MONTE CARLO ASSESSMENT OF TIME-OF-FLIGHT BENEFITS ON THE LYSO-BASED DISCOVERY RX PET/CT SCANNER

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ABSTRACT

Time-Of-Flight (TOF) positron emission tomography (PET) was studied and preliminarily developed in the 80s, but the lack of a scintillator able to deliver proper time resolution and stopping power at the same time had prevented it becoming viable technique. Today newly discovered scintillators with greater light yield and/or stopping power, along with advances in photomultiplier tubes and electronics, are rekindling interest in TOF. In this study we performed Monte Carlo simulation using GATE to explore what gains in PET performance could be achieved if the timing resolution in the LYSO-based PET component of Discovery RX PET/CT scanner were improved. For this investigation, count rate performance in different activity concentrations was simulated for different coincidence timing windows and temporal resolutions. Strong evidence of the simulation accuracy was found in the good agreement between measured and simulated data. The results show that the random event rate can be reduced by using a narrower coincidence timing window with increasing the peak NECR by 50%. However, utilization of TOF information improves NECR proportionally with the dramatical reduction of random coincidences as a function of timing resolution. As the TOF performance potential improvements are substantial and the fast electronics and newly scintillators gives us the means to obtain them without other sacrifices, efforts to improve PET timing should resume after their long dormancy.

Index Terms — **Positron emission tomography (PET), time of flight (TOF), timing resolution, GATE**.

1. INTRODUCTION

Positron Emission Tomography is a functionally based medical imaging modality that utilizes coincidence detection of collinear annihilation photons to reconstruct a quantitative image of the in vivo radiotracer distribution. Like most imaging modalities, PET is limited by statistical noise. By accurately measuring the arrival time of the two 511 keV positron annihilation photons in the ring of detectors that surrounds the patient, the location of the positron can be constrained. This technique is known as time-of-flight (TOF) PET. Simple theory predicts that the statistical noise variance in PET can be reduced by using TOF information. This reduction can be obtained by improving the coincidence timing resolution, and so would be achievable in clinical, whole-body studies using with PET systems that differ little from existing cameras. TOF PET was extensively studied in the 1980s but died away in the 1990s, as it was impossible to reliably achieve sufficient timing resolution without sacrificing other important PET performance aspects, such as spatial resolution and efficiency. Today newly discovered scintillators with greater light yield and/or stopping power, along with advances in photomultiplier tubes and electronics, are rekindling interest in TOF.

The key advance that enabled modern TOF PET was the development of new scintillator materials. One of the best cerium-doped oxyorthosilicate PET scintillators is LYSO (lutetium yttrium orthosilicate). This scintillator possess excellent characteristics for detecting 511-keV photons in PET: The effective atomic number is 65; the density is 7.1 g/cm^3, and the attenuation coefficient is 0.83 cm^{-1} at 511 keV; the scintillation decay time is 42 ns and it has a light yield that is similar to that of LSO. It should be mentioned that the values of these properties depend on the relative yttrium content.

The aim of this study was to predict what gains in PET performance could be achieved if the timing resolution in the LYSO-based PET component of Discovery Rx PET/CT scanner were improved. The assessment has been conducted by Monte Carlo simulation, following accurate validation of simulation through comparison with measured data.

