Assessment of image quality in photon-counting detector computed tomography of the wrist – An ex vivo study

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ABSTRACT

Purpose: The aim of this study was to evaluate the effect of reconstruction parameters on image quality in wrist imaging using photon-counting detector CT (PCD-CT) and to compare the results with images from an energy-integrating detector CT (EID-CT).

Methods: Twelve cadaveric wrist specimens were examined using a prototype PCD-CT and a clinical EID-CT using similar radiation dose. Reconstruction parameters were matched between scanners. Also, sharper reconstruction kernels, a larger matrix size, and smaller slice thicknesses were evaluated for PCD-CT. Image noise, contrast-to-noise ratio (CNR) and image sharpness in trabecular structures were quantitatively measured. Image quality with respect to the visibility of cortical and trabecular bone structures was assessed by six radiologists using visual grading methods.

Results: Images obtained with PCD-CT had lower noise (42.6 ± 3.9 HU vs 75.1 ± 6.3 HU), higher CNR (38.9 ± 4.5 vs 19.0 ± 2.4) and higher trabecular sharpness (63.5 ± 6.0 vs 53.7 ± 8.5) than those obtained with EID-CT using similar scan and reconstruction parameters (p < 0.001). The image sharpness in trabecular structures was further improved by using sharper kernels, despite higher noise levels. Radiologists had a strong preference for PCD-CT images both in terms of spatial resolution and suitability for bone imaging. Visual grading analysis showed an improved visibility of cortical bone, trabeculae and nutritive canals (p < 0.005).

Conclusion: PCD-CT offers improved image quality regarding bone structures in the wrist relative to EID-CT systems, particularly when sharper reconstruction kernels, smaller slice thickness and a larger image matrix size are used.

1. Introduction

The wrist is a complex structure, and its function is dependent on the integrity of the bones, joints and ligaments. Radiographic wrist images are often the clinical routine for diagnosis of fractures and malalignment, degenerative and inflammatory changes, as well as for the assessment of healing. Because of the complex anatomy of the wrist, the role of computer tomography (CT) has increased as it provides multi-planar reconstructions and better diagnostic accuracy [1–3]. However, the limited spatial resolution of the current generation of CT detectors makes it difficult to identify small pathological alterations such as subtle fractures, early erosions in arthritis or changes in osteoporotic bone [4–8].

Conventional CT scanners, also known as energy-integrating detector CT or EID-CT scanners, make use of scintillators that upon interaction with X-ray photons generate visible light which is detected by photodiodes and converted to electric signals. However, to avoid cross talk between neighboring detector elements, there is a need for separating septa. Photon counting detector computed tomography (PCD-CT) has recently been commercialized and enables improvements in imaging performance compared with conventional EID-CT. PCD-CT uses a direct-conversion technique where X-ray photons are, upon absorption in a
semiconductor layer, directly converted into electron hole pairs. The moving charges are collected and generate an electrical signal proportional to the photon energy. Unlike with EID-CT, the number of individual photons with an energy level that exceeds a preset threshold can be counted, and different energy levels can be separated and weighted in the images. The detector technique also enables smaller detector elements without the need for separating septa. As a result of these improvements in technology, PCD-CT allows for a higher spatial resolution, increased contrast-to-noise ratio, and a higher dose efficiency [9,10].

Earlier studies have shown image quality advantages for PCD-CT compared with EID-CT. Improvements are shown in phantoms [11] as well as in several different musculoskeletal applications, such as imaging of temporal bone [12], wrist [13], small bone structures [14] and bone metastases [15]. However, the effect of variations in reconstruction kernel, image matrix size and slice thickness has not been elucidated in the context of bone imaging. The aim of this study was to assess the improvement of image quality quantitatively and qualitatively in wrist imaging using PCD-CT as compared with a state-of-the-art EID-CT using the same radiation dose. We specifically investigated the effect of the reconstruction kernel, matrix size and slice thickness on the visualization of trabecular and cortical bone structures in cadaveric wrist specimens.

2. Material and methods

2.1. Cadaver wrist specimens

Twelve human cadaveric wrists specimens from 12 different anonymous individuals who had donated their bodies for study and research purposes (6 female and 6 men, 47–90 years of age, mean age 63 years) were included. The specimens included hand and forearm. The specimens were handled and scanned in accordance with the regulations of our institute.

