European Journal of Radiology Open 11 (2023) 100538

Contents lists available at ScienceDirect

European Journal of Radiology Open

journal homepage: www.elsevier.com/locate/ejro

Photon-counting detector CT allows significant reduction in radiation dose while maintaining image quality and noise on non-contrast chest CT

Achala Donuru [a,*,1], Tetsuro Araki [a,1], Farouk Dako [a,1], Jaydev K. Dave [b,2], Raul Porto Perez [a,1], Dongming Xu [a,1], Arun Nachiappan [a,1], Eduardo Mortani Barbosa Jr [a,1], Peter Noel [a,1], Harold Litt [a,1], Friedrich Knollman [a,1]

[a] *Department of Radiology, Hospital of the University of Pennsylvania, Philadelphia, PA 19104, USA*
[b] *Department of Radiology, Mayo Clinic, Rochester, MN 55905, USA*

ARTICLE INFO

Keywords:
Photon counting computed tomography
Energy integrating detectors
Virtual monoenergetic imaging

ABSTRACT

Purpose: To investigate if clinical non-contrast chest CT studies obtained with PCD CT using much lower radiation exposure can achieve the same image quality as with the currently established EID protocol.
Materials/methods: A total of seventy-one patients were identified who had a non-contrast chest computed tomography (CT) done on PCD CT and EID CT scanners within a 4-month interval. Five fellowship trained chest radiologists, blinded to the scanner details were asked to review the cases side-by-side and record their preference for images from either the photon-counting-detector (PCD) CT or the energy-integrating detector (EID) CT scanner.
Results: The median CTDIvol for PCD-CT system was 4.710 mGy and EID system was 7.80 mGy ($p < 0.001$). The median DLP with the PCD-CT was 182.0 mGy.cm and EID system was 262.60 mGy.cm ($p < 0.001$). The contrast to noise ratio (CNR) was superior on the PCD-CT system 59.2 compared to the EID-CT 53.3; ($p < 0.001$). Kappa-statistic showed that there was poor agreement between the readers over the image quality from the PCD and EID scanners ($\kappa = 0.19$; 95 % CI: 0.12 – 0.27; $p < 0.001$). Chi-square analysis revealed that 3 out of 5 readers showed a significant preference for images from the PCDCT ($p \leq 0.012$). There was no significant difference in the preferences of two readers between EID-CT and PCD-CT images.
Conclusion: The first clinical PCD-CT system allows a significant reduction in radiation exposure while maintaining image quality and image noise using a standardized non-contrast chest CT protocol.

1. Introduction

The use of medical imaging has increased substantially over the last two decades [1]. A recent publication by Kwan et al. addressed the risk of childhood and adolescent cancer associated with ionizing radiation in general North American population undergoing routine medical imaging [2]. In their study, the authors collected the individual radiation technique parameters from CT examinations, which enabled the calculation of individual patient-specific organ doses.

Photon-counting-detector (PCD) CT systems have demonstrated radiation dose reduction compared to energy-integrating-detector (EID) CT for the same image quality [3–6]. The image quality on ultra-high resolution photon counting detector CT of the lung using novel iterative reconstruction algorithm was analyzed by Sartoretti et al. [7].

The PCD system counts and directly converts incoming photons into electronic signals proportionally to their deposited energy [8,9]. PCDs also have a higher dose efficiency than EID mainly because of electronic noise suppression [10–15]. PCDs have the possibility to provide spectral measurement bins by differentiating incoming photons according to their energy. This spectral information can be used to reconstruct virtual monoenergetic images (VMI) [16]. PCD-CT can eliminate electronic noise and reduce artifacts due to the use of energy thresholds.

Being a recently introduced CT system for clinical routine PCCT has gained increasing interest in all areas of imaging [17,18]. The median

* Correspondence to: 3400 Spruce Street, Philadelphia, PA 19104, USA.
E-mail address: achala.donuru@pennmedicine.upenn.edu (A. Donuru).
[1] 3400 Spruce Street, Philadelphia, PA 19104, USA.
[2] Department of Radiology, Mayo Clinic in Rochester, MN, USA.

https://doi.org/10.1016/j.ejro.2023.100538
Received 16 September 2023; Received in revised form 25 October 2023; Accepted 3 November 2023

CT effective dose for a routine, non-contrast CT chest is 6.1 mSv (with a range of 1.7–24 mSv), which is equivalent to obtaining 117 chest radiographs [19]. For dedicated screening applications like lung cancer screening the effective dose is relatively lower (about 1.5 mSv).

With the advent of PCDCT systems, and increasing clinical adoption of these systems, there are scenarios where both the PCD-CT and EID-CT scanners may be available in the same imaging department. Moreover, the protocols associated with the new PCD-CT systems are based on recommendations by the vendors. Therefore, the purpose of our study was to determine the radiation dose, noise and image quality of non-contrast-enhanced chest CTs performed on PCD-CT system in comparison with conventional EID-CT systems.

