Validation of peneloPET simulations of the Biograph PET/CT scanner with TOF capabilities

K. M. Abushab[1], J. López Herraiz[1], E. Vicente Torrico[1, 3], S. España Palomares [2], J.J. Vaquero López[4], J.M. Udías Moinelo [1]

[1] Grupo de Física Nuclear, Dpto. Física Atómica, Molecular y Nuclear, UCM, Madrid, Spain

[2] Department of Radiation Oncology, Massachusetts General Hospital and Harvard Medical School, Boston, MA, USA,

[3] Instituto de Estructura de la Materia, Consejo Superior de Investigaciones Científicas (CSIC), Madrid

[4] Dpto. de Bioingeniería e Ingeniería Espacial, Universidad Carlos III, Madrid

email: khaled@nuclear.fis.ucm.es

Abstract

Monte Carlo simulations are currently widely used in positron emission tomography (PET) imaging for optimizing detector design and acquisition protocols, and for developing and assessing corrections and reconstruction methods [1],[2]. PeneloPET [3] is a Monte Carlo code for PET simulations with basic components of detector geometry, acquisition electronics and material and source definitions. The purpose of the present study was to validate the simulations of the Siemens Biograph PET/CT scanner with TOF capabilities performed with peneloPET. The scanner components incorporate four rings of 48 detector blocks. Each block comprises 13 × 13 matrix of 4 × 4 × 20 mm^3. Results were compared with experimental data obtained in accordance with the NEMA-2007 performance measurement protocol done by Jakoby, et al. [4].

1. Introduction

Positron emission tomography (PET) is a nuclear medicine imaging technique based on the detection of gamma rays emitted by positron-emitting short lived isotopes. It is one of the noninvasive technologies that can routinely and quantitatively measure metabolic, biochemical, and functional activity in living tissue. It assesses changes in the function, circulation, and metabolism of body organs. PET images can demonstrate pathologic changes in the human body even before they are seen on the other imaging modalities such as CT and MRI. It also allows the validation of newly developed radio tracers and it plays a growing role in research on diseases and genome.

Monte Carlo methods give us a chance to estimate scanner properties which can not be obtained experimentally as well as well as testing the changes in the performance of PET scanners due to changes in the scanner without having to builds all these prototypes [5].

PeneloPET is a Monte Carlo code based on PENELOPE [2], [6], which allows fast and easy simulation of common PET scanners.

Sensitivity is one of the most important parameters of PET scanners. The sensitivity of a PET scanner represents the ability to detect 511 KeV photons resulting from positron annihilation, with respect to the number of emitted positrons**.** The calculation of the sensitivity usually follows National Electrical Manufacturers Association (NEMA) protocol [7].

Another important parameter of a PET scanner is the peak count rate which refers to the maximum amount of events that can be processed by the system in a given time. This includes scatter and random coincidences along with the true events [2]. The fraction of the total coincidences recorded in the energy window which have been scattered is known as scatter fraction [8].

Time-of-flight (TOF) in PET, refers to the capability of using the time difference between the detection of the two coincidental photons which constitute every PET event to better locate the annihilation position of the emitted positron along the line joining the opposite detectors hits by the two photons. The position can be estimated by determining the difference in time arrival ($\Delta t = t_1 - t_2$) of the photons (Figure 1); the time-of-flight difference (Δt) is immediately related to the distance Δx of the annihilation point from the center of the line of response (LOR) by:

$$\Delta t = 2 \cdot \Delta x / c \qquad (1)$$

Where c is the speed of light (2.998 10^{10} cm/s) (Figure 1).

The TOF resolution $\delta(\Delta t)$ of the scanner is defined as the Full-Width-at-Half-Maximum (Δt_{FWHM}) of the distribution of time-differences collected from a centered source (see Figure 4). According to relation (1), in order to achieve a spatial resolution lower than 1 cm, a TOF resolution better than 66 picoseconds is required. In many commercially available scanners, the TOF resolution is worse than 1 ns, so the TOF information is not useful. Recently, modern PET/CT scanners have obtained TOF resolutions of the order of 500 ps, which offer the opportunity of using the TOF information to improve the quality of the reconstructed images.