2.2. Image acquisition and reconstruction

All wrist specimens were scanned with a commercially available EID-CT system (SOMATOM Force; Siemens Healthineers, Forchheim, Germany) and a prototype PCD-CT system (SOMATOM Count Plus; Siemens Healthineers, Forchheim, Germany). An overview of the system and scan parameters is given in Table 1. The EID-CT and PCD-CT scans were made in ultra-high resolution (UHR) mode using 120 kV, rotation time 1 s, pitch 0.85 and CTDIvol 5.3 mGy. For the EID-CT, collimation was 192 × 0.6 mm, and for the PCD-CT 120 × 0.2 mm. The EID-CT system has a focal spot size of 0.4 × 0.6 mm (in-plane × z-direction), while the focal spot size of the PCD-CT system is dependent on the tube load and varies between 0.4 × 0.6 mm and 0.4 × 0.4 mm (in-plane × z-direction). Iterative reconstruction algorithms were used; for EID-CT, ADMIRE level 3 and for PCD-CT, PNR (QIR) level 3. Axial images were reconstructed using the smallest possible slice thickness on each system, which was 0.4 mm on EID-CT. For PCD-CT, both 0.2 mm and 0.4 mm slice thickness were used. For all reconstructions, there was a 50 % overlap between slices. The field of view (FOV) was set to 90 mm. Matrix size was 512 × 512 for EID-CT, while both 512 × 512 and 2048 × 2048 were used for PCD-CT. The standard kernel for clinical use, optimized for imaging of bone structures, Ur77, was used for images from EID-CT. For PCD-CT the most similar kernel available, Br76u, was used with addition of sharper kernels, Br80u, Br84u and Br89u (Table 2).

2.3. Quantitative assessment

CT numbers (Hounsfield units, HU) were measured in the axial images by placing circular 2 mm2 regions of interest (ROI) in the cortical bone of the scaphoid, and 10 mm2 ROI in subcutaneous fat (Fig. 1). All ROI were placed by the first author (NK). Noise was defined as the standard deviation (SD) value of the CT number within a ROI in subcutaneous fat. Bone contrast to noise ratio (CNRbone) was defined as:

\[
\text{CNR}_{\text{bone}} = \frac{\text{CT}_{\text{bone}} - \text{CT}_{\text{fat}}}{\text{SD}_{\text{fat}}}
\]

To evaluate the spatial resolution in the images, we used multi-slice histogram analysis, adapted from Grunz et al. [16]. In each image stack, a cuboid, 10 × 10 × 10 mm volume of interest (VOI) was selected in the trabecular bone of distal radius. The number of voxels which are not “intermediate” CT numbers (100–500 HU) relative to the total number of voxels in the VOI was used as a measure of image sharpness at boundaries between trabecular bone and bone marrow:

\[
\text{trabecular sharpness} = \frac{N_{\text{ROI}} - N_{\text{ROI-500 HU}}}{N_{\text{ROI}}} \cdot 100\%
\]

Thus, a higher value indicates better separation of the trabecular structure from the bone marrow and hence a higher spatial resolution.

2.4. Qualitative assessment

Six radiologists, with specialist qualifications (between 5 and 33 years of experience), were asked to assess axial image stacks from each of the twelve wrist specimens. Images were assessed on diagnostic relevance for dispensing informed consent and for cancer diagnosis and staging. To evaluate the spatial resolution in the images, we used multi-slice histogram analysis, adapted from Grunz et al. [16]. In each image stack, a cuboid, 10 × 10 × 10 mm volume of interest (VOI) was selected in the trabecular bone of distal radius. The number of voxels which are not “intermediate” CT numbers (100–500 HU) relative to the total number of voxels in the VOI was used as a measure of image sharpness at boundaries between trabecular bone and bone marrow:

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Fig. 1. Regions of interest (ROI) in subcutaneous fat and cortical bone for noise measurements in an EID-CT image (Ur77 / 0.4 mm / 512 × 512) and in a PCD-CT image (Br89u / 0.2 mm / 2048 × 2048). Display W/L = [3000 / 500] HU.

Alvsborg Hospital [17]. The ViewDEX program randomized the cases and logged the responses of the observers in a separate log file.

