Development of a Flexible Benchtop Spectral Photon Counting CT System for Tissue and Material Characterization.

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ABSTRACT

Purpose:
Spectral photon-counting CT (SPCCT) counts individual X-ray photons and separates them into different energy windows, producing energy-resolved images from a single scan. However, commercial SPCCT systems offer limited flexibility to vary system geometry and acquisition parameters. We describe the design and initial scanning of a flexible benchtop SPCCT system intended for quantitative image development and tissue/material characterization.

Methods:
The system integrates a 120 kVp X-ray tube and a Medipix3RX photon-counting detector mounted on motorized linear and rotational stages. Adjustable source-to-object, source-to-detector distances, magnification, tube voltage and current, beam filtration, energy windows and thresholds, sample rotation speed, number of projections, and scan time. The setup is installed in a lead-shielded enclosure with a door interlock tied to the X-ray tube. A cross-line laser is used to align the focal spot, detector center, and rotation axis, and a cross-hair wire phantom supports geometric calibration and alignment. In-house software synchronizes tube exposure, detector readout, and stage motion, enabling step-and-shoot circular CT and multi-energy acquisitions.

Results:
Initial multi-energy scans of a material phantom and an ex vivo chicken heart produced stable reconstructions with clear anatomical detail, confirming correct alignment and basic system performance. Ring artifacts from detector non-uniformity are present and are being mitigated with improved calibration and ring-reduction algorithms.

Conclusion:
The benchtop SPCCT platform enables controlled studies of geometry, filtration, and energy-threshold configuration and will serve as a testbed for optimizing quantitative spectral imaging and downstrtream physics-based and AI-based methods for tissue characterization and material analysis.

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INTRODUCTION

Spectral photon-counting CT (SPCCT) measures the energy of each detected X-ray photon, producing several energy-resolved images from a single scan **[1,2]**. This energy information enables material decomposition and quantitative mapping of effective atomic number and electron density **[3]**, along with K-edge imaging of high-Z contrast agents **[4]**. Capabilities beyond those of conventional energy-integrating CT in a single scan.
These quantitative measurements are sensitive to system geometry, beam filtration, and energy-threshold selection, yet commercial SPCCT scanners fix these parameters and expose little of the acquisition chain, limiting their use as research platforms **[1]**.
We present a flexible benchtop SPCCT system with direct control over geometry and acquisition, and report its initial implementation together with a first characterization of detector performance and image preprocessing.

METHODS AND MATERIALS

- 120 kVp X-ray tube + photon-counting camera (Medipix3RX, CdTe, 110 µm) [5] on motorized linear/rotational stages.
- Adjustable geometry, kV/mA, filtration, collimation, energy thresholds, projections, and scan time. Lead-shielded enclosure with tube-tied door interlock.
- Laser + wire-phantom alignment and geometric calibration. In-house software syncs exposure, readout, and motion for helical CT and multi-energy scans.
- Flat-field, dead-pixel, and outlier correction; resolution via slanted-edge method (system MTF, M = 2). Samples: QRM phantom, ex vivo chicken heart, lead-edge phantom

Parameter	QRM & heart	Edge (MTF)
Tube voltage	120 kVp	120 kVp
Tube current	80 µA	80 µA
Frames	20	20
Projections	360	1
Thresholds	25, 32, 37, 42 keV	25, 32, 37, 42 keV
Filtration	1.1 mm Al equiv.	1.1 mm Al equiv.
SOD / SDD	320 / 420 mm	210 / 420 mm

