Monte Carlo Based Performance Assessment of Four Commercial GE Discovery PET/CT Scanners Using GATE

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Abstract— Combined PET/CT scanners now play a major role in medicine for in vivo imaging in oncology, cardiology, neurology, and psychiatry. As the performance of a scanner depends not only on the scintillating material but also on the scanner design, with regards to the advent of newer scanners, there is a need to optimize acquisition protocols as well as to compare scanner performances on an objective basis. In this study we evaluate and compare the performance of four Commercial GE PET/CT cameras, the (i) BGO-based Discovery LS PET/CT (DLS), (ii) the BGO-based Discovery ST PET/CT (DST), (iii) the BGO-based Discovery STE PET/CT (DSTE) and finally (iv) the LYSO-based Discovery RX PET/CT (DRX) scanner using the Geant4 Application for Tomographic Emission (GATE) Monte Carlo code. GATE is an open source Monte Carlo simulation platform mostly developed for PET and SPECT studies and is supported by the OpenGATE collaboration. In accordance with the National Electrical Manufacturers Association (NEMA) NU 2-2001 protocols, the validation of models is carried out against actual published measurements and the performance comparison is done for sensitivity, scatter fraction and count rate performance, showing very similar performance compared with published results, thus enabling investigations to better model system performance (e.g. resolution degradation) within the reconstruction task. The simulated results demonstrate highest sensitivity performance with the DST (though with the highest scatter fraction), and highest NECR performance for the LYSO-based DRX. The results also show that DRX, DLS and DSTE PET/CT cameras have nearly the same amount of scatter fraction.

I. INTRODUCTION

A nalysis of retrospectively aligned PET and CT images is, however, error-prone, time-consuming, and tedious. Moreover, true image fusion is difficult given the different patient positioning between the PET and the CT scan.

To avert these problems, a team at the University of Pittsburgh headed by Drs. David Townsend in collaboration with CTI (Knoxville, TN) and Siemens Medical Solutions (Hoffman Estates, IL) developed a dual-modality PET/CT tomograph combining both PET and CT scanning in one device. This first prototype to be used clinically consisted of a rotating partial-ring PET system and single-slice CT scanner mounted to the same rotating support. Since the introduction of this prototype, several PET/CT devices have been introduced and are now available commercially.

Today PET/CT scanning plays a major role in medicine for in vivo imaging in oncology, cardiology, neurology, psychiatry, and is considered as a major advance in imaging technology and patient care. PET/CT provides physicians with superior information for determining tissue characterizations and classifications, staging of cancers, restaging of cancers, patient prognosis and monitoring the effectiveness of cancer therapies.

As the performance of a scanner depends not only on the scintillating material but also on the scanner design, with regards to the advent of newer scanners, there is a need to optimize acquisition protocols as well as to compare scanner performances on an objective basis. In this study we evaluate and compare the performance characteristics of the PET components of four commercial GE PET/CT cameras, namely (i) the BGO-based Discovery LS PET/CT (DLS), (ii) the BGO-based Discovery ST PET/CT (DST), (iii) the BGO-based Discovery STE PET/CT (DSTE) and finally (iv) the LYSO-based Discovery RX PET/CT (DRX) scanners using the Geant4 Application for Tomographic Emission (GATE). After validation of the GATE models, we also demonstrate the flexibility and accuracy of GATE besides showing the potential benefits of a validated PET scanner simulation in design optimization and performance prediction.
II. MATERIAL AND METHODS

GATE was used to build our three-dimensional PET simulation models. To validate the simulation results, standard phantoms, used in performance assessment experiments, were modeled for simulating the system sensitivity, scatter fraction and count rate response.

A. Monte Carlo Simulation

Full scanners simulations are based on the GATE toolkit which is an open source Monte Carlo simulation platform developed for PET and SPECT studies and is supported by the OpenGATE collaboration [1]. 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 provides the ability of modeling time-dependent phenomena, such as geometry element movements and source decay kinetics, allowing the simulation of time curves under realistic acquisition conditions. It also provides the ability to model and account for the effects of photon noncollinearity, off-axis detector penetration, detector size and response, positron range, photon scatter, and patient motion on the resolution and quality of PET images. The software’s limitations with regard to generating adequately complex shapes are well within the tolerance and design of these scanners.

GATE also has the ability to convert photon interactions into counts in a manner analogous to that of a real scanner’s detectors and electronics. This is accomplished in GATE by a series of signal processing chain called digitizer. Each module of the digitizer mimics a separate portion of a scanner’s signal processing chain. The crystal quantum efficiency, crystal blurring, thresholder, upholder, dead time and other electronics delay are defined in this module. To mimic 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.

