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GATE Simulation of a Clinical PET Scanner: Influence of Windows Timing Coincidences and Dead Time on Count Rate Performance

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***Abstract*—This paper present an evaluation of the Count rate performance and noise equivalent count rate (NECR) in different coincidence timing windows arranging from 8 to 12 ns, with different dead-time electronic 5000ns paralyzable and 4900ns nonparalyzable. The clinical PET ECAT EXACT HR+ is validated according to the National Electrical Manufacturers Association (NEMA NU 2-2012). The simulated results (scatter fraction (SF), sensitivity(S) and NECR) show a good agreement with the experimental data. the results show that decreasing the coincidence time windows cause a decrease of 28% of the NECR. Moreover, the NECR is increased by 4,28% using 4900ns non paralyzable deadtime instead of 5000ns parlyzable.**

Keywords*—PET, scatter fraction, *sensitivity, NECR, dead time

I. INTRODUCTION

Positron emission tomography (PET) is a medical diagnostic method for cancers based on distribution of radio-tracer in the target organ [1-2]. The radio-tracer emits a positron that annihilates with an electron to produce two back to back 0,511 MeV photons. The physics of PET is based on detection of the pair photons in coincidence [3,4]. In accordance with the specifications of the manufacturers we applied a coincidence time windows(CTW), and dead time module to a specific volume within the Sensitive Detector system. The CTW is defined as the maximum time period within which two single events are considered as a coincidence event by the coincidence sorter module of the PET acquisition system [5].

The dead time it's one of the parameters that characterizes the counting behaviour of the radiation detection systems at high event rate. It is defined as the minimum amount of time required between successive events to consider the detection of those events as separates. The loss of events frequently occurs during the system dead time. Thus, information loss can become very significant in PET systems. The parameter approximations known as nonparalyzable and paralyzable models is the most common way to estimate detector dead time [6].

In the present study, in one hand, a clinical PET called ECAT EXACT HR+ is simulated and validated using GATE [4,7]. The validation is done according the NEMA NU 2-2012 protocol [8]. In the other hand, the effect of changing the CTW and dead time model on the NECR is presented.

II. METHODS AND MATERIALS

The simulation of a GATE-modeled ECAT EXACT HR+ was performed using the geometrical parameters [2]. This scanner was validated according to the standard performance parameters (SF, S and NECR) proposed by NEMA NU 2-2012 [8].

The geometrical details of the simulated ECAT Exact HR+ is summarized in the following Table I

TABLE I
GEOMETRIC CHARACTERISTIC OF CLINICAL PET ECAT EXACT HR+[1,9]

Detector Materiel	Bismuth germinate (BGO)
Crystal Dimensions(mm^3)	4.05x4.39x30
Detector Ring Diameter (cm)	82.4
Number of crystal per detector	256
Number of detector per ring	72
Detector total number	18432
Axial Field of view (mm)	155

Fig 1 shows the geometry of ECAT EXACT HR+ and NEMA Scatter fraction phantom. This phantom is used to calculate the scatter fraction and the noise equivalent count rate.

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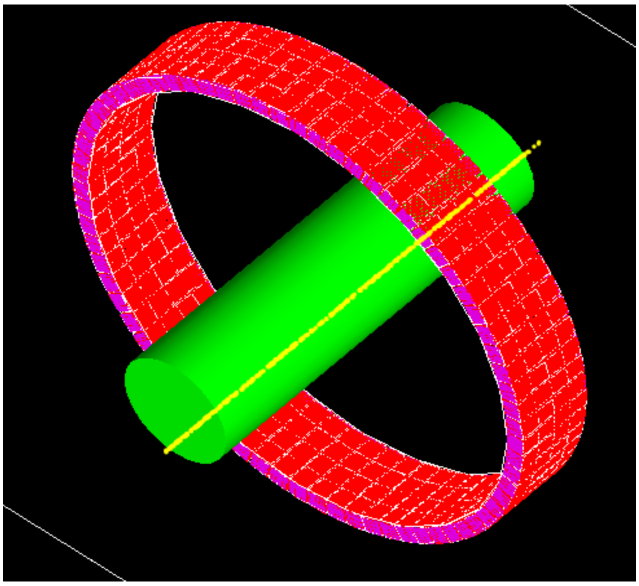

