Kidney stone differentiation in photon counting computed tomography: a feasibility study

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Aims and objectives

The medical treatment of a kidney stone strongly depends on its chemical composition, size and its precise location inside the urinary tract of the human body [1-3]. Yet, kidney stones are highly prevalent and show increased recurrence-rates [4-6], therefore an early detection and robust characterization of the crystalline accumulations is desired. Whereas medical imaging technologies became an important tool for kidney stone diagnosis, low dose non-contrast CT is considered as today's gold standard [7-9]. Several CT-based approaches of kidney stone characterization and differentiation were investigated in previous work [10-12]. The purpose of this study, however, is to detect and differentiate two particularly prominent kidney stone-materials using image information acquired by a research Photon Counting Detector CT-scanner (PCD-CT) [13-15]. PCD-CT provides scans with a full Field of View, fully registered image data, stability against motion artifacts and no cross scatter from a second X-ray source. Compared to conventional energy integrating CT-detectors, PCD-CT technology promises to provide an increased spatial resolution, due to the absence of optical septa, a negligible level of electronic noise and an increased dose efficiency especially for materials providing comparably higher absorptions in the lower energy ranges of the energy spectrum. Furthermore, the polychromatic spectrum as emitted by the X-ray tube can be resolved in energy bins by the introduction of energy thresholds; this allows applications of dual/multi energy algorithms as used in this study [14, 16].
Methods and materials

Each of the two phantoms used for this evaluation has a cylindrical shape with 10 cm diameter mimicking kidney-equivalent CT-values in clinical energy ranges up to 150 keV. Inside each cylinder 16 inserts of different shapes (8 spherical and 8 stretched spherical) and various sizes (from 1 to 10 mm) are embedded. The inserts imitate kidney stones based on either hydroxypatite (APA, phantom 1) or uric acid (UA, phantom 2). Additional scans were performed expanding the phantoms size to a realistic scale with a phantom ring mimicking water equivalent CT-values encircling either of the two aforementioned phantoms (Fig. 1). The eventual phantom's diameter amounts to 30 cm.

All investigated CT-images were acquired by a research PCD-CT system configured applying an abdominal sequence protocol with a tube potential of 140 kV, a collimation of $32 \times 0.5$ mm, a rotation speed of 1.0 s, tube currents of 50 mA and 156 mA respectively for the 10 cm and 30 cm wide phantoms, and beam shaping as used in conventional abdominal CT-imaging. Two energy thresholds of 25 keV and 65 keV were used, resulting in two energy bins providing an approximately equal photon distribution: 46.1% vs. 47.1% of the emitted photons are detected in bin1 and bin2 respectively (the mentioned distribution is based on a simulation). However, the resulting energy bins (i.e. [25, 65] keV and [65, 140] keV) were not distinct due to inherent physical effects in PCD-technology, such as charge sharing, K-escape, as the most prominent ones [15, 17-19].

The images were reconstructed in 1.5 mm thick slices and increments of 1 mm, using a weighted filter backprojection (WFBP) technique with a quantitative and medium smooth reconstruction kernel (D30) [20].

The calculated Dual Energy Ratio (DER) and Dual Energy Index (DEI) combine the information of the two energy bins' characteristic material attenuation and allows to derive the effective atomic number of a measured material. Furthermore, the actual differences of the DER or the DEI allow to assess the quality of differentiation between the two assessed kidney stone materials. The DER and DEI are defined as follows:

$$\text{DER} = \frac{(\text{HU(Bin1)} - \text{HU}_{\text{Kidney}}(\text{Bin1}))}{(\text{HU(Bin2)} - \text{HU}_{\text{Kidney}}(\text{Bin2}))}$$

$$\text{DEI} = \frac{(\text{HU(Bin1)} - \text{HU(Bin2)})}{(\text{HU(Bin1)} + \text{HU(Bin2)} + 2000)}$$

Whereas $\text{HU}_{\text{Kidney}}$ refers to the CT-value of kidney-tissue in the respective energy bin. Since the DEI refers to the CT-value of air, eventual partial volume effects impair the quality of determination of a material's effective atomic number. Hence our commercially
available image-based post processing software (syngoMMWP, Siemens Healthcare, Forchheim, Germany) restricts to use the DER for the detection and classification of a kidney stone. The software's parameter sets were tailored for evaluations of PCD-CT data. The modified parameters regard eventual correlations of CT-values in the two bin-based images, as well as patient size related contrast and noise characteristics.
Fig. 1: Two kidney stone phantoms with either APA based or UA based kidney stone-surrogates, plus water equivalent phantom expansion (from left to right).

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Results

The CT-scatterplot in Fig. 2 shows the measured CT-values of the detected stones in the respective energy bin for the two kidney stone surrogates and both phantom sizes. Fig. 3 and Fig. 4 indicate the distribution of DER and DEI in the patient size and kidney stone surrogate specific evaluations. A Wilcoxon rank sum test showed a highly significant difference (p < 0.005) between the measured CT-values of both kidney stone surrogates in all of the performed scans.

For our algorithm this study's results demonstrate a high sensitivity of detecting kidney stone-materials using a standard protocol for syngoMMWP - 15 (with diameters down to 1.5 mm, Fig.5, Fig. 6) out of 16 stones were detected; only one stone (1 mm) was not detected. By using further adjusted parameters (i.e. applying a lower strength of spatial smoothing), all stones were detected. However, the adjustment also leads to an increased detection rate of false positives (Fig. 7). Using either of the parameters, a correct distinction of the different types of kidney stone materials was achieved in 100% of all assessed cases.
Fig. 2: CT-value scatterplot of the kidney stone measurements on both phantom sizes.

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**Fig. 3:** DER results for both kidney stone surrogates from the measurement on both phantom sizes.

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Fig. 4: DEI results for both kidney stone surrogates from the measurement on both phantom sizes.

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**Fig. 5:** APA stones (blue) - Detection of all stones with standard parameters.

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Fig. 6: APA stones (blue) - All detected objects in a volumetric view.

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Fig. 7: UA stones (red) - Detection of false positive (white arrow) using modified parameters.

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Conclusion

Processing image information of a research PCD-CT system allowed a robust detection and characterization of two different kidney-stone-mimicking materials. A good dual-energy performance, as well as a robust detection and characterization of all investigated kidney-stone surrogates was observed even for small inserts with a diameter of 1.5 mm. However, an overtuning of our algorithm results in the successful detection of kidney-stone surrogates with 1 mm diameter, but also in detection of false positives. The differentiation of other kidney stone materials in phantom studies as well as in vivo studies (regarding realistic shapes, sizes and materials) is subject of further investigations. Finding optimal scan parameters using the presented application using PCD-CT data is considered an additional interest.
References


