Realistic PET Monte Carlo Simulation With Pixelated Block Detectors, Light Sharing, Random Coincidences and Dead-Time Modeling

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***Abstract*—We have developed and validated a realistic simulation of random coincidences, pixelated block detectors, light sharing among crystal elements and dead-time in 2D and 3D positron emission tomography (PET) imaging based on the SimSET Monte Carlo simulation software. Our simulation was validated by comparison to a Monte Carlo transport code widely used for PET modeling, GATE, and to measurements made on a PET scanner. Methods: We have modified the SimSET software to allow independent tracking of single photons in the object and septa while taking advantage of existing voxel based attenuation and activity distributions and validated importance sampling techniques implemented in SimSET. For each single photon interacting in the detector, the energy-weighted average of interaction points was computed, a blurring model applied to account for light sharing and the associated crystal identified. Detector dead-time was modeled in every block as a function of the local single rate using a variance reduction technique. Electronic dead-time was modeled for the whole scanner as a function of the prompt coincidences rate. Energy spectra predicted by our simulation were compared to GATE. NEMA NU-2 2001 performance tests were simulated with the new simulation as well as with SimSET and compared to measurements made on a Discovery ST (DST) camera. Results: Errors in simulated spatial resolution (full width at half maximum, FWHM) were 5.5% (6.1%) in 2D (3D) with the new simulation, compared with 42.5% (38.2%) with SimSET. Simulated (measured) scatter fractions were 17.8% (21.3%) in 2D and 45.8% (45.2%) in 3D. Simulated and measured sensitivities agreed within 2.3% in 2D and 3D for all planes and simulated and acquired count rate curves (including NEC) were within 12.7% in 2D in the [0: 80 kBq/cc] range and in 3D in the [0: 35 kBq/cc] range. The new simulation yielded significantly more realistic singles' and coincidences' spectra, spatial resolution, global sensitivity and lesion contrasts than the SimSET software.**

***Index Terms*—Block detectors, dead-time, light sharing, Monte Carlo simulation, positron emission tomography, random coincidences.**

I. Introduction

MONTE CARLO simulation allows accurate modeling of photon interactions in the object and the PET detector, while yielding perfect knowledge of the underlying reference activity and attenuation distributions as well as the distributions of scattered, unscattered and random coincidences. Simulation System for Emission Tomography (SimSET) [1] is a free software package available from the University of Washington Imaging Research Laboratory that models voxel-based activity and attenuation distributions and continuous PET detectors operating in 2D and 3D modes. Previous studies have validated the modeling of photon transport in non-uniform attenuation distributions with SimSET [2]–[4] but reported a systematic overestimation of the performances of PET scanners based on the block design (spatial resolution [3], [5]; scatter fraction [3]–[6]; sensitivity [3], [5], [6]) because of the absence of modeling of pixelated detectors, light-sharing among crystal elements, random coincidences and detector dead-time in SimSET. In PET scanners utilizing the block-design scheme [7], spatial resolution is fundamentally limited by the size of crystal elements [8] and the light-sharing read-out which makes use of less than one photo-multiplier tube (PMT) per crystal element [9], while the system sensitivity is degraded by the presence of gaps between blocks [10]. Modeling these detector effects would yield more realistic simulations of the detector response at low count rates. Modeling dead-time and the distribution of random coincidences for specific attenuation/activity distributions and activity levels allows accurate modeling of acquisitions at high count rates as well as the noise equivalent count rate (NEC), a metric widely used to assess PET scanner performance [11].

In this work, we modified the SimSET software to include modeling of block detectors and crystals, random coincidences and detector dead-time and used it to simulate the Discovery ST PET scanner (General Electric Medical Systems, Milwaukee, WI). We compared our simulation with the original version of SimSET, the validated Monte-Carlo software GATE [23] and with measurements made on a DST camera.

II. Description of the Monte-Carlo Model

A. Photon Propagation

1) Photon Generation: SimSET was used to generate coincidence events and simulate positron range as well as photon non-colinearity. Photon transport was modeled in two steps. The first step consisted of particle transport through the object and septa and the second step consisted of propagation through the detector, modeling of detector effects and binning.

