Simulation of Triple Coincidences in PET

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***Abstract*–Most PET scanners are designed to detect and record gamma-ray coincidences from the annihilation of positrons coming from radiotracers. Multiple coincidences, those for which more than two gamma-rays are detected within the coincidence time window, are usually discarded. Those events can be registered and used to increase the sensitivity of the scanner and to differentiate positron-gamma emitters from pure positron emitters, enabling multiplexed PET. To assess the effect of triple coincidences in PET scanners, an accurate and reliable simulation toolkit is compulsory. In this work we extend and validate the Monte Carlo (MC) simulator PeneloPET to deal with multiple-coincidences in PET scanners. Details of gamma-rays cascades from several positron-gamma emitters, such as ^{124}I, were incorporated in the simulation. Furthermore, a new tool to analyze doubles and triples datasets generated by the simulation was added to the software package. Results from simulations were first compared against data acquired with a modified version of the preclinical Argus PET/CT scanner (Sedecal S.A., Madrid, Spain), which is enabled to acquire and process multiple coincidence events. A good agreement in the energy spectra as well as in the double/triples ratio between simulations and experiments was found (differences below 10 %). Once validated, the simulator was used to evaluate the feasibility of using multiple-coincidence events in several clinical PET/CT scanners, such as the Siemens Biograph TruePoint TrueV (B-TPTV), the GE Discovery-690 and the Philips Ingenuity scanners.**

I. Introduction

SINCE the initial PET scanners, there have been significantly improvements in terms of resolution and sensitivity [1]. Nevertheless, there is still room for improvement and new generations of PET scanners with better capabilities are being developed [2]. Currently, PET scanners are designed to detect and record double coincidences. Multiple coincidences, in which more than two events are detected within the time coincidence window are usually discarded or not used in an effective way.

As an improvement of current PET technology, multiple coincidences might be recorded by modified versions of PET scanners or by new ones designed with this capability. The modifications may involve modifying just the acquisition software, or may require small hardware adaptations.

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There are several situations in which multiple coincidences may occur (see Fig. 1). One case corresponds to Inter-Detector Scatter (IDS) events [3], in which one gamma-ray interacts with more than one detector (Fig. 1A). Another case corresponds to random triple (R_T) events, in which a normal double coincidence is detected in coincidence with one or more gamma-rays coming from a different decay (Fig 1B). Finally, when positron-gamma emitters like ^{124}I [4] are used, prompt gamma rays and annihilation gamma rays can be detected in coincidence from the same decay ($\beta^+\gamma$ triple events, Fig. 1C).

Multiple coincidences in PET have interesting applications. On one hand, $\beta^+\gamma$ events may be used to differentiate standard positron emitters from positron-gamma emitters [5] that may enable multiplexed PET imaging [6]. On the other hand, IDS and R_T events can be used for increasing the sensitivity of PET scanners [7].

In order to evaluate the relevance of triple coincidences in PET scanners in each of these situations and evaluate the optimal settings of the scanner to use them, it is useful to have a complete and accurate model of the emission and detection of the radiation. Monte Carlo (MC) simulations are commonly used for this task. They allow tracking all possible emissions and interactions which is especially important for studying multiple-coincidences in PET scanners. Nevertheless, as multiple-coincidences are not usually considered in PET acquisitions, these MC simulators require some modifications in the code and additional tools to analyze the simulated results.

PeneloPET [8] is a MC simulation software based on Penelope [9]. It is fast and flexible, and it incorporates the most relevant physical effects. PeneloPET has been validated with preclinical [8] and clinical [10] scanners.

The goal of this work was to implement, validate and use the modifications in a MC simulator like PeneloPET to study multiple-coincidences in PET scanners. The simulations were compared against data acquired with the preclinical PET/CT scanner Argus. Once validated, the simulator was used to evaluate the feasibility of using multiple-coincidences in clinical scanners.