2.4.1. Preference tests

Pairwise comparisons were made between PCD-CT and EID-CT images, and between PCD-CT images reconstructed with different matrix sizes and slice thicknesses (Table 3). The axial image stacks, covering about 1 cm at the level of the distal radioulnar joint, were assessed with respect to bone imaging and spatial resolution using a five-point preference rating scale (the score was set to 1 when the quality of the images from group A was rated as “much better” or “slightly better” and to −2 or −1 when the images from group B were rated as “much better” or “slightly better”, respectively). A score of zero indicated no preference for either group A or group B.

2.4.2. Visual grading analysis

Visual grading analysis is a visual grading technique for clinical settings, based on the hypothesis that the possibility to detect pathology correlates with the clarity of the reproduction of important anatomy [18]. The visibility of anatomical structures in test images is graded and compared against the visibility of the same structures within reference images [19]. The image stacks were reconstructed from scans using EID-CT with our clinical protocol described above, and from PCD-CT scans with two different reconstructions: one with parameters similar to EID-CT (Br76u, matrix size 512 × 512 and slice thickness 0.4 mm) and the other with parameters hypothesized to further improve image quality, i.e., sharper kernel (Br84u), larger matrix size (2048 × 2048) and smaller slice thickness (0.2 mm). The stacks covered about 1 cm of the wrist at the level of the lunate bone. Image stacks, reconstructed in the axial plane, were displayed one at a time in random order.

The visualization of bone structures and overall imaging quality was assessed using a 7-point ordinal rating scale (1 = very poor, 2 = poor, 3 = acceptable, 4 = fair, 5 = good, 6 = very good, 7 = excellent), regarding the following four questions:

• How well are the nutritive canals in the lunate visualized?
• How well is the trabecular architecture visualized?
• How well is the delineation/integrity of the cortical bone visualized?
• What is your opinion of image quality in general?

2.5. Statistics

Data in text, tables and figures are presented as mean (standard deviation). Comparisons between results of the quantitative analyses were made using one-way analyses of variance (ANOVA). Results of the preference tests were analyzed using Wilcoxon signed rank tests. Sidak’s post-tests were used to correct for multiple comparisons. The null hypothesis was that there was no difference in image quality between scanners or reconstruction parameters. For the visual grading analysis, area under curve (AUC) was calculated using VGC Analyzer software with settings “paired data” and “random readers” [20]. Results were considered significant if the 95% confidence interval of AUC did not overlap the 0.5 level. Statistical calculations were done using GraphPad Prism version 9 for macOS (GraphPad Software, San Diego, USA). Statistical significance was assumed for p values < 0.05.

3. Results

3.1. Quantitative assessment

Results of the assessment of noise, CNR and spatial resolution (measured as trabecular sharpness) are shown in Table 4. With similar reconstruction parameters, there was less noise in PCD-CT images (42.6 ± 3.9 HU) than in EID-CT images (75.1 ± 6.3 HU), while CNR was higher in PCD-CT images (38.9 ± 4.5) than in EID-CT images (19.0 ± 2.4). Also, trabecular sharpness was higher in PCD-CT (63.5 ± 6.0 %) than in EID-CT (53.7 ± 8.5 %). Noise increased and CNR decreased with sharper reconstruction kernels in PCD-CT images. Trabecular sharpness increased significantly using smaller slice thickness when using Br80u and increased even further up to 73.0 ± 3.1 when using sharper reconstruction kernels. Matrix size did not significantly affect noise, CNR or trabecular sharpness.

3.2. Qualitative assessment

3.2.10 Preference tests.

Two of the twelve cases were excluded from the comparison between EID-CT and PCD-CT images due to accidental deletion of image stacks during preprocessing of image metadata. Radiologists strongly preferred the PCD-CT images (median score +2, “strong preference”, p < 0.001).
Solid lines indicate the median score, dotted lines show the 25th and 75th percentiles. AUC indicates significant difference between PCD-CT and EID-CT. * indicates significant difference between reconstructions with 0.2 mm slice thickness compared with 0.4 mm. † indicates significant difference between reconstructions with 2048 × 2048 matrix size compared with 512 × 512. **/***: p < 0.05, ***/****: p < 0.01, ***/***: p < 0.001.

