Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2017 March 9; 10132: . doi:10.1117/12.2255651.

Renal Stone Characterization using High Resolution Imaging Mode on a Photon Counting Detector CT System

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Abstract

In addition to the standard-resolution (SR) acquisition mode, a high-resolution (HR) mode is available on a research photon-counting-detector (PCD) whole-body CT system. In the HR mode each detector consists of a 2x2 array of 0.225 mm × 0.225 mm subpixel elements. This is in contrast to the SR mode that consists of a 4x4 array of the same sub-elements, and results in 0.25 mm isotropic resolution at iso-center for the HR mode. In this study, we quantified *ex vivo* the capabilities of the HR mode to characterize renal stones in terms of morphology and mineral composition. Forty pure stones - 10 uric acid (UA), 10 cystine (CYS), 10 calcium oxalate monohydrate (COM) and 10 apatite (APA) - and 14 mixed stones were placed in a 20 cm water phantom and scanned in HR mode, at radiation dose matched to that of routine dual-energy stone exams. Data from micro CT provided a reference for the quantification of morphology and mineral composition of the mixed stones. The area under the ROC curve was 1.0 for discriminating UA from CYS, 0.89 for CYS vs COM and 0.84 for COM vs APA. The root mean square error (RMSE) of the percent UA in mixed stones was 11.0% with a medium-sharp kernel and 15.6% with the sharpest kernel. The HR showed qualitatively accurate characterization of stone morphology relative to micro CT.

Keywords

Computed tomography (CT); photon-counting detector CT (PCD-CT); high resolution CT

1. INTRODUCTION

Clinical x-ray CT systems are limited in the spatial resolution they can achieve by many physical factors, including, but not limited to: the focal spot size, the detector pixel size and the magnification [1, 2]. While the size of the focal spot is limited by physical constraints, as well as tube output and anode heating considerations, the size of the detector pixels is limited by the need for energy-integrating detectors (EIDs) to have septa between adjacent elements to prevent optical cross-talk. For the vast majority of clinical CT applications, the spatial resolution that can be achieved by conventional EID-CT systems is more than

adequate to provide images of diagnostic quality, and noise is rather the limiting factor. However, there are a subset of clinical applications, including but not limited to: imaging of the temporal bone and inner ear, lung imaging, and imaging of the extremities for musculoskeletal applications, for which the spatial resolution that can be achieved with standard focal spot sizes (1–2 mm) and detector pixel sizes (0.5 to 0.625 mm at the iso-center) is suboptimal [3]. To address this limitation, state-of-the-art CT systems offer acquisition modes with enhanced spatial resolution for those specific clinical applications that may benefit from additional anatomical detail. Higher spatial resolution can be achieved on a conventional CT system by selectively covering part of each detector element with the use of comb or grid z-ray attenuators to reduce the effective detector aperture [3–5]. However, limiting the detector aperture is dose-inefficient, with only less of 25% of the x-rays contributing to the image formation when half the detector pixel area is covered in both directions, compared to a conventional acquisition mode. This severe dose penalty prevents the use of high resolution CT acquisition modes for large body parts, like the thorax and the abdomen.

In recent years, photon-counting-detector (PCD) technology has been adopted in research CT systems with promising results [6–14]. In PCDs, detected x-ray photons are individually counted and their energy measured using direct conversion techniques that make possible the use of septa-free detector arrays. Therefore, smaller detector elements - and hence improved spatial resolution - are possible in PCD-CT without compromising the fill-factor and the dose efficiency, opening the door to higher-resolution CT for unexplored clinical applications.

Unenhanced CT is the imaging modality of choice for the diagnosis, monitoring and treatment planning of urinary calculi. Dual-energy CT has emerged as a reliable tool to characterize the mineral composition of urinary stones, effectively discriminating uric acid from non-uric acid stones [15–17]. However, limited success has been reported in the characterization of small (<3mm) and mixed stones, as well as in the classification of non-uric acid subtypes [18–20]. The purpose of this study was to investigate the potential of a new high-resolution (HR) acquisition mode available on a research PCD-CT system for the characterization of renal stone composition and morphology.

2. METHODS

2.1 High resolution PCD-CT

A research whole-body PCD-based CT scanner is available in our lab, which was developed on the platform of a 2nd generation dual-source CT system by replacing one of the two conventional detectors with a PCD [21]. Although the native detector size of the PCD is $225 \times 225 \mu\text{m}^2$, the standard readout mode uses macro pixels that group 4 by 4 native detector elements, resulting in a detector size of $0.9 \times 0.9 \text{ mm}^2$. Multi-energy CT data can be acquired in PCD-CT by applying 2 to 4 energy thresholds to the detected photons. A high resolution (HR) mode was recently introduced using 2 by 2 native detector elements. However, preliminary investigations using this mode were limited to only one energy threshold, thus effectively limiting the HR data to single energy applications [22]. An acquisition mode with

2 by 2 detector elements and up to 2 energy thresholds was recently made available by the manufacturer, which enabled the collection of dual-energy HR CT data.

