Intra-individual comparison of coronary artery stenosis measurements between energy-integrating detector CT and photon-counting detector CT

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ABSTRACT

Purpose: To compare intra-individual percentage diameter stenosis (PDS) measurements of coronary artery stenoses between energy-integrating detector computed tomography (EID-CT) and a clinical photon-counting detector computed tomography (PCD-CT) systems using similar acquisition and reconstruction settings.

Methods: Patients (n = 23, mean age of 65 ± 12.1 years, out of these 16 (69.6%) male) were imaged on a conventional EID- and a clinical PCD-CT system with a median of 5.5 (3.0–12.5) days apart. Sequential CCTA scans were acquired and reconstructed using similar settings, including a vascular Bv36 kernel, a tube voltage of 110 kVp for EID-CT vs 120 kVp for PCD-CT, a slice thickness of 0.5 for EID-CT vs 0.6 for PCD-CT, and an iterative reconstruction strength of 3 on EID-CT vs a virtual monoenergetic reconstruction at 55 keV and quantum iterative reconstruction level of 3 on PCD-CT. Radiation dose, contrast volume, and injection parameters were matched as similarly as possible between the systems. PDS measurements were performed according to the coronary artery disease reporting and data system (CAD-RADS) by two trained readers and compared between the different modalities using the Wilcoxon rank sum test, Spearman correlation, and Bland-Altman analysis.

Results: PCD-CT measured significantly lower PDS values than EID-CT [PDS_{EID-CT}: 45.1% (35.1%–64.0%) vs. PDS_{PCD-CT} 44.2% (32.4%–61.0%), P < 0.0001]. This difference led to a mean bias of 1.8 (LoA/Co 3.0/6.5) with an excellent ICC (0.99) value among EID- and PCD-CT. The mean intra-individual deviation between the examinations was 1.8% between the scanners. This led to CAD-RADS re-classification in 3/23 cases (13.0%, new-lower class) for the first reader, and in 4/23 cases (13.0%, new-lower and 4.4%, new-higher class) for the second reader. Inter-reader agreement between the two readers for each stenosis was very strong (ICC = 0.98).

Conclusions: Coronary artery stenosis measurements from PCD-CT correlate strongly to EID-CT-based measurements, despite the tendency of the measurement from PCD-CT being lower. This difference led to a change in CAD-RADS classification in 17.4% of patients. The effects on clinical decision-making, downstream testing, and prognosis have to be evaluated in future studies.

KEYWORDS

stenosis, coronary artery disease, photon-counting detector computed tomography, energy-integrating detector computed tomography
**Introduction**

Coronary artery disease (CAD) is the leading cause of death worldwide [1]. Over the last two decades, coronary CT angiography (CCTA) has emerged as one of the most commonly used modalities for the clinical evaluation of stable CAD [2, 3]. Accurate CT-based quantification of coronary artery stenosis is critical because stenosis severity in combination with calcium scoring guides clinical decision-making [4]. In this context, CCTA has already been shown to have excellent negative predictive value and moderate positive predictive value for the detection and evaluation of CAD, especially in patients with low or intermediate risk [5, 6]. However, the positive predictive value of CCTA suffers as the burden of calcium in the coronary arteries increases due to calcium blooming artifacts [7].

Recently, photon-counting detector computed tomography (PCD-CT) has become clinically available, enabling direct conversion of x-ray photon radiation into an electrical signal instead of using an intermediate conversion into visible light photons through a scintillator [8]. Compared with conventional energy integrating detector CT (EID-CT), PCD-CT offers several distinct advantages, including higher spatial resolution, lower image noise, and constantly available spectral image information [9–16]. These advantages have the potential to allow for more accurate stenosis quantification and overcome previous limitations in CT-based cardiac imaging. However, due to the novelty of this technique, analyses comparing intra-individual measurements from PCD- and EID-CT using similar settings are required to ensure transferability into clinical practice.

We hypothesized that percentage diameter stenosis (PDS) measurements with PCD-CT yield similar results compared to the conventional, clinical-standard EID-CT when acquired and reconstructed similarly. Thus, this study aims to intra-individually compare PDS measurements between a first-generation dual-source PCD-CT and a state-of-the-art conventional dual-source EID-CT.

**Materials & methods**

**Patients**

The protocol of this single-center, Health Insurance Portability and Accountability Act-compliant, study was approved by the local Institutional Review Board (IRB). Patients were prospectively enrolled based on the following inclusion criteria: (1) clinical indication for cardiac imaging; and (2) >18 years of age. The following exclusion criteria were applied: (1) contraindication to iodine-based contrast media; (2) reduced kidney function (glomerular filtration rate <45 mL min$^{-1}$ m$^{-2}$); (3) pregnancy or lactation, and (4) unable to be consented. All patients provided written informed consent and underwent an electrocardiogram (ECG)-gated CCTA examinations on both CT systems between August 2021 and March 2022.