2. Materials and methods

A full waiver of informed consent was obtained from the institutional review board for this study. Between November 2021 and September 2022, a total of seventy-one patients were included in this retrospective study using following criteria: age over 18 years old, clinically indicated non-contrast CT scan of the chest, the patient obtained an additional non-contrast-enhanced CT scan of the chest on a third-generation dual source CT with EID in our institution within 4 months of obtaining the chest CT on PCD-CT system. The patients who had the two scans more than 4 months apart were excluded from the study. The body mass index (BMI) did not change by more than 2 kg/m^2 between the 2 scans. This was one of the exclusion criteria.

2.1. CT scanning protocol and CT image reconstruction

2.1.1. Energy-integrating CT

All EID-CT scans were performed on a third-generation 192-slice dual-source CT scanner (SOMATOM Force, Siemens Healthineers, Forchheim, Germany) equipped with two conventional EIDs (Stellar Technology, Siemens Healthineers, Forchheim, Germany). All scans were performed with automated tube voltage selection (CARE kV, Siemens) optimized for chest CT scan and automated tube current selection (CARE Dose4D, Siemens) with reference tube voltage at 90–120 kV. Tube current was adjusted automatically based on patient size (Care mA, ref mAs = 80). Images were reconstructed using a smooth mediastinal kernel (Br40) with a slice thickness of 2 mm. An advanced modeled iterative reconstruction algorithm (ADMIRE, Siemens) at a level of 3 was applied. Volume CT dose index (CTDIvol) and dose length product (DLP) values were retrieved from the picture archiving and communication system (PACS).

2.1.2. Photon-counting detector CT

All scans were performed on a first-generation dual-source CT scanner with quantum imaging (NAEOTOM Alpha, Siemens Healthineers, Forchheim, Germany) equipped with two photon counting detectors. All scans were performed with vendor specified protocols at 140 kV (we did not change the factory settings). Series with slice thickness of 2 mm on soft tissue windows, soft (Bf40) convolution kernels were used for the analysis. Scans performed on PCD-CT system used a virtual monoenergetic images at 85 keV. Tube current was adjusted automatically based on patient size (Care mA – IQ level 60). Quantum iterative reconstruction at level 3 was used.

2.1.3. Objective image quality

All measurements were performed by a radiologist with over 10 years of experience in chest imaging. Noise measurements were taken in the subcutaneous fat and within the lung parenchyma on both the scans. Noise measurements in subcutaneous fat were obtained in soft tissue windows. Noise measurements in lungs were obtained in normally ventilated portions of the lung in lung windows by selecting an area that was free of disease and by avoiding airways and vessels. This would avoid the confounding factor of changing parenchymal findings in an acute setting on comparison studies. Mean attenuation values of the subcutaneous fat (Fig. 1) and lung parenchyma (Fig. 2) were also obtained by placing a total of three circular regions-of-interest (ROI) in the lung and subcutaneous fat. Mean attenuation of lung parenchyma and subcutaneous fat was calculated by averaging the attenuation values of the three measurements.

CNR was calculated using the formula –.

$$\text{CNR} = \frac{\text{meansignal(lungparenchyma)} - \text{meanbackgroundnoise(subcutaneousfat)}}{\text{meannoisebackground}}$$

2.1.4. Subjective image quality

Subjective image quality was independently assessed by five radiologists blinded to the scanner information. The following subjective image quality features were assessed using a 5-point Likert scale: overall image quality (5 = excellent, 4 = good, 3 = moderate, 2 = bad, 1 = non diagnostic), image noise (5 = no/very little image noise, 4 = little image noise, 3 = moderate image noise, 2 = strong image noise, 1 = very strong image noise). All five radiologists had at least 1 year experience in chest radiology and they were not involved in the assessment of objective image quality.

The readers analyzed the scans in soft tissue windows only. Lung windows were not evaluated (we did not include scans performed per high resolution CT protocol). The radiologist's assessment was not a detailed assessment of the lung, but overall image quality of chest wall, pleura, mediastinum, heart, great vessels, lower neck and upper abdomen. We use 2 mm thick slices in our standard clinical protocol for all non-contrast chest CT interpretation. Considering all factors, the radiologists were requested to select the scanner they preferred for reviewing the images for each case.

