

Evaluation of the Impact of Out-of-Axial FOV Scattering Medium on Random Coincidence Rates on Discovery 690 PET/CT Scanner: A Simulation Study

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Abstract

Purpose: Positron Emission Tomography (PET) imaging is a nuclear medicine imaging technique based on the recording of two photons as coincidence created by positron annihilation.

Materials and Methods: PET coincidence events include true and unwanted coincidences (random, scattered, multiple coincidences). We modeled the Discovery 690 (D-690) PET scanner using the GATE simulation tool and estimated the effect of the diameter of the scattering medium out of the Axial Field Of View (AFOV) on the random coincidence rates.

Results: The validation results indicated that the average difference between simulated and measured data for sensitivity and scatter fraction tests are 5% and 3%, respectively. Moreover, the results revealed that the increasing diameter of the scattering medium out of the AFOV has a direct effect on the random coincidence rates within the Field Of View (FOV).

Conclusion: The study concluded that the presence of a scattering medium near the FOV increases the rate of random coincidences.

1. Introduction

One of the nuclear medicine imaging techniques used to diagnose the disease is a Positron Emission Tomography (PET) scan that shows the metabolic process of body. The PET systems are equipped with a coincidence recording system that detects two photons in the opposite direction. These photons are created by the interaction of positrons (caused by radionuclide decay)

with electrons in the body. The most crucial point in a coincidence recording system is the simultaneous recording of photons, leading to a highly-sensitive PET system.

The PET coincidence events include true and unwanted coincidences. In order to locate the spatial information of the positron source, the PET scanner must detect the events that resulted from positron annihilation. Ideally,

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this positron annihilation should occur alongside the line of response that connects the two detectors to record two photons resulting from the annihilation. Coincidence events are usually accepted in a finite interval known as a time window [1]. Therefore, two unrelated photons may be detected and recorded as coincidence events. Random coincidences are undesirable and do not provide accurate spatial information about the positron source [2]. The noise level generated by random coincidences may increase at high count rates. This will increase the background in the final images. Other undesirable coincidences include multiple and scattered coincidences. Since the recorded photons have been involved in adverse events on their way to the detector, these undesirable coincidences can damage image quality.

Monte Carlo (MC) techniques are a convenient tool for simulating the statistical processes involved in radiation detection. There are several MC packages available, including MCNP, EGSnrcMP, GEANT4. However, due to the flexibility in tomographic modalities, GATE (GEANT4 Application for Tomographic Emission) has been used extensively in the PET imaging. The advantages of MC codes for modeling particle transportation for high energy physics experiments [3] or dosimetry applications [4] include exhaustive testing of the different code components as well as the experience of a wide variety of users. In the study by Cal-González *et al.* [5] the MC simulator PeneloPET extended to assess the proportion of triple coincidences in the PET acquisitions and to evaluate their possible applications.

Over the past few years, several different works have evaluated the effects of random coincidences to improve the performance of the PET scanners and enhance their capabilities. According to an article by Badawi *et al.* [6], in the PET, the random coincidence events must be removed. They have investigated the effects of the random coincidences variance reduction on the noise-equivalent count rate. The Noise Equivalent Count Rate (NECR) analysis suggests that for the ECAT 951R scanner operating in the 3D mode, only modest gains in image signal to noise ratio may be obtained from random coincidence variance reduction in typical imaging situations using 18F-FDG [6]. Direct measurements of the Signal to Noise Ratios (SNRs) of the image confirm

this study, and it is challenging to distinguish images reconstructed with and without using the technique visually.

In a study by Oliver *et al.* [7] a novel sorting procedure based on Artificial Neural Network (ANN) techniques has been developed. It has been compared to a conventional coincidence sorting algorithm based on a time coincidence window. They concluded that at matched efficiencies, the ANN-based method always produces a sorted output with a smaller random fraction.

In order to evaluate the relevance of random coincidences in the PET acquisitions and to determine the scanner settings that would be optimal to register or filter randoms, it is useful to have a complete and accurate model of the emission and detection of the radiation [8]. MC simulations are commonly used for this task since they allow tracking all possible emissions and interactions.

The purpose of this study is to investigate the effect of the size of the activity and scattering medium on the rate of random coincidences using MC simulation.

