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RADIOLOGICAL SCIENCES

Molloi Imaging Physics Lab · Department of Radiological Sciences

Experimental Benchmarking and Validation of a Clinical Photon-Counting CT Simulation

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ABSTRACT

We develop and validate the **first open-source, CdTe-based photon-counting CT (PCCT) simulation framework** in CATsim, emulating a clinical scanner (Siemens NAEOTOM Alpha) and quantitatively comparing simulated vs. experimental iodine and calcium Hounsfield units (HU) across concentrations.

Simulations reproduce experimental trends with high linearity ($R^2 > 0.99$) but a **systematic underestimation of HU** , localizing error to analytical simplifications in the detector-efficiency model.

KEY FINDINGS

R^2>0.99

Linearity — both materials & both tube voltages

0.93

Lin's CCC · iodine — moderate agreement

0.89

Lin's CCC · calcium — poor agreement

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INTRODUCTION

Photon-counting CT (PCCT) with CdTe detectors — e.g. the Siemens NAEOTOM Alpha — is entering clinical use, yet **validated open-source simulation tools remain scarce** . Reliable simulation underpins protocol optimization, material-decomposition research, and reproducible benchmarking.

We build the first open-source CdTe-based PCCT framework in CATsim and quantify simulated vs. experimental iodine and calcium HU across concentrations to **localize systematic bias** .

METHODS & MATERIALS

Scanner model — CATsim replicates the NAEOTOM Alpha: CdTe detector, clinical z-coverage, focal-spot size, Sn pre-filtration, bow-tie filter.

Simulation — spectral modeling + scatter estimation at 120 & 140 kVp, with a simplified Beer–Lambert detector-efficiency model.

Experiment — Gammex 472 phantom with iodine 2–20 mg/mL and calcium 50–400 mg/mL inserts; scanned using Siemens NAEOTOM Alphaat 120 & 140 kVp

Analysis — linear regression (R^2) and Lin's CCC on the McBride scale (N = 16 iodine, N = 10 calcium).

DIGITAL TWIN & PHANTOM

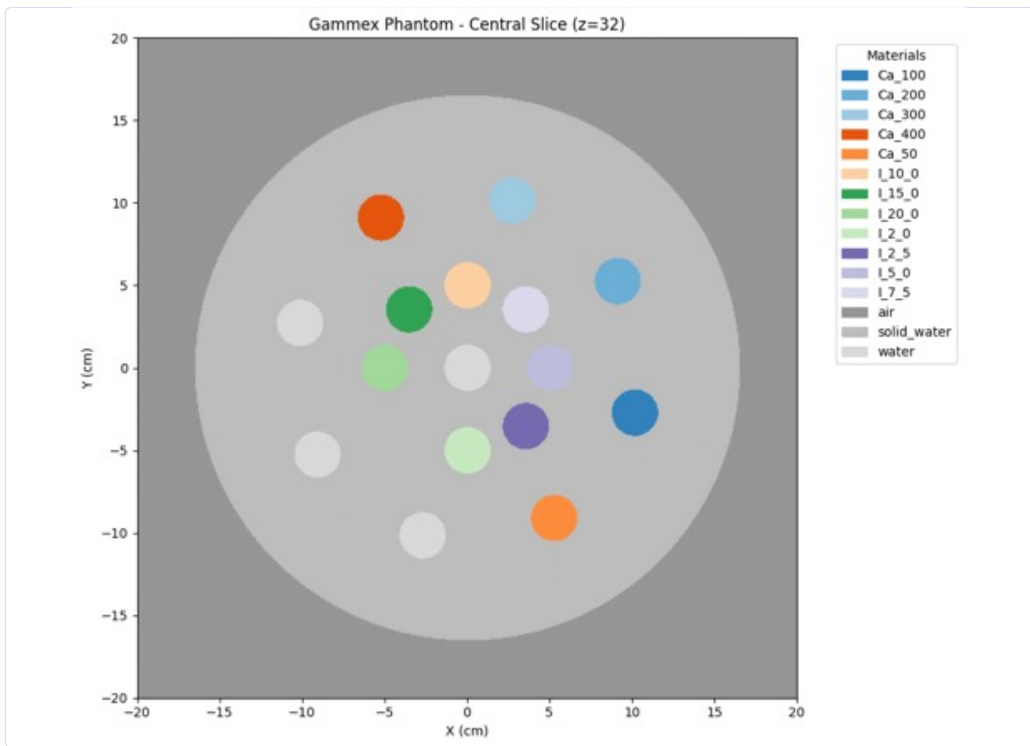

Figure 1. Digital twin of the Gammex 472 phantom — simulated central slice.