B. Simulated PET/CT Scanners

Regarding the geometrical information kindly provided by the manufacturer (i.e. GE Healthcare Technologies, Waukesha, WI, USA), the aforementioned cameras simulated in this work are utilizing the block design technology, where each block is an array of several crystals. The crystal dimensions are 4x8x30 mm³ for the DLS, 6.25x6.25x30 mm³ for the DST, 4.7x6.3x30 mm³ for the DSTE and 4.2x6x3.3x30 mm³ for the DRX, in transaxial, axial, and radial directions, respectively.

There are 18 rings with 672 BGO crystals per ring in the DLS, 24 rings with 420 BGO crystals per ring in the DST, 24 rings with 560 BGO crystals per ring in the DSTE and 24 rings with 630 LYSO crystals per ring in the DRX. The DLS scanner has the largest ring diameter of 92.7 cm compared to 88.6 cm for the DST, DSTE and DRX scanners.

Furthermore, the DLS has smaller axial and transaxial FOVs of 15.2 cm and 55 cm, respectively, compared to the axial and transaxial FOVs of 15.7 cm and 70 cm for the other three scanners. The GATE model utilized for the PET components of these cameras was that of a cylindricalPET scanner system. The system which is a key-concept of GATE provides a template of a predefined geometry to simulate a scanner. The geometrical volumes containing crystals are grouped in matrices, themselves assembled in submodules and modules.

C. Simulations Setup

As specified by the National Electrical Manufactures Association (NEMA) NU 2-2001 (NU01) protocols [2], six concentric aluminum tubes all 700 mm in length were simulated to calculate camera sensitivity. A 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 scatter fraction and counting rate measurements were performed using the NEMA scatter phantom: a 70 cm-in-length cylindrical tube with an outside diameter of 20.3 cm and a 6.4 mm hole size at an offset distance of 4.5 cm. The 80 cm line source is placed in the hole with different activities.

The same shielding and packing materials within the detector blocks and the shielding surrounding the scanner rings used for all four cameras. Also 10 micron teflon used around each crystal in all four models. Both the material and dimension of shields within detector block and the ring have been selected alike reference [3].

After accurate modeling of the scanners’ geometry into the code the simulations setup were as follows.

The coincident window width of 12.5 ns for the DLS, 11.7 ns for the DST, 9.75 ns for the DSTE and 5.85 ns for the DRX is used. It should be emphasized that these coincidence windows normally use in clinical environment when using these scanners. The lower energy threshold is set to 300 keV for the DLS model, 375 keV for the DST model and 425 keV for both the DSTE and DRX models. Furthermore, the upper energy threshold is set 650 keV for all four cameras.

For the DLS, DST and DSTE, a 20% mean energy resolution while for the DRX a 14% amount is applied to all crystals at the energy reference of 511 keV.

Two non paralyzable dead times, a dead time for the singles at the Block level followed by a dead time for the coincidence count rate are used for all four cameras. A 150 ns and a 75 ns dead time for the DRX, a 400 ns and a 200 ns
dead time for the DLS, a 380 ns and a 190 ns dead time for the DST, a 320 ns and a 160 ns dead time for the DSTE is set for singles and coincidences count rate, respectively. In all the simulations the acquisition time of 10 seconds was selected.

III. RESULTS

The codes verification is done on axial sensitivity (3D), axial and transaxial detection position, gamma non-collinearity angle distribution (deg) and positron annihilation distance (mm). As the aforementioned cameras simulated in this work are utilizing the block design technology and have the same cylindrical geometry, the verification results is described for one model (the DRX) while the procedure is same for the others.

Figure 1 illustrates the axial sensitivity (3D) of the DRX scanner. The 3D sensitivity is not uniformly distributed axially and falls off rapidly as one approach the edges of the axial FOV.

Figure 2 shows the transaxial detection position which is a 2D histogram of the X and Y coordinates of the annihilation photons in the DRX detector rings. The distribution of detection is completely homogeneous.

The DRX axial detection position is shown in Figure 3. It is a 1D histogram of the Z coordinate of detected annihilation photons. It illustrates the behavior of the detectors in axial direction. The histogram drops in inactive areas.

Finally, the code verification is done on positron annihilation distance. Figure 4 shows the number of 18F positrons as a function of their annihilation distance. Most of the positrons annihilate in distances less than 0.5 mm while a few annihilate in distances more than 1 mm.