**Data acquisition and image reconstruction**

Both the conventional EID-CT (SOMATOM Force, Siemens Healthineers, Erlangen, Germany) and a first-generation, clinical PCD-CT (NAEOTOM Alpha, Siemens) were used to perform CCTA examinations. The PCD-CT is equipped with two photon-counting cadmium telluride (CdTe) detectors, each with a collimation of 144 × 0.4 mm, which enables spectral CT data acquisition at a high temporal resolution. The tube voltage was set to 110 kVp for the EID-CT, which was the standard protocol used at our institution, while it was set to 120 kVp for the PCD-CT per vendor recommendations.

A sequential cardiac protocol was used for all scans, which included ECG triggering and a triphasic contrast injection protocol and a constant injection rate for all three phases (4 mL s$^{-1}$). This involved injecting an initial bolus of nonionic iodinated contrast agent (50 mL, iopromide 370 mgI mL$^{-1}$, Ultravist, Bayer Healthcare), followed by a 50% mixture of contrast agent and saline solution (20 mL), and a saline chaser (25 mL). If it was not clinically contraindicated, patients were given 0.4 mg nitroglycerin about 5 min before the scan, and those with heart rates above 70 beats per minute received 5 mg metoprolol intravenously.

CT images were directly reconstructed on the scanners. All reconstructions were performed in the phase with the least motion artifacts (best diastolic or systolic phase), using a body vascular kernel (Bv36) a slice thickness of 0.5 and 0.6 mm for the EID-CT and the PCD-CT, respectively. Iterative reconstruction algorithms were applied at strength level 3 for both scanners, using advanced modeled iterative reconstruction (ADMIRE) for the EID-CT and quantum iterative reconstructions (QIR) for the PCD-CT. Detailed acquisition and reconstruction parameters for both scanners can be found in Table 1.

**Stenosis measurements**

Measurements were performed by two readers with 2 and 4 years of experience in cardiovascular radiology and under the supervision of a board-certified cardiovascular radiologist with 12 years of experience. The supervisor selected relevant stenoses with at least 20% of vessel obstruction. Both readers independently assessed each stenosis in a blinded fashion.

<table>
<thead>
<tr>
<th>Table 1. CT acquisitions and reconstructions</th>
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<tbody>
<tr>
<td><strong>Modality</strong></td>
</tr>
<tr>
<td>Tube potential (kVp)</td>
</tr>
<tr>
<td>Monoenergetic level (keV)</td>
</tr>
<tr>
<td>Iterative reconstruction</td>
</tr>
<tr>
<td>Reconstruction kernel</td>
</tr>
<tr>
<td>Slice thickness (mm)</td>
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<tr>
<td>Field of View (mm)</td>
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<tr>
<td>Matrix size</td>
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</table>

QIR, quantum iterative reconstruction; EID-CT, energy-integrating computed tomography; PCD-CT, photon-counting detector computed tomography.
Stenosis measurements were based on a semi-automated segmentation of the remaining coronary artery lumen using a commercially available software solution (CT Coronary, syngo.via Version VB60, Siemens). An example case illustrating the visualization for stenosis measurements is shown in Fig. 1. Quantitative analysis of the stenoses was conducted on cross-sectional images and according to established methods using the diameter proximal and distal to the stenosis as reference [17]. The reference diameters were measured in a plaque-free portion of the same vessel as close as possible to the selected stenosis.

Based on these measurements, the PDS was calculated with a validated formula as described previously [18]:

\[
PDS = 1 - \frac{D_S}{D_V}
\]

in which \(D_S\) is the minimal remaining vessel lumen of the coronary artery stenosis and \(D_V\) represents the average reference diameter proximal and distal to the stenosis.

For reliable results, window-level settings were kept constant (C450 HU/W1500 HU) in the PCD- and EID-CT measurements. The readers also classified the plaques as being either calcified or mixed.

Furthermore, patients were assessed according to the Coronary Artery Disease Reporting and Data System (CAD-RADS) depending on the measured PDS as follows: CAD-RADS 0 – 0%; CAD-RADS 1 – 1-24%; CAD-RADS 2 – 25-49%; CAD-RADS 3 – 50-74%; CAD-RADS 4 – 75-99%; CAD-RADS 5 – 100% [19].