2) Propagation of Photons in the Object and Septa: We modified the currently available version of SimSET to allow independent tracking of photons originating from the same annihilation event, i.e., single photons were simulated even if

Manuscript received June 23, 2006; revised December 17, 2007. This work was supported in part by grants from the Rotary and Arthur-Sachs foundations and in part by NIH R01-EB005876.

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Digital Object Identifier 10.1109/TNS.2008.924064

Representative Results:

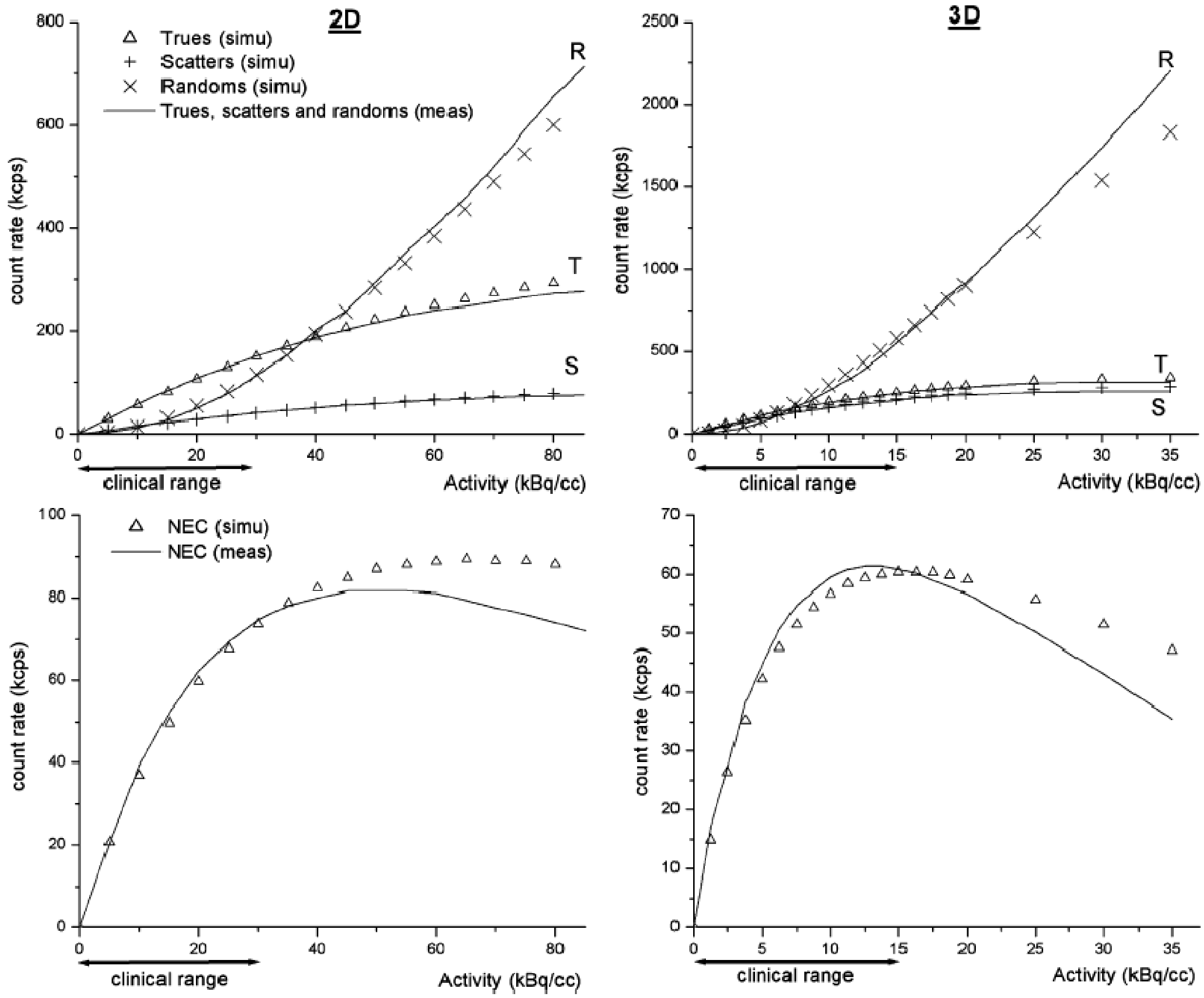

Fig. 6. Simulated and measured count rates in 2D and 3D mode (trues, scatters and randoms rates are shown in the upper row; NEC rates in the lower row). The maximum total activities modeled are 48 mCi (80 kBq/cc) and 21 mCi (35 kBq/cc).