2.2 Classification of pure stones

40 stones were used to test the classification capabilities of the HR acquisition mode. The sample consisted of 10 uric acid (UA) stones, 10 cystine (CYS) stones, 10 calcium oxalate monohydrate (COM) and 10 apatite (APA) stones. Reference composition was provided by infrared spectroscopy. Only stones with purity higher than 90% were included in the sample. Each set of stones was placed in a 20 cm water phantom and scanned at the dose level matched to our routine practice (3.8 mGy). Data were acquired in HR mode with 140 kVp tube potential and two energy thresholds (25 and 75 keV) and reconstructed with a small field of view (110 mm) and thin slices, resulting in a voxel size of $0.21 \times 0.21 \times 0.25 \text{ mm}^3$. A medium-sharp (D50f) and a very sharp (S80) reconstruction kernel were both evaluated. Each stone was subsequently segmented from the water background and single- and dual-energy metrics extracted using custom software. The CT number ratio was computed as the ratio of average CT number of each stone in the two energy bins (CT number of 25–75 keV bin divided by the CT number of the 75–140 keV bin). Using the CT number ratios, receiver operating characteristic (ROC) curves were generated for the classification of stone type. The area under the ROC curve (AUC) was used as the figure of merit to assess the classification performance.

2.3 Characterization of mixed stones

14 stones of mixed uric acid (UA) and non-uric acid (nUA) composition were used to determine the accuracy of the HR mode in measuring the morphology and percent of UA in each stone. microCT scans were used to provide an accurate reference [23]. PCD-CT data were acquired in HR mode and processed following the same procedure outlined for the pure stones above. The CT number ratio was computed for each pixel in each stone and the optimal threshold identified as that which resulted in the lowest root mean squared error (RMSE) in the estimation of the percent UA for the stone sample analyzed [20]. Additionally, qualitative analysis of stone morphology was performed by visually assessing the internal structure of the stones.

3. RESULTS

3.1 Classification of pure stones

In Figure 2, we show the ROC curves for the classification of each stone type using the HR mode. Accurate classification of UA and nUA stones ($\text{AUC} = 1$) as well as between nUA subtypes (CYS vs. COM, $\text{AUC} = 0.89$; COM vs APA, $\text{AUC} = 0.84$) was achieved with a medium-sharp kernel despite the small pixel size (Figure 2(a)). Furthermore, no degradation was observed when a very sharp kernel was used (Figure 2(b)). This indicates that the increase in spatial resolution (and associated increase in image noise) did not compromise the ability of the technique to classify stone composition.

3.2 Characterization of mixed stones

In Figure 3, we show a visual comparison of the HR PCD-CT images of a sample mixed stone (volume, 224 mm³), together with a reference microCT image. The same medium-sharp and sharp reconstruction kernels (D50 and S80) were used for the PCD-CT image reconstruction. The visual assessment shows significantly improved detail of the internal structures of the stone, with the COM core and the outer UA layer clearly distinguishable in the HR images. Quantification of the UA component of each stone with the optimal CT number threshold resulted in a root-mean-squared-error of 11.0% for the D50 reconstruction kernel [20]. We believe that this value was limited by the increased noise in the CT number ratios when measured on smaller pixels. This hypothesis is supported by the observation that with the sharper kernel, the RMSE increased substantially (Table 1). However, the increased detail of the stone internal structure could prove beneficial for the task of classification of mixed stones. In particular, an approach that includes a segmentation step to quantify the percent amount of different components, followed by a classification step using CT number ratios to identify the mineral composition of each sub-region in the stone, could be feasible with the higher spatial resolution offered by the new HR acquisition mode.

4. CONCLUSIONS

In this study, we reported the first *ex vivo* characterization of renal stones using a high resolution imaging mode on a research CT system using a photon-counting detector. Results from this investigation demonstrate that accurate classification of pure renal stones is maintained with the HR mode while providing a detailed characterization of the stone morphology compared to the reference micro-CT data.

The additional detail of internal stone structure provided by the HR acquisition mode on PCD-CT might enable more accurate classification of mixed renal stones, which make up to 80% of all renal stones. However, the additional sharpness needs to be balanced against the increased noise associated with using smaller voxels at the same radiation dose. Therefore, appropriate noise reduction techniques may be required to take full advantage of the increased spatial resolution offered by HR PCD-CT.

Acknowledgments

Research reported in this publication was supported by The National Institute of Biomedical Imaging and Bioengineering of the National Institutes of Health under award numbers EB016966 and DK100227, and in collaboration with Siemens Healthcare. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. The scanner and algorithm discussed here are not commercially available.

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Figure 1.
Native pixel (blue) and HR pixel (red) of PCD detector.

Figure 2. ROC curves for the classification of 4 stone types using the HR mode on a PCD-CT prototype. (a) Images reconstructed with a medium-sharp kernel (D50). (b) Images reconstructed with a very sharp kernel (S80).

Figure 3.

Visual assessment of internal stone morphology with different reconstruction kernels for the HR mode of the PCD-CT system. (a) Reference micro CT scan. (b) Images reconstructed with a medium-sharp kernel (D50). (c) Images reconstructed with a very sharp kernel (S80). Clinical dose level used to obtain HR PCD-CT images.

Table 1

Root-mean-squared-error for the quantification of the percent UA component of mixed stones for different acquisition modes and reconstruction kernels

	D50 kernel	S80 kernel
RMSE (%) vs micro CT	11.0	15.6