Fig. 1 *GATE geometry model of the clinical ECAT EXACT HR+ PET scanner. magenta indicates shielding, red, BGO blocks, and view of the NEMA NU 2-2012 scatter fraction phantom (solid tube), and source line place in 4.5 cm yellow tube*

In addition to the specification parameters used for the design of the geometry of the scanner, other parameters such as the physics process and the digital detection chain, summarized in table II, are also taken into accounts in the simulation.

TABLE II

PARAMETERS OF THE PHYSICS PROCESS AND THE DIGITAL DETECTION CHAIN USED IN SIMULATING MODELS OF THE CONSIDERED PET SCANNERS [9]

Physics process	**ECAT EXACT HR+**	
Physics	Photoelectric	Low energy
	Compton	Low energy
	Rayleigh Scattering	Low energy
Cuts	Electron (cm)	0.2
	Ray-X (keV)	10
	Second Electron (keV)	10
Energy resolution @ 511 keV	Aleatory between 0.2-0.3	
Dead-Time (ns)	Singles	5000
	Coincidences	500
CTW (ns)	12	
Energy Windows (kev)	300-650	

A. *Sensitivity*

The sensitivity performance parameter of a scanner represents the efficiency to detect the annihilation radiation. The scanner sensitivity expressing the count rate per seconds (cps) [1,10,12].

The sensitivity parameter was performed using the NEMA NU 2-2012 sensitivity phantom. It is a 70 cm long plastic tube, filled with radioactivity F-18 (Fluorine-18), and surrounded by five aluminium tubes with 1mm of thickness and different radius (sleeves) [1, 8].

The used activity is sufficiently low that count losses and random event rate are negligible (less than 5% of the total count rate).

The phantom is placed at two positions in field of view (center and at 10cm offset). The sensitivity is defined by the following expression:

$$S=\frac{T}{A} \qquad (1)$$

Where T is the count rate of the true coincidences and A the activity of the source.

B. *Scatter fraction and noise equivalent count rate*

The Scatter Fraction (SF) and Noise Equivalent Count Rate measurements was performed using the NEMA NU 2-2012 phantom. This phantom is a polyethylene cylinder with 70 cm in length and a diameter of 20.3 cm. A Plexiglas tube (with an outer diameter of 5 mm and the inner diameter of 3 mm) filled F-18 and placed at 4.5cm from the phantom axis [1-3,8,9].

The SF parameter is calculated following the expression:

$$SF=\frac{S}{S+T} \qquad (2)$$

The Noise Equivalent Count Rates is calculated using as follow:

$$NECR=\frac{T^2}{T+S+R} \qquad (3)$$

Where S, T and R are scattered, true and random coincidences respectively [9, 10, 12].

III. RESULTS AND DISCUSSION

The SF, Sensitivity, and NECR performance parameters, as well as the true count rates, obtained from the described simulations are presented in this section. These parameters were compared with experimental data extracted from the published works in [1,3,9].

Tables III and IV show respectively a comparison of the obtained SF and Sensitivity with the measured ones.

The SF presents an agreement of 9,7% with the experiment. This difference can be explained by the approximation of the scanner geometry using GATE and the absence of some compositions as the bed patient.

In table IV, the comparison of the simulated Sensitivities with the experimental data [1,3,10], shows a 2,9% agreement for R=0 and 0,15% for R=10.

The difference may be explained by limitations of the photo-multiplier tubes (PMT) resolution and the absence modelling of the light shielding between the detector blocks [2]. furthermore, the application of a varied quantum efficiency factor (QE), might provide better agreement.

Concerning the NECR values, Table V shows the NECR peak value for the scanner. A deviation of 4% (NECR with paralyzable

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dead time) and 2.9% (NECR with non-paralyzable dead time) is observed between the simulations and the experimental data.

TABLE III

Scatter Fraction (SF) parameter for the ECAT EXACT HR+ PET Scanner.