2. Materials and Methods

2.1. Monte Carlo Simulations

The simulations of this study have been performed using the GATE toolkit (ver. 8.0.0), which is based on Geant4 for generation and tracking of particles [9]. MC methods are beneficial for simulating new detectors for nuclear medicine applications. The validation of these software packages has been widely confirmed in various scenarios.

2.1.1. PET/CT Scanner

The D-690 system detectors are a combination of an Lutetium Yttrium Oxyorthosilicate (LYSO) block detector in a PET module and also includes a 64-slice CT scanner. The D-690 consists of 24 rings of detectors for an AFOV of 157 mm. The trans-axial FOV is 70 cm. The system consists of 13824 LYSO crystals with dimensions of $4.2 \times 6.3 \times 25 \text{ mm}^3$. The PET detection unit is a block of 54 (9×6) individual LYSO crystals coupled to a single squared photomultiplier tube with four anodes. All compensations including scattering, random, dead time,

attenuation, and normalization are incorporated into the iterative reconstruction scheme using a fully 3D Ordered Subset Expectation Maximization (3D-OSEM) algorithm. In this study, the cylindrical geometry of the GATE toolkit [9] was used to simulate the geometry of the scanner with the specifications mentioned above.

2.1.2. Digitizer: Energy and Coincidence Timing Resolution

The electromagnetic interactions used in GATE are derived from Agostinelli [10]. The electromagnetic physics package manages electrons, positrons, γ -rays, X-rays, optical photons, muons, hadrons, and ions. In order to mimic a realistic detection process by building the physical observables from the hits, digitizer specifications were based on simulated scanner digitizer specifications. One of the parameters of the digitizer is the low energy threshold, which is considered to be 425 keV in the D-690. The system uses a coincidence time window of 4.9 ns. The random correction method in the GATE simulation is a delayed window and the dead of D-690 is non-paralyzable.

2.1.3. Phantom

To investigate the dependence of the effect of scattered medium on random coincidences rate with respect to the source distribution and diameter of the scattering medium, we have implemented NEMA phantom and several cylindrical phantoms with different volumes. In this study, an in-house image quality phantom, with a volume of 9.18 liters and six fillable cylindrical inserts, was used (Figure 1). The internal diameters of the inserts were 10, 13, 17, 22, 28, and 37 mm. Six cylindrical phantoms with different diameters were simulated to evaluate the effect of the size of the scattering medium on the random coincidences rate. The diameters of these phantoms are 15, 20, 25, 30, 35, and 40 cm, respectively.

2.2. Validation

In order to ensure the accuracy of the simulated scanner performance and to validate the simulation results, two critical tests, including sensitivity and scatter fraction tests were simulated, and the simulation results were compared with the values reported in the scanner data sheet provided by GE Company. The performance of the simulated D-690 (PET component) was assessed

according to the NEMA NU-2-2007 standard procedures [11].

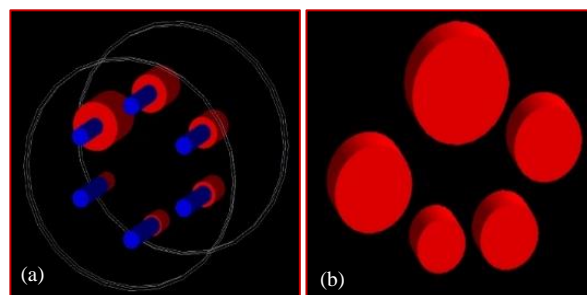


Figure 1. (a) Simulated NEMA phantom geometry (b) Simulated cylindrical phantoms

2.2.1. Sensitivity

In this study, a phantom containing five 70-cm-length concentric aluminum sleeves was used which the sleeves were stacked one inside the other. For conducting the test, the source was composed of a polyethylene tube, with an internal diameter, external diameter, and a length of 2 mm, 3.5 mm, and 70 cm, respectively it was filled with radioactivity. This tube was modeled with 23 MBq activity in its inside, inserting in the smallest tube of the five aluminum tubes mentioned above. A dynamic scan of 29 frames (5 min each) with an interval of 20 min between successive frames was employed as the acquisition protocol. At the end of each scan, random, scatter, and true coincidence rates were recorded using the benchmarks to calculate sensitivity of scanner in both position of ($X = 0$ and $Y = 0$) & ($X = 10$ and $Y = 10$) [12].