2.2. Statistical analyses

Radiation dose parameters (CTDIvol and DLP) and CNR were compared using the Wilcoxon signed rank test. Fleiss multirater kappa statistic was used to evaluate inter-rater agreement. Strength of agreement was evaluated by the value of kappa statistic using the following criteria; values < 0.20 were considered as poor, 0.21–0.40 were considered as fair, 0.41–0.60 were considered as moderate, 0.61–0.80 were considered as good and 0.81–1.00 were considered as very good. Frequency of scanner preference in the reader response was evaluated. Additionally, based on inputs of 5 readers, a "consensus" reader was simulated for each case by selecting the scanner that a majority of the readers preferred for each case. Chi-square goodness of fit test was used with the null hypothesis that each reader will have no preference for the images coming from the EID or the PCD scanners (i.e., the proportion of cases with good image quality will be equally distributed between the two scanners for each reader). Chi-square test was repeated for the consensus reader with the same null hypothesis. P-values less than 0.05 were considered significant. We used MedCalc statistical software and IBM's SPSS Statistics (Armonk, New York, US, version 28) for analysis.

3. Results

A total of seventy-one patients who were scanned twice (as a routine part of their standard-of-care) were included in this study. There were a total of 25 females and 46 males. Median age of participants was 62 years. Body mass index (BMI) categories were underweight = <18.5 kg/m2, normal weight = 18.5–24.9 kg/m2, overweight = 25–29.9 kg/m2 and obesity = BMI of 30 kg/m2 or greater. Median BMI was 26.83. There were 3 % of patients who were underweight, 32 % of the patients were in the normal range, 36 % were overweight and 29 % were obese. The reason for performing the study was noted. The clinical symptoms included interstitial lung disease [2], postsurgical [21], pre-op [2] and sepsis [46]. Of the 2 patients who had pre-op as a reason for the studies, one patient was pre-op for Impella device placement, both the scans were performed 7 days apart. The patient had surgery after the 2nd scan.

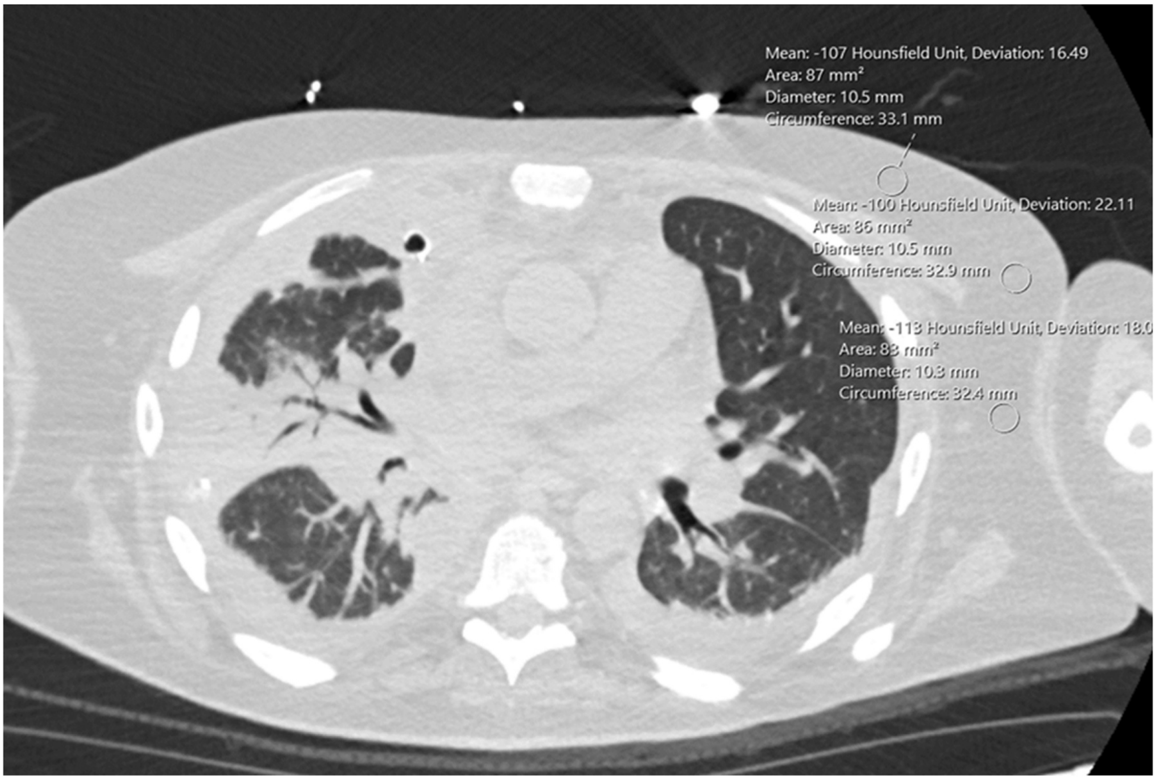

Fig. 1. Noise measurements taken in the subcutaneous fat on PCD-CT. 3 measurements taken in the subcutaneous fat with attenuation value of –107 HU (Standard deviation = 16.49), –100 HU (SD = 22.11) and –113 HU (SD = 18).

