Mixed coronary plaque characterization with the first clinical dual-source photon-counting CT scanner: a phantom study

Thomas Wesley Holmes*[a], Leening P. Liu[b,c], Nadav Shapira[b], Elliot McVeigh[d], Harold I. Litt[b], Amir Pourmorteza[a,e], Peter B. Noël[b]

[a]Department of Radiology and Imaging Sciences and Winship Cancer Institute, Emory University, Atlanta, GA.; [b]Department of Radiology, Perelman School of Medicine, University of Pennsylvania, Philadelphia, PA.; [c]Department of Bioengineering, University of Pennsylvania, Philadelphia, PA.; [d]Departments of Medicine, Radiology, and Biomedical Engineering, University of California San Diego, San Diego, CA.; [e]Department of Biomedical Engineering, Georgia Institute of Technology, Atlanta, GA

ABSTRACT

Purpose: to investigate image quality of the ultra-high-resolution (UHR) mode of a dual-source photon-counting CT scanner in visualizing mixed (soft and hard) coronary artery plaques.

Materials and methods: We scanned a custom-made phantom with 10 mixed plaques of various sizes and compositions. Each scan was repeated three times. Images were reconstructed with FBP, and model-based quantum iterative reconstruction (QIR). Image quality was investigated by measuring mean CT numbers, noise standard deviation (SD), and by line profiles.

Results: UHR mode provided sharper difference between soft and hard plaques, and the lumen by reducing blooming artifacts. Furthermore, it improved the true CT number of the values by reducing partial volume However, SD of noise increases by a factor of ~8 in FBP reconstructions at thinnest slice thickness (0.2 mm). Quantum iterative reconstruction algorithm reduced image noise x4 of the SR FBP without any apparent loss of spatial resolution.

Conclusion: UHR PCCT improves plaque characterization through improved spatial resolution which results in lower blooming artifacts and partial volume effects. The increase in image noise can be mitigated by using model-based iterative reconstruction algorithms without any loss of spatial resolution. Depending on the imaging task, further noise reduction can be achieved by reconstructing thicker slices. A more detailed investigation with noise power spectrum analysis and observer model studies is warranted.

Keywords: photon-counting, computed tomography, cardiac CT, coronary plaque, plaque characterization, ultra-high-resolution imaging, dual-source, phantom study

1. INTRODUCTION

Photon-counting CT (PCCT) has proven to be the next leap in CT imaging technology with many studies performed on prototype scanners developed by all major CT manufacturers [1], [2]. In this study, we investigate the image quality and ultra-high-resolution (UHR) performance of the first clinical dual-source PCCT scanner to characterize coronary artery plaques. It is well understood that increasing in spatial sampling frequency of a CT scanner results in wider image noise bandwidth while reducing blooming and partial-volume artifacts [3]. In this work we present preliminary results of imaging mixed, i.e. soft and hard coronary artery plaques with such a system using a custom-made CT phantom.

** Corresponding Author: T. W. Holmes (twholme@emory.edu)*

7th International Conference on Image Formation in X-Ray Computed Tomography,
edited by Joseph Webster Stayman, Proc. of SPIE Vol. 12304, 123041U
 · doi: 10.1117/12.2647009

2. METHODS

2.1 Test Object

We used a custom-made mixed plaque phantom with eight tissue types and ten simulated plaques with different compositions of hard (calcium) and soft (cholesterol-rich) materials and contrast materials (Fig-1). The phantom has multiple empty holes that can be filled with desired concentrations of iodinated contrast material. We diluted the contrast material to have CT number of ~500 HU at 120 kVp, which is high enough to provide good contrast but low enough not to cause severe beam hardening artifacts.

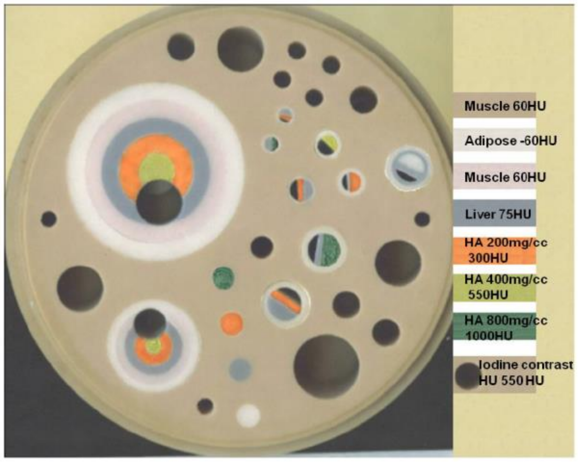

Figure. 1. Custom-made mixed plaque phantom with eight tissue types and ten simulated mixed plaques of various compositions. Contrast agents can be added to the empty holes at desired concentrations. The diameter of the phantom is 100 mm and it can be fit inside a standard QRM thorax phantom.