Scatter fraction	Experimental results	46,9%
	Simulation results	42,3%

TABLE IV

Sensitivity parameter for the ECAT EXACT HR+ PET scanner, calculated using the NEMA NU2-2012 protocols [13]

Sensitivity	Experimental results cps/MBq	R=0 cm	6650
		R=10 cm	7180
		Ratio (R=0/R=10 cm)	0.926
	Simulated results cps/MBq	R=0 cm	6853
		R=10 cm	7169
		Ratio (R=0/R=10 cm)	0,955

TABLE V

THE PEAK NECR OF ECAT EXACT HR+ PET SCANNER

NECR	Experiment @ 8kBq	36897cps
	Simulation @ 6 kBq paralyzable dead time	35397 cps
	Simulation @ 7 kBq non-paralyzable dead time	36553 cps

Fig.2,3 shows successively the true count rates and NECR obtained from the simulation as a function of the source activity concentration. Measured parameters are also extracted from [10,12] and reported for comparison.

Fig. 2 shows a 10,7% agreement with the experiments data for the true count rate. The differences are mainly due to the simple dead time model used in the simulation.

Fig. 3 exhibit that using a non-paralyzable dead time model, an agreement of a 2,9% is observed. Whereas an agreement of 4% is observed using a paralyzable dead time model. Here again, the differences are mainly due to the simple dead time model used in the simulation.

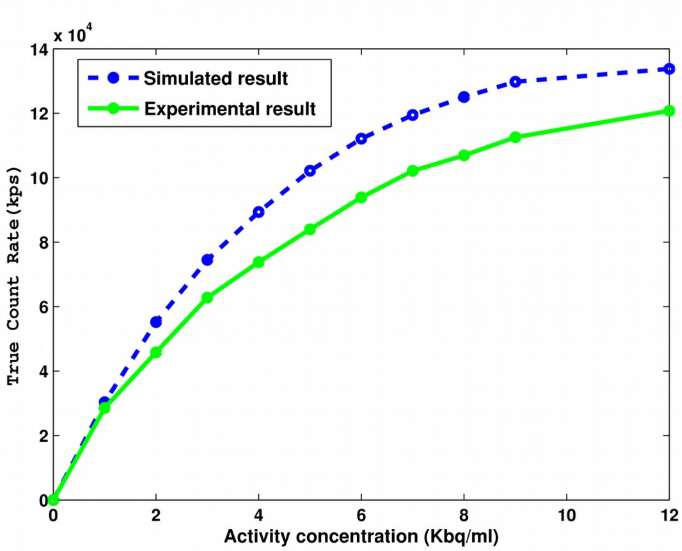

Fig. 2 *True count rates as a function of the source activity. Simulation (dotted line), experimental data (solid line)*

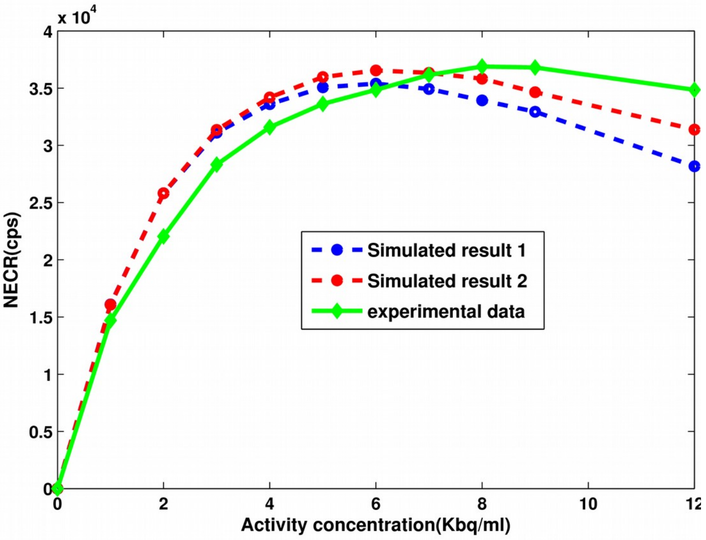

Fig. 3 *NECR as a function of the source activity. Simulation paralyzable dead-time ((lower dotted line), non-paralyzable dead-time (upper dotted line), experimental data (solid line).*

Fig 4 shows for different CTW (8ns, 12ns) and dead-time (5000ns paralyzable, 4900ns non paralysable) the true count rates as a function of the source activity concentration.