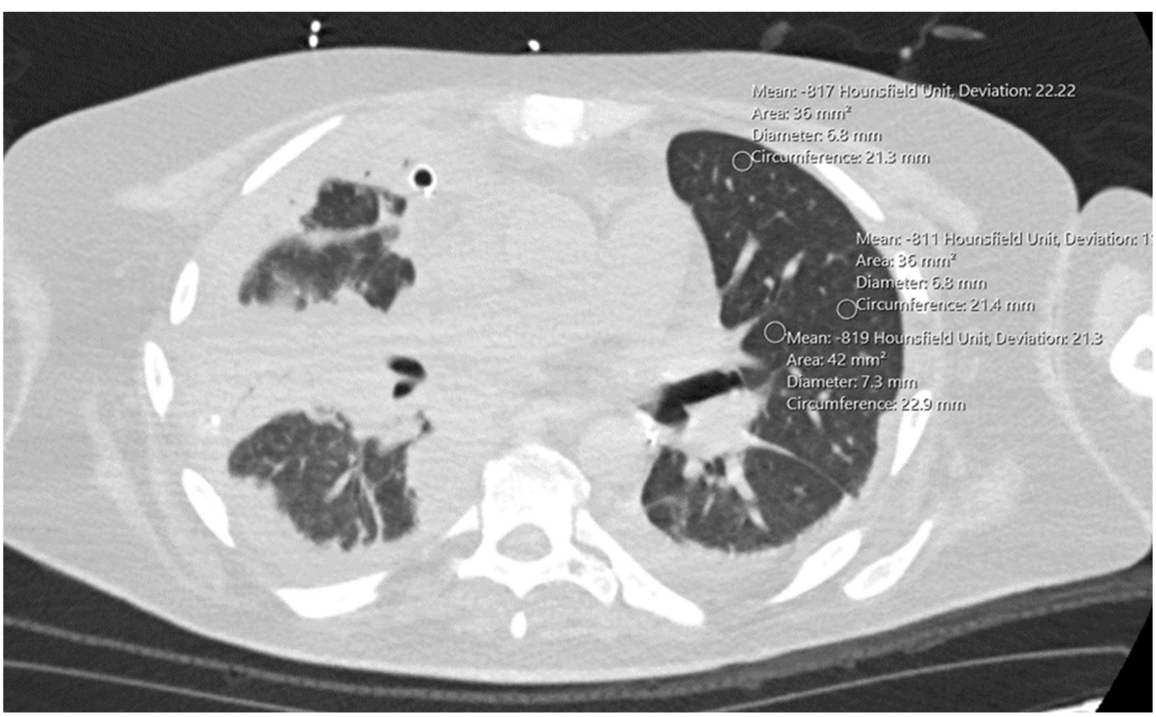

Fig. 2. Noise measurements taken in the lung parenchyma on EID-CT. 3 measurements taken in the lung parenchyma with attenuation value of –817 HU (Standard deviation = 22.22), –811 HU (SD = 19.99) and –819 HU (SD = 21.3).

The other patient had a scan on the EID scanner prior to surgery and the follow up scan was 7 days later on the PCD CT scanner. This is a small percentage of the patient group that we analyzed (2.8 %) and we feel that this will not impact the results significantly. Demographics are included in Table 1. The median time between the scans was 11 days and the range was 109 days.

We understand that the imaging findings change rapidly in an in-patient setting. We obtained a mixed cohort of patients. 52 of the 71

Table 1
Demographics of patient population and their clinical characteristics.

Number of participants	71
Gender	25 females and 46 males
Mean Age+/− Standard Deviation	58.91+/− 16.62
Median Age	62 years
Interquartile Range of Ages	25 years
Mean BMI+/− Standard Deviation	27.63+/− 6.313
Median BMI	26.83
Interquartile Range of BMI	7.85
Clinical Symptoms	ILD [2], Postsurgical [21], Pre-op [2], Sepsis [46]

Table 3
Summary of comparison of CT dose index-volume (CTDIvol), Dose length product (DLP) and Contrast to noise ratio (CNR) between Photon counting CT scanner (PCD) and Conventional CT (EID).

Parameter	EID	PCD	p-value	95 % Confidence Interval of the difference	
	Median (range)	Median (range)		Lower	Higher
CTDIvol (mGy)	7.8 (6.3–9.2)	4.7 (4.6–5.5)	<0.001	2.2	3.9
DLP (mGy. cm)	262.6 (224.0–303.1)	182.0 (172.4–187.0)	<0.001	65.3	125.2
CNR	53.3 (50.9–56.7)	59.2 (57.3–66.7)	0.001	4.7	13.2

patients (73 %) were scanned on the EID scanner first and 19 patients (27 %) were scanned on the PCCT scanner first. There was a mixed pool of cases in the present study. This randomization would mitigate any bias in reported radiation dose reductions and image quality scores.

