JULY 19–22 VANCOUVER, BC
2026 JOINT AAPM | COMP MEETING

Comparison of quantitative Monte Carlo versus OSEM based SPECT reconstructions for ^{177}Lu using two energy windows

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ABSTRACT

Purpose: Accurate ^{177}Lu SPECT quantification is essential for patient-specific dosimetry in radiopharmaceutical therapies. Monte Carlo (MC) based reconstruction uses comprehensive system modeling to stochastically simulate photon transport and detector interactions, potentially improving quantitative accuracy and enabling more effective use of both the 113- and 208-keV photopeaks. However, evaluations of MC reconstruction for ^{177}Lu remain limited.

Methods: The MC reconstruction algorithm was implemented using SIMIND integrated within the open-source PyTomography toolbox. OSEM reconstructs in counts and relies on an external calibration factor (CF) that can introduce bias, while the MC method directly estimates activity in MBq. Performance was evaluated using recovery coefficients (RCs). First, simulated 1-hour post-injection ^{177}Lu-DOTATATE SPECT data from Siemens Symbia scanner were analyzed. For tumor quantification, OSEM CFs were derived from simulated point sources placed in attenuation phantoms of varying sizes for comparison. The MC method was then validated with an anthropomorphic phantom.

Results: The reconstructed activity map shows that our MC based reconstruction yields lower noise, especially at 113 keV, as confirmed by line profiles with fewer artificial fluctuations than OSEM. RC results at 113 keV vary substantially with the attenuation-phantom size used for OSEM calibration, largely due to increased impact of scatter. Although applying an ROI mask improves 208 keV accuracy, the 113 keV RC still show at least a 25% positive bias. In contrast, MC reconstruction provides stable and accurate RC (bias: 2.54% at 208 keV and 6.54% at 113 keV after 25 iterations). For the anthropomorphic phantom data, a central liver ROI was used to avoid partial-volume effects. Both photopeaks converge to similar RC, indicating good cross-energy consistency.

Conclusion: Compared with conventional OSEM, MC reconstruction offers substantial improvements in noise suppression and scatter correction, enabling reliable quantitative use of the highly scatter-affected 113 keV photopeak and potentially reducing the required scan time.

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INTRODUCTION

- ^{177}Lu-based radiopharmaceutical therapies are increasingly used for targeted cancer treatment, including neuroendocrine tumors and prostate cancer.
- ^{177}Lu emits therapeutic β− particles and imaging-capable gamma photons, enabling post-therapy quantitative SPECT.
- Quantitative ^{177}Lu SPECT plays an important role in treatment verification, activity quantification, and patient-specific dosimetry.
- Accurate quantification remains challenging due to attenuation, scatter, collimator-detector response, septal penetration, and down-scatter effects.
- Conventional analytical reconstruction methods rely on approximate physical corrections, which may limit quantitative accuracy.
- Monte Carlo (MC)-based reconstruction can more realistically model photon transport and detector interactions.
- This study evaluates MC-based reconstruction for ^{177}Lu SPECT, focusing on image quality and quantitative accuracy.

METHODS AND MATERIALS

Conventional reconstruction:

$$\hat{f}^{(n+1)} = \frac{\hat{f}^{(n)}}{H^T_{\text{Analytic}}1} H^T_{\text{Analytic}} \left(\frac{g}{H_{\text{Analytic}}\hat{f}^{(n)} + s_{\text{TEW}}} \right)$$

$$s_{\text{TEW}} = \left(\frac{g_{\text{upper}}}{W_{\text{upper}}} + \frac{g_{\text{lower}}}{W_{\text{lower}}} \right) \cdot \frac{W_{\text{peak}}}{2}$$

MC-based reconstruction:

$$\hat{f}^{(n+1)} = \frac{\hat{f}^{(n)}}{H^T_{\text{Analytic}}1} H^T_{\text{Analytic}} \left(\frac{g}{H_{\text{MC}}\hat{f}^{(n)}} \right)$$

- Conventional iterative reconstruction used an analytical system matrix with TEW scatter correction, whereas the proposed MC-based reconstruction used SIMIND as the forward projector to model SPECT imaging physics.
- SIMIND was integrated into PyTomography. The MC model incorporated key SPECT physical effects, enabling direct activity estimation in MBq.
- Simulated ^{177}Lu-DOTATATE SPECT data were generated using the XCAT phantom, with 113 keV and 208 keV photopeak windows.
- Conventional reconstruction required external calibration factors (CFs) from point-source scans, which were simulated in this study to reflect practical calibration conditions.
- The MC reconstruction was further evaluated using an anthropomorphic phantom scan.