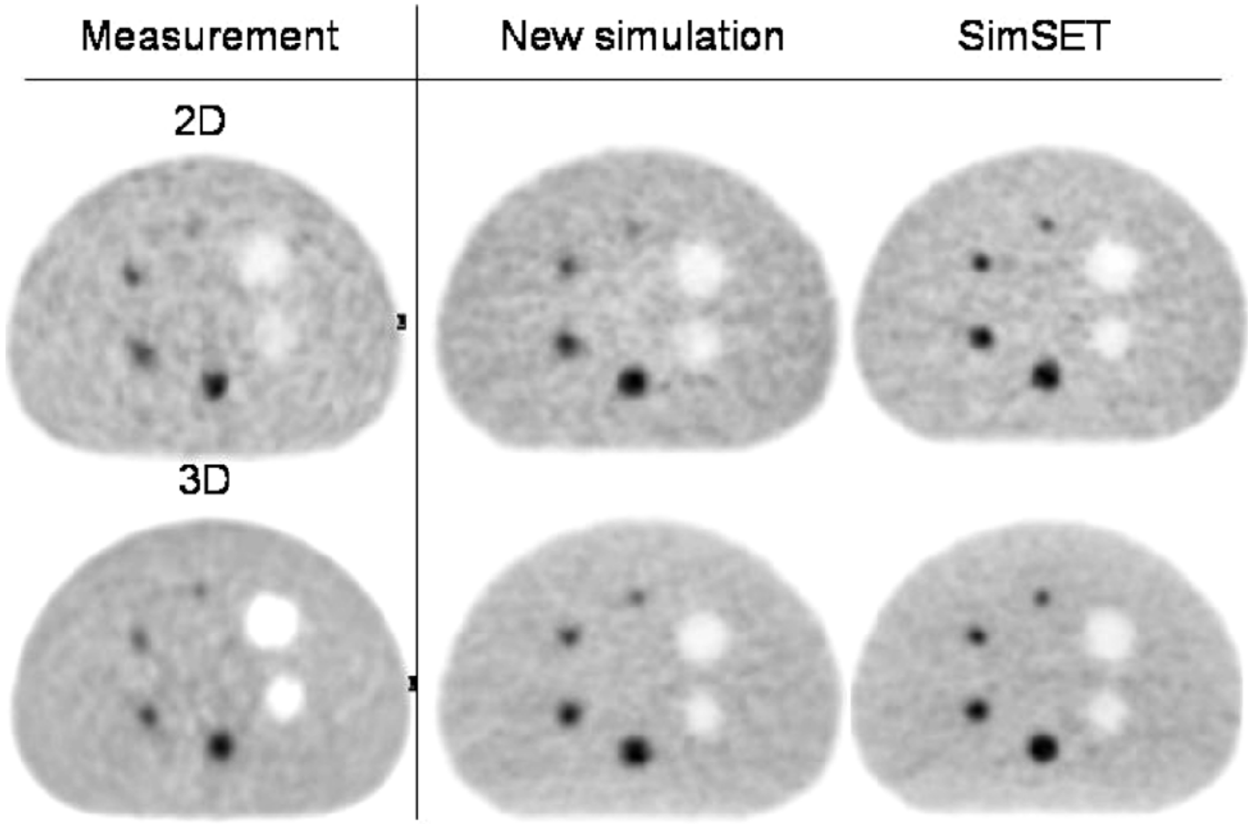

Fig. 7. Central slice of the measured and simulated NEMA NU-2 2001 image quality phantom acquisitions.