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JOINT AAPM | COMP MEETING

# Development and Characterization of a High-Resolution Photon-Counting Tabletop Cone-Beam CT System and End-to-End Module for Streamlined Workflow

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## ABSTRACT

**Purpose:** Photon-counting detector (PCD) cone-beam CT (CBCT) provides high-resolution and spectrally rich imaging. We developed a tabletop platform to serve as a reproducible research environment.

**Methods:** We integrated a microfocus X-ray source and a high-resolution PCD using a custom 3D Slicer workflow.

**Results:** The system achieved a limiting spatial resolution of 8.42 lp/mm.

**Conclusion:** This platform provides a robust, fully automated foundation for future PCD-CBCT research.

## INTRODUCTION

Photon-counting detectors directly convert X-ray photons into electrical signals, enabling highly dose-efficient imaging and inherent multi-energy spectral separation. Fully exploiting the high spatial resolution of small PCD pixels requires a mechanically stable platform and a matched microfocus X-ray source to ensure focal-spot blur does not dominate detector sampling.

Current benchtop systems often rely on small detectors that require complex rotational or translational movements, which can lengthen acquisition workflows and compromise geometric precision.

We developed a highly reproducible, large-area tabletop PCD-CBCT platform engineered specifically to preserve ultra-high spatial resolution for structural characterization and advanced preclinical imaging.

## METHODS AND MATERIALS

The static platform features a tungsten-target microfocus X-ray source and a direct-conversion Cadmium Telluride (CdTe) PCD. The active detector region utilized for processing is strictly 2048 pixels wide and 512 pixels tall, mapped precisely in reference to the center pixel of the field of view. Standard acquisitions operated at 60 kVp and 600 μA, collecting 1200 projections over 80 seconds for a total exposure of 48.0 mAs.

Dual-energy thresholds partitioned the projection data into a low-energy bin (15 to 31 keV) and a high-energy bin (31 to 60 keV). Analytical geometric calibration established a stable static configuration, yielding a source-to-detector distance of 437.11 mm and a source-to-axis distance of 205.88 mm, while actively accounting for a geometric tilt angle of -0.0767° and a yaw angle of -0.1615°.

A custom 3D Slicer module automates the entire pipeline, from hardware synchronization to GPU-accelerated FDK volumetric reconstruction, eliminating manual procedural variability.

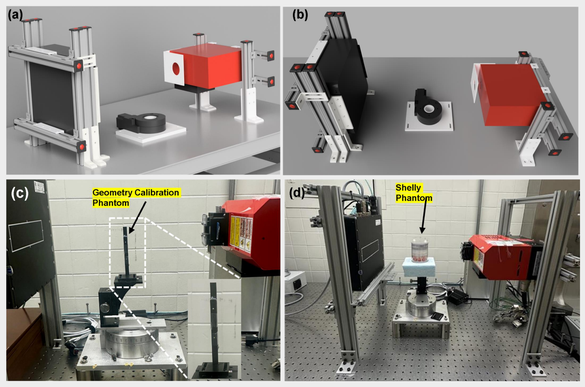


Figure 1: 3D CAD renderings detailing the system architecture from (a) a side view and (b) an elevated top-down view. (c) The fully assembled platform configured for geometry calibration. The inset provides a magnified view of the custom fixture with the embedded ball-bearing (BB) phantom. (d) The physical CBCT system loaded with the Shelley micro-CT phantom.

## RESULTS

Quantitative evaluation using a micro-CT phantom demonstrated that the high-energy bin delivered exceptional spatial sharpness, achieving a limiting spatial resolution (MTF10) of 8.42 lp/mm and a contrast resolution (MTF50) of 4.62 lp/mm.

Spectrally, bracketing the iodine K-edge within the 31 to 60 keV bin suppressed low-energy scatter and maximized contrast detectability, delivering a signal-to-noise ratio of 7.77 at 30 mg/mL iodine alongside a high spatial uniformity characterized by a maximum deviation of 5.09%.

Dosimetric evaluation confirmed that the optimized protocol delivered a weighted computed tomography dose index of 0.16 mGy to a 2 cm dosimetry phantom, remaining well within safe biological limits for longitudinal in vivo studies.

High-resolution ex vivo scans of a mouse specimen successfully translated these quantitative limits into practical diagnostic viability, cleanly separating high-density microscopic anatomy such as delicate trabecular networks and individual molars without severe partial volume blurring.

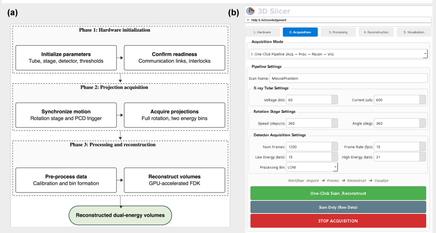


Figure 2. (a )Workflow implemented in 3D slicer (b) Data Acquisition Panel from the custom 3D slicer module

| Parameter | Value |
|---|---|
| **Acquisition Settings** | |
| Tube Potential | 60 kVp |
| Tube Current | 600 μA |
| Operating Power | 36.0 W |
| X-ray Focal Spot | 59.3 μm |
| Number of Projections | 1200 |
| Frame Rate | 15 frames/s |
| Acquisition Time | 80 s |
| Total Exposure | 48.0 mAs |
| Detector Thresholds | 15 keV, 31 keV |
| **Calibrated Geometry** | |
| Source-to-Detector Distance (SID) | 437.11 mm |
| Source-to-Isocenter Distance (SAD) | 205.88 mm |
| Horizontal Pixel Offset | 20.69 pixels |
| Vertical Pixel Offset | -17.89 pixels |
| Tilt Angle | -0.07° |
| Yaw Angle | -0.16° |
| Reconstruction | |
| Voxel Matrix (Phantom) | 1600 x 1600 x 512 |
| Voxel Matrix (Specimen) | 600 x 600 x 512 |
| Isotropic Voxel Size | 0.05 mm |

Table 1. Summary of the acquisition settings, calibrated geometry, and reconstruction parameters for the tabletop photon-counting cone-beam CT platform.