2. METHODS AND MATERIALS

2.1. Monte Carlo Simulation

Full scanner simulation is based on GATE (Geant4 Application for Tomographic Emission) toolkit which is developed and maintained by the Open-GATE collaboration [1]. It is an open-source extension of the GEANT4 Monte Carlo toolkit and the ROOT object oriented data analysis framework. The most advantageous features are its broad international support and the well validated and constantly updated underlying physics data and algorithms. Thus, as new features and refinements become available they are easily linked to GATE allowing it to continually expand and improve in order to meet rising technological demands and to incorporate new capabilities. GATE uses combinations of simple shapes (e.g., boxes, spheres, and cylinders), as defined in GEANT4 to generate complex geometric structures [2]. The software's limitations with regard to generating adequately complex shapes are well within the tolerance and design of these scanners. In GATE, electronic processing is modeled as a list of elementary processors, called pulse processors, through which signal (i.e. energy deposit within a sensitive detector element) is transformed and filtered-out. This structure of control, so-called digitizer in GATE, yields the signal as it will be measured, given the physical signal as an input [5]. Each module of the digitizer mimics a separate portion of a scanner's signal processing chain. The crystal QE, crystal blurring, thresholder, upholder, dead time and other electronics delay are defined in this module. To mimics the effect of limited transfer rate, a module allows to simulate the data loss due to an overflow of a memory buffer, limited bandwidth of wires or buffer capacities of the I/O interfaces.

2.2. Discovery Rx PET/CT Scanner

The Discovery Rx (GE Healthcare Technologies, Waukesha, WI, USA) PET/CT scanner uses LYSO scintillator. The scanner possesses high NECR, low scatter fraction, and good spatial resolution characteristics. It uses 4.2 x 6.3 x 30 mm^3 LYSO crystals grouped in 9 x 6 blocks. There are 24 rings with 630 crystals per ring for a grand total of 15120 crystals and the ring diameter is 88.6 cm. The transaxial and axial fields of view are 70 and 15.7 cm, respectively. The scanner has retractable septa and can operate in both 2-dimensional (2D) and 3-dimensional (3D) modes. The coincident window width is 5.85 ns and the energy window is 425-650 keV. The Scanner has transaxial resolution of 4.8 mm @1cm in both 2D and 3D mode.

2.3. Simulation Setup

As specified by NEMA, six concentric aluminum tubes all 700 mm in length were used to detect camera sensitivity. The Line source with 16 MBq of 18F was placed in the innermost tube, a fillable polyethylene tube with inside diameter of 1 mm and outside diameter of 3 mm. The SF and counting rate measurements were performed using the NEMA scatter phantom, The 70 cm in length cylindrical tube with outside diameter of 20.3 cm and a 6.4 mm hole size at offset distance of 4.5 cm. The 80 cm line source is placed in the hole with different activity of 220 MBq to 1 GBq. In all the simulations the acquisition time of 10 seconds was selected. After accurate modeling of the scanner's geometry into the code the simulation setup were as follows.

A 14% mean energy resolution is applied to all crystals at the energy reference of 511 keV. Also two non paralyzable dead times, a 150 ns dead time for the singles at the Block level followed by a 75 ns dead time for the coincidence count rate are used. Finally, a memory buffer of 32 coincidences, in an event by event basis was applied. In order to explore what gains in PET performance could be achieved if the timing resolution were improved count rate performance and NECR curves have been obtained in different activity concentrations for various coincidence timing windows of 4, 5.85, 6, 6.5, 8, 10 and 12 for different electronics timing resolutions of 100 to 900 ps with 50 ps step. The code was validated via comparison with measured data for NEMA measurements [3] test of the Discovery RX scanner published by Kemp *et al.* [4].

3. RESULTS

The results are compared to published data from Kemp et al [4] for the sensitivity, scatter fraction and count rates. A comparison of the sensitivity of the GATE simulation to experimental values is presented in table 1. The third column contains GATE data without efficiency corrections. The fourth column lists the results when a 92.5% quantum efficiency (QE) is applied to individual events within the blocks in the digitizer. This efficiency was varied as a free parameter until the best agreement with experimental results was obtained.

Table 1

Comparison of 3D sensitivity measurements between the GE

Discovery RX PET scanner and the GATE simulation with and without efficiency corrections.

Radial position (cm)	Published data [4] (cps/kBq)	GATE w/o eff corrections (cps/kBq)	GATE w/eff corrections (cps/kBq)
R0 = 0	7.30	8.70	7.36
R10 = 10	7.54	8.94	7.55
Ratio R0 / R10	0.968	0.973	0.974

A comparison of the scatter fraction results of the GATE simulations to those of the measured data shows that the simulation scatter fractions are very close to the measured values (within 1% to 4%). The difference between the two experimental data points for the 425 to 650 keV energy window is also about 4%.

