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Task-driven Optimization of Minimum Acquisition Time for Total-body PET Whole-body Bone Imaging

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ABSTRACT

Purpose To determine the minimum acquisition time for total-body PET whole-body bone imaging using a validated Monte Carlo simulation framework and task-driven image quality assessment.

Methods A 194-cm axial field-of-view PET scanner based on the uEXPLORER design was implemented in GATE and validated using NEMA-like sensitivity and spatial-resolution measurements. An XCAT-derived skeletal activity phantom was simulated, converted to TOF list-mode data, and reconstructed using GPU-accelerated TOF-OSEM. Acquisition duration and reconstruction parameters were jointly optimized using quantitative image-quality metrics and whole-body skeletal visualization.

Results Simulated sensitivity agreed with published measurements within 1–4%, and spatial resolution reproduced the expected radial degradation observed experimentally. For 120-s acquisitions, one iteration with ten subsets achieved the best compromise between skeletal recovery, image noise, and numerical stability, whereas twenty OSEM updates produced non-finite voxels and regional signal loss. Under the current true-coincidence simulation, 120 s was the shortest evaluated acquisition that consistently preserved complete skeletal visualization.

Conclusions The proposed framework enables reproducible optimization of total-body PET acquisition protocols by jointly evaluating scanner performance, acquisition duration, reconstruction convergence, and task-specific image quality.

INTRODUCTION

Total-body PET substantially increases imaging sensitivity through its extended axial field of view, enabling shorter acquisition times and lower administered activity than conventional PET systems.

Whole-body bone imaging is particularly demanding because it requires accurate visualization of both high-uptake cortical bone and low-count peripheral skeletal structures. Although long-axial-field-of-view PET scanners have demonstrated outstanding performance, the minimum acquisition time required to maintain diagnostic image quality remains uncertain.

Monte Carlo simulation provides a reproducible approach for protocol optimization by allowing scanner geometry, acquisition parameters, and reconstruction algorithms to be evaluated against known ground truth.

The aim of this study was to establish a validated total-body PET simulation platform and determine the minimum task-appropriate acquisition duration through joint optimization of acquisition time and TOF reconstruction parameters.

METHODS AND MATERIALS

Scanner and simulation

- GATE v9.3 model of a uEXPLORER-like PET system: 194-cm AFOV, 564,480 LYSO crystals, 430–645 keV energy window, and 500-ps coincidence timing resolution.
- A 658 × 280 × 1764, 1-mm isotropic XCAT-derived skeletal activity phantom[1] was used as the Monte Carlo source. Photon transport, detector response, energy blurring, timing blurring, dead time, and coincidence sorting were modeled.

Data conversion and reconstruction

- ROOT coincidences were converted to CASToR TOF list mode and then to YRT-PET format with verified event-wise preservation of time, detector IDs, and TOF values. Discontinuous timestamps from independently simulated segments were corrected before reconstruction.
- GPU-accelerated TOF-OSEM used a Siddon projector, 500-ps Gaussian TOF kernel truncated at ±3σ, a 128 × 128 × 512 matrix, and 5.8 × 5.8 × 3.8 mm^3 voxels.
- OSEM configurations from 1 × 1 to 2 × 10 were evaluated; all images underwent automated checks for NaN/Inf values and axial truncation.

Evaluation

- System validation: NEMA-like sensitivity and point-source FWHM.
- Imaging task: whole-body skeletal continuity, regional recovery, coefficient of variation, SNR/CNR, RMSE/NRMSE, Pearson correlation, SSIM, and edge sharpness relative to the digital source and the longest-duration reconstruction.

Table 2. Sensitivity results[3].

Transaxial Position	700mm Phantom Experimental (kcps/MBq)	700mm Phantom Simulation (kcps/MBq)	1700mm Phantom Experimental (kcps/MBq)	1700mm Phantom Simulation (kcps/MBq)
0 cm	174	172	147	148
10 cm	177	170	151	147

Table 3. The result of point source spatial resolution[3].