The median CTDIvol for PCD-CT system was 4.710 mGy and EID system was 7.80 mGy ($p < 0.001$), whereas the median DLP with the PCD-CT was 182.0 mGy.cm and EID system was 262.60 mGy.cm ($p < 0.001$); The CNR was superior on the PCD-CT system (59.2) compared to the EID-CT (53.3); $p < 0.001$; (Table 3).

Fleiss multirater kappa showed that there was poor agreement between the readers over the image quality from the EID and PCD scanners ($\kappa = 0.19$; 95 % CI: 0.12 – 0.27; $p < 0.001$). The frequency of the scanner preference from the responses is presented along with the results of the chi-square analysis (Table 2; Fig. 3). Based on the chi-square analysis, only 3 out of 5 readers showed a significant preference for images from the PCD-CT scanner ($p \leq 0.012$). The other 2 readers preferred the images from the EID_CT scanner, but with no significant difference ($p \geq 0.075$). For the consensus reader, the null hypothesis was accepted, suggesting that the proportion of cases with good image quality was equally distributed between the two scanners.

4. Discussion

Our hypothesis was that clinical non-contrast chest CT studies obtained with much lower radiation exposure can achieve the same image quality as with the currently established EID protocol. Rajendran et al. assessed the technical performance of the PCD-CT system and compared the scans to same-day exams performed using energy-integrating-detector (EID) CT on four participants. They concluded that PCD-CT images showed lower noise and/or improved spatial resolution compared to EID-CT [18].

We have shown similar results in this study, but with a higher number of patients. We compared the radiation dose parameters as well as image quality, dose and noise on non-contrast enhanced chest CT. The radiation dose parameters were compared between the optimized and currently used clinical protocol on the EID-CT scanner, and the vendor-recommended protocol on the PCD-CT scanner. We postulate that the vendor-recommended protocol will be further refined in the future based on results from other such clinical studies – consequently, these refinements may influence the radiation dose reduction noted in this study with PCD-CT systems.

Symons et al. compared lung cancer screening in PCD CT in a specialized lung tissue phantom with respect to a conventional EID CT system [20]. They concluded that there was better Hounsfield unit stability for lung, ground-glass, and emphysema equivalent foams at lower radiation dose settings on PCD with better reproducibility than EID. This study suggested that we can further reduce the radiation dose in lung cancer screening without compromising on the diagnostic quality. Kopp et al. evaluated custom-made lung nodules of varying sizes and shapes in lung phantoms on PCD-CT and conventional CT and concluded that higher spatial resolution of PCD-CT leads to a more precise assessment of lung nodules [21].

Studies performed by Si-Mohamed et al. and Bartlett et al. showed improved visualization of the distal airways with PCD system compared to EID CT [15,22]. These initial studies indicate that the PCD system can help with more accurate classification of interstitial lung diseases.

Woeltjen et al. compared the image quality and radiation dose of low-dose high-resolution (LD-HR) lung CT scans compared to an EID-CT. LD-HR PCCT examinations of the chest showed better image quality, while allowing a significant dose reduction of up to 35.7 % compared to EID-CT scans [23].

There are a number of dose reduction strategies available for CT. Fixed tube current technique charts, tube current modulation, using iterative reconstruction algorithms, limiting the number of CT slices acquired, and AEC can all be used to reduce dose without sacrificing image quality. Radiologists should work with technologists to select the appropriate dose reduction strategy for each patient [24,25].

Our study had the following limitations. First, all scans on PCD-CT were performed using only the manufacturer-recommended tube potential, whereas scans on EID-CT were performed using automated tube voltage selection. Second, the image characteristics may not be completed reflected in CNR. Visual assessment is still superior to CNR measurement. The alternative to CNR is image noise power spectrum analysis which is typically done in phantoms. Image quality of PCD-CT can be further improved by performing studies at different tube potentials to optimize the scanning protocol for different clinical tasks. Third, all our patients underwent scans in an in-patient setting. While the most accurate comparison can be made between both the scans by scanning the patients on the same day on both scanners; however, this would significantly increase the radiation dose to the patients without any clinical benefit. We tried to counteract this bias by mixing patients who were imaged on PCD-CT scanner first and on the EID scanner first. Fourth, in this study we used vendor-recommended protocols for PCD-CT scanner that may have directly influenced the radiation dose

Table 2
Summary of scanner preferences and the results of the chi-square analysis for each reader and the simulated consensus reader.

