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Ultra-High Spatial Resolution, Multi-Energy CT using Photon Counting Detector Technology

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Abstract

Two ultra-high-resolution (UHR) imaging modes, each with two energy thresholds, were implemented on a research, whole-body photon-counting-detector (PCD) CT scanner, referred to as sharp and UHR, respectively. The UHR mode has a pixel size of 0.25 mm at iso-center for both energy thresholds, with a collimation of 32×0.25 mm. The sharp mode has a 0.25 mm pixel for the low-energy threshold and 0.5 mm for the high-energy threshold, with a collimation of 48×0.25 mm. Kidney stones with mixed mineral composition and lung nodules with different shapes were scanned using both modes, and with the standard imaging mode, referred to as macro mode (0.5 mm pixel and 32×0.5 mm collimation). Evaluation and comparison of the three modes focused on the ability to accurately delineate anatomic structures using the high-spatial resolution capability and the ability to quantify stone composition using the multi-energy capability. The low-energy threshold images of the sharp and UHR modes showed better shape and texture information due to the achieved higher spatial resolution, although noise was also higher. No noticeable benefit was shown in multi-energy analysis using UHR compared to standard resolution (macro mode) when standard doses were used. This was due to excessive noise in the higher resolution images. However, UHR scans at higher dose showed improvement in multi-energy analysis over macro mode with regular dose. To fully take advantage of the higher spatial resolution in multi-energy analysis, either increased radiation dose, or application of noise reduction techniques, is needed.

Keywords

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

1. INTRODUCTION

Photon counting detector based CT (PCCT) has been extensively investigated in recent years, in both technology development and potential clinical applications [1–10]. Photon counting detector (PCD) differs from the current energy integrating detector (EID) as it counts individual photons and allocates them to a predetermined energy bin based on the

energy of each photon. The potential benefits of PCD have been demonstrated through simulations and experimental studies [2–8, 10]. Meanwhile, substantial progress has also been made to address the physical challenges of PCD, especially regarding the high photon flux encountered in CT imaging [1]. Whole body CT scan at clinical relevant dose and dose rate has been shown to be feasible using a research PCCT system, and preliminary studies demonstrate comparable image quality to that of commercial scanners with EIDs [11, 12].

One benefit of PCCT is that improved spatial resolution can be achieved with smaller detector cells without decreasing fill factors and dose efficiency as PCD uses direct conversion technique. An ultra-high-resolution (UHR) imaging technique was recently developed on a research PCCT system with the effective detector size of 0.25 mm at the isocenter, compared to the 0.5 mm of standard macro mode on PCD and 0.5–0.625 mm on commercial EIDs [13]. Phantom and cadaveric studies demonstrated improved spatial resolution compared to regular imaging mode without sacrificing dose efficiency, unlike the UHR mode achieved with attenuating comb filters on EID systems [13]. This imaging technique can benefit lung, temporal bone, musculoskeletal and vascular imaging where excellent spatial resolution is required to delineate small anatomy and pathology. In the previous study, however, only one threshold was available. One major benefit of PCD, i.e. the energy discrimination capability which enables a single-detector, single-source, and single-tube-potential multi-energy imaging technique, was not possible.

The purpose of this study was to evaluate new ultra-high-resolution, multi-energy imaging techniques available on a research PCCT system and to compare the performance of different imaging modes in terms of spatial resolution and material decomposition capabilities.

2. METHODS AND MATERIALS

Photon-counting-detector CT

A whole-body research PCCT scanner has been installed in our lab. The research scanner was built based on a second-generation dual-source CT scanner (Definition Flash, Siemens Healthcare, Forchheim, Germany), with the energy integrating detector (EID) subsystem covering 50 cm field of view (FOV) and the PCD subsystem covering a 27.5 cm FOV [11, 14]. The PCD system is capable of acquiring energy selective data with 2 or 4 energy thresholds, consequently yielding 2 or 4 energy bins. Detailed descriptions of the system can be found elsewhere [11, 14]. The native detector pixel size is 0.225 mm by 0.225 mm for the PCD subsystem. However, the system is usually operated using macro pixels (0.9 mm by 0.9 mm) by grouping together 4 by 4 native detector cells (0.5 mm by 0.5 mm pixel size at iso-center). To increase spatial resolution, an UHR mode was recently introduced in which $0.45 \text{ mm} \times 0.45 \text{ mm}$ detector pixels were used, which corresponded to a pixel size of $0.25 \text{ mm} \times 0.25 \text{ mm}$ at the iso-center [13]. This mode, however, only had one energy threshold and therefore lacked energy discrimination information. One major benefit of PCCT, i.e. spectral imaging, was therefore not feasible due to the lack of energy discrimination capability.