		Full width at half maximum (mm)					
		Radial		Tangential		Axial	
Location	Position	Experimental	Simulation	Experimental	Simulation	Experimental	Simulation
Center of AFOV	1 cm	3.0	2.6	3.0	2.7	2.8	3.0
	10 cm	3.4	3.7	3.1	3.2	3.2	2.7
	20 cm	4.7	4.1	4.0	3.8	3.2	2.6
1/8th FOV	1 cm	3.0	2.5	2.9	2.8	2.9	3.1
	10 cm	3.6	3.5	3.2	3.7	3.1	3.0
	20 cm	4.6	3.8	4.4	5.0	3.3	2.7

RESULTS

System validation The simulated total-body PET system accurately reproduced published uEXPLORER performance. Extrapolated sensitivities differed from reported experimental measurements by only 1–4%, while simulated spatial resolution demonstrated the expected radial degradation with increasing source offset. These findings confirm the accuracy of both the Monte Carlo model and the reconstruction framework. The close agreement between simulation and experimental measurements indicates that the proposed framework provides a reliable basis for subsequent acquisition optimization and quantitative image-quality assessment.

Reconstruction optimization Image quality improved during the early stages of iterative reconstruction. Compared with a single subset, increasing the number of subsets enhanced skeletal continuity, cortical delineation, and bone-to-background contrast while maintaining numerical stability. Although quantitative consistency improved with convergence, the incremental benefit diminished as reconstruction progressed. Among all evaluated configurations, one iteration with ten subsets provided the best balance between image quality, convergence behavior, quantitative accuracy, and computational efficiency. Increasing the total number of OSEM updates to twenty resulted in non-finite voxels, degraded quantitative consistency, and regional skeletal signal loss, suggesting that excessive iterative updates may compromise reconstruction robustness.

Acquisition time optimization Image quality improved progressively with acquisition duration. Under the current true-coincidence simulation, 120 s represented the shortest evaluated acquisition that consistently preserved continuous whole-body skeletal visualization and stable quantitative performance.

Table 1. Total-body uEXPLORER PET design parameters[2].

Parameter Name	Value
Ring Diameter	76.79 cm
Axial FOV	194 cm
Crystal material	LYSO
Crystal element size	2.76×2.76×18.1 mm^3
Crystal pitch	2.85 mm
Crystals per block	6×7 (axial×transaxial)
Blocks per module	14×5 (axial×transaxial)
Number of units	8(axial direction)
Number of modules per unit	24
Energy resolution @ 511keV	11.7%
Energy window	430-645 keV
Coincidence time resolution	500 ps

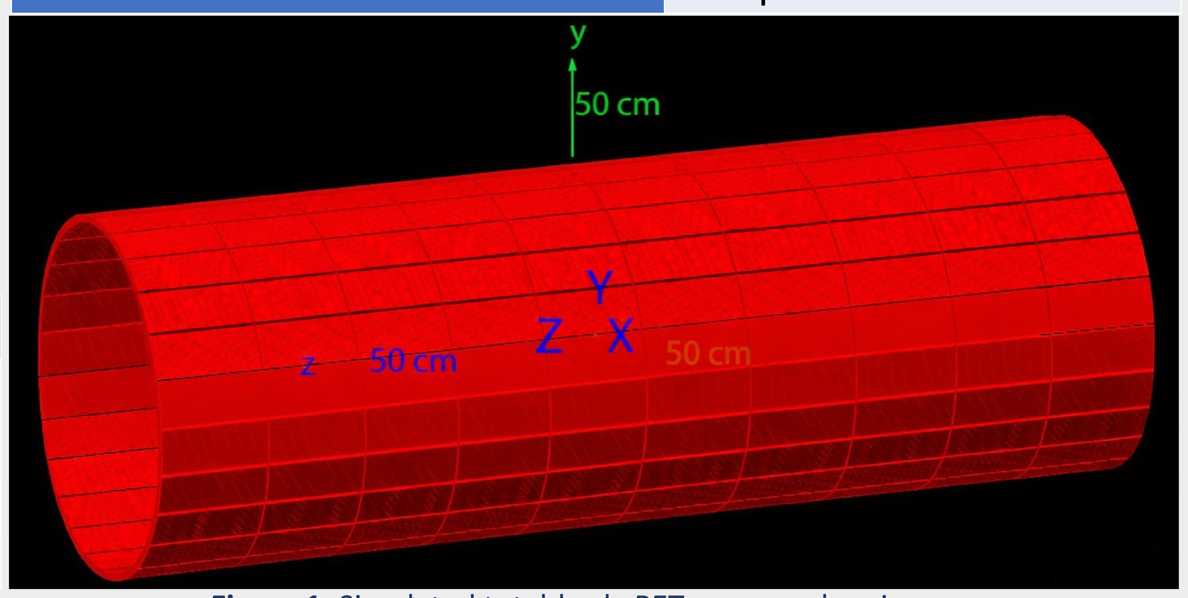

Figure 1. Simulated total-body PET scanner showing.