CT Scanner	Reader 1	Reader 2	Reader 3	Reader 4	Reader 5	Consensus Reader	Overall (from 5 readers)
EID CT	25	43	22	8	42	28	140
PCD CT	46	28	49	63	29	43	215
Total	71	71	71	71	71	71	355
χ^2[1,71]	6.21	3.17	10.27	42.61	2.38	3.17	NA
p-value	0.012	0.075	0.001	<0.001	0.123	0.075	NA

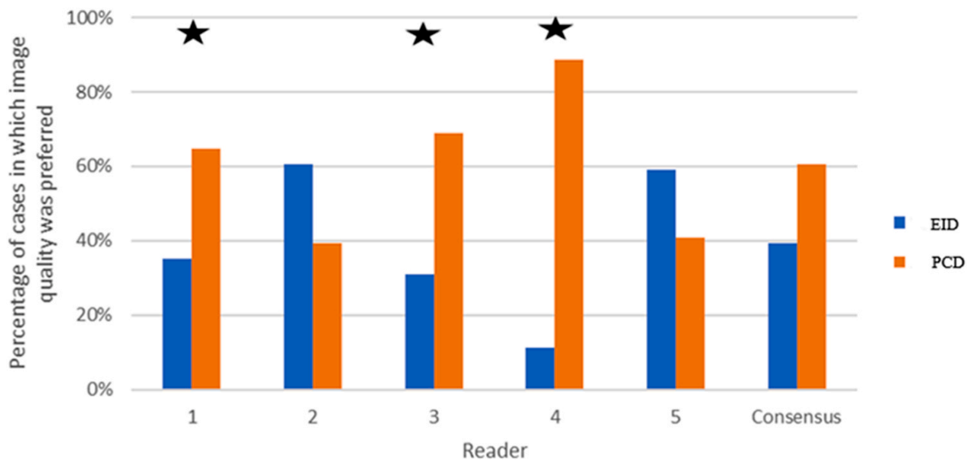

Fig. 3. Results of chi-square analysis comparing the scanner preference for each reader and the simulated consensus reader (star indicates significant differences in the scanner preference).

reduction observed; nonetheless even though the radiation dose reduction with PCD-CT may be a direct consequence of the protocol parameters, the image quality improved with the PCD-CT scanners. If the radiation dose of PCD-CT would have been increased to match the dose associated with EID-CT, then due to increased dose, the enhancement in image quality with PCD-CT would be relatively higher. In future for dose and image quality comparisons, we aim to use similar technical parameters for data acquisition when assessing the performance of different imaging systems. Such an approach would inform us which system is relatively more dose efficient as described in prior publications.

In conclusion, our intra-individual analysis indicates that the clinical PCD-CT allows a significant reduction in radiation exposure while maintaining image quality and image noise using a standardized non-contrast chest CT protocol. Other studies have focused on other applications of PCD-CT with fewer patients. Our sample size is more than double the patients studied in most of the cited references. Additionally, our results related to image quality and radiation dose associated with photon counting CT as reported in this manuscript are based on a clinically realistic imaging scenario where patients may be scanned on either type of CT scanner as a part of their standard-of-care and the time between these scans can be variable based on clinical indications. With the above considerations, we justify how our study will add value and evidence to this innovative technology of PCD-CT which has the potential to be clinically impactful for our patients.

Ethical statement for solid state ionics

Hereby, I, Achala Donuru consciously assure that for the manuscript /insert title/ the following is fulfilled:

1) This material is the authors' own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.
3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in the context of prior and existing research.
6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

I agree with the above statements.

Summary statement

We find that the image quality can be maintained in clinical non-contrast chest PCD-CT with a significantly lower radiation exposure compared to a state-of-the-art EID system. This confirms one important application of the new detector technology in clinical chest imaging practice.

Funding statement

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Araki Tetsuro: Formal analysis. **Dako Farouk:** Formal analysis. **Dave Jaydev:** Writing – review & editing, Validation, Data curation. **Nachiappan Arun:** Formal analysis. **Barbosa Eduardo:** Project administration. **Porto Perez Raul:** Formal analysis. **Xu Dongming:** Formal analysis. **Knollman Friedrich:** Writing – review & editing, Validation, Project administration, Methodology. **Donuru Achala:** Writing – original draft. **Noel Peter:** Supervision, Software, Resources, Methodology, Conceptualization. **Litt Harold:** Validation, Supervision, Resources, Project administration.

Declaration of Competing Interest

None of the authors have any conflict of interest.

Acknowledgements

I thank all the co-authors for their expertise and assistance throughout all aspects of our study and for their help in writing the manuscript.

References

[1] R. Smith-Bindman, et al., Use of diagnostic imaging studies and associated radiation exposure for patients enrolled in large integrated health care systems, 1996–2010, JAMA 307 (22) (2012) 2400–2409.