The results show that the true coincidence rate at lower activity concentrations, is not affected by varying the CTW. However, at higher activity concentrations, the true rates increase slightly for shorter CTW (peak true rate increased by 12.29%).

The true rate also increased successively by 11.93% and 19.9% using two CTW (12ns and 8ns) and changing the dead time from 5000ns paralyzable to 4900ns non-paralyzable.

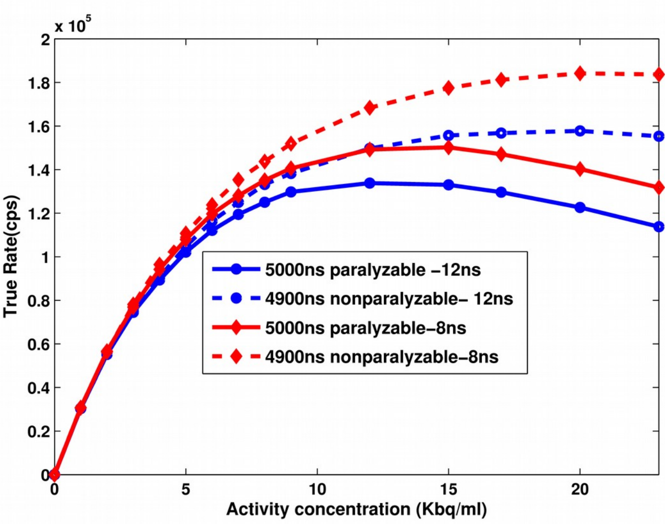

Fig. 4 *True rates vs. activity concentration for varying CTW and dead-time (value and model).*

Fig 5 shows significant improvements based on NECR. Using the smaller CTW, the NECR peak was increased by 28%. The NECR peak also increase respectively by 4.28% and 6.48% using two CTW (12ns and 8ns) and changing the dead time from 5000ns paralyzable to 4900ns non-penalizable. This improvement is mainly due to the number of event recorded in the non -paralyzable dead time which is bigger than the number of event recorded in the paralyzable dead time [7].

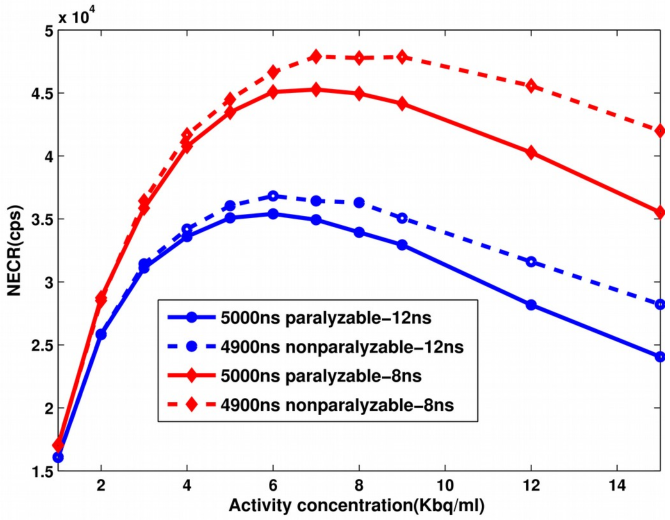

Fig.5 *NECR vs. activity concentration for different CTW (12ns and 8ns) and dead-time model (nonparalyzable and paralyzable)*

IV. CONCLUSIONS

In this work, we have presented the influence of CTW and the dead time on the count rate performance using a Gate model of a clinical PET called ECAT EXACT HR+. The obtained simulation results show that the true coincidences and NECR increase when we minimize CTW and change the dead time from paralyzable model to non-paralyzable. This factor can help to improve of the PET image quality.

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