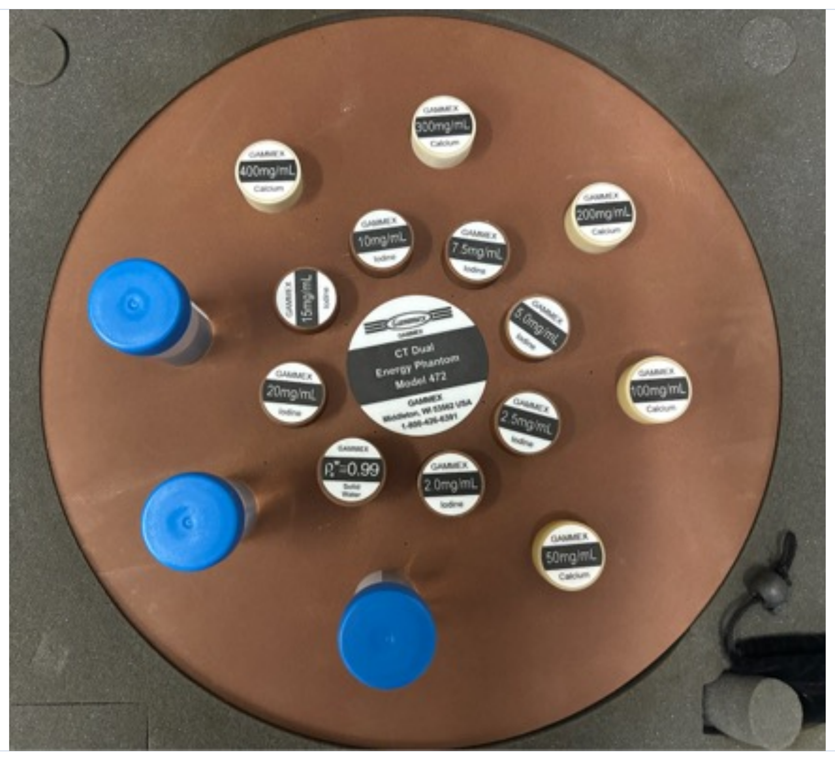

Figure 2. Physical Gammex 472 phantom used for the experimental acquisition.

RESULTS — HU ACCURACY

Across both materials and tube voltages, simulated HU is **underestimated at every concentration** , while tracking experimental values with high linearity. The magnitude of underestimation grows with concentration.