2.2.2. Scatter Fraction and Random Measurement

The NEMA NU-2-2007 scatter phantom was used for the scatter fraction test. The phantom was composed of a polyethylene cylinder (diameter: 20 cm; length: 70 cm) with a hole (at a radial distance of 4.5 cm) parallel to the central axis of the cylinder with the possibility of inserting a radioactive source. The simulated source filled with a solution of ^{18}F -FDG in water, resulting in the total activity of 1315 MBq. In order to sample the response of the system at different count rates during the decay of the source, 38 emission frames were recorded. The random and scatter coincidence rates were recorded for each measurement.

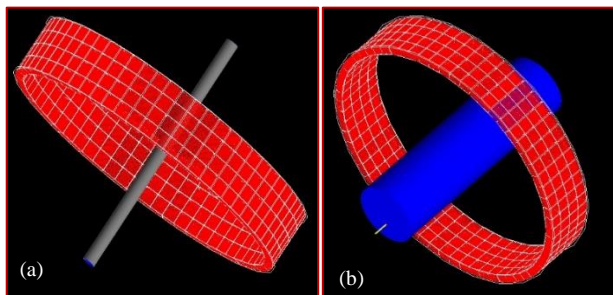


Figure 2. (a) Simulated sensitivity phantom – (b) Simulated scatter phantom

2.3. Data Acquisition

The simulated NEMA phantom is located in the center of the field of view of the scanner, and imaging has been performed with various activities with LBR:2:1.

In order to investigate the effect of the size of the scattering medium on random coincidence rates, the NEMA phantom was placed inside the FOV, and the cylindrical phantom outside the FOV was placed next to the NEMA image quality phantom. This setup was performed with a cylindrical phantom with different diameters, and the ratio of random to the true coincidence rates was recorded in each imaging.

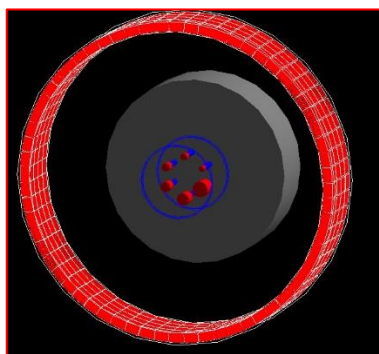


Figure 3. The geometry of the NEMA phantom inside the FOV and the cylindrical phantom outside the AFOV

2.4. Analysis

The random, scatter, and true coincidence rates were recorded at each simulation. The ratio of random to real coincidences was then calculated. The ratio of random to real coincidence rate was plotted in terms of the size of the scattering medium. NECRs were calculated for each scan and plotted according to different activities.

3. Results

Table 1 reports the results of our simulation of the NEMA NU-2-2007 measurements for sensitivity and scatter fraction. The plot of scatter fraction as a function of the activity concentration is shown in Figure 4.

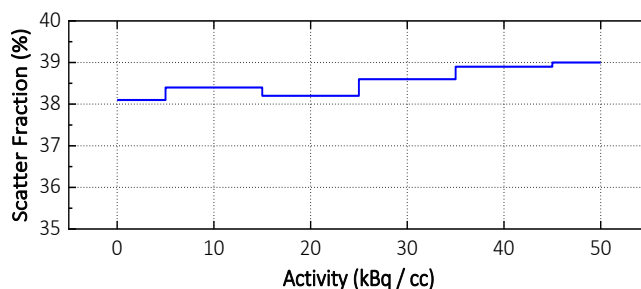


Figure 4. The scatter fraction versus activity concentration

The scatter fraction obtained from the simulation results has a 3% error compared to the data provided by manufacturer (GE Company). In this study, sensitivity is determined by plotting random ratio as a function of source activity to perform a sensitivity test in the simulation.