RESULTS

- The ground-truth activity map is shown in **Fig. 1**, where a 20-mm-diameter sphere with an activity concentration of 0.9564 MBq/mL was placed within a liver background containing 0.2531 MBq/mL of ^{177}Lu.
- For the Calibration experiment, water-filled cylindrical phantoms with different diameters and a centrally positioned point source are shown in **Fig. 2**. The projection data and corresponding CT map of the anthropomorphic phantom are shown in **Fig. 3**.
- Coronal views of the reconstructed images obtained using the two methods at the 208-keV and 113-keV photopeaks are shown in **Fig. 4**.
- **Fig. 5** compares RC results from conventional reconstruction using different CFs with the single CF-independent result from MC reconstruction. Results are shown with and without applying a mask to the point-source reconstruction for CF measurement.
- **Fig. 6** presents the physical phantom validation results, showing that the reconstructed concentrations from both photopeaks converged to similar values close to the true concentration.

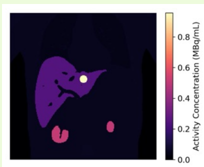

Figure 1. Ground-truth activity distribution in the XCAT phantom.

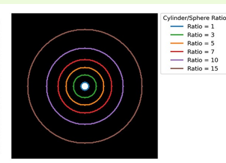

Figure 2. Attenuation maps with different diameters for the calibration experiment.

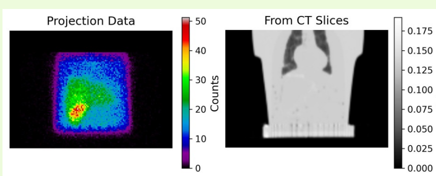

Figure 3. Projection data (left) and corresponding CT map (right) of the scanned anthropomorphic phantom.

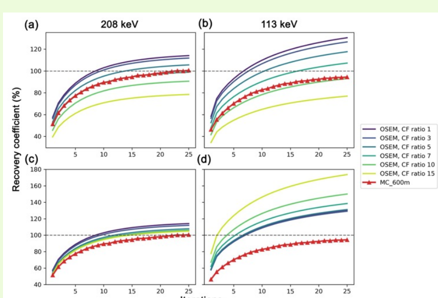

Figure 5. RC comparison between conventional and MC-based reconstruction methods without (a–b) and with (c–d) masking in the point-source reconstruction.

DISCUSSION

- MC-based reconstruction improved noise suppression and quantitative accuracy, particularly at 113 keV, where scatter and down-scatter produced substantial noise and artifacts in the conventional reconstruction (Fig. 4).
- Masking the point-source reconstruction reduced scatter-related errors in CF estimation. However, conventional reconstruction remained more accurate at 208 keV than at 113 keV, which showed greater bias and uncertainty. In contrast, the MC-based method required no separate CF measurement and provided more stable RC estimates across both photopeaks (Fig. 5).
- Physical phantom validation confirmed the practical accuracy of the SIMIND-based MC model, with consistent activity estimates between the two photopeaks and RC values close to the ground truth (Fig. 6).

CONCLUSION

SIMIND-based MC reconstruction provided more accurate, stable, and energy-consistent quantitative ^{177}Lu SPECT estimates than conventional CF-based reconstruction, with the greatest improvement at 113 keV.

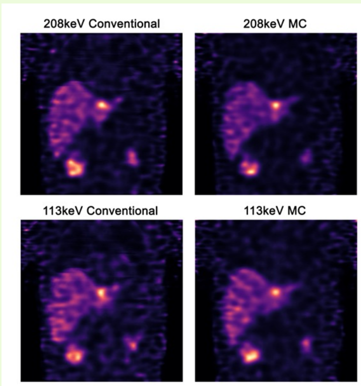

Figure 4. Coronal views of reconstructed images at 208 keV and 113 keV

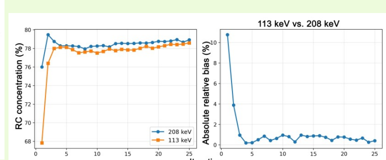

Figure 6. Anthropomorphic phantom validation and cross-energy consistency