A Reconstruction-Agnostic Fan Phantom for Task-Relevant PET Spatial Resolution Assessment

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Introduction

Conventional PET spatial resolution assessment methods (ACR, NEMA NU 2-2018)[1,2] offer limited insight into the effective resolution achieved under clinical conditions. Modern PET routinely uses iterative reconstruction (OSEM, AI-enhanced) rather than filtered back projection (FBP).

Key limitations of current approaches:
Derenzo-type phantoms provide only a discrete set of rod sizes, limiting continuous frequency analysis. **NEMA NU 2-2018** and ACR point-source protocols were designed for FBP and do not reflect AI-based reconstruction performance.
Task-specific reconstruction optimization proceeds without a practical tool to evaluate effective spatial resolution.

Proposed solution:
We adapt fan-pattern line phantoms used in X-ray imaging to PET imaging. This enables **modulation transfer function (MTF) analysis**, providing continuous spatial resolution characterization beyond conventional FWHM metrics.

Phantom Architecture

Fan-pattern paper phantom:
The phantom consists of a fan-shaped arrangement of line structures with **continuously varying spatial frequency**, enabling visual identification of the smallest resolvable feature and MTF analysis.

Fabrication:
Laser-cut fan geometry in paper (0.08 mm thickness)
Gap widths decreasing from **5 mm to 1 mm** over an 8 cm length
Briefly soaked in F-18 solution (3–5 seconds)
Air-dried for 1 min, then sealed between 0.1 mm plastic sheets

Key advantage:
Low cost, reproducible, and can be prepared in **< 5 minutes** total.

Imaging Protocol

Scanner:
uEXPLORER PET/CT (United Imaging Healthcare)

Phantom positioned 1 cm off-axis with CT laser alignment system.
Each scan: 5 minutes at center of axial FOV.

MTF Analysis:
Assuming a Gaussian system response, FWHM is derived directly from the spatial frequency f_{50} at which the MTF = 50%:

$FWHM = \sqrt{2 \ln 2} / (\pi \cdot f_{50})$ (Assuming Gaussian distributions)

Reproducibility & Repeatability

Reproducibility:
5 independently prepared phantoms (2 soaked 5 s, 3 soaked 3 s) scanned once each

Repeatability:
1 phantom scanned 5 consecutive times under identical conditions

Activity concentration:
0.69–1.05 mCi/mL at time of scan

Reconstruction:
FBP, voxel size 0.6×0.6×0.6 mm³

Phantom Setup (Figure 1)

