Assessment of visibility of bone structures in the wrist using normal and half of the radiation dose with photon-counting detector CT

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ABSTRACT

Purpose: To quantitatively and qualitatively assess the visibility of bone structures in the wrist on photon-counting detector computed tomography (PCD-CT) images compared to state-of-the-art energy-integrating detector CT (EID-CT).

Method: Four human cadaveric wrist specimens were scanned with EID-CT and PCD-CT at identical CTDIvol of 12.2 mGy and with 6.1 mGy (half dose PCD-CT). Axial images were reconstructed using the thinnest possible slice thickness, i.e. 0.4 mm on EID-CT and 0.2 mm on PCD-CT, with the largest image matrix size possible using reconstruction kernels optimized for bone (EID-CT: Ur68, PCD-CT: Br92). Quantitative evaluation was performed to determine contrast-noise ratio (CNR) of bone/fat, cortical and trabecular sharpness. An observer study using visual grading characteristics (VGC) analysis was performed by six observers to assess the visibility of nutrient canals, trabecular architecture, cortical bone and the general image quality.

Results: At equal dose, images obtained with PCD-CT had 39 \pm 6\% lower CNR (p = 0.001), 71 \pm 57\% higher trabecular sharpness in the radius (p = 0.02) and 42 \pm 8\% (p < 0.05) sharper cortical edges than those obtained with EID-CT. This was confirmed by VGC analysis showing a superior visibility of nutrient canals, trabecular and cortical bone area under the curve (AUC) > 0.89 for PCD-CT, even at half dose.

Conclusions: Despite a lower CNR and increased noise, the trabecular and cortical sharpness were twofold higher with PCD-CT. Visual grading analysis demonstrated superior visibility of cortical bone, trabecular, nutrient canals and an overall improved image quality with PCD-CT over EID-CT. At half dose, PCD-CT also yielded superior image quality, both in quantitative measures and as evaluated by radiologists.

Abbreviations: AUC, area under the curve; CNR, contrast-to-noise ratio; CT, computed tomography; EID, energy-integrating detector; FWHM, full width at half maximum; HU, Hounsfield unit; MDCT, multi-detector CT; PCD, photon-counting detector; ROI, region of interest; SD, standard deviation; VGC, visual grading analysis; VGC, visual grading characteristics; VOI, volume of interest.

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1. Introduction

Computed tomography (CT) is a reliable, widely available and fast imaging tool and is therefore frequently used to evaluate fine bone structures, especially in the detection or follow-up of bone trauma. As the wrist is a joint with complex anatomy, high-resolution imaging of trabecular and cortical bone is of clinical importance to delineate bone edges, localize fractures and visualize anatomic relationships. Ultra-high-resolution (UHR) is provided by so called dedicated UHR-CT scanners with smaller detector elements than current multi-detector CT (MDCT) systems or the use of a special high-resolution imaging mode in MDCT by the insertion of a moveable grid and comb filter in front of the multi-row detector in both in-plane and z-axis direction [1,2]. Both techniques require an increase in radiation dose to achieve comparable noise characteristics compared to a normal scan mode without high-resolution. Current MDCT scanners are energy-integrating detector (EID) CT scanners and use solid-state scintillation detectors where X-rays are first converted to visible light which is subsequently converted to an electric signal. Photon-counting detector (PCD) CT scanners have the ability to provide energy-resolved signals and allow for a direct conversion of the absorbed X-rays. This comes with the advantage of increased geometrical dose efficiency, absence of electronic noise in the image and allows for smaller detector sub-pixels without the use of a moveable comb filter [3]. Therefore, PCD-CT may allow for UHR imaging with improved spatial resolution, possibly at a lower radiation dose. In recent studies, PCD-CT has been shown to result in higher sharpness, improved delineation of fine bone structures and superior image quality than EID-CT [4-7]. However, a detailed assessment of improvements in image quality and the ability to reduce radiation dose in imaging of the wrist using PCD-CT remains limited.

The aim of this study is to quantitatively and qualitatively assess the visibility of the cortical and trabecular bone structures in the human wrist on UHR PCD-CT images at equal and half of the dose compared to UHR EID-CT images.

