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UTSouthwestern Medical Center

A Dose-Leveled Parametric NPS Modeling Library for Photon-Counting CT

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ABSTRACT

Purpose:
Photon-counting CT (PCCT) denoising requires realistic dose-specific noise targets; however, repeated acquisitions at every dose level are impractical. We developed a dose-leveled Noise Power Spectrum (NPS) modeling library capable of continuously predicting CT noise characteristics across dose levels, reconstruction strengths, and image types.

Methods:
An ACR CT accreditation phantom was scanned on a PCCT scanner (NAEOTOM Alpha, Siemens) using CTDI_{vol} values from 1–12 mGy. T3D and virtual monoenergetic images (50 and 70 keV) were reconstructed with QIR-3 and QIR-0. Two-dimensional NPS was measured using multiple ROIs, and a parametric model was fitted using odd-dose datasets and evaluated on independent even-dose datasets.

Results:
The proposed model accurately predicted both NPS magnitude and spectral shape across all reconstruction conditions. Predicted NPS closely matched measurements, achieving $R^2 > 0.99$ and MSE = 10^{-3}–10^{-2}, with minimal domain shift between training and testing dose levels.

Conclusions:
The proposed dose-leveled parametric NPS modeling library enables robust prediction of CT noise characteristics across dose and reconstruction settings. This framework provides a practical tool for dose-aware image quality assessment, protocol optimization, and simulation-based PCCT denoising.

I. INTRODUCTION

- Photon-counting CT (PCCT) denoising requires accurate characterization of image noise to reproduce realistic low-dose image quality. Conventional approaches measure the Noise Power Spectrum (NPS) independently for each dose level and reconstruction setting, requiring repeated phantom acquisitions.
- **To develop a dose-leveled parametric NPS modeling library that continuously predicts CT noise magnitude and texture across dose levels and reconstruction settings without additional scans.**

II. MATERIALS AND METHODS

Phantom acquisition
- ACR CT Accreditation Phantom
- NAEOTOM Alpha (Siemens Healthineers)
- CTDIvol = 1 - 12 mGy
- Reconstructions:
  - T3D
  - VMI 50 keV
  - VMI 70 keV
- QIR-3 and QIR-0 (FBP-like)
- Br44 reconstruction kernel

NPS calculation
- Multiple square ROIs placed in the uniformity module
- 2D Noise Power Spectrum calculated using an in-house software
- Validation performed against commercial software (CTPro)

Parametric NPS model
The measured NPS was modeled usi

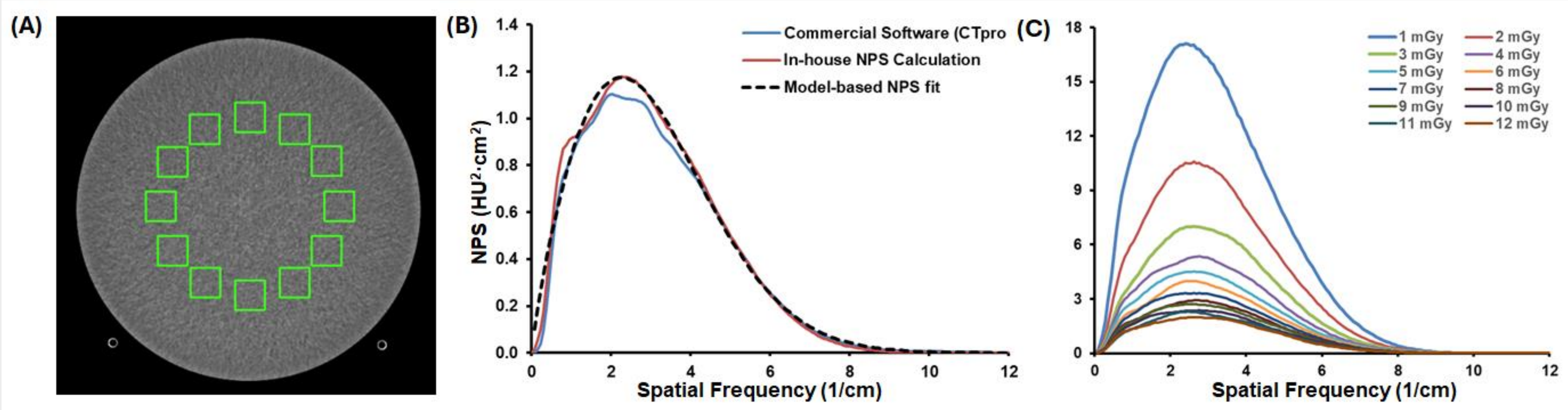
$$NPS(f) = a f^p \exp\left[-\left(\frac{f}{f_c}\right)^q\right]$$

- a : amplitude
- p : low-frequency behavior
- fc : cutoff frequency
- q : high-frequency roll-off

Odd-dose datasets (1, 3, 5...) were used for training and even-dose datasets (2, 4, 6...) for independent testing.