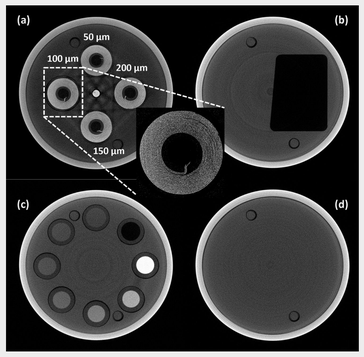


Figure 3: Cross-sections of the Shelley Micro-CT Phantom used for quality assessment: (a) resolution coils (50–200 μm), (b) slanted edge for sharpness derivation, (c) linearity inserts (water, air, iodine), and (d) uniform plate for noise analysis. Display window: [0.1, 1.0] mm⁻¹.

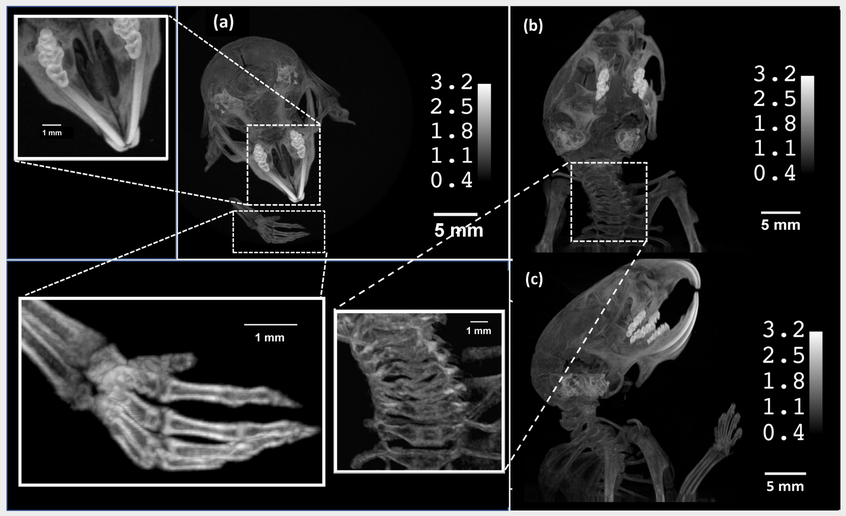


Figure 4. Ultra-high-resolution ex vivo imaging of a mouse specimen utilizing the full energy spectrum (15–60 keV). Maximum Intensity Projections (a: axial, b: coronal, c: sagittal) displaying local attenuation (mm−1) and highlighting the continuous3D architecture of the skeletal structure. Magnified insets detail the boundary preservation of the molars and the fine skeletal structure of the forelimb from (a),and the cervical spine from (b)

## DISCUSSION

The system pushes the spatial limits of tabletop preclinical imaging by achieving a limiting resolution of 8.42 $lp/mm$. This performance established multi-institutional micro-CT benchmarks, delivering an $MTF_20$ beyond 4.0 $lp/mm$ compared to the acceptable standard of >1.5 $lp/mm$.

Structuring the high-energy bin (31–60 keV) to bracket the iodine K-edge is critical for spectral optimization. Because this bin selectively filters out low-energy scatter and beam-hardening artifacts, it maximizes photoelectric contrast detectability while maintaining high spatial uniformity (5.09% maximum deviation) and suppressing noise.

Executing the entire imaging pipeline through the custom 3D Slicer module enforces strict parameter continuity. By eliminating disjointed software transitions, the workflow minimizes procedural inconsistencies and secures the physical alignment required to consistently maintain high spatial resolutions.

Future hardware modifications will address current alignment limitations by incorporating a motorized linear stage to automate vertical calibration offsets. Additionally, advanced sinogram-domain algorithms will be integrated to correct the faint residual ring artifacts driven by pixel-response non-idealities under high-contrast conditions.

## CONCLUSIONS

Our integrated tabletop PCD-CBCT platform successfully combines a large-area detector, a microfocus source, and a fully automated computational workflow to push the spatial limits of preclinical imaging.

Executing hardware control and data processing entirely through the 3D Slicer module maintains strict parameter continuity, directly protecting the sub-pixel geometric calibration and spatial resolving power from manual inconsistencies.

Future modifications will incorporate a motorized linear stage to automate calibration offsets and implement advanced sinogram-domain algorithms to correct residual ring artifacts.

1. X. Jia, Y. Lou, R. Li, W. Song, S. Jiang Gpu-based fast cone beam ct reconstruction from under sampled and noisy projection data via total variation, Medical Physics 27(4):1757 1760, 2010.
2. Hu X, Zhong Y, Vaughan H, Clark DP, Badea CT. Contrast-enhanced photon-counting micro-ct of tumor xenograft models. *Phys. Med. Biol.* 2024;69(9):095004.

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