

# Collimator-Free Non-Collinear Cascade Gamma Coincidence Imaging: A GATE-Based Study Achieving Sub-Millimeter Resolution and High Sensitivity

This study presents the GATE-based Monte Carlo model and performance evaluation of a non-time-of-flight, collimator-free tomographic medical imaging system based on non-collinear cascade gamma-ray Coincidence (CGC) imaging. A CGC imaging model was developed to reconstruct three-dimensional decay vertices from valid coincidence events. A custom geometric back-projection reconstruction algorithm was implemented to generate tomographic images in transverse, coronal, and sagittal views, enabling quantitative assessment of spatial resolution, sensitivity, and coincidence detection efficiency (CDE). The results show, with  $^{111}\text{In}$ -ion point source at the center of field of view (FoV), the modeled imaging system achieved sub-millimeter isotropic spatial resolution of approximately 0.477 mm (FWHM) along all axes and demonstrated resolving capability between 1.5-2.0 mm for closely spaced point sources. The CGC imager achieved a coincidence efficiency of  $1.50588 \times 10^{-2}$  and sensitivity of 15,058.8 cps/MBq for a  $^{111}\text{In}$  source at the center of the FoV in air, their corresponding values for source in PMMA phantom were  $1.25279 \times 10^{-2}$  and 12,527.9 cps/MBq, respectively. These values were significantly higher than those reported for conventional parallel-hole, focused, and hybrid collimator-based systems, representing improvements of several orders of magnitude. For positional reconstruction, the analysis confirmed the reconstructed source position within  $\pm 16$  mm transaxially and  $\pm 17$  mm axially resembles to simulated position. To evaluate the impact of radionuclide decay characteristics on imaging performance, four cascade gamma emitters ( $^{43}\text{K}$ ,  $^{73}\text{Se}$ ,  $^{111}\text{In}$  and  $^{177}\text{Lu}$ ) were simulated under identical conditions.  $^{111}\text{In}$  and  $^{73}\text{Se}$  exhibit the highest CDEs, followed by  $^{177}\text{Lu}$ , while  $^{43}\text{K}$  shows the lowest due to its extremely short intermediate-state half-life of 46 ps, which is below the detector timing resolution ( $\sim 0.549$  ns), leading to missed valid coincidence events. The higher CDE for  $^{111}\text{In}$  is partly from random coincidences caused by its longer half-life and wider timing window. These results emphasize that detector timing resolution, isotope selection, and coincidence window design are critical for optimizing cascade gamma imaging performance. On the other hand, spatial resolution remained the same ( $\sim 0.477$  mm FWHM) across radionuclides. This finding confirms that system resolution is governed by detector geometry and reconstruction parameters rather than decay properties. The findings demonstrate that non-collinear CGC imaging enables the simultaneous achievement of both high sensitivity and sub-millimeter spatial resolution. However, experimental testing of the system should be conducted to assess its practical performance.

**Primary authors:** JUNIOR, Innocent (Dar es Salaam University College of Education); MWITA, Enoch Mtatiro (University of Dar es Salaam); Dr NKUBA, Leonid (Tanzania Atomic Energy Commission); MOHAMMED, Najat (University of Dar es Salaam); LUGENDO, Innocent Jimmy (University of Dar es Salaam)

**Presenter:** MWITA, Enoch Mtatiro (University of Dar es Salaam)

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