II. Methods

A. Prompt gamma simulations with PeneloPET

PeneloPET code was adapted to accurately include the cascade of prompt photons emitted from a large variety of isotopes (^{124}I, ^{86}Y, ^{94m}Tc…). In this modeling, only cascades with a branching ratio (number of times that a certain decay mode occurs per disintegration) greater than 2% were considered.

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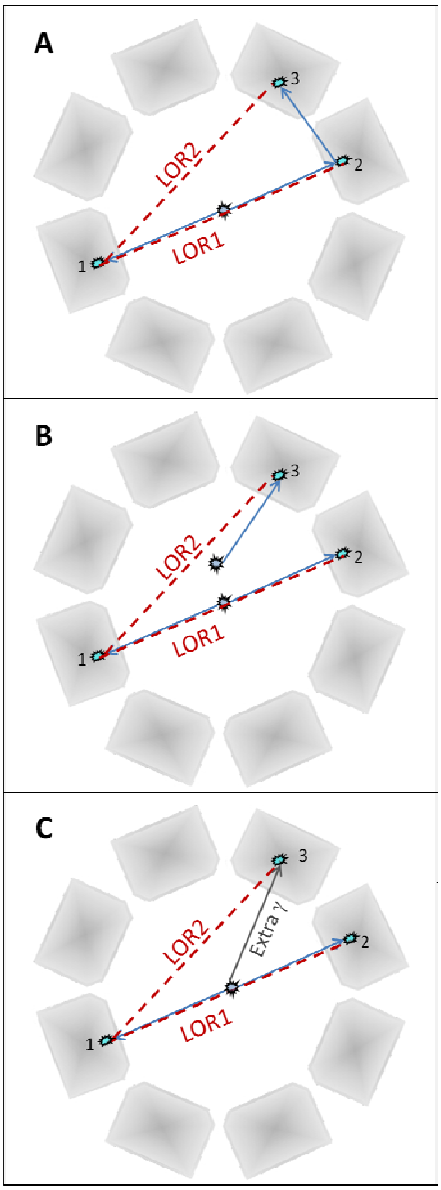

Fig. 1. Selected scenarios in which multiple coincidences may occur. A: Inter-Detector Scatter (IDS) events. B: (R_T) random event of a double coincidence with one gamma-ray coming from a different decay. C: detection in coincidence of one extra gamma-ray emitted by a non-pure β+ isotope with the two annihilation photons. Note that usually one of the three possible LORs (between 2 and 3 in the figure) can be directly discarded, as it lies outside the field-of-view (FOV) of the scanner.

The half-life of the intermediate excited states in the daughter nuclei, being always inferior to 100 ps, was neglected. This short half-life is about one order of magnitude lower than the typical timing resolution of these scanners. Therefore, in these simulations, the prompt gamma-rays are emitted simultaneously with the positron emission.

B. Preclinical validation and simulation of clinical scanners

The acquisition software of the preclinical Argus PET/CT scanner [11] was adapted so that it may provide two data sets, one for double coincidences and another one with triple coincidences. These triple coincidences may be due to inter-detector scatter events, random triple events, or to multiple gamma rays emitted per decay (from non-pure emitters like ^{124}I). The energy windows applied are adapted for each type of triple coincidence taking into account the energy of the gamma-rays emitted. Coincidences of four or more gamma-rays, being much less likely, were not considered in this work.

In order to measure the effect of taking into account the triple coincidences in preclinical image quality, PeneloPET simulations and real acquisitions of an Image Quality phantom (IQ, NEMA NU-4 2008 [12]) filled with different isotopes were performed for the preclinical Argus PET/CT scanner, which simulated geometry is presented in Fig. 2A.

Finally, to estimate the relative abundance of triple coincidences in clinical PET systems, we simulated acquisitions, following the NU 2-2007 protocol [13], for three clinical scanners: the Siemens Biograph True-Point True-V (B-TPTV) [14], the GE Discovery-690 [15] and the Philips Ingenuity [16]. For the clinical scanners, we assumed that the events in each block detector are processed independently. The simulated geometries for these scanners are depicted in Fig. 2B, C, and D.