4. Discussion

In the current study twelve human wrist specimens were examined with a prototype PCD-CT scanner and compared with scans obtained from a clinical EID-CT scanner using our clinical protocol. The PCD-CT images were reconstructed using different reconstruction kernels, matrix sizes, and slice thicknesses. The main finding was that PCD-CT offers better image quality compared with conventional EID-CT in terms of noise, CNR, and spatial resolution in visualizing the trabecular bone structures of the wrist. Quantitative analysis showed that PCD-CT images had less noise, higher CNR and better spatial resolution (sharper visualization of trabecular structures) compared with EID-CT at matched radiation doses and similar reconstruction parameters. These results were confirmed by qualitative image assessments showing that the radiologists preferred images obtained from PCD-CT to EID-CT for evaluation of bone structures. Visual grading analysis showed that PCD-CT is superior in visualizing cortical delineation and small bone

Table 5
Mean AUC values from visual grading analysis. AUC is a measure of the difference in image quality between two image sets. AUC value = 0.5 indicates same image quality, AUC > 0.5 indicates better image quality for the test images, in this case PCD-CT images. p < 0.005 for all results.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Nutritive canals of the lunate</th>
<th>Trabecular architecture</th>
<th>Cortical integrity</th>
<th>Overall image quality</th>
</tr>
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<tbody>
<tr>
<td>PCD-CT vs EID-CT (Br76u, 0.4 mm, 512 × 512)</td>
<td>0.96 (0.03)</td>
<td>0.97 (0.02)</td>
<td>0.93 (0.04)</td>
<td>0.95 (0.04)</td>
</tr>
<tr>
<td>PCD-CT vs EID-CT (Br84u, 0.2 mm, 2048 × 2048)</td>
<td>0.90 (0.05)</td>
<td>0.93 (0.03)</td>
<td>0.97 (0.02)</td>
<td>0.91 (0.04)</td>
</tr>
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Fig. 2. Observer preference for scanner type (EID-CT vs PCD-CT), as well as for different slice thicknesses (0.4 mm vs 0.2 mm) and different matrix sizes (512 × 512 vs 2048 × 2048) in PCD-CT, both in terms of resolution and visualization of bone structures. The plot shows the frequency distribution of the scores by the observers. Solid lines indicate the median score, dotted lines show the 25–75% interquartile range.
structures, including trabeculae and nutritive canals. Importantly, the results of this study show that the remarkable improvements in qualitative and quantitative image quality measures can be attributed to the smaller slice thickness and the possibility to use sharper reconstruction kernels with PCD-CT.

Spatial resolution is dependent on several factors, such as size of the detector elements, focal spot size and choice of reconstruction parameters, kernel such as kernel, FOV, slice thickness and matrix size. The improved sharpness of trabecular structures seen in this study can be attributed mainly to the smaller detector elements (0.151 × 0.176 mm² at isocenter) and reduced slice thickness (0.2 mm) of the PCD-CT compared to the EID-CT (0.25 × 0.25 mm², 0.4 mm when the UHR mode is used). While reducing detector element size and slice thickness results in an improved spatial resolution, this typically comes at the cost of higher noise and therefore, lower CNR. However, because of the direct conversion of X-ray photons to electrical signals, the count weighting of photons and the absence of septa between detector elements, detector efficiency is substantially improved in PCD-CT at comparable reconstruction kernels [21].

Reconstruction kernels can be chosen depending on which balance is preferred between noise and sharpness. In our clinical protocol for the EID-CT, Ur77 is used, and therefore a kernel with similar characteristics, Br76u, was chosen for the PCD-CT to make comparisons of image quality. Using Br76u, the radiologists preferred the thinner slices for skeletal imaging, and they experienced spatial resolution superior. This was in agreement with the measured noise level using a slice thickness of 0.2 mm (58.8 ± 4.4) which was well below that of the EID-CT images (75.1 ± 6.3).

Preliminary experience of the images from our prototype PCD-CT had shown that sharper kernels could be used while still having acceptable noise levels, which can be explained by the better noise characteristics of the PCD-CT [21]. Therefore, additional qualitative assessments in this study were made using Br84u. Although this reconstruction kernel together with the smaller slice thickness yields a somewhat higher noise level and slightly lower CNR compared with the clinical protocol with EID-CT, radiologists considered the images superior in terms of overall image quality and visualization of cortical and trabecular bone structures, and nutritive canals.

Increasing the matrix size from 512 × 512 to 2048 × 2048 did not significantly affect noise, CNR or trabecular sharpness. However, the results of the preference tests showed that the radiologists preferred the images reconstructed at larger matrix size, both in terms of suitability for bone imaging and spatial resolution.