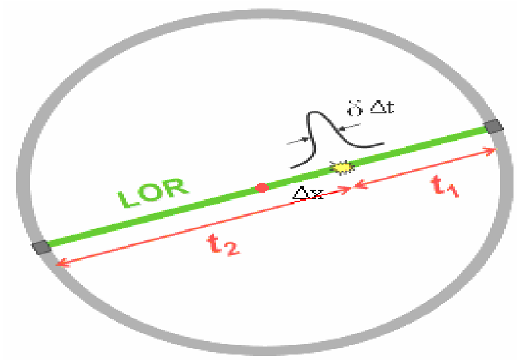

Figure 1. *Principle of time-of-flight for an off centered annihilation.*

This work was based on peneloPET simulations of several acquisitions with the Siemens Biograph True point PET/CT with True V (B-TPTV) scanner. Validation has been done following the NEMA protocol for Noise Equivalent Counts Rate (NECR), random and scatters events and scatter fraction, in addition to TOF characterizations. The results were compared with the experimental results obtained by Jakoby et al. [4].

2. Materials and methods

The geometry of the Biograph scanner simulated comprises 48 detector modules arranged in four block rings. Each one of these modules consists of four blocks in axial direction. Each block is made of 13 × 13 LSO (Lutetium Oxyortho-silicate) crystals (169 crystals per block). The whole scanner consists of 32,448 crystals. The surface area and the thickness of individual crystals are 4 × 4 mm^2 and 20 mm, respectively. The scanner has an axial field of view (FOV) of 21.8 cm. A sketch of the scanner detectors modeled is shown in Figure 2.

The National Electrical Manufactures Association (NEMA) protocol has been followed [7]. Thus a cylinder with 20 cm diameter and 70 cm length, with a line source of 4.5 cm off-centred filled with 1.04 GBq of ^{18}F where used in order to study the noise equivalent count (NEC), random scatter and true events in addition to Scatter Fraction (SF), sensitivity and TOF.

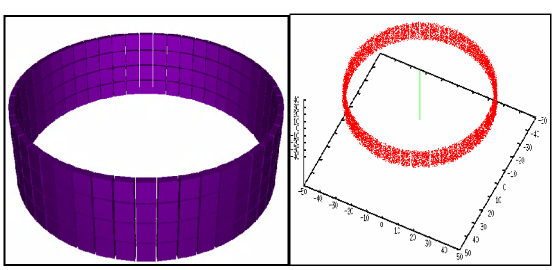

Figure 2. *PeneloPET geometry of the Biograph scanner; (left) detector module and (Right) source (Green) and interaction of the crystal (Red).*

2.1. Noise-equivalent-count rates (NEC) and scatter fraction

The noise-equivalent-count rates (NEC) and scatter fraction measurements were simulated by filing the 70 cm long line source with a solution of water and ^{18}F. The phantom was placed at the centre of the axial and trans-axial field of view with line source is at the lowest position. Using the simulation the NEC was calculated as;

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

Where S and T are the scattered and true coincidences respectively and R is the random coincidence [9]. In addition, the scatter fraction was calculated from the simulation using the following expression (3).

$$SF(\%) = \frac{\text{Scatter counts}}{(\text{total counts}(T+S+R))} \times 100 \qquad (3)$$

2.2. Time of Flight (TOF) resolution

The TOF distributions for centered and off-centered sources were simulated. These distributions contain a random background (as random coincidences are uncorrelated in time), so they were fit to a Gaussian plus a constant. The FWHM of the Gaussian were used as a measurement of the TOF resolution.

3. Results

3.1. Sensitivity

The absolute sensitivity values and experimental values are reported in Table 1. The results show an average sensitivity of 8.1 kcps both at 0 and 10 cm off-centered in good agreement with measured values in Jakoby et al [4].

3.2 Noise equivalent count rate (NECR) and scatter fraction

Table 1 shows the sensitivity, peak NECR and scatter fraction for both simulation and experimental results taken from Jakoby et al [4]. The peak NECR was 161 Kcps at a concentration of 32.5 kBq/ml and scatter fraction of 31.3%.