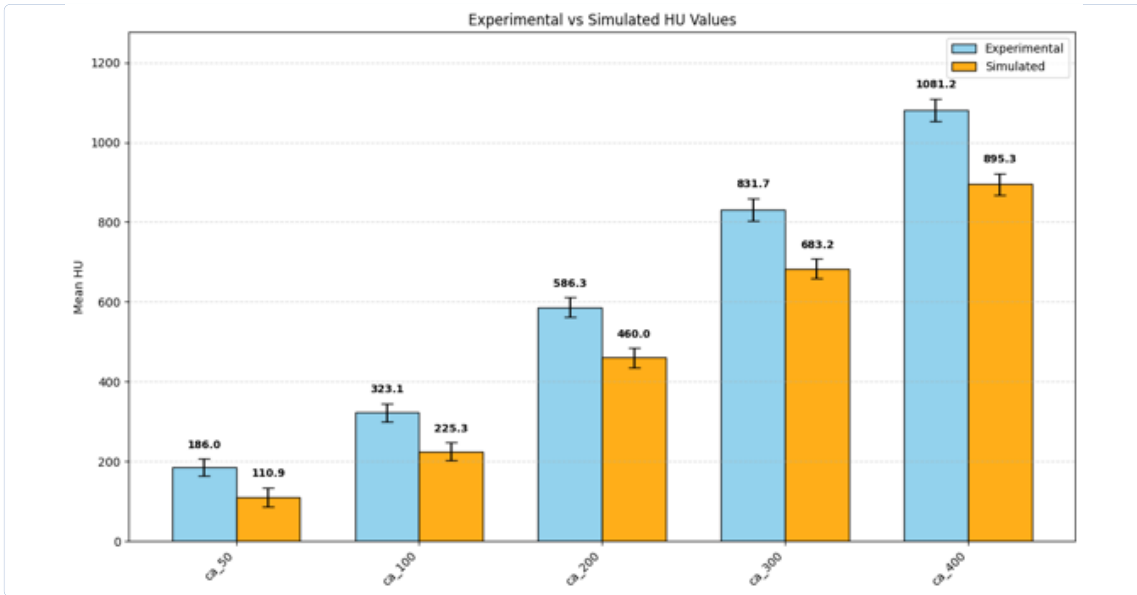

Figure 3. Clinical vs. simulated HU, calcium 50–400 mg/mL, 120 kVp.

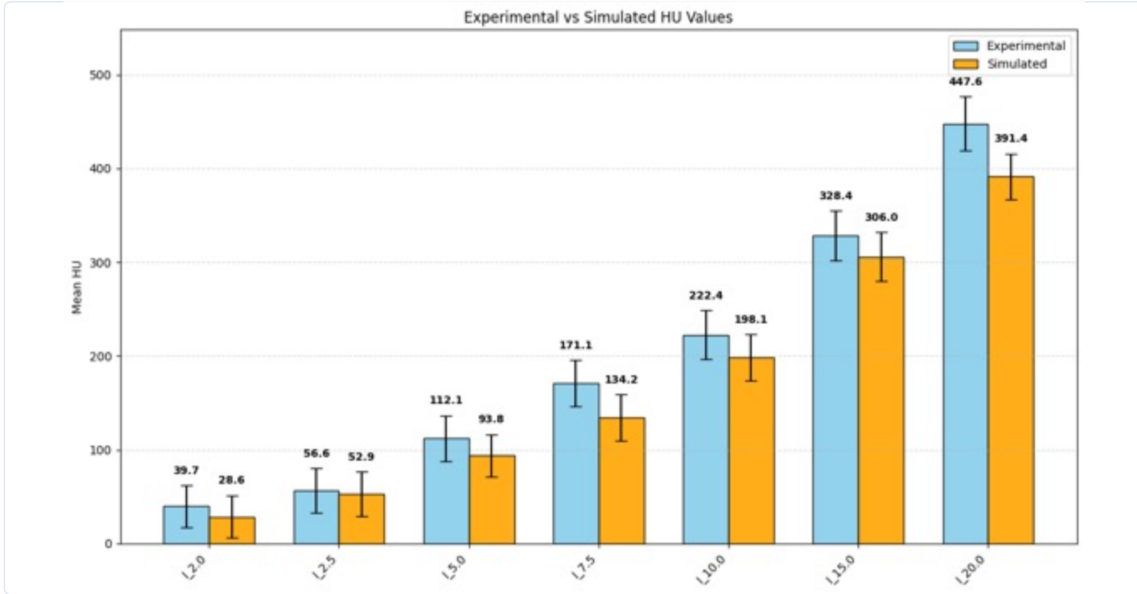

Figure 4. Clinical vs. simulated HU, iodine 2–20 mg/mL, 120 kVp.