2.2 Image Acquisition

The phantom was scanned on a clinical dual-source PCCT scanner with cadmium-telluride detectors (NAEOTOM Alpha, Siemens Healthcare, Germany). This scanner can operate in standard resolution mode, and UHR mode with apparent detector pixel sizes of 0.2 and 0.50 mm at the isocenter, respectively. The detailed description of the scanner can be found in [4]. Table-1 summarizes the scan and reconstruction parameters. Each scan was repeated three times. All values are reported as mean and SD of the three measurements. While the scanner is dual-source, the UHR scan mode was only available in single-source mode. We used the image reconstructed from all detected photons with energies > 25 keV (T3D) in this study. Hence no spectral analysis was possible in UHR mode.

Scanner Model	**NAEOTOM Alpha**
Tube Voltage	120 kVp
Revolution Time	0.5 sec
Spiral Pitch Factor	1
Slice Thickness	0.2, 0.4, 1.5 mm
Total Collimation Width	24 mm
Iterative Reconstruction	QIR: 0, 2, 4
Reconstruction Filter	Qr40, Qr72
Reconstruction Diameter	102 mm
Matrix Size	1024x1024
$CTDI_{vol}$	5, 10, 15 mGy
Pixel Spacing	0.0996 mm

Table 1. PCCT scan and reconstruction parameters.

2.3 Image Analysis

We investigated the effective spatial resolution of the scans by comparing line profiles drawn in different regions of the plaques as seen in Fig-2. Image noise was measured as the SD of large circular region of interest (ROI) with diameter=20 mm in the difference image of two repetitions of a scan divided by √2.

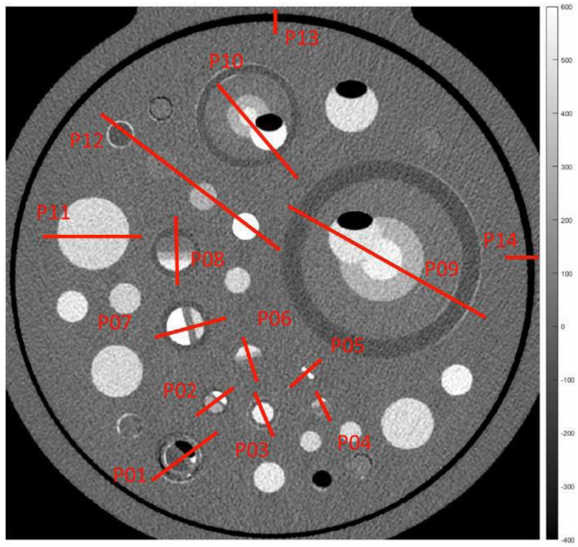

Figure 2. The locations of line profiles in the mixed plaque phantom. (WC: 100, WW: 500). The black regions inside contrast material regions were caused by air bubbles.

The noise was measured for images reconstructed FBP and QIR with thinnest (0.2mm) possible slice thickness, as well as 0.4, and 1.5 mm thicknesses, which are more commonly used in the clinic.

3. RESULTS

Figure 3 compares the line profiles for standard (Qr40) and UHR (Qr72) images reconstructed with FBP and QIR. UHR acquisition mode provided sharper delineation of soft and hard plaques, and the lumen albeit with amplified noise. This can be attributed to the reduced blooming artifacts due to the doubling of spatial sampling frequency. Furthermore, UHR showed more accurate CT number values due to the reduced partial volume effects. For example, P13 and P14 pass through air and therefore should have a minimum at -1000HU. The standard mode failed to resolve the true CT number due to partial volume effect, while UHR images all showed the correct CT number. Sample closeup images and profile lines are shown in figures 4,5.

Image noise, as measured by SD of difference image, was approximately 8 time higher in UHR mode compared to standard resolution for images reconstructed with FBP for all slice thicknesses. Images reconstructed with different strengths of QIR reduced the image noise by approximately 2 folds in maximum strength (fig-6).

4. DISCUSSION

In this preliminary study we compared the spatial resolution and noise of UHR mode compared to standard resolution for imaging various shapes and compositions of calcified plaques. Our study had several limitations which warrant further detailed studies: 1- we used a stationary phantom; future experiments with a dynamic phantom are planned to assess the effect of motion on the effective spatial resolution of the system. 2- the phantom has relatively simple geometries; we plan to assess the image quality in a series of excised heart with various levels and shapes of coronary calcification. 3- We measured image noise as the SD of a large ROI; a more detailed study with noise power spectrum (NPS) measurements is warranted.