The count rate performance for trues, randoms, and noise equivalent counts without randoms subtraction for 6.5 ns coincidence window are shown in figure 1. The random event rates were divided by a factor of 5 to enable both rates to be shown in one Figure. The noise equivalent count rate without randoms subtraction is calculated via NECR= $T^2/(T+S+R)$; where T, S, and R are the true, scatter, and random count rates, respectively. The simulated peak true count rate is 455.19 kcps occurring at 30.8 kBq/ ml and the simulated peak NECR is 120.41 kcps at 22.5 kBq/ ml.

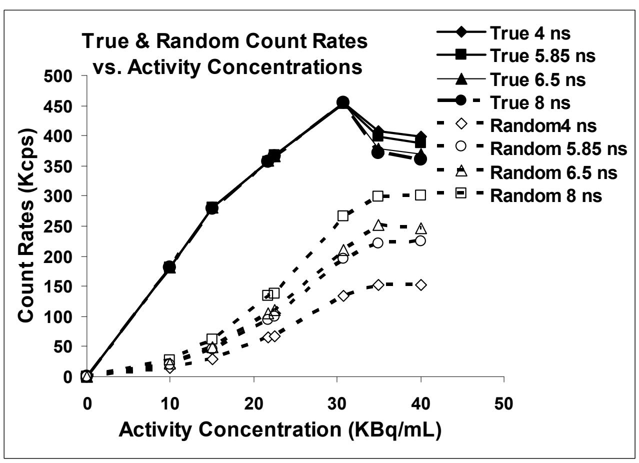

Figure 1. Random and True rates vs. activity concentration for varying coincidence window width. The object imaged was the NEMA 2001 scatter phantom. The random event rates were divided by a factor of 5 to enable both rates shown in one figure.

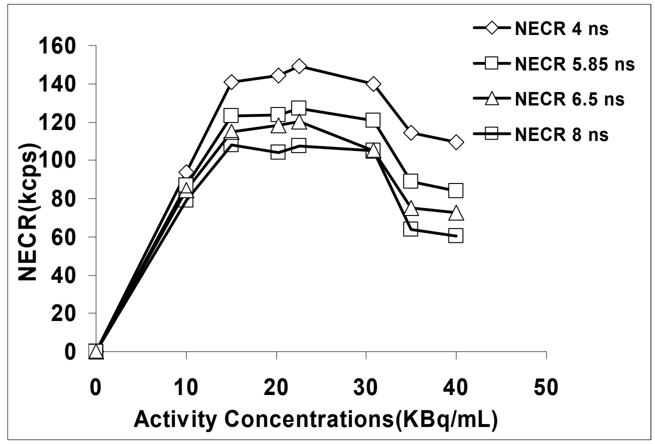

Figure 2. NECR vs. activity concentration for varying coincidence window width in the non-TOF scanner. The object imaged was the NEMA 2001 scatter phantom.

Figures 1 and 2 plot, for various hardware coincidence windows, the random and true rates and NECR for the NEMA 2001 scatter phantom in a 3-D mode as a function of activity concentrations. The data have been obtained without TOF information utilization. It is noticeable that the reduction in randoms depends linearly on coincidence window width. shows that true event rates at lower activity concentrations had not been affected by the variation of coincidence window. However, regarding the maximum total event rate of the coincidence processor and limited bandwidth of wires or buffer capacities of the I/O interfaces, true rates had improved for lower coincidence window at higher activity concentrations. In figure 2 these major improvements are more noticeable when NECR curves are used. The peak NECR had increased by ~50%. Figure 3 shows NECR values as a function of activity concentrations for varying timing resolutions. These values were obtained for a 4 ns coincidence window. Also the NECR for a non-TOF scanner was plotted. Major improvements can be realized just by reducing the timing resolution. The behavior of NECR curve for timing resolution of less than 500 ps is noticeable.