LINEARITY — FIT AND UNITY

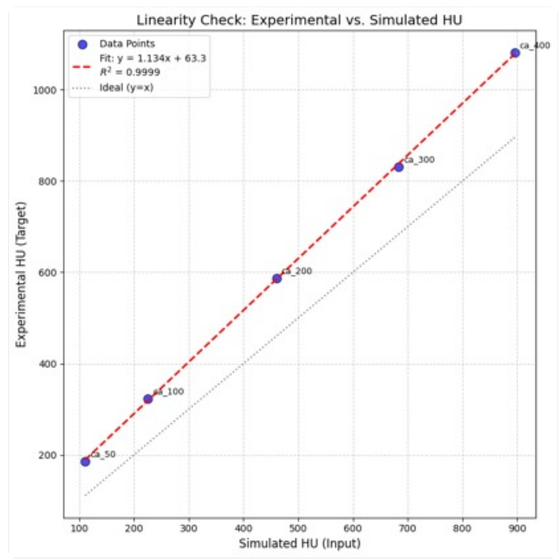

Figure 5. Calcium linearity, 120 kVp; regression fit vs. unity (y = x). **R^2 = 0.9999.**

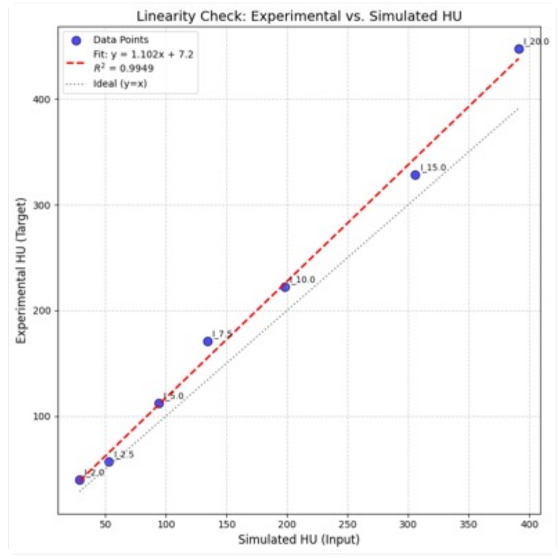

Figure 6. Iodine linearity, 120 kVp; offset grows with concentration. **R^2 = 0.9949.**

> The offset is **systematic and highly linear ($R^2 > 0.99$)** — and therefore correctable — rather than random.

QUANTITATIVE SUMMARY

Table 1. Combined-energy summary (120 + 140 kVp), McBride scale.

Material	R^2	Lin's CCC	McBride
Iodine (2–20 mg/mL)	> 0.99	**0.93**	Moderate
Calcium (50–400 mg/mL)	> 0.99	**0.89**	Poor

DISCUSSION

The offset between simulated and experimental HU is **highly linear and concentration-independent** , indicating a systematic — and therefore correctable — bias rather than random error.

Combined-energy Lin's CCC unites **precision** (linearity) with **accuracy** (deviation from unity): iodine reaches moderate agreement (0.93), while calcium remains poor (0.89), reflecting calcium's larger absolute HU and greater sensitivity to spectral mismodeling.