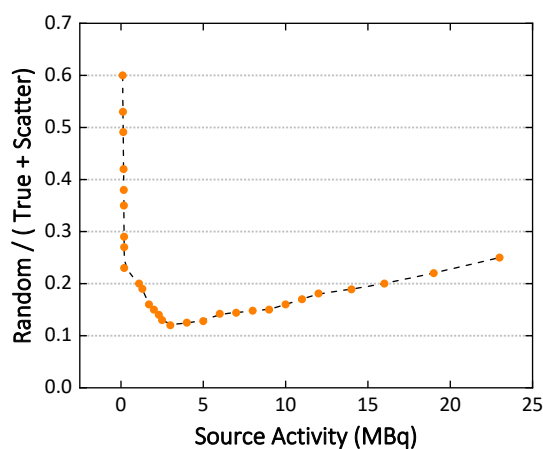
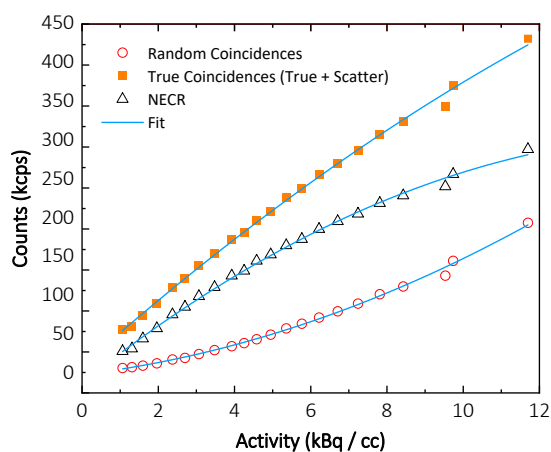


Figure 5. The ratio of random to (trues + scatter) versus activity in the line source

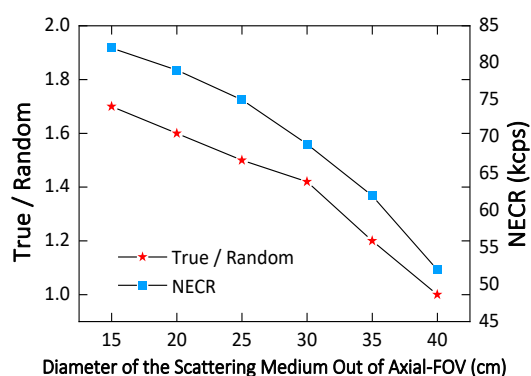
As shown in Figure 5, the minimum (sensitivity) of this ratio was observed at 4.1 MBq activity. It is noteworthy that Figures 4 and 5 corroborate the validity of the simulated scanner. The plot of random and true coincidence rates and NECR were plotted in terms of activity in the NEMA phantom.

Table 1. NEMA NU-2-2007 Performance Characteristics

		Simulated Scanner	D – 690 Data Sheet
Sensitivity (cps/kBq)	0 cm	7.3	NA
	10 cm	7.5	7
Scatter Fraction (%)		38.2%	37%

**Figure 6.** True, random coincidence rate diagram and equivalent count noise rate in terms of activity

A closer look at Figure 6 reveals that the rate of random coincidences is less than the true coincidences in NEMA phantom imaging. In order to investigate the effect of the scattering medium on the rate of true and random coincidences, the ratio of true to random coincidences was plotted in terms of the diameter of the scattering medium in Figure 7.

**Figure 7.** True to random coincidence ratio in terms of Diameter of the Scattering Medium

4. Discussion

The latest generation of the PET/CT family, including the D-690 scanner, has several advantages, such as using

fast LYSO crystals [13-17]. LYSO crystals offer a great combination of the important features of PET/CT scintillators. Therefore, simulating and modeling of this highly sensitive scanner can be very practical. Because of the simulated scanner validation, many features can be tested, and much research can be done using the generated MC model. In other words, the effect of many parameters on the destructive factors of the image quality can be investigated.

As shown in Figure 7, the rate of true and random coincidences increased with increasing activity, but within the FOV, the rate of random coincidences was lower than in the true ones. Therefore, it is realized that only high activity does not increase the random to true coincidence rate.

According to the previous study by Poon *et al.* [18], extending the AFOV while maintaining detector thickness has significant cost implications. In addition, random coincidences, dead time, and object attenuation may reduce scanner performance as the AFOV increases. In this study, we showed that the rate of random coincidences rises by increasing the AFOV by adding an out the AFOV scattering medium. On the other hand, increasing the diameter of the scattering medium results in the enhancement of the rate of random coincidences over the true coincidences. As long as the diameter of the scattering medium is 40 cm, the rate of random coincidence equals the rate of true coincidences. As a result, increasing the random to true coincidences ratio will reduce the noise equivalent count rate.

For further investigation, we propose to investigate the effect of activity inside the scattering medium on the random coincidence rates.

5. Conclusion

In this study, we modeled the D-690 scanner mainly due to its highly sensitive and practical design, which

based on the LYSO scintillator. In the simulated scanner, increasing the length of the AFOV by adding a scattering medium will lead to the enhancement of the rate of random coincidences. In other words, the existence of a heterogeneity next to the FOV augments the rate of random coincidences. This issue should be taken into consideration for patient imaging that the length of AFOV is longer and whose body is highly heterogeneous (as a scattering medium).