2. Material and methods

2.1. Data acquisition and reconstruction parameters

Four randomly chosen cadaveric human wrist specimens (mean age 88.6 ± 1.3 years) were scanned on an EID-based CT system (SOMATOM Edge Plus with Syngo CT version VB20, Siemens Healthineers, Forchheim, Germany) and the first clinical PCD-based CT system (NAEOTOM Alpha with Syngo CT version VA40A, Siemens Healthineers, Forchheim, Germany) [8]. The wrist specimens were thawed at the time of imaging. The dose of the PCD-CT was matched to the dose level of 12.2 mGy of the clinically used EID-CT protocol and with tube current modulation disabled for methodological reasons. An UHR-comb filter is no longer needed with the use of the PCD-CT system. As the detector is covered for 50 % in the EID-CT system, adapting and optimization of the radiation dose of a scan protocol from the EID-CT to the PCD-CT is feasible. Therefore, additional scans with 6.1 mGy were performed on the PCD-CT to evaluate the effect on image quality and acceptance by radiologists when using half of the clinically used radiation dose. The wrists were positioned in the isocenter of the CT gantry. Axial images were reconstructed using the thinnest possible slice thickness, i.e., 0.4 mm on EID-CT and 0.2 mm on PCD-CT (UHR-mode), with the largest image matrix size possible (EID-CT: 512 × 512; PCD-CT: 1024 × 1024) using reconstruction kernels optimized for bone (EID-CT: Ur68; PCD-CT: Br92). A detailed overview of the acquisition and reconstruction parameters is given in Table 1.

2.2. Image analysis

2.2.1. Quantitative assessment

Contrast-to-noise ratio (CNR) was determined for bone/fat by measuring CT numbers (Hounsfield units, HU) in circular regions of interest (ROI) in the axial images of approximately 20 mm in subcutaneous fat and in the cortical bone of the distal radius (Fig. 1). All ROI were placed by one of the authors (NK) at the same occasion to overcome differences in anatomical locations. Noise was defined as the standard deviation (SD) of CT numbers within the ROI. Bone contrast was defined as:

\[ \text{CNR}_{\text{bone}} = \frac{CT_{\text{bone}} - CT_{\text{fat}}}{SD_{\text{roi}}} \]

Trabecular sharpness was evaluated by multi-slice histogram analysis, as described and used by Kämmerling et al. [6]. A volume of interest (VOI) of approximately 10 mm³ was selected in the trabecular bone of the distal radius and the histogram of the voxels in the VOI was calculated (Fig. 2). Measurements were performed in the same area and visually matched between scans by one of the authors (ET). Bone marrow is fatty and has low CT-numbers (<100 HU), while bone has higher HU-values (>500). Intermediate CT numbers (100–500 HU) are assumed to be caused by blurring due to the finite spatial resolution in the images and partial volume effects. The number of voxels representing marrow and bone 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:

\[ \text{trabecular sharpness} = \frac{N_{\text{BBM}} - N_{100-500\text{HU}}}{N_{\text{VOI}}} \times 100\% \]

Table 1

<table>
<thead>
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<th>Table 1</th>
<th>Acquisition and reconstruction parameters.</th>
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<tr>
<td>Scanner name / software version</td>
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<td>Reconstruction matrix size</td>
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</tr>
</tbody>
</table>

*Data-acquisition = 16 × 0.3 mm by UHR comb-filter.

Fig. 1. Measurement of contrast-to-noise ratio. Circular regions of interest (red circles) were positioned in subcutaneous fat and in the cortical bone of the distal radius for measuring CT numbers (HU) to determine the contrast-to-noise ratio for bone/fat.
Thus, a higher value indicates better separation of the trabecular structure from the bone marrow.