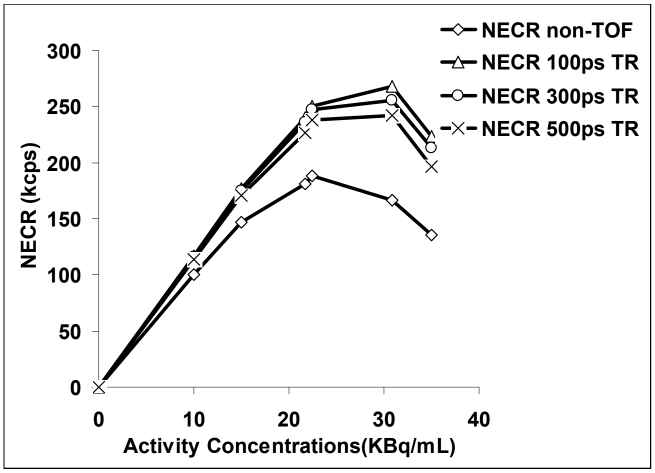

Figure 3. NECR vs. activity concentration for varying timing resolutions. The values were obtained for a 4 ns coincidence window.

Table 2 summarizes the potential benefits that could be obtained if the timing resolution in Discovery Rx PET/CT scanner can be improved. It should be noted that the calculation in Table 2 are based on 4 ns coincidence window with NEMA2001 scatter and count rate measurement phantom as the object.

Table 2

Predicted benefits as a function of coincidence timing resolution in LYSO-based Discovery Rx PET/CT scanner when using 4 ns coincidence window.

Timing Resolution	Performance Gain
500 ps FWHM	Factor of 2.2-2.3 reduction in random rates. Factor of 1.48 increase in NECR
300 ps FWHM	Factor of 2.6 reduction in random rates. Factor of 1.6 increase in NECR.
100 ps FWHM	Factor of 2.7 reduction in random rates. Factor of 1.75 increase in NECR.

4. CONCLUSION

TOF PET was extensively studied in the 1980s and eventually discarded, as other performance tradeoffs imposed by the CsF and BaF scintillator then used for TOF PET outweighed the advantages. The new scintillators have the potential to give the advantages of TOF without the disadvantages, and so it appears that the investigation of TOF PET should resume after its long dormancy.

The development of LYSO scintillator has already given PET cameras improved performance characteristics. However, the excellent timing properties have not yet been fully exploited in PET. If the timing resolution in Discovery Rx PET/CT scanner can be improved, significant improvements can be realized which are summarized in table 2. The results of this study shows in addition to the high sensitivity of Discovery Rx PET/CT scanner the implementation of TOF with proper timing resolution can efficiently improve the image quality in this scanner (table 2). For example, with timing resolution of 500 ps which seems to be possible with current technology, a factor of 2.3 reduction in random rates and factor of 1.48 increase in NECR is achieved.

REFERENCES

[1] D. Strul, G. Santin, D. Lazaro, V. Breton, and C. Morel, "GATE (Geant4 application for tomographic emission): A PET/SPECT general purpose simulation platform," Nucl. Phys. B 125, 75–79 (2003).

[2] OpenGATE Collaboration, *GATE Users Guide, Version 1.0.0*, May 2004, http://www-lphe.epfl.ch/GATE/

[3] "NEMA standards publication NU 2-2001: Performance measurements of positron emission tomographs," *Technical report* (National Electrical Manufactures Association, Washington, DC, 2001).

[4] B. J. Kemp; C. Kim; J. J. Williams; A. Ganin; Val J Lowe, "NEMA NU 2-2001 Performance Measurements of an LYSO-Based PET/CT System in 2D and 3D Acquisition Modes," *The Journal of Nuclear Medicine;* 47,12, (2006).

[5] S. Kerhoas-Cavata; D. Guez, "Modeling electronic processing in GATE," Proceedings of the 3rd International Conference on Imaging Technologies in Biomedical Sciences; 569, 330-334 (2006)