III. RESULTS

NPS Validation and Dose Characterization



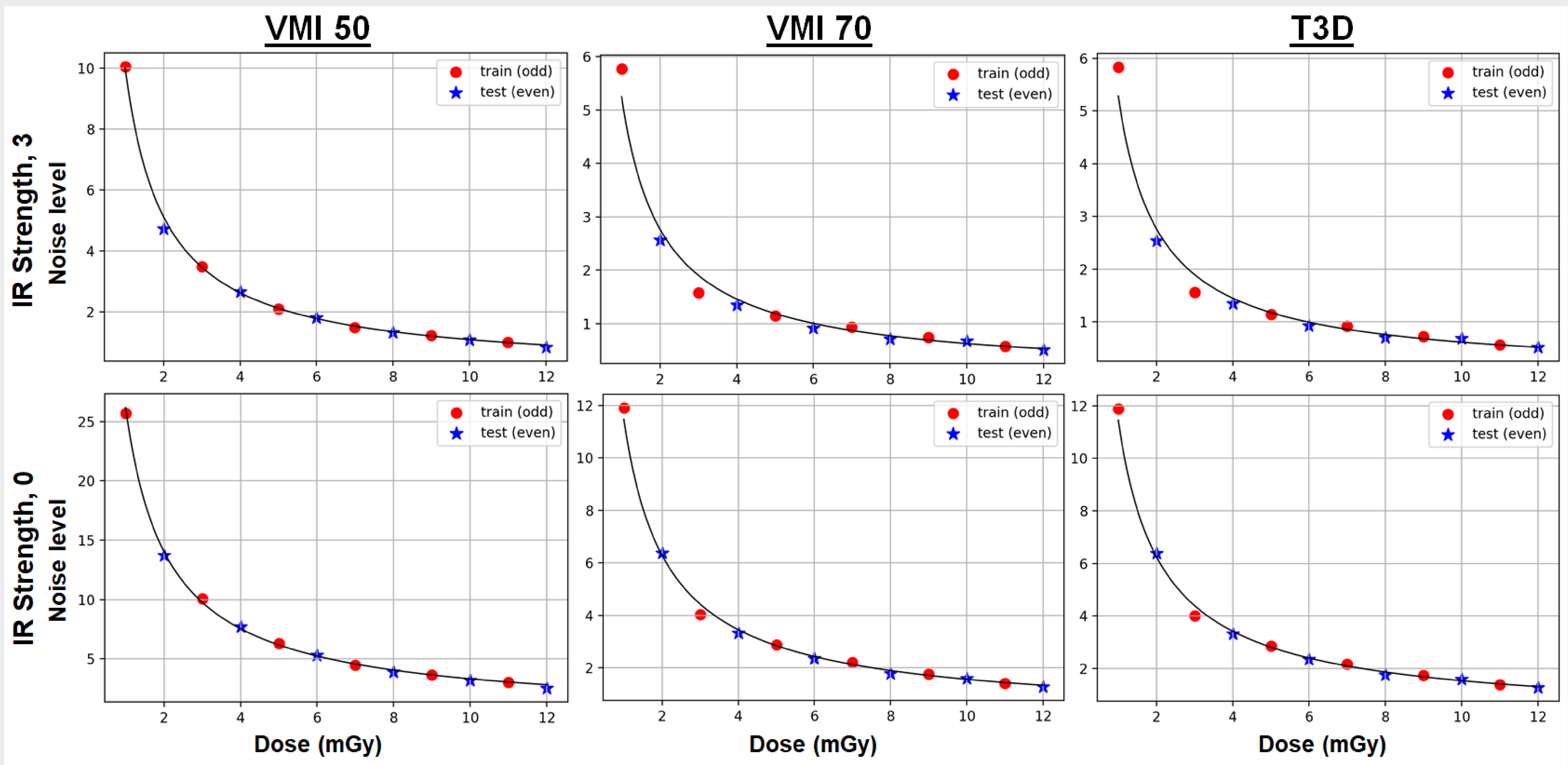
Validation of the proposed NPS modeling framework.
(A) ROI placement for NPS estimation. (B) Agreement between commercial software (CTPro) and the in-house NPS calculation with model fitting (dashed line). (C) Dose-dependent NPS measured from 1 - 12 mGy, showing reduced noise magnitude while maintaining spectral shape.