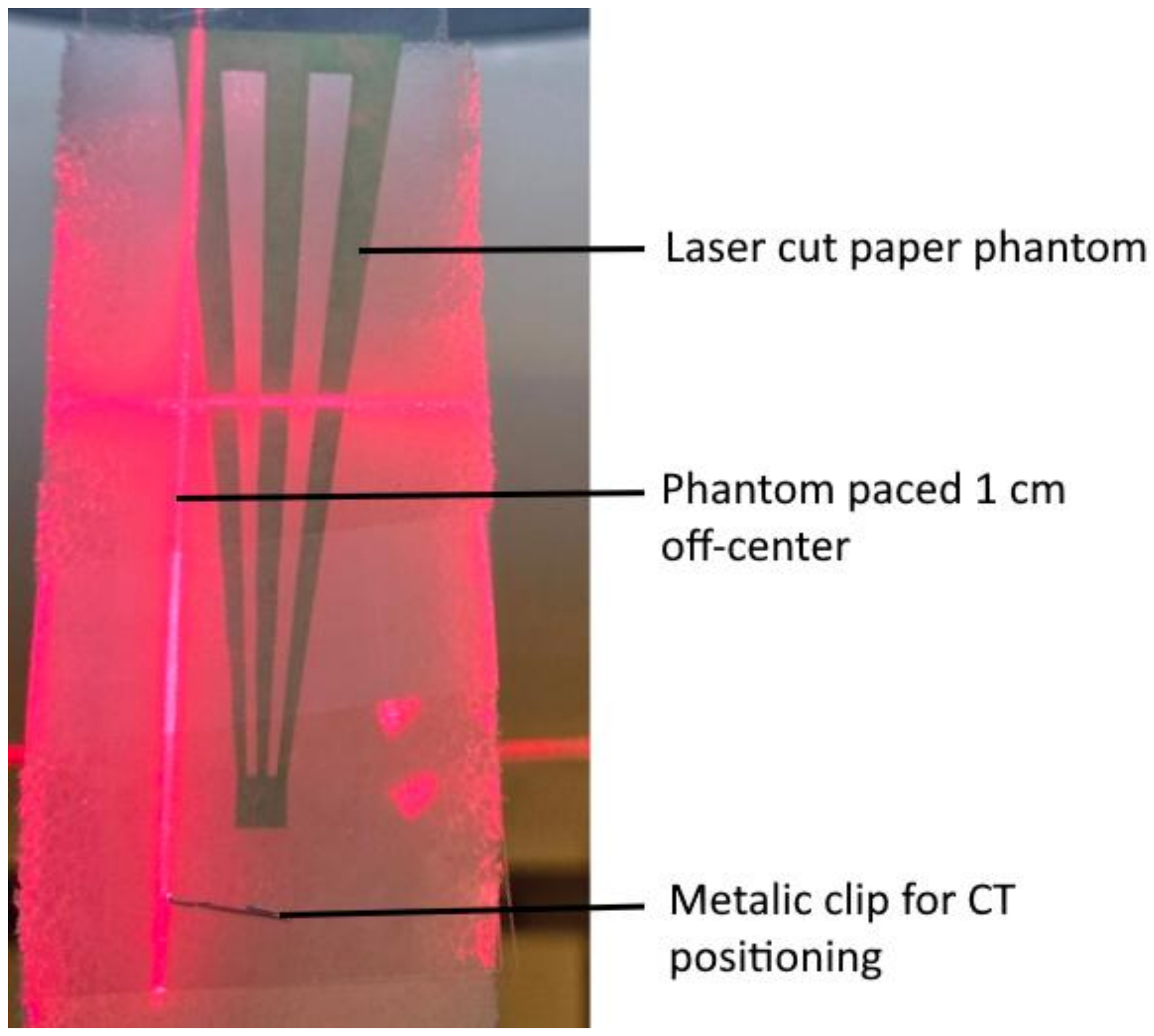

Fig. 1 — Laser-cut fan paper phantom soaked in F-18 solution, positioned with CT laser alignment system to evaluate radial resolution.

MTF Analysis (Figure 2)