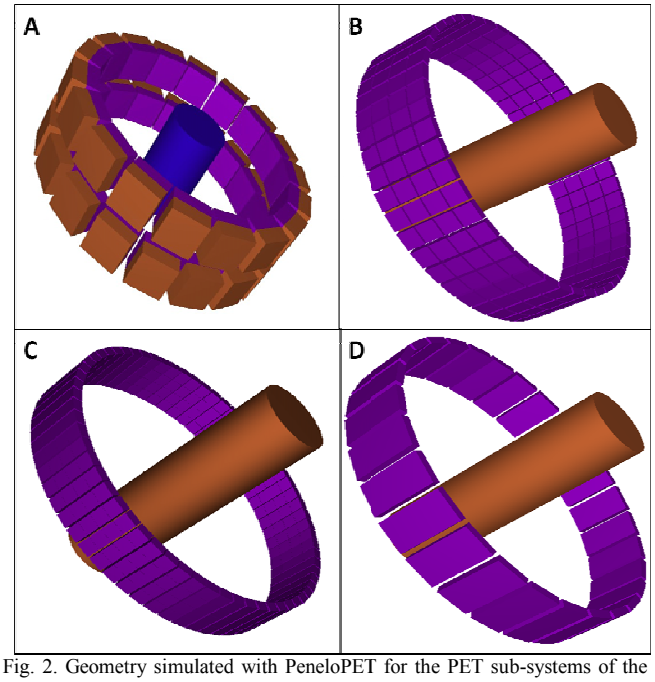

Fig. 2. Geometry simulated with PeneloPET for the PET sub-systems of the Argus PET/CT preclinical scanner (A) and the clinical scanners: Siemens Biograph TPTV (B), GE Discovery-690 (C) and Philips Ingenuity (D).

C. Analysis of triple coincidences

The energy window for doubles (EW_D) was: 400 – 700 keV for the Argus scanner, 425 – 650 keV for the Biograph and Discovery scanners and 460 – 665 keV for the Ingenuity scanner.

We use different criteria to identify each type of triple coincidence:

- IDS events: the energy of one single and the sum of the other two should be within the EW_D.

- $\beta^+\gamma$ events: Two singles should be within the EWD and the third single should be above a threshold selected according the energy of the prompt gamma ray
- R_T events: The three singles should be within the EW_D.

III. Results

In this section we present the results obtained for ^{18}F (pure positron emitter) and ^{124}I (positron-gamma emitter). First we validate our simulation tool by comparison of our simulations with measured data from the Argus PET/CT preclinical scanner (subsection A). Once validated, we use our simulator to evaluate the number of triple coincidences in three clinical scanners of the main vendors (subsection B).

A. Validation of the simulation tool

Fig. 3 shows the comparison of the simulated and measured energy spectrums (LYSO and GSO crystals) for ^{18}F and ^{124}I radioisotopes in the Argus scanner.

Table 1 presents the ratio of each type of triple coincidence versus the double coincidence events within the energy window for doubles. Simulated and measured results for the Argus preclinical scanner are also compared in the table.