- In-house NPS calculation showed excellent agreement with commercial software (CTPro).
- The parametric model accurately fit measured NPS curves.
- Increasing dose reduced noise magnitude while preserving the overall spectral shape.

- Noise level followed a power-law relationship with CTDIvol.
- Similar dose-dependent trends were observed for VMI 50, VMI 70, and T3D under both IR strengths.
- The fitted model generalized well from odd-dose training to even-dose testing.

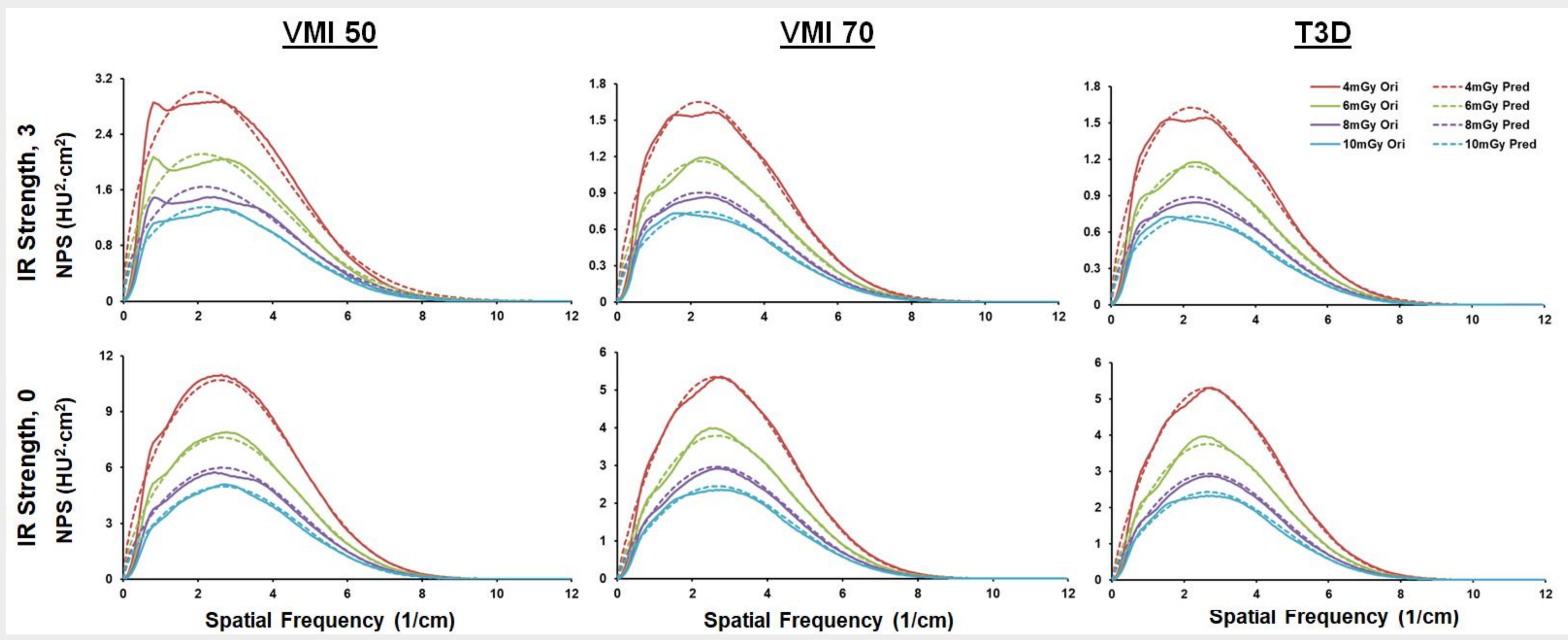
- Predicted NPS closely reproduced measured NPS across all dose levels.
- Both noise magnitude and frequency characteristics were accurately preserved.
- High prediction accuracy was achieved for all reconstruction settings ($R^2 > 0.99$, MSE = 10^{-3}–10^{-2}).

Dose-Dependent NPS Modeling



Dose-dependent power-law fitting of noise levels. Odd doses were used for training and even doses for testing.

Measured vs. Predicted NPS



Measured (solid) and model-predicted (dashed) NPS curves for VMI 50, VMI 70, and T3D across dose levels (1–12 mGy) at IR = 3 (top) and IR = 0 (bottom).

IV. CONCLUSIONS

- A compact parametric model enables continuous prediction of CT noise characteristics across dose levels.
- Accurate NPS prediction was achieved for multiple reconstruction types and IR strengths.
- The proposed framework eliminates the need for repeated NPS measurements at every target dose.
- The resulting NPS library supports realistic, dose-specific PCCT simulations and denoising applications.

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