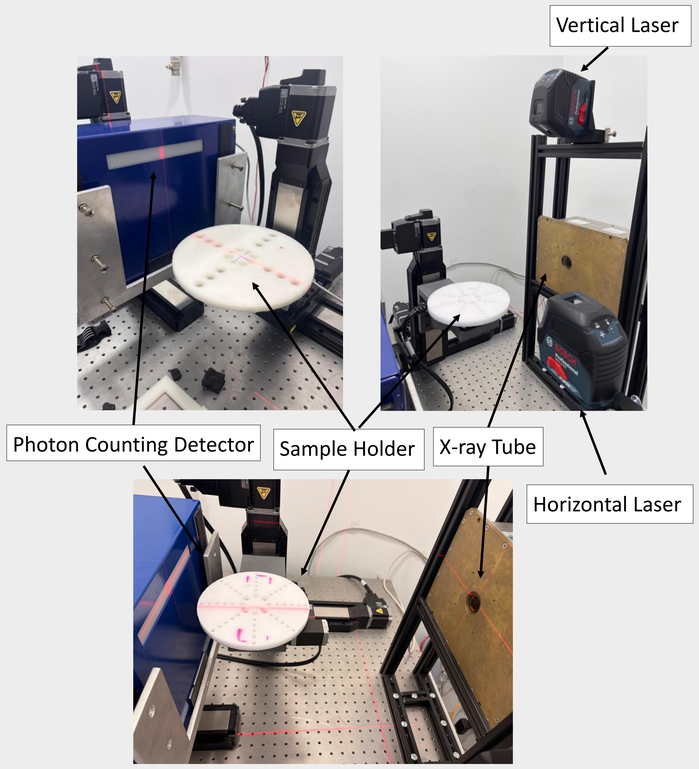

Figure 1. Benchtop SPCCT system showing the X-ray tube, Medipix3RX photon counting detector (128x1536) (X, Y, Z movement), cross-line alignment lasers, and sample holder (X, Y, Z and rotation movement)

RESULTS

Figure 3. QRM phantom (left) and reconstructed image at 25–120 keV (right). 120 kVp, 80 µA, 360 projections.

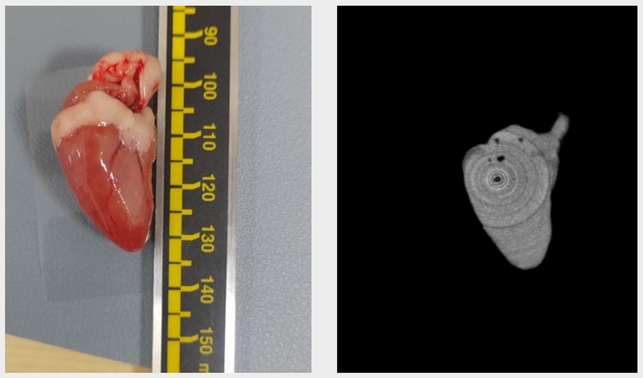

Figure 4. *Ex vivo chicken heart (left) and reconstructed slice (right). Same acquisition as Fig. 3.*

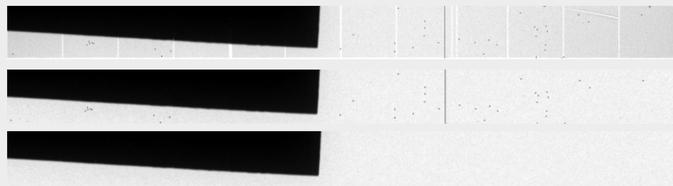

Figure 5. Edge-phantom preprocessing (M ≈ 2): raw, flat-field corrected, and dead-pixel corrected (331 pixels, 0.17%).

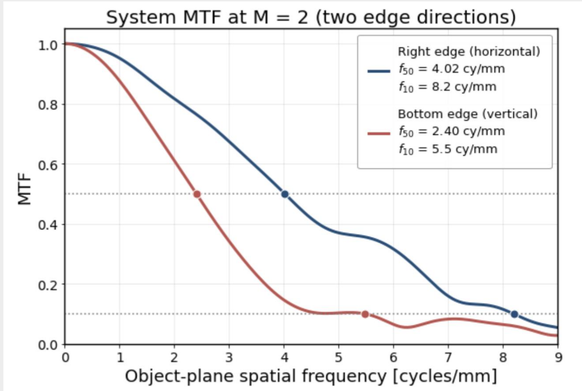

Figure 6. Presampled detector MTF (slanted-edge, M ≈ 2)

DISCUSSION

Validation. Stable reconstructions of a phantom and biological tissue confirm that the SPCCT pipeline works from acquisition to reconstruction.
Flexibility. User-controlled geometry, spectral filtration, adjustable energy thresholds, varying magnification for resolution, and spectral optimization with flexibility not available in commercial systems.
Limitations and next steps. Ring artifacts from detector non-uniformity remain the main limitation; ongoing work targets improved flat-field calibration and ring reduction. Building on the detector MTF reported here, planned work includes NPS, DQE, and material-specific imaging (effective atomic number, electron density, K-edge contrast agents).

CONCLUSIONS

We developed a flexible benchtop SPCCT system with full user control over geometry, filtration, and energy thresholds.
Initial multi-energy scans of a phantom and ex vivo tissue, together with a first detector characterization (presampled MTF, f_{50} = 3.27 cycles/mm), confirm correct operation.
The platform provides an open testbed for quantitative spectral imaging and tissue/material characterization.

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