DISCUSSION

This work establishes a complete simulation-to-reconstruction framework for task-driven optimization of total-body PET whole-body bone imaging.

The validated Monte Carlo model accurately reproduced published system performance and provides a reliable platform for protocol optimization without repeated physical experiments.

Importantly, reconstruction performance was governed by both convergence and numerical stability. Increasing iterative updates beyond the optimal range did not improve image quality and instead introduced numerical instability, highlighting the importance of jointly optimizing acquisition duration and reconstruction parameters.

The proposed framework is readily extendable to future studies incorporating attenuation correction, scatter, random coincidences, patient motion, and clinical validation.

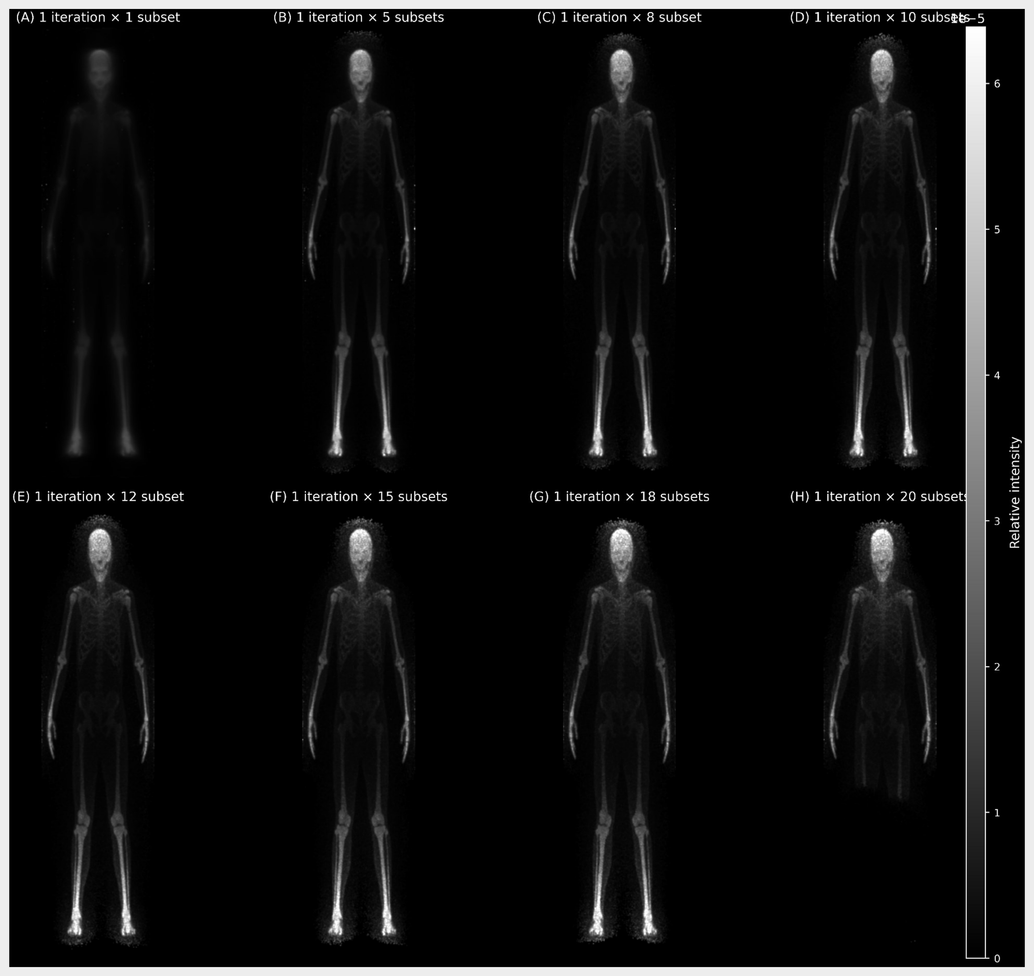

Figure 2. Reconstruction results of different subsets after 120s of 1 iteration.

CONCLUSIONS

- A validated Monte Carlo framework for total-body PET whole-body bone imaging was successfully established.
- Simulated NEMA performance closely matched published experimental results.
- One iteration × ten subsets provided the most favorable balance between image quality and reconstruction stability.
- Under the investigated true-coincidence conditions, 120 s was the shortest acquisition that preserved continuous whole-body skeletal visualization.
- The proposed task-driven framework provides a practical strategy for future optimization of total-body PET acquisition protocols.

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