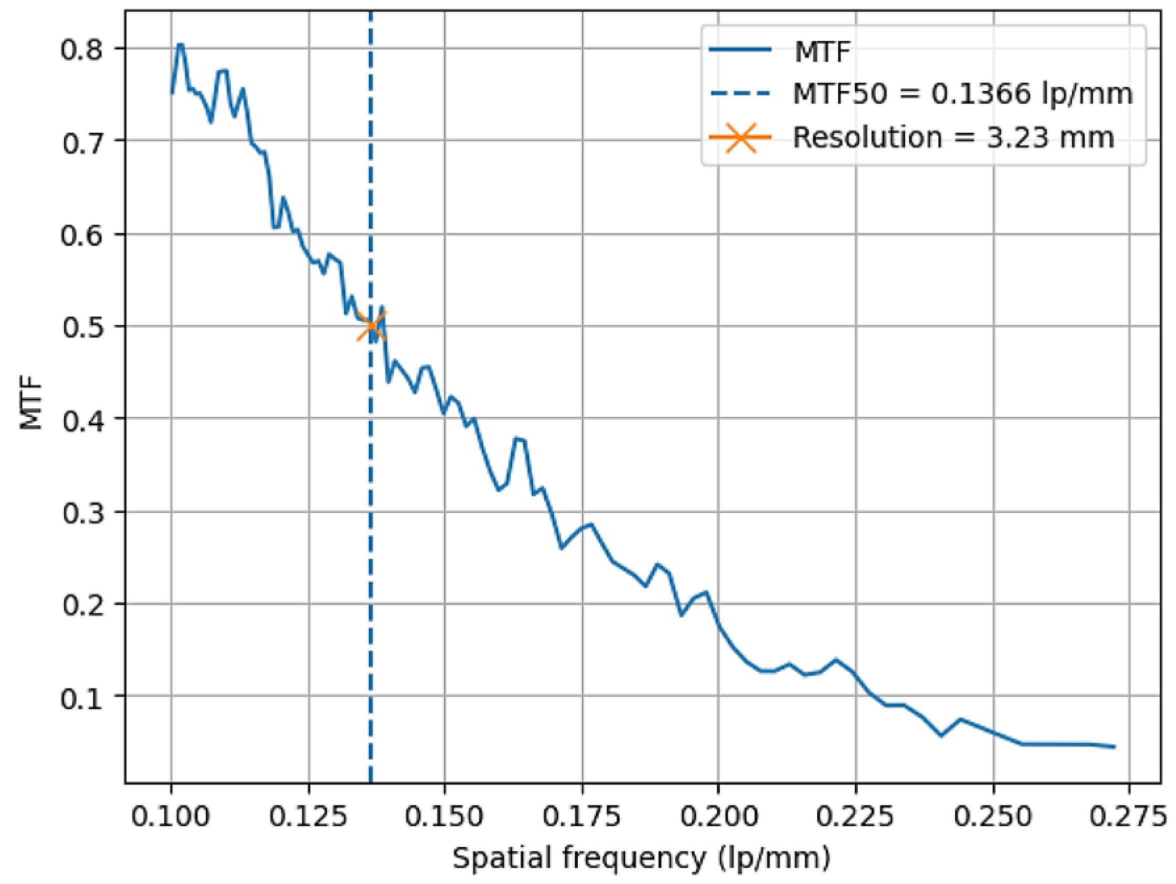

Fig. 2 — MTF from FBP reconstruction at center of uEXPLORER axial FOV. f_{50} = 0.137 lp/mm → Resolution = 3.23 mm.

Reproducibility & Repeatability - Results

Reproducibility
3.23 ± 0.034 mm
(radial FWHM, n=5)

Repeatability
3.22 ± 0.054 mm
(radial FWHM, n=5)

Comparison with NEMA NU-2
NEMA reproducibility: 3.18 ± 0.20 mm
NEMA repeatability: 3.32 ± 0.23 mm

→ Fan phantom uncertainty ~6× lower attributed to MTF curve interpolation

Evaluating Reconstruction Kernels (Table 1)

Label	Algorithm	Voxel (mm³)	PSF
1 – OSEM	OSEM	0.6×0.6×0.6	Off
2 – OSEM+PSF	OSEM	0.6×0.6×0.6	On
3 – Hyper DL	Deep Learning	1×1×1	On
4 – Hyper	Reg. OSEM	1×1×1	On
5 – FBP	FBP	0.6×0.6×0.6	N/A

Spatial Resolution by Kernel – Results (Table 2)

Label	Radial (mm)	Tangential (mm)	Axial (mm)
1	2.98	2.77	2.31
2	**2.18**	**2.08**	**2.19**
3	2.30	2.25	**2.13**
4	2.72	2.65	2.60
5 (FBP)	*3.23*	*3.22*	*3.16*

Green = best in-plane or axial resolution. All values accurate to ±0.06 mm (confirmed by reproducibility study).

Key Results Summary

Phantom is reconstruction agnostic and improves repeatability/reproducibility as compared to NEMA NU-2018
OSEM+PSF: 2.18 mm radial (best)
Hyper DL: 2.13 mm axial (best)
FBP: 3.23 mm radial (best)
AI and OSEM resolutions are comparable, with improvement by ~1 mm compared to FBP

Discussion

Superior measurement stability compared to NEMA NU-2:
Uncertainties of ±0.034 mm (reproducibility) and ±0.054 mm (repeatability) are lower than NEMA NU-2 (±0.20 and ±0.23 mm). MTF interpolation from multipoint measurements drives this improvement.

AI reconstruction advantage quantified:
The phantom directly demonstrates that PSF-corrected OSEM and AI-enhanced kernels improve in-plane resolution by ~27% over FBP, providing objective data for radiologist communication and protocol optimization.

Practical implementation: Phantom preparation and scan setup completed in < 5 minutes, compatible with routine clinical workflows. Low-cost and reproducible at any institution with laser-cutting access.

Conclusion

We propose a simple, low-cost fan-pattern paper phantom enabling **MTF-based PET spatial resolution assessment** that:
✓ **Works across all reconstruction methods** (i.e. FBP, OSEM, AI)
✓ **Provides continuous spatial frequency characterization**
✓ **Achieves ~6× lower uncertainty than NEMA NU-2**
✓ **Preparation & setup in < 5 minutes**
Phantom will be made available to the community to facilitate broader adoption.
Future work: Evaluate the effect of activity concentration and acquisition time on measurement uncertainty.

References

[1] NEMA NU 2-2018. National Electrical Manufacturers Association; 2018.
[2] Measurements of Positron Emission Tomographs. ACR; 2025.

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