**Statistical analysis**

Dedicated software (SPSS Statistics for Windows, Version 21.0, IBM Corp Armonk, NY; MedCalc for Windows, version 15.0, MedCalc Software, Ostend, Belgium; GraphPad Prism, Version 9 for macOS, San Diego, CA, USA) was used for statistical analysis. The data was tested for normality using the Kolmogorov-Smirnov test. For normally distributed data, mean ± standard deviation (SD) was used, while median with interquartile range was used for non-normally distributed data. Categorical variables were reported as frequencies and proportions. The mean’s distribution was compared with independent samples t-test for normally-distributed variables or Mann-Whitney U test for non-parametric variables. The difference between the two CT stenosis measurements was compared using the Wilcoxon rank sum test, and a p-value of 0.05 was deemed significant. The mean bias and the upper and lower limits of agreement (LoA) between the two approaches were evaluated using Bland-Altman analysis. The correlation between PDS values from EID- and PCD-CT was measured using the Spearman correlation coefficient (r). The agreements between the two CT systems and the two readers were measured using intraclass correlation coefficients (ICC), with the following interpretations: 0.0 to 0.3, lack of agreement; 0.31 to 0.5, weak agreement; 0.51 to 0.7, moderate agreement; 0.71 to 0.9, strong agreement; and 0.91 to 1.00, very strong agreement [20].

**Results**

The study included 23 patients (16 men) with a mean age of 65 ± 12.1 years and a total of 42 evaluated stenoses, comprised of 31 (73.8%) mixed and 11 (26.2%) calcified plaques. The PCD-CT scan was conducted a median of 5.5 (3.0–12.5) days after the EID-CT scan. The median radiation dose for scans obtained with PCD-CT was significantly lower compared to those performed with EID-CT [CTDIvol EID-CT: 38.3 (20.9–58.0) mGy vs PCD-CT: 28.0 (18.2–54.2) mGy, \(P < 0.05\)]. Clinical CT examinations included the following indications: 13 (56.5%) stable chest pain/CAD, 7 (30.4%) valvular disease, 3 (13.0%) structural heart disease. A detailed listing of the study population, scan conditions, and plaque characterization is given in Table 2.

**Stenosis evaluation**

Overall, the \(PDS_{PCD-CT}\) measurements were significantly lower than corresponding \(PDS_{EID-CT}\) values (\(PDS_{EID-CT}\) 45.1% (35.1%–64.0%) vs. \(PDS_{PCD-CT}\) 44.2% (32.4%–61.0%), \(P < 0.0001\), mean bias 1.8, LoA –3.0/6.5). Nevertheless,
PDSPCD-CT showed very strong correlation and agreement with PDSEID-CT ($r = 0.988$, ICC = 0.99). The mean measurement deviation between individual stenoses amounted to a 1.8% difference between the scanners. Figure 2 demonstrates the correlation between PDS values from EID- and PCD-CT. Figure 3 displays the differences between the individual measurements from the EID- and PCD-CT.

**Reclassification of CAD-RADS categories**

Based on the degree of stenosis, patients were assigned a CAD-RADS score. Compared to the initial classification based on the EID-CT scan, measurements derived from PCD-CT scans led to a new-lower classification in three patients (3/23 cases, 13.0%) for both readers and to a new-higher classification in one patient (1/23 cases, 4.4%) for reader 2. This led to a per-patient CAD-RADS re-classification in 17.4% of cases. Details of the per-patient and per-vessel CAD-RADS category re-classifications are provided in Fig. 4, Table 3 and Supplementary Table S1. Agreement between the readers was very strong for stenosis measurements (ICC = 0.97) between the two CT systems.

**Discussion**

This prospective study investigated coronary artery stenosis measurements between EID- and PCD-CT in an intra-individual patient setting. Major findings were: 1) PCD-CT PDS values measured lower on average compared to the measurements on EID-CT. 2) This led to CAD-RADS re-classification in approximately 17% of patients. 3) Despite the instances of re-classification, there was still a very strong

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**Table 2. Patient characteristics**

<table>
<thead>
<tr>
<th></th>
<th>EID-CT</th>
<th>PCD-CT</th>
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<tbody>
<tr>
<td>Heart rate (bpm)</td>
<td>64.1 ± 11.0</td>
<td>65.3 ± 10.8</td>
</tr>
<tr>
<td>CTDI ($\text{mGy}^\text{cm}$)</td>
<td>647.8 (339.4–1055.1)</td>
<td>575.5 ± 384.7</td>
</tr>
</tbody>
</table>

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**Fig. 2.** Scatterplot (A) and Bland-Altman plot (B) show the correlation of percent diameter stenosis (PDS) between EID-CT and PCD-CT

**Fig. 3.** Box plot with line diagram shows the comparison of percent diameter stenosis (PDS) values between EID-CT and PCD-CT with a $p$-value from a paired Wilcoxon test.
correlation and agreement of coronary stenosis measurements between the two CT systems.

