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Experimental Study of Convergence and Quantification in Monte Carlo-Based Image Reconstruction

Monte Carlo–based iterative reconstruction (MCIR) methods hold significant promise for improving the quantitative accuracy and spatial fidelity of Single Photon Emission Computed Tomography (SPECT) imaging, yet their practical implementation requires careful validation and optimization. In this study, a comprehensive evaluation of SIMREC will be presented. SIMREC is a MCIR algorithm developed within the SIMIND simulation framework, and its performance will be compared to that of Siemens' clinically established Flash3D reconstruction (CIR). This investigation encompasses convergence analysis, activity quantification, and contrast recovery using both standard and anthropomorphic phantom data, as well as clinical patient studies.

Initial assessments were conducted using the NEMA IEC phantom to evaluate the convergence behavior of image contrast and noise as a function of iteration number. Metrics such as hot-sphere contrast, contrast-to-noise ratio, and sphere count-to-activity ratios were examined. SIMREC demonstrated rapid convergence, achieving stable contrast with as few as three iterations when optimized for smaller lesions, and requiring only a single iteration with appropriate regularization. In contrast, CIR required more iterations to reach comparable convergence, with inferior contrast recovery. These findings guided the selection of optimal reconstruction parameters for subsequent analysis.

To further validate SIMREC under anatomically realistic conditions, an anthropomorphic Kyoto thorax phantom was used to simulate hepatic lesions with radiotracer distributions modeled on ^{99m}Tc-EDDA/HYNIC-TOC uptake. Custom 3D-printed spheres of 5.5 mL and 11.5 mL volume were employed to simulate lesions at varying lesion-to-liver activity ratios (ranging from 2:1 to 27:1). Due to geometric constraints, lesion data were acquired separately and merged with whole-phantom scans via custom software-based registration. Reconstructed using both SIMREC and CIR, the datasets revealed that SIMREC not only maintained contrast stability over fewer iterations but also produced quantitatively accurate activity estimates within 10% of the true values, even for small volumes. CIR yielded lower accuracy, despite the application of sensitivity calibration using a long acquisition image realizing the identical geometry.

Finally, the optimized reconstruction protocols were applied to clinical SPECT/CT data, including tektrotyde and bone studies. Both qualitative assessment and quantitative analysis revealed that SIMREC consistently outperformed CIR in terms of lesion contrast, noise suppression, and overall image fidelity.

These results provide compelling evidence for the superiority of Monte Carlo–based reconstruction using SIMREC. Its ability to achieve accurate quantification and high-quality image reconstruction with fewer iterations underscores its potential for clinical integration and its value in advanced medical physics SPECT/CT imaging research.