Spatial resolution in clinical images determines the sharpness with which small, high-contrast details, such as bone structures, can be visualized. In this study, we used multi-slice histogram analysis as a method for evaluating spatial resolution in wrist images. Visualizing human trabeculae requires a high spatial resolution, since they are about 0.2 mm in diameter, and there are about 1.5 trabeculae per mm in the distal radius [22,23]. The trabeculae are thus approximately the same diameter as the theoretical size of the pixels of the PCD-CT images when using FOV 90 mm and matrix size 512 × 512, i.e., 0.18 × 0.18 mm². With the larger matrix size, 2048 × 2048, the pixels are 0.04 × 0.04 mm². While this in theory allows a better image resolution, the limiting in-plane spatial resolution of the PCD-CT scanner using the Br89u kernel is 0.3 mm (0 % MTF 33 cm⁻¹) [11]. This explains why increasing the matrix size beyond 512 × 512 did not have a large effect on the spatial resolution as observed in this study, even though it resulted in a perceived difference in visibility of bone structures to the observers. Another factor that might limit the spatial resolution, despite a large matrix size, is that the minimal reconstructed slice thickness is 0.2 mm, which limits the voxel size in z-direction regardless of matrix size. Since using a matrix size of 2048 × 2048 increases the amount of storage needed for storing and viewing the images by a factor of 16 compared with the standard matrix of 512 × 512, the slight increase in image quality is probably not worth it in most clinical applications.

Our results are in line with earlier studies by Grunz et al. showing superior visualization in terms of higher SNR and observer ratings for the PCD-CT system compared to conventional EID-CT in wrist imaging [13]. Improved sharpness in cortical bone, as well as higher SNR, has also been shown by Bette et al. in a study reporting on bone detail imaging in rodents [14]. The novelty in the current study is that we specifically investigated the added value of sharper reconstruction kernels, larger matrix sizes and smaller slice thickness available in the PCD-CT scanner. Also, while earlier studies have evaluated SNR and CNR, these measures are not specific for spatial resolution and sharpness of the trabecular bone structures. In this study, we have quantitatively measured the sharpness of the trabecular structure using histogram analysis. Finally, our observer study assessed specific diagnostic aspects in the images, including the visualization of cortical integrity, trabecular structures and of the nutritive canals, while earlier studies instead evaluated “general image quality”.

There were several limitations in our study. Because we used cadaveric wrists without any metallic implants, the effect of metal artefacts was not considered. Also, the specimens did not have any traumatic bone injuries. The visibility of fractures and the observers’ confidence in distinguishing a fracture line from normal anatomic structures such as nutritive canals were therefore not evaluated. Also, the visibility of soft tissues was not evaluated in this study.

The number of specimens included was limited, and donors were between 47 and 90 years of age (mean 63 years). Factors such as osteopenia, degenerative bone changes and patient age might have influenced the results. Although imaging and reconstruction parameters were not presented to the observers, they might have become familiar with the different image characteristics, which might have influenced the ratings.

By using our clinical protocol for skeletal imaging with the EID-CT, we might not have used the system to its full potential since it offers a larger matrix size (1024 × 1024). Thus, comparisons between both systems’ best possible performances were not made. Based on our results, however, we think it is unlikely that using the increased matrix size would have made a large impact on the results.

Finally, the study was carried out on a prototype PCD-CT scanner of which an updated version, the NAEOTOM Alpha (Siemens Healthineers, Forchheim, Germany) has recently become commercially available. Although we expect the results of this study to apply to images acquired using the new system, which is based on the same detector technology, we cannot rule out that the performance will differ between the current prototype version and the commercial system.

In conclusion, this study adds to the evidence that PCD-CT improves image quality in terms of lower noise, higher CNR and observer preference in wrist imaging compared with EID-CT. Importantly, this study for the first time shows the added value of sharper reconstruction kernels and lower slice thickness in PCD-CT for visualizing bone details and structures, and a more limited effect of increased image matrix size. The results suggest that PCD-CT may enable more exact diagnosis of subtle fractures and other bone pathologies, better visualization of bone with decreased mineral density or osteopenia, and more accurate assessment of fracture healing. However, this needs to be evaluated in future patient studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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