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References

- 1- J. F. Oliver and M. Rafecas, "Modelling random coincidences in positron emission tomography by using singles and prompts: a comparison study," *PloS one*, vol. 11, no. 9, p. e0162096, 2016.
- 2- N. Belcari *et al.*, "A novel random counts estimation method for PET using a symmetrical delayed window technique and random single event acquisition," in *2009 IEEE Nuclear Science Symposium Conference Record (NSS/MIC)*, 2009, pp. 3611-3614: IEEE.
- 3- S. Jan *et al.*, "GATE: a simulation toolkit for PET and SPECT," *Physics in Medicine & Biology*, vol. 49, no. 19, p. 4543, 2004.
- 4- X. Jia, X. Gu, J. Sempau, D. Choi, A. Majumdar, and S. B. Jiang, "Development of a GPU-based Monte Carlo dose calculation code for coupled electron-photon transport," *Physics in Medicine & Biology*, vol. 55, no. 11, p. 3077, 2010.
- 5- J. Cal-González *et al.*, "Simulation of triple coincidences in PET," *Physics in Medicine & Biology*, vol. 60, no. 1, p. 117, 2014.
- 6- R. D. Badawi, M. Miller, D. Bailey, and P. Marsden, "Randoms variance reduction in 3D PET," *Physics in Medicine & Biology*, vol. 44, no. 4, p. 941, 1999.
- 7- J. F. Oliver, E. Fuster-Garcia, J. Cabello, S. Tortajada, and M. Rafecas, "Application of artificial neural network for reducing random coincidences in PET," *IEEE Transactions on Nuclear Science*, vol. 60, no. 5, pp. 3399-3409, 2013.
- 8- K. Assie *et al.*, "Monte Carlo simulation in PET and SPECT instrumentation using GATE," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 527, no. 1-2, pp. 180-189, 2004.
- 9- S. Agostinelli *et al.*, "GEANT4—a simulation toolkit," *Nuclear instruments and methods in physics research section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 506, no. 3, pp. 250-303, 2003.
- 10- G. Bolard *et al.*, "Performance comparison of two commercial BGO-based PET/CT scanners using NEMA NU 2-2001," *Medical physics*, vol. 34, no. 7, pp. 2708-2717, 2007.
- 11- B. McIntosh and A. L. Goertzen, "Validation of GATE simulations of the ^{176}Lu intrinsic activity in LSO detectors," in *2009 IEEE Nuclear Science Symposium Conference Record (NSS/MIC)*, 2009, pp. 3426-3428: IEEE.
- 12- V. Bettinardi, L. Presotto, E. Rapisarda, M. Picchio, L. Gianolli, and M. Gilardi, "Physical Performance of the new hybrid PET/CT Discovery-690," *Medical physics*, vol. 38, no. 10, pp. 5394-5411, 2011.
- 13- M. Teräs, T. Tolvanen, J. Johansson, J. Williams, and J. Knuuti, "Performance of the new generation of whole-body PET/CT scanners: Discovery STE and Discovery VCT," *European journal of nuclear medicine and molecular imaging*, vol. 34, no. 10, pp. 1683-1692, 2007.
- 14- P. Geramifar, M. R. Ay, M. Shamsaie Zafarghandi, G. Loudos, and A. Rahmim, "Performance comparison of four commercial GE discovery PET/CT scanners: A monte carlo study using GATE," *Iranian Journal of Nuclear Medicine*, vol. 17, no. 2, pp. 26-33, 2009.
- 15- P. Beltrame *et al.*, "The AX-PET demonstrator—Design, construction and characterization," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 654, no. 1, pp. 546-559, 2011.
- 16- A. DURNEY, "RECENT DEVELOPMENTS IN INSTRUMENTATION," 1982.
- 17- P. Geramifar, M. Ay, M. S. Zafarghandi, S. Sarkar, G. Loudos, and A. Rahmim, "Investigation of time-of-flight benefits in an LYSO-based PET/CT scanner: A Monte Carlo study using GATE," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 641, no. 1, pp. 121-127, 2011.
- 18- J. K. Poon *et al.*, "Optimal whole-body PET scanner configurations for different volumes of LSO scintillator: a simulation study," *Physics in medicine & biology*, vol. 57, no. 13, p. 4077, 2012.