CCTA is considered a first-line test in the evaluation of CAD due to its high sensitivity and negative predictive value in patients with low and intermediate risk of CAD [5, 6]. Additionally, CCTA enables the evaluation of coronary stenosis and plaque composition, providing valuable information for prognostic stratification [21, 22]. However, CCTA is restricted by a moderate positive predictive value due to artifacts that can lead to overestimation of stenoses, particularly from high-density calcifications or stents [23–25]. For high-density calcifications, errant stenosis measurements are induced by calcium blooming artifacts, which occur more frequently as calcium density increases [26]. The inappropriate stenosis measurements are caused by different tissue attenuations within the same imaged voxel [27]. Inaccurate PDS measurements with a stenosis overestimation can lead to unnecessary ICA [25, 26].

It has been demonstrated that PCD-CT reduces calcium blooming through increased spatial resolution and better decomposition of materials [28]. Despite similar reconstructions in our study between the PCD- and EID-CT systems, PCD-CT seemed to be less prone to calcium blooming and therefore resulted in lower PDS value measurements. However, the overestimation of PDS by standard resolution CCTA has been investigated by several phantom studies using EID- and PCD-CT [18, 29, 30]. Based on these prior publications, it can be implied that the PCD-CT in-vivo measurements in our study are more accurate than the EID-CT measurements, which is currently one of the state-of-the-art CT systems in clinical settings.

The lower PDS measurements would follow with a new-lower risk classification in patients and therefore has an impact on the CAD-RADS system. We demonstrated a new per-patient CAD-RADS classification in approximately 17% of our patients. Similarly, a previous study compared the intra-individual coronary artery calcium score using identical scan parameters between EID- and PCD-CT [12]. The study revealed a new-lower reclassification rate for the PCD-CT of approximately 5% compared to the EID-CT, which suggests a role in evaluating the plaque burden in patients. An accurate CT-based quantification of stenosis degrees is of great importance and represents the basis for the risk assessment of CAD, which guides clinical management [31]. However, most patients still received the same CAD-RADS category with the PCD-CT acquisition compared to the EID-CT, and there was a high degree of agreement between stenosis grading and CAD-RADS classification from both CT systems. On the other hand, through further improvements such as of the spatial resolution on the PCD-CT, it might have the potential

**Table 3. Re-classification of CAD-RADS categories**

<table>
<thead>
<tr>
<th>CAD-RADS Score Category</th>
<th>New-lower risk classification</th>
<th>Original classification</th>
<th>New-higher risk classification</th>
<th>Reader 1</th>
<th>Reader 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New-lower risk classification</td>
<td>Original classification</td>
<td>New-higher risk classification</td>
<td>Reader 1</td>
<td>Reader 2</td>
</tr>
<tr>
<td>0</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>Reader 1</td>
<td>Reader 2</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>Reader 1</td>
<td>Reader 2</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>6</td>
<td>5</td>
<td>Reader 1</td>
<td>Reader 2</td>
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<tr>
<td>3</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>Reader 1</td>
<td>Reader 2</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>Reader 1</td>
<td>Reader 2</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Reader 1</td>
<td>Reader 2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3</strong></td>
<td><strong>23</strong></td>
<td><strong>1</strong></td>
<td>Reader 1</td>
<td>Reader 2</td>
</tr>
<tr>
<td><strong>Difference (%)</strong></td>
<td><strong>13.0</strong></td>
<td><strong>13.0</strong></td>
<td><strong>4.4</strong></td>
<td>Reader 1</td>
<td>Reader 2</td>
</tr>
</tbody>
</table>
Conclusion

In conclusion, PDS measurements on PCD-CT are highly correlated but generally lower compared to the measurements from EID-CT using similar reconstruction settings. The discrepancy in stenosis measurements between the two CT systems resulted in per-patient CAD-RADS re-classification in 17.4% of cases. Further studies are expected to evaluate optimized PCD-CT imaging protocols for PDS evaluation and to investigate its effects on the clinical decision-making process.

Authors’ contribution: EVW, CG, MCH and TE designed the study, interpreted the study data and drafted the manuscript. NF and EZ performed data analysis, supported statistical analysis, and substantially revised the manuscript. JOD advised data reconstruction, supervised data analysis and edited/revised the manuscript. AV-S and UJS supervised the study conception and data interpretation and substantially edited the manuscript. All authors read and approved the final manuscript.

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Ethical statement: The studies involving human participants were reviewed and approved by Institutional Review Board, Medical University of South Carolina, SC, United States. The patients/participants provided their written informed consent to participate in this study.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1556/1647.2023.00156.

REFERENCES


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