The sharpness of the visualization of the cortical bone structures was determined by fitting the CT-numbers across the cortical boundary to a so-called error function, which is defined as:

\[ y = b + c \cdot \text{erf}\left(\frac{x}{d}\right) \]

where \( b \) represents the CT number in soft tissue, \( c \) is the difference in CT numbers between the cortical bone and soft tissue, and \( d \) is related to the full width at half maximum (FWHM) of the Gaussian used to compute the error function:

\[ FWHM = d \cdot 2\sqrt{\ln 2} \]

The FWHM is thus a measure of the sharpness of the cortical edge, with a smaller value indicating a sharper edge (Fig. 3). Cortical sharpness was measured on the medial cortical interface of the distal radius. The areas are indicated in Fig. 3 of the manuscript and were performed by one of the authors (ET). Analysis were performed for all exams from both scanners for the clinical dose and the half dose level of the PCD-CT.

Fig. 2. Measurement of trabecular sharpness. A. Volume of interest (VOI) in the distal radius; B. Histogram of CT numbers in the VOI, showing voxels representing bone marrow (dark grey), voxels representing trabeculae (light grey), and intermediate voxels due to partial volume effects. A smaller number of intermediate voxels indicates sharper delineation of the trabecular bone.

Fig. 3. Example showing quantitative assessment of cortical interface in the distal radius. A,D: overview of distal radioulnar joint; B,E: detailed view of the cortical interface; C, F: cortical profile with fitted edge function and full width half maximum (FWHM). A, B and C represent EID-CT, while D, E and F represent PCD-CT.
2.2.2. Qualitative assessment

Visual grading analysis (VGA) was performed by six radiologists with experience as certified musculoskeletal radiologists (between 6 and 20 years of experience) to assess and grade the visualization of bone structures and image quality by means of four questions:

- Q1 How well are the nutrient canals in the lunate visualized?
- Q2 How well is the trabecular architecture visualized?
- Q3 How well is the delineation/integrity of the cortical bone visualized?
- Q4 What is your opinion of the image quality in general?

The images were rated using a 7-point ordinal rating scale: 1 = very poor, 2 = poor, 3 = acceptable, 4 = fair (not good/not bad), 5 = good, 6 = very good, 7 = excellent.

The observers were provided with image stacks covering the entire wrist reconstructed from EID-CT and PCD-CT data: 1. EID-CT normal dose versus PCD-CT normal dose and 2. EID-CT normal dose versus PCD-CT half dose. Images were assessed using ViewDex 3.0, a validated Java-based software for presentation and evaluation of medical images in observer performance studies [9–11]. All cases were randomly presented to the observers and without technical or demographic details.

2.3. Statistical analysis

Data in text, tables and figures are presented as mean (SD). Comparisons for the preference tests were made using Wilcoxon signed rank tests. For the visual grading analysis, area under curve was calculated using visual grading characteristics (VGC) Analyzer software with settings “paired data” and “random readers” [12]. The output of the analyzer software is the area under the VGC curve (AUCVGC). Values of > 0.5 indicate a superior image quality of PCD-CT. 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

3.1.1. CNR and noise

At equal dose, the CNR and noise levels with PCD-CT were 39%±6% lower (p = 0.002) and 120 ± 37% higher (p = 0.006) than with EID-CT (Fig. 4). Mean CNR values were 15.8 ± 2.4 HU and 25.7 ± 1.9 HU with PCD-CT and EID-CT, respectively. The CNR and noise levels with PCD-CT at half dose were 59 ± 12% lower (p = 0.002) and 252 ± 160% higher (p = 0.05) than with EID-CT at normal dose (Fig. 4). Absolute CNR values ranged between 10.6 ± 3.5 HU with PCD-CT at half dose.

3.1.2. Trabecular sharpness

The trabecular sharpness with PCD-CT was 71 ± 57 % and 66 ± 59% higher (p = 0.04) for normal dose and half dose, respectively, compared with the trabecular sharpness with EID-CT (Fig. 5).

3.1.3. Cortical sharpness

The FWHM of the cortical edge was 0.28 ± 0.02 mm with EID-CT and was 0.16 ± 0.02 mm and 0.15 ± 0.03 mm with PCD-CT at normal dose and half dose, respectively. Therefore, the cortical edge sharpness with PCD-CT was 42 ± 8 % and 45 ± 8 % (p < 0.05) higher for the normal and half dose, respectively than the cortical sharpness with EID-CT (Fig. 6).