[2] M.L. Kwan, D.L. Miglioretti, E.J.A. Bowles, S. Weinmann, R.T. Greenlee, N.K. Stout, A.K. Rahm, S.A. Alber, P. Pequeno, L.M. Moy, C. Stewart, C. Fong, C.L. Jenkins, D. Kohnhorst, C. Luce, J.M. Mor, J.R. Munneke, Y. Prado, G. Buth, S.Y. Cheng, K. A. Deosaransingh, M. Francisco, M. Lakoma, Y.T. Martinez, M.K. Theis, E. C. Marlow, L.H. Kushi, J.R. Duncan, W.E. Bolch, J.D. Pole, R. Smith-Bindman, Quantifying cancer risk from exposures to medical imaging in the risk of pediatric and adolescent cancer associated with medical imaging (RIC) study: research methods and cohort profile, Cancer Causes Control 33 (5) (2022) 711–726, https://doi.org/10.1007/s10552-022-01556-z. Epub 2022 Feb 2. PMID: 35107724; PMCID: PMC9596345.

[3] K. Rajendran, B.A. Voss, W. Zhou, S. Tao, D.R. DeLone, J.I. Lane, J.M. Weaver, M. L. Carlson, J.G. Fletcher, C.H. McCollough, S. Leng, Dose reduction for sinus and temporal bone imaging using photon-counting detector CT with an additional tin filter, Invest. Radiol. 55 (2) (2020) 91–100, https://doi.org/10.1097/RLI.0000000000000614.

[4] L. Jungblut, A. Euler, J. von Spiczak, T. Sartoretti, V. Mergen, V. Englmaier, A. Landsmann, C.M. Mihai, O. Distler, H. Alkadhi, T. Frauenfelder, K. Martini, Potential of photon-counting detector CT for radiation dose reduction for the assessment of interstitial lung disease in patients with systemic sclerosis, Invest. Radiol. 57 (12) (2022) 773–779, https://doi.org/10.1097/RLI.0000000000000895. Epub 2022 May 28. PMID: 35640003; PMCID: PMC10184807.

[5] D. Graafen, T. Emrich, M.C. Halfmann, P. Mildenberger, C. Düber, Y. Yang, A. E. Othman, J. O' Doherty, L. Müller, R. Kloeckner, Dose reduction and image quality in photon-counting detector high-resolution computed tomography of the chest: routine clinical data, J. Thorac. Imaging 37 (5) (2022) 315–322, https://doi.org/10.1097/RTI.0000000000000661. Epub 2022 Jun 14. PMID: 35699680.

[6] A. Inoue, T.F. Johnson, D. White, C.W. Cox, T.E. Hartman, J.E. Thorne, E. R. Shanblatt, M.P. Johnson, R.E. Carter, Y.S. Lee, K. Rajendran, S. Leng, C. H. McCollough, J.G. Fletcher, Estimating the clinical impact of photon-counting-detector CT in diagnosing usual interstitial pneumonia, Invest. Radiol. 57 (11) (2022) 734–741, https://doi.org/10.1097/RLI.0000000000000888. Epub 2022 May 6. PMID: 35703439.

[7] T. Sartoretti, D. Racine, V. Mergen, L. Jungblut, P. Monnin, T.G. Flohr, K. Martini, T. Frauenfelder, H. Alkadhi, A. Euler, Quantum iterative reconstruction for low-dose ultra-high-resolution photon-counting detector CT of the lung, Diagn. (Basel) 12 (2) (2022) 522, https://doi.org/10.3390/diagnostics12020522. PMID: 35204611; PMCID: PMC8871296.

[8] M.J. Willemink, M. Persson, A. Pourmorteza, et al., Photon-counting CT: technical principles and clinical prospects, Radiology 289 (2) (2018) 293–312.

[9] T. Flohr, M. Petersilka, A. Henning, et al., Photon-counting CT review, Phys. Med. 79 (2020) 126–136.

[10] R. Symons, D.S. Reich, M. Bagheri, et al., Photon-counting computed tomography for vascular imaging of the head and neck: first in vivo human results, Invest. Radiol. 53 (3) (2018) 135–142.

[11] R. Symons, A. Pourmorteza, V. Sandfort, M.A. Ahlman, T. Cropper, M. Mallek, S. Kappler, S. Ulzheimer, M. Mahesh, E.C. Jones, A.A. Malayeri, L.R. Folio, D. A. Bluemke, Feasibility of dose-reduced chest CT with photon-counting detectors: initial results in humans, Radiology 285 (3) (2017) 980–989, https://doi.org/10.1148/radiol.2017162587.