Ultra-High Spatial Resolution, Multi-Energy Imaging Modes

Recently, two different imaging modes with ultra-high spatial resolution, both capable of discriminating multi-energy information, have been implemented on the whole body, research PCD CT scanner installed at our institution. These two modes are referred to as sharp mode and UHR mode throughout the manuscript. Both modes have 2 energy thresholds which enable single-source, single-kV, and simultaneous dual energy CT. In UHR mode, both the low- and high-energy acquisitions use $0.45 \text{ mm} \times 0.45 \text{ mm}$ detector pixels, resulting in $0.25 \text{ mm} \times 0.25 \text{ mm}$ pixel size at iso-center. The collimation along z is limited to $32 \times 0.25 \text{ mm}$ resulting in a longitudinal coverage of 8 mm in one rotation. In sharp mode, to increase the detector coverage and scanning speed without exceeding data handling capabilities, the low-energy acquisition maintains the same pixel size as the UHR mode, while the high-energy acquisition uses the $0.9 \text{ mm} \times 0.9 \text{ mm}$ pixel ($0.5 \times 0.5 \text{ mm}$ at isocenter). The reasoning is that low-energy threshold image, which uses all photons, can be used with high spatial resolution to accurately delineate fine anatomic structures, whereas the multi-energy processing (in this case dual-energy) may not require very high spatial resolution, so the $0.9 \text{ mm} \times 0.9 \text{ mm}$ pixel may be sufficient. The collimation along z is $48 \times 0.25 \text{ mm}$ resulting in a longitudinal coverage of 12 mm in one rotation. The information regarding each mode, including collimation, pixel size, and energy thresholds are summarized in Figure 1. This study focused on the investigation and comparison of three acquisition modes: macro, sharp and UHR modes.

Phantom Experiments

A series of phantom experiments were conducted to evaluate system performance and to demonstrate potential clinical applications of the sharp and UHR modes. Studies focused on both the high resolution aspect and the dual energy capabilities of the scanning modes, and comparisons among macro, sharp and UHR modes to provide guidance on selection of appropriate mode based on imaging task.

Fourteen renal stones with mixed composition, i.e. each stone contains both uric acid (UA) and non-uric acid (NUA) component, were scanned on the PCCT using macro, sharp and UHR modes. All scanning and reconstruction parameters were the same for all three modes except the collimation. The stones were scanned at 140 kV with energy thresholds of 25 and 75 keV. Tube current was adjusted so that the resulted radiation dose, quantified by volume CT dose index (CTDI_{vol}) matched to clinical routine stone protocols (3.8 mGy). Images were reconstructed with 3 quantitative kernels, medium smooth (D30), medium sharp (D50), and sharp (S80), at the thinnest slice thickness available for each mode (0.5, 0.25/0.5, and 0.25 mm for macro, sharp and UHR mode, respectively). Additional scans were performed with higher radiation dose (CTDI_{vol} = 30.4 mGy) for the mixed composition stones to assess the influence of image noise and radiation dose.

In addition, 20 lung nodules with sphere and star shapes were placed in a semi-anthropomorphic phantom and scanned with macro and sharp modes of the PCCT. The scanning parameters for the two modes were identical except the collimation, with 140 kV, 25 and 75 keV energy thresholds, 1.0 s rotation time, 36 effective mAs and 4.4 mGy volume CT dose index (CTDI_{vol}). Low-energy threshold images were reconstructed with sharp

kernel (S80) at the thinnest slice thickness: 0.5 mm for macro mode and 0.25 mm for sharp mode.

The low-energy threshold images used all photons for the reconstruction, therefore had the lowest image noise. Since the low-energy threshold images are the same for the sharp and UHR modes, comparison focused on macro mode and sharp mode. Conclusion drawn from this comparison directly applies to that of comparison between macro and UHR mode. Visual assessment of the low-energy threshold images of the stones were performed and compared between scanning modes. Lung nodule shape delineation was assessed using the low-energy threshold images of the macro and sharp modes.

For dual energy analysis, sharp mode uses 0.5 mm pixels which are the same as that of the macro mode. Therefore, comparison of dual energy analysis focused on the sharp mode and UHR mode (0.25 mm pixels). The same 14 renal stones with mixed compositions were also used to assess the influence of spatial resolution and image noise in dual energy applications. Dual-energy analysis was performed to differentiate stone composition and quantify the amount of UA and NUA based on the CT number ratio (CTR) of each pixel inside the stone, which was calculated as the ratio of the CT numbers in the low-energy bin (25 to 75 keV) to those in the high-energy bin (75 to 140 keV) [13]. The results were compared with the reference standard achieved with microCT scans [15]. Root mean square error (RMSE) in the % UA composition was calculated for each scan mode.

3. RESULTS

Figure 2 shows low-energy threshold images of a small stone (volume of 249 mm³) composed of both UA (darker pixels) and NUA (brighter pixels) scanned with sharp mode and reconstructed at 0.25 mm slice thickness and D30, D50 and S80 kernels, together with the microCT image. Layers of different compositions, confirmed by the microCT images, were visible from the PCCT images. As seen from these images, the sharper kernel (e.g. D50) showed sharper boundaries between the two components of the stone. However, image noise also substantially increased with sharper kernels, especially the S80 kernel.