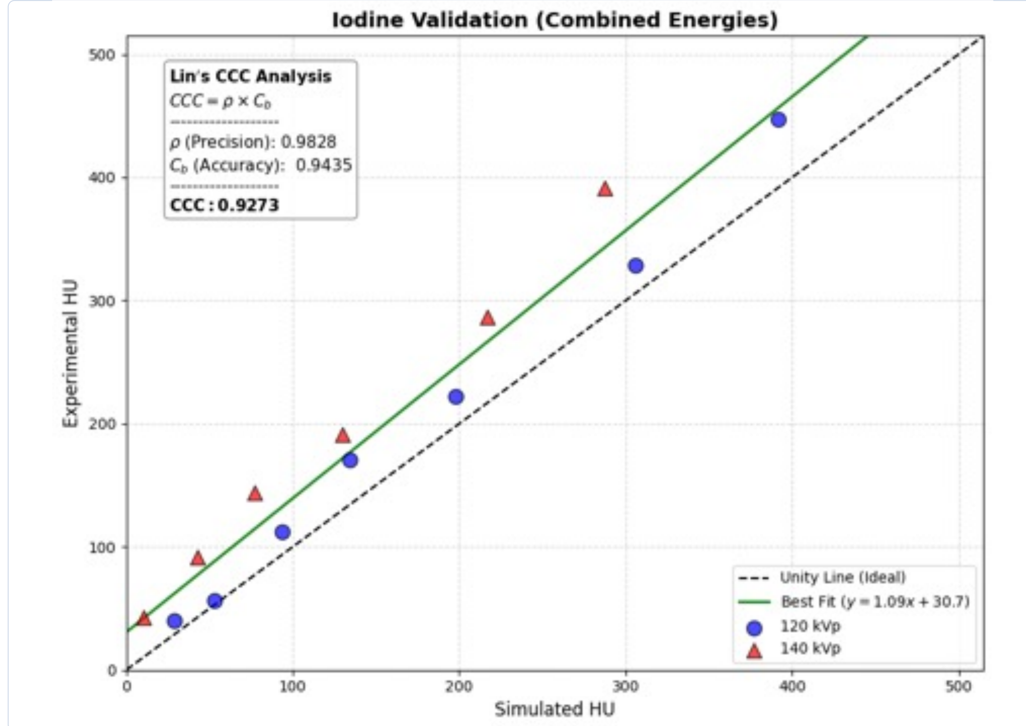

Figure 7. Iodine agreement, 120 + 140 kVp. CCC = 0.93.

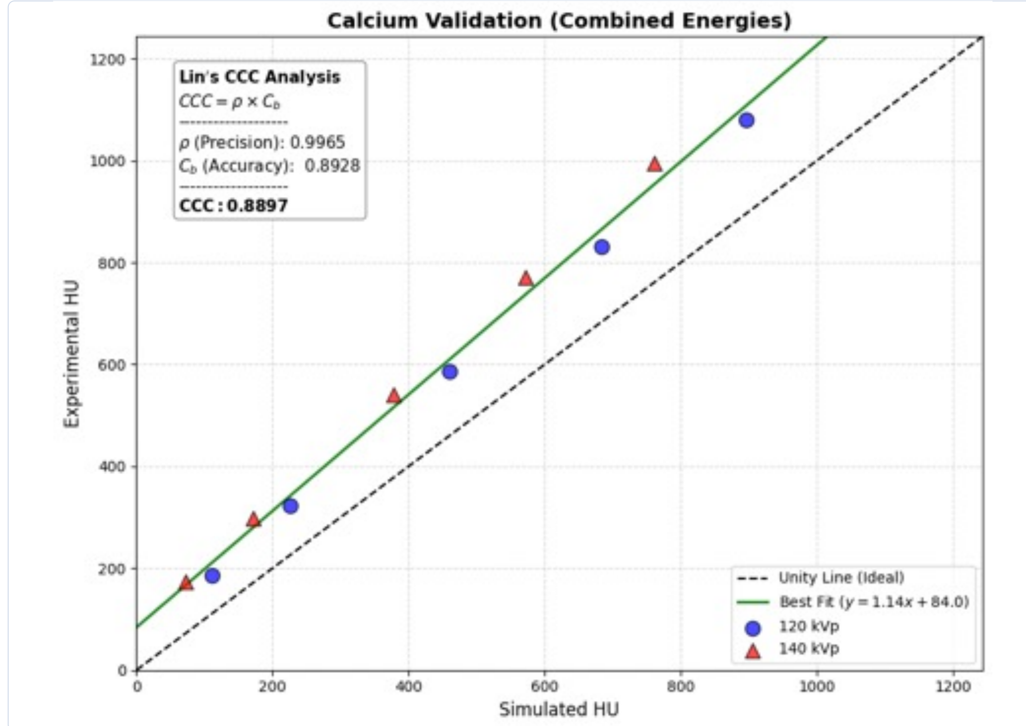

Figure 8. Calcium agreement, 120 + 140 kVp. CCC = 0.89.

CONCLUSIONS

We present the **first open-source CATsim model for clinical PCCT benchmarking** . Simulated HU is linearly underestimated for both materials ($R^2 > 0.99$) — a systematic bias that is quantifiable and correctable. The pattern points to analytical simplifications in the Beer–Lambert detector-efficiency model, and a softer real-scanner beam, as the primary error drivers.

FUTURE WORK Replace the analytical efficiency model with **Monte Carlo transport** to capture the full spectral response of CdTe detectors.

REFERENCES & ACKNOWLEDGEMENTS

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