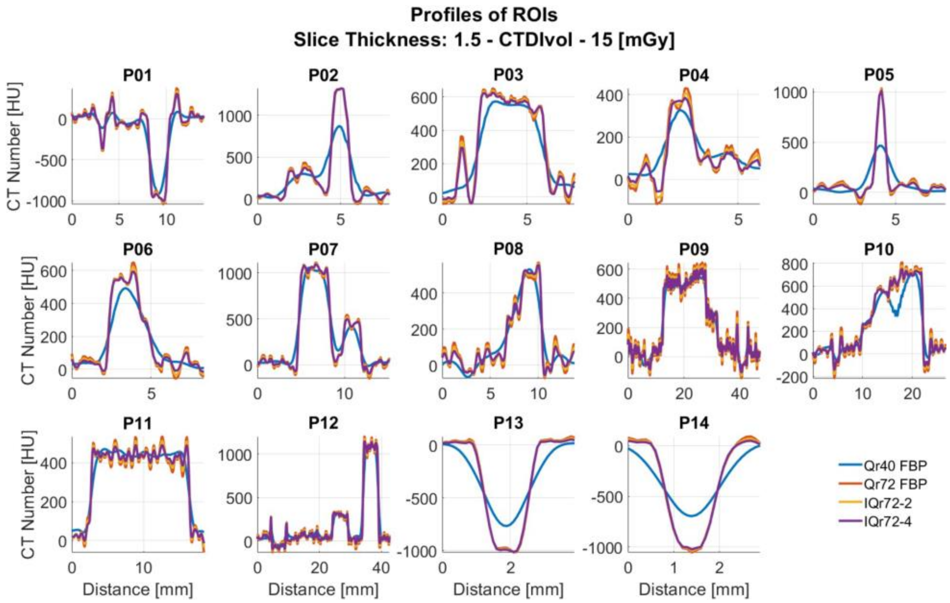

Figure 3. Comparison of line profiles drawn through the regions depicted in fig-2 for various scan and reconstruction modes. standard resolution mode: (Qr40 FBP), UHR mode with FBP (Qr72 FBP), and with QIR of strengths 2 and 4: IQr72-2, IQr72-4. Overall, UHR profiles showed sharper separation between different parts of the plaques due to reduced blooming artifacts. P13 and P14 pass through air and therefore should have a minimum at -1000HU. The standard mode failed to resolve the true CT number due to partial volume effect.

5. CONCLUSION

UHR PCCT improves plaque characterization through improved spatial resolution which results in lower blooming artifacts and partial volume effects. The increase in image noise can be mitigated by using model-based iterative reconstruction algorithms without any loss of spatial resolution. Depending on the imaging task, further noise reduction can be achieved by reconstructing thicker slices. A more detailed investigation with noise power spectrum analysis and observer model studies is warranted.

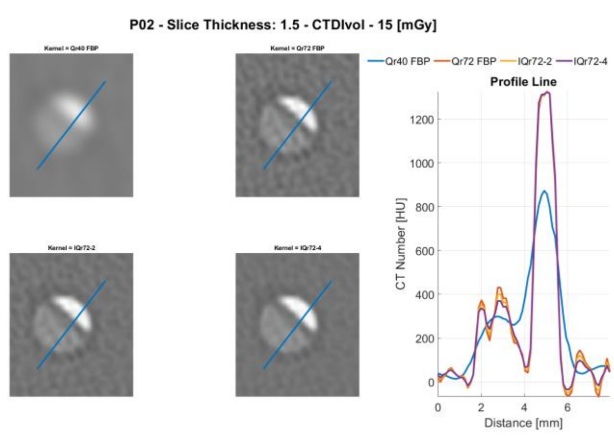

Figure 4. Sample closeup images of a mixed calcified plaque and their corresponding line profiles. Standard resolution image (top left), and UHR images with various strengths of QIR algorithm.