Figure 3 shows sample low-energy threshold images of the stone scanned with macro mode and sharp mode. The images were reconstructed with the same D50 kernels, but different slice thickness: 0.5 mm for macro mode and 0.25 mm for sharp mode, which was the thinnest slice thickness for each mode. Sharp mode image showed a better delineation of the boundaries between the different compositions, and the shell of the stone appeared to be brighter due to decreased partial volume effect.

Figure 4 shows images of a star-shape nodule images with macro and sharp mode, which showed improved delineation of the star-shape of the nodule using the high spatial resolution mode. This helps more accurately characterize the morphology of lung nodules, which is an important feature related to different types of lung diseases.

Figure 5 shows the CT number ratio (CTR) map of the mixed composition stone, scanned with both sharp and UHR mode. The sharp mode images were reconstructed to 0.5 mm pixels, while the UHR mode images were reconstructed to 0.25 mm pixels. Two kernels,

D50 and S80, were used for reconstruction. D50 images of both sharp mode and UHR mode showed some separation between the two components of UA and NUA. However, noise of the CTR map increased in the CTR map using UHR D50 images. The CTR maps generated from S80 images were very noisy, especially for UHR mode, making it difficult to accurately quantify the two components. For D50 images, the RMSE for percent UA quantification was similar among these two modes: 12.6% and 11% for sharp and UHR modes, respectively. For S80 images, the RMSE was 15.7% and 15.6% for sharp and UHR mode, respectively. These results demonstrated that D50 kernel and 0.5 mm slice thickness were sufficient to be used in dual-energy analysis, e.g. stone composition quantification. The benefit of increasing spatial resolution was overshadowed by the excessive image noise. To fully utilize the increased spatial resolution in dual energy process, either higher dose need to be applied or noise reduction techniques used. Figure 6 showed images scanned with UHR mode and 30.4 mGy. The S80 low-energy threshold image showed sharper boundaries than the D50 images, both with substantial improvement compared to the original dose images in Figure 2. The CTR map is much less noisier and RMSE decreased from 11 to 9.1% for D50 images, and from 15.6 to 10.8% for S80 images.

4. DISCUSSIONS AND CONCLUSIONS

In this study, we described two ultra-high-resolution, multi-energy imaging modes on a PCCT scanner: sharp mode with 0.25 mm pixels for low-energy threshold image and 0.5 mm pixels for high-energy threshold image, and UHR mode with 0.25 mm pixels for both threshold low and high images. As such, the low-energy threshold images, similarly as conventional single energy images, were the same for the sharp and UHR modes. For dual energy analysis, sharp mode used 0.5 mm pixels as determined by the high-energy threshold image, while UHR mode maintained the 0.25 mm pixels. Our study demonstrated that the ultra-high spatial resolution (with 0.25 mm pixels) from low-energy threshold images improved spatial resolution and delineation of fine structures compared to regular macro mode. For dual energy applications, standard resolution (with 0.5 mm pixels) images from low- and high-energy threshold images were sufficient for material differentiation and quantification. The substantial increase of image noise diminished the benefit of increased resolution. Sharp mode, with ultra-high resolution in single energy and regular resolution in dual energy, appeared to be the scanning mode that can be useful in a wide range of clinical tasks. UHR mode should only be used where dual energy information at very high spatial resolution is needed, and the influence of noise is well controlled, either using higher doses or noise reduction techniques. Given the differences in z collimation, the relative scanning speed of macro, sharp and UHR modes is 4:3:2, keeping all other parameters the same. This may need to be considered in exams where patient motion could potentially be an issue, such as chest and cardiac exams. In these scenarios, the tradeoff of spatial resolution and scanning speed should be considered based on the clinical need and macro mode could be a viable solution if scanning speed outweighs the need of high spatial resolution.

In conclusion, we have presented two imaging modes with both ultra-high spatial resolution and multi-energy capabilities on a PCCT. Phantom studies have demonstrated the benefit of these scanning modes and comparisons between different scanning modes provides guidance for selection of an appropriate imaging mode based on a specific imaging task.

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Figure 1.

The read out of the low (green) and high (red) energy thresholds at 3 acquisition modes: macro, sharp and UHR, and their corresponding collimations. Native detector pixels are delineated by the dashed lines.

Figure 2. MicroCT and PCCT low-energy threshold images of a mixed stone scanned with sharp mode and reconstructed with 3 different kernels.

Figure 3. Images of a mixed stone scanned with macro and sharp modes and reconstructed with a D50 kernel.

Figure 4.
Photo and volume rendered images of a star-shaped lung nodule scanned with macro and sharp mode.

Figure 5.
CTR maps of a mixed composition kidney stone scanned with sharp and UHR modes, reconstructed with D50 and S80 kernels.

Figure 6. Threshold low images (gray scale) and CTR map (color) of a mixed stone scanned with UHR mode and 30.4 mGy.