dose was maintained at the same low level as the 100 kVp conventional scan protocol, i.e., 1.5 mSv. Several studies have recently reported that the radiation dose can be reduced to the 2-4 mSv level in CCTA using DECT. Our results have extended this further, with dose reductions of 25-62% compared with all above mentioned radiation levels.

Predictably, the 120 kVp conventional images showed a trend towards lower mean attenuation and qualitative scores than 100 kVp images (shown in Table IV). However, the low keV mono-energetic reconstructions improved the attenuation and maintained an equivalent level of image contrast. As demonstrated in the results, both the quantitative and qualitative IQ under mono-energetic 40-50 keV reconstructions were superior to that of 100 kVp reconstructions (also exhibited in Figures 1-4). However, our findings are somewhat in contrast with previously published studies, that showed optimized results at slightly higher mono-energetic values (60 keV). One possible reason could be due to significant increases in noise at lower mono-energetic levels along with the CT attenuation enhancement, thereby causing a reduction in image SNR and CNR. But in our study, the image noise remained consistent even at lower keVs, thus contributing to better performances of 40-50 keV compared with higher keV levels. Due to the alignment of projection data, the noise can be reduced efficiently by the application of appropriate noise models and anti-correlated statistical reconstruction techniques. However, it must also be stated that the previous studies focused more on the calcification where the relatively higher keV levels have more advantages in reducing beam hardening as well as calcium blooming artifacts.

In addition, the low keV mono-energetic spectral reconstructions with their ability to boost contrast enhancement can also facilitate reductions in the contrast dosage in CCTA scans with the range of 40-64% (36 mL compared with traditional 60-100 mL). Previous studies investigated the promising “double-low” technique in single-energy acquisitions, most of them limiting the contrast volume to 40-60 mL with a tube voltage of 80 kV or higher. Recently, Zhang, et al. performed CCTA with a 30-ml contrast volume at 70 kVp in patients with BMIs < 25 kg/m² using a high-pitch mode. However, our contrast load was reduced to the same level but with the use of higher tube voltage (120 kVp).

The polychromatic 100 kVp tube voltage setting shifts the energy spectrum toward the k-absorption edge of iodine (33.2 keV) and results in increased contrast enhancement compared to higher conventional tube voltages. This approach has also been applied in the optimization of contrast media injection protocols in previous DECT studies. Our results verified this approach by showing that the attenuation of images at 40-60 keV mono-energetic spectral levels are at least comparable or even higher than with the use of 100 kVp, which has been illustrated in Figure 1. Since chronic renal insufficiency and kidney disease are very common among patients with CAD, this significant reduction in iodine load could enormously benefit patients with borderline renal function and increased risk of contrast-induced nephropathy, which has been increasingly discussed and widely recognized.

Multiple studies have demonstrated DECT’s expanded role in providing a more comprehensive cardiac assessment. For instance, the reduction of beam hardening artifacts in DECT makes it possible to provide complementary information, such as myocardial perfusion. Lastly, DECT has also been used to study the composition of non-calcified plaques, and for the visualization of in-stent stenosis. All these benefits can facilitate a comprehensive evaluation of CAD, and hence provide a “one-stop” shop cardiac examination.

This study has some limitations. First, only patients with a BMI between 20 and 25 kg/m² were included in this single-center research protocol and the sample size was relatively small. Additional studies need to be performed with an expanded BMI range to reflect a more typical patient population. Second, the performance of 40-50 keV may not always be optimal. While they certainly improve the contrast opacification (and benefit normal arteries), they can also increase calcium blooming and so
may not help with the assessment of calcium and mixed lesions. Therefore, one may have to assess other spectral reconstructions when calcium is present. Third, we only evaluated the IQ of the coronary arteries and no diagnostic accuracy assessment was performed. Since the included samples of our study were symptomatic patients with low-to-intermediate risk of suspected CAD, patients with a higher risk/possibility of suffering from severe stenosis would have been more likely to be sent directly to invasive coronary angiography. Thus, as expected, our study population only had mild to moderate stenosis (81.6%). Consequently, further studies for the assessment of different types of lesion and stenosis degree as well as diagnostic performance are needed, since the choice of optimal keV may indeed differ according to the severity of CAD.

Conclusion

The low keV (40-50 keV) mono-energetic spectral reconstructions from 120 kVp CCTA on dual-layer spectral detector CT provide improved coronary IQ compared to conventional reconstructions obtained from low tube voltage (100 kVp) scans in patients with normal BMI while at the same time facilitating reduced contrast media and the radiation dose.

Disclosure

Conflicts of interest: None.

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