Parameter	simulation	experimental
Peak NEC (Kcps)	161@ 32.5 KBq/ml	161 @ 31.5 KBq/ml
Peak True (Kcps)	873@ 46 KBq/ml	804 @ 38 KBq/ml
Scatter fraction %	31.3	32.5
Sensitivity	8.1Kcps/MBq	8.1Kcps/MBq

Table 1. *Simulated and measures values*

Figure 3. *Comparison of random true and NEC of both simulated and experimental results versus different activities*

3.3. Time of flight (TOF)

Figure 4 shows a simulated TOF and background random events for a source located at the center of the scanner. The TOF resolution of 550 ps is similar to the experimental values obtained for this scanner [10]

Figure 4. *Time resolution with random events*

This TOF resolution would allow determining the position of the source within a distance of:

$\delta(\Delta x) = 2.998\times10^{10}$ cm/s$\times550\times10^{-12}$s /2 = 8.24 cm**.**

4. Discussion

The results show an agreement between true and random events and NEC peak of the simulated results and experimental measurements obtained by Jakoby et al. (2009) (Figure 3). Agreement with NEC is worse at higher rates, probably due to subtle differences in dead time and pile-up rejection mechanisms of the real scanner and the ones included in the simulation. Also comparison of the simulated scatter fraction results of the peneloPET simulation to that of the measured data shows that the simulated scatter fraction (Table 1) is very close to the measured values. Furthermore, we have included in PeneloPET crystal time resolution in order to mach the observed FWHM TOF. Time resolution (FWHM) obtained is 550 ps which reflect a distance difference of 8.24 cm between the two detected photons, and agree by Kadrams et al. [10] study.

5. Conclusion

The validation of PeneloPET simulations of the siemens Biograph (B-TPTV) scanner would allow to use these simulations to study the effect of changing the geometry of the scanner (adding extra rings , for instance), as well as to study the impact in the reconstruction of using different TOF windows. This will be the goal for a further study.

Acknowledgments

This work has been supported by MEC (FPA2007-62216), UCM (Grupos UCM, 910059), CPAN (Consolider-Ingenio 2010) CSPD-2007-00042, the RECAVA-RETIC network, ARTEMIS S2009/DPI-1802, European Regional Development, ENTEPRASE grant, PSE-300000-2009-5 and TEC2008-0675-C02-01, Ministerio de Ciencia e Innovación. Spanish Government.

References

[1] Buvat I and Castiglioni I. Monte Carlo simulations in SPET and PET. *The Quarterly Journal of Nuclear Medicin,* Vol. 46, 2002, pp 48–61 (ISSN 1125-0135).

[2] Salvat F, Fernández-Varea J M and Sempau J. PENELOPE-2006: A Code System for Monte Carlo Simulation of Electron and Photon Transport. *Nuclear Energy Agency* (NEA`6222), Barcelona, Spain, 2006 (ISBN 92-64-02301-1).

[3] España S, Herraiz JL, Vicente E, Vaquero J J, Desco M and Udías JM. PeneloPET, a Monte Carlo PET simulation tool based on PENELOPE: features and validation. *Physics in medicine and biology*, Vol. 54, 2009, pp 1723-42 (ISSN: 1079-5642).

[4] Jakoby BW, Bercier M Y, Watson CC, Rappoport V, Bendriem B, Townsend DW. Performance characteristics of a new LSO PET/CT scanner with extended axial field of view and PSF reconstruction. *IEEE Transactions on Nuclear Science,* Vol. 56, 2009, pp 633-9 (ISSN:0018-9499).

[5] Zaidi H, Relevance of accurate Monte Carlo modelling in nuclear medical imaging. *Medical Physics*. Vol. 26, 1999, pp 574–608.(ISSN: 0094-2405).

[6] Sempau, J & Andrewo P. Configuration of the electron transport alogarthim of PENELOPE to simulate ion chamber. *Physics in medicine and biology*, vol. 51, 2006, pp 3533-48 (**ISSN** 1361-6560).

[7] National Electrical Manufactories Association. Performance Measurement Positron Emission Tomography. NEMA N2-2007.

[8] Bailey DL, Karp JS, Surti S. Positron emission tomography: basic sciences London: Springer 2003 (ISBN: 1-85233-798-2).

[9] Strother SC, Casey ME and Hoffman EJ, Measuring PET scanner sensitivity: relating count rates to image signal to noise ratios using noise equivalent counts. *IEEE Transactions on Nuclear Science* vol. 37, 1999, 783-8(ISSN: 0018-9499).

[10] Kadrmas DJ, Casey ME, Conti M, Jakoby BJ, Loise C, Townsend DW. Impact of Time-Flight on PET Tumor detection. *Journal of Nuclear Medicine*, vol. 50, 2009, pp 1315-23 (ISSN: 0161-5505).