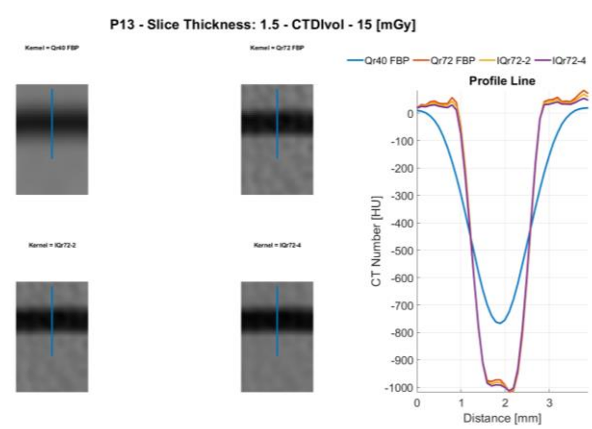

Figure 5. Sample closeup images of a mixed calcified plaque and their corresponding line profiles. Standard resolution image (top left), and UHR images with various strengths of QIR algorithm.

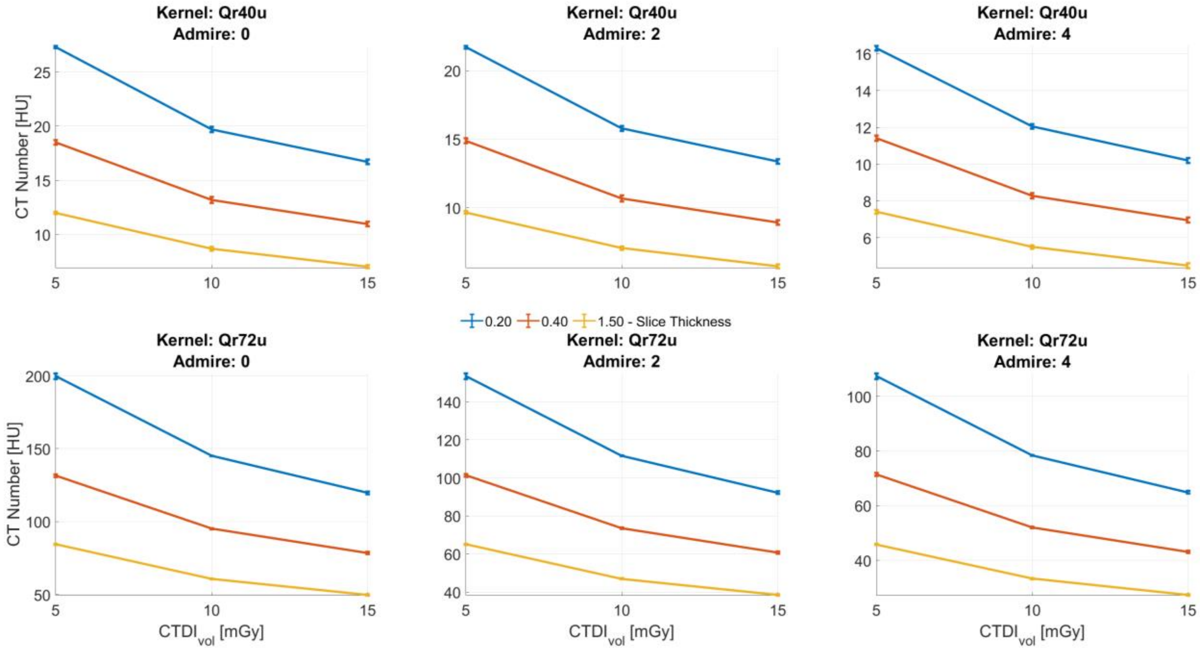

Figure 6. Image noise measured as SD of a uniform ROI with diameter = 20 mm for standard resolution and UHR mode images reconstructed with FBP (strength = 0) and QIR (strength = 2,4) at different slice thicknesses and radiation doses.

REFERENCES

[1] V. Sandfort, M. Persson, A. Pourmorteza, P. B. Noël, D. Fleischmann, and M. J. Willemink, “Spectral photon-counting CT in cardiovascular imaging,” J. Cardiovasc. Comput. Tomogr., 2020.

[2] M. J. Willemink, M. Persson, A. Pourmorteza, N. J. Pelc, and D. Fleischmann, “Photon-counting CT: Technical Principles and Clinical Prospects,” Radiology, vol. 289, no. 2, p. 172656, 2018, doi: 10.1148/radiol.2018172656.

[3] A. Pourmorteza, R. Symons, A. Henning, S. Ulzheimer, and D. A. Bluemke, “Dose Efficiency of Quarter-Millimeter Photon-Counting CT: First-in-human Results,” Invest. Radiol., vol. epub ahead, 2018, doi: 10.1097/RLI.0000000000000463.

[4] M. Eberhard et al., “Coronary calcium scoring with first generation dual-source photon-counting CT—first evidence from phantom and in-vivo scans,” Diagnostics, vol. 11, no. 9, p. 1708, 2021.