3.2. Qualitative assessment

Radiologists’ evaluation results are visualized in Fig. 7. On average, the observers rated the visibility of bone structures and general image quality as ‘very good’ to ‘excellent’ for PCD-CT images at normal and half dose compared to a rating of ‘acceptable’ to ‘fair (not good/not bad)”
PCD-CT offers superior visibility of bone structures in the wrist even at half dose compared to EID-CT at normal dose. These results are relevant for several pathologies, especially the detection, characterization and follow-up of fractures, but also other pathologies such as degenerative and inflammatory disease.

Our results are in line with previous results by Bette et al. and Grunz et al. [4,5]. These papers also demonstrated that despite a decrease in CNR and increase in noise, the overall image quality and bone assessment was superior with PCD-CT. Grunz et al. also described visualization of bone microarchitecture of the wrist. Their findings were based on an investigational PCD-CT system (SOMATOM Count Plus; Siemens Healthineers) with lower kernel sharpness and lower matrix size than used in our study and the image quality was semi-quantitatively assessed with signal-to-noise ratio’s and CNR only. Two other recent studies performed on the same investigational PCD-CT system assessed the image quality of the wrist with PCD-CT as well. Kammerling et al. investigated the effect of reconstruction parameters on image quality of the (cadaveric) wrist and used a similar visual grading method, but used equal radiation dose levels and an EID-CT without comb filter [6]. Rajendran et al. performed a clinical study for the improved visualization of the wrist with PCD-CT [7]. They also performed a subjective analysis of bone structures with a focus on diagnostic confidence. Our study differs from their study in a few distinct ways: Two dose levels, quantitative measurements of both cortical and trabecular sharpness and a VGC analysis of specific anatomical features relevant for wrist imaging. Interestingly, our study demonstrated a much higher noise level for PCD-CT than was found in their study. This can be explained by using a higher kernel number (Br92 instead of Br84), matrix size (1024 instead of 512) and thinner slice width (0.2 mm instead of 0.4 mm).

Our study has some limitations that need to be considered. First, we compared the clinical CT protocol of the EID-CT with the clinical CT protocol of the PCD-CT to evaluate the best possible performance of both CT systems. Consequently, differences in kernel, matrix and slice thickness were introduced. Second, the number of specimens used was limited, but were of comparable age and did not contain obvious pathological characteristics. However, because of that, the diagnostic performance of PCD-CT to visualize specific pathologic findings could not be assessed. Third, because of the use of cadaveric specimens, the effect of wrist motion could not be assessed. However, exam times were already reduced.

In this study, a comparison between UHR of a PCD-CT and UHR of EID-CT was qualitatively and quantitatively assessed with the aid of cadaveric human wrists. The results show that sharper reconstructions kernels can be used with PCD-CT and that, despite an increase in noise and subsequent reduction in CNR, PCD-CT offers superior visibility of bone structures in the wrist even at half dose compared to EID-CT at normal dose. These results are relevant for several pathologies, especially the detection, characterization and follow-up of fractures, but also other pathologies such as degenerative and inflammatory disease.

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reduced by a factor of 2.5 (at equal pitch and rotation time) with the UHR mode of the PCD-CT compared to the UHR with comb filter of EID-CT. Consequently, it is more likely that UHR PCD-CT would result in less risk of motion artifacts.

The findings of our study were based on equal radiation dose levels used in clinical practice and our results demonstrated that half of the dose could be used with equal tube voltage. Future research focusing on the further reduction of radiation dose with lowering the tube voltage or the use of additional tin filtration at the tube side would be warranted.

In conclusion, PCD-CT allows for a twofold higher visibility of bone structure sharpness and an overall improved image quality of the wrist compared to images obtained from an EID-CT. Even at half dose, PCD-CT yielded superior image quality, both in quantitative measures and as evaluated by radiologists.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: CMIV and Erasmus MC receive institutional research support from Siemens Healthineers.

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