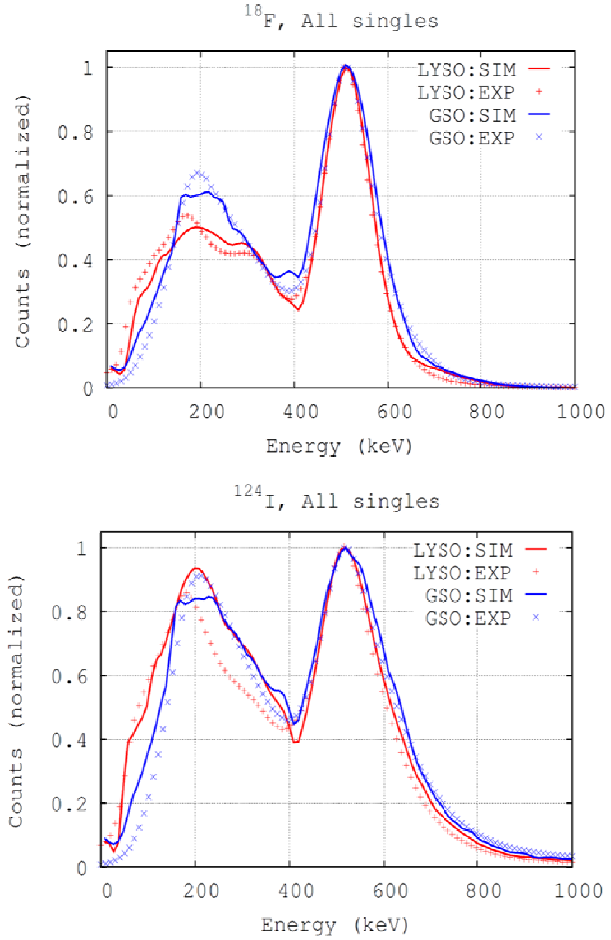

Fig. 3. Simulated (lines) and experimental (points) energy spectra obtained for LYSO (red) and GSO (blue) scintillator crystals. Top: ^{18}F. Bottom: ^{124}I.

TABLE I. STATISTICS OF DOUBLE AND TRIPLE COINCIDENCES REGISTERED IN ACQUISITIONS OF AN IQ PHANTOM FILLED WITH EITHER ^{18}F OR ^{124}I IN THE ARGUS PRECLINICAL SCANNER.

	^{18}F		^{124}I	
	Simulated	Measured	Simulated	Measured
Doubles (D) kcps	30.9	31.3	19.9	20.1
IDS / D (%)	19.0	17.0	22.9	24.0
$\beta^+\gamma$ /D (%)	-	-	2.2	2.8*
R_T / D (%)	0.3	0.6	0.5	

*Since main prompt gamma ray emitted by ^{124}I cannot be distinguished in energy from 511 keV annihilation photons, this number represents the sum of $\beta+\gamma$ and R_T events divided by the Doubles.

B. Results from simulations in clinical scanners

Table 2 shows the statistics of double and triple coincidences for the three clinical scanners considered in this work with ^{18}F and ^{124}I.

TABLE II. STATISTICS OF DOUBLE AND TRIPLE COINCIDENCES REGISTERED IN ACQUISITIONS OF A 70 CM LONG LINE SOURCE (10 MBQ) FILLED WITH EITHER ^{18}F OR ^{124}I THE OBJECT SIMULATED IN ALL CASES WAS THE NEMA CYLINDER.

	Biograph	Discovery	Ingenuity
		^{18}F	
Doubles (D) kcps	20.3	18.0	13.9
IDS / D (%)	14.1	22.2	10.0
$\beta^+\gamma$ /D (%)	-	-	-
R_T / D (%)	0.7	0.9	0.8
		^{124}I	
Doubles (D) kcps	7.5	8.4	6.4
IDS / D (%)	24.4	33.2	18.9
$\beta^+\gamma$ /D (%)	2.3	2.5	1.5
R_T / D (%)	0.7	1.1	0.9

IV. Summary and Conclusions

In this work we have adapted the PeneloPET code to simulate accurately the cascade of gamma-rays from the most common positron-gamma emitters of interest for PET imaging. In addition, we have also developed a new analysis tool to generate doubles and triples datasets from the singles list-mode output of PeneloPET.

The conclusions from this work are the following:

- Agreement between simulated and real data (discrepancies below 10% in most cases) was very good, both in the energy spectra and in the triples-to-doubles ratio.
- IDS events are significative in all the situations studied. In the Argus preclinical scanner, these events represents a potential increase in sensitivity (measured (simulated)) of 17(19) % for ^{18}F and 24(23) % for ^{124}I.
- Simulations project a potential sensitivity increase using IDS events between 10 and 33 % for clinical scanners and ^{18}F and ^{124}I radionuclides.
- The ratio between $\beta^+\gamma$ events and double coincidences for ^{124}I is 2 to 3 % both for preclinical and clinical scanners (using the proper energy window).

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