[12] Z. Yu, S. Leng, S. Kappler, et al., Noise performance of low-dose CT: comparison between an energy integrating detector and a photon counting detector using a whole-body research photon counting CT scanner, J. Med. Imaging (Bellingham) 3 (4) (2016), 043503.

[13] R. Gutjahr, A.F. Halaweish, Z. Yu, et al., human imaging with photon counting-based computed tomography at clinical dose levels: contrast-to noise ratio and cadaver studies, Invest. Radiol. 51 (7) (2016) 421–429.

[14] J.R. Rajagopal, F. Farhadi, J. Solomon, P. Sahbaee, B. Saboury, W.F. Pritchard, E. C. Jones, E. Samei, Comparison of low dose performance of photon-counting and energy integrating CT, Acad. Radiol. 28 (12) (2021) 1754–1760.

[15] S.A. Si-Mohamed, J. Miailhes, P.A. Rodesch, S. Boccalini, H. Lacombe, V. Leitman, V. Cottin, L. Boussel, P. Douek, Spectral photon-counting CT technology in chest imaging, J. Clin. Med. 10 (24) (2021) 5757.

[16] N.R. van der Werf, S. Si-Mohamed, P.A. Rodesch, R.W. van Hamersvelt, M.J. W. Greuter, S. Boccalini, J. Greffier, T. Leiner, L. Boussel, M.J. Willemink, P. Douek, Coronary calcium scoring potential of large field-of-view spectral photon-counting CT: a phantom study, Eur. Radiol. 32 (1) (2022) 152–162.

[17] F. Farhadi, J.R. Rajagopal, M. Nikpanah, P. Sahbaee, A.A. Malayeri, W.F. Pritchard, E. Samei, E.C. Jones, M.Y. Chen, Review of technical advancements and clinical applications of photon-counting computed tomography in imaging of the thorax, J. Thorac. Imaging 36 (2) (2021) 84–94.

[18] K. Rajendran, M. Petersilka, A. Henning, E.R. Shanblatt, B. Schmidt, T.G. Flohr, A. Ferrero, F. Baffour, F.E. Diehn, L. Yu, P. Rajiah, J.G. Fletcher, S. Leng, C. H. McCollough, First clinical photon-counting detector CT system: technical evaluation, Radiology 303 (1) (2022) 130–138.

[19] R. Smith-Bindman, J. Lipson, R. Marcus, K.P. Kim, M. Mahesh, R. Gould, A. Berrington de González, D.L. Miglioretti, Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer, Arch. Intern. Med. 169 (22) (2009) 2078–2086.

[20] R. Symons, T.E. Cork, P. Sahbaee, M.K. Fuld, S. Kappler, L.R. Folio, D.A. Bluemke, A. Pourmorteza, Low-dose lung cancer screening with photon-counting CT: a feasibility study, Phys. Med. Biol. 62 (1) (2017) 202–213, https://doi.org/10.1088/1361-6560/62/1/202. Epub 2016 Dec 17. PMID: 27991453; PMCID: PMC5237389.

[21] F.K. Kopp, H. Daerr, S. Si-Mohamed, A.P. Sauter, S. Ehn, A.A. Fingerle, B. Brendel, F. Pfeiffer, E. Roessl, E.J. Rummeny, D. Pfeiffer, R. Proksa, P. Douek, P.B. Noël, Evaluation of a preclinical photon-counting CT prototype for pulmonary imaging, Sci. Rep. 8 (1) (2018), 17386, https://doi.org/10.1038/s41598-018-35888-1. PMID: 30478300; PMCID: PMC6255779.

[22] D.J. Bartlett, C.W. Koo, B.J. Bartholmai, K. Rajendran, J.M. Weaver, A. F. Halaweish, S. Leng, C.H. McCollough, J.G. Fletcher, High-resolution chest computed tomography imaging of the lungs: impact of 1024 matrix reconstruction and photon-counting detector computed tomography, Investig. Radiol. 54 (2019) 129–137.

[23] M.M. Woeltjen, J.H. Niehoff, A.E. Michael, S. Horstmeier, C. Moenninghoff, J. Borggrefe, J.R. Kroeger, Low-dose high-resolution photon-counting CT of the lung: radiation dose and image quality in the clinical routine, Diagn. (Basel) 12 (6) (2022) 1441, https://doi.org/10.3390/diagnostics12061441. PMID: 35741251; PMCID: PMC9221815.

[24] T. Adejoh, C.C. Nzotta, Head computed tomography: dose output and relationship with anthropo-technical parameters, West Afr. J. Radiol. 23 (2) (2016) 113–117.

[25] C.H. McCollough, A.N. Primak, N. Braun, J. Kofler, L. Yu, J. Christner, Strategies for reducing radiation dose in CT, Radiol. Clin. North Am. 47 (2009) 27–40.