The codes were also validated via comparison with published measured data for NU01 measurements test of these four GE scanners [3, 4, 5 and 6]. The results are compared to published data for the sensitivity, scatter fraction and count rates.
TABLE I
COMPARISON OF 3D SENSITIVITY MEASUREMENTS BETWEEN THE GE DISCOVERY PET/CT SCANNERS AND THE GATE MONTE CARLO SIMULATIONS

<table>
<thead>
<tr>
<th>Radial position (cm)</th>
<th>DLS published data [3] (cps/kBq)</th>
<th>DLS GATE Model (cps/kBq)</th>
<th>DST published data [4] (cps/kBq)</th>
<th>DST GATE Model (cps/kBq)</th>
<th>DSTE published data [5] (cps/kBq)</th>
<th>DSTE GATE Model (cps/kBq)</th>
<th>DRX published data [6] (cps/kBq)</th>
<th>DRX GATE Model (cps/kBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0 = 0</td>
<td>6.41</td>
<td>6.54</td>
<td>9.11</td>
<td>9.23</td>
<td>8.8</td>
<td>8.43</td>
<td>7.30</td>
<td>7.36</td>
</tr>
<tr>
<td>R10 = 10</td>
<td>6.56</td>
<td>6.70</td>
<td>9.30</td>
<td>9.36</td>
<td>8.9</td>
<td>8.68</td>
<td>7.54</td>
<td>7.55</td>
</tr>
<tr>
<td>Ratio R0 / R10</td>
<td>0.977</td>
<td>0.976</td>
<td>0.979</td>
<td>0.986</td>
<td>0.988</td>
<td>0.971</td>
<td>0.968</td>
<td>0.974</td>
</tr>
</tbody>
</table>

TABLE II
COMPARISON OF 3D SCATTER FRACTION MEASUREMENTS BETWEEN GE DISCOVERY PET/CT SCANNERS AND THE GATE MONTE CARLO SIMULATIONS

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>42.85%</td>
<td>40.9%</td>
<td>45%</td>
<td>46%</td>
<td>33.9%</td>
<td>35.8%</td>
<td>31.8%</td>
<td>33.2%</td>
</tr>
</tbody>
</table>

Fig. 5. Random and True rates vs. activity concentration for GE PET cameras. 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.

A comparison of the sensitivity of the GATE simulations to experimental values is presented in table I. Also, a comparison of the scatter fraction results of the GATE simulations to those of the measured data is presented in table II.

The count rate performance for trues and randoms for each PET scanner is shown in Figure 5. The noise equivalent counts without randoms subtraction for each PET scanner are shown in Figure 6. 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 = T² / (T+S+R); where T, S, and R are the true, scatter, and random count rates, respectively.

IV. DISCUSSION

In Figure 1, the increase in 3D sensitivity is due to the increase in the effective geometrical solid angle covered by the scanner. In 3D mode, as the increase in the number of LORs depends on the number of crystal rings, there is a much stronger variation in sensitivity, which peaks in the center of the axial FOV.

The homogeneity of the distribution in Fig.2 shows the isotropic radiations besides the uniformity of detection. Behavior of the detectors in axial direction is shown in Fig.3. As a matter of fact, the DRX has 4 modules of crystals in the
axial direction and therefore 3 layers of packing material has been used between them, so no counts should be detected in those inactive areas. But, due to the scatter and the LOR mispositioning, the axial position of the corresponding LORs is improperly histogramed in those areas.

It should be noted that the selection of the annihilation photons is not based on the physical process that produced the photon (annihilation of the emitted positron with an electron), but rather on the energy of the photon (greater than 425 keV for the DRX) and on the occurrence of the photon (should be the first two photons radiated from the positron).

The distribution of 18F positron annihilation distances, as the result of Figure 4, is in good agreement with published measure data by Sanchez-Crespo et al [7].

GATE data in table I is presented with efficiency correction. Quantum efficiency (QE) is applied to individual events within the blocks in the digitizer and varied as a free parameter until the best agreements with experimental results were obtained.

Table II shows that the simulation's scatter fractions are very close to the measured values (within 1% to 4.5%). DST has the greater scatter fraction compared to the DLS, DSTE and DRX scanners.

The simulated peak of true count rates and NECR curves (Fig.5 and Fig.6) are very close to the published measurements. Because of better NECR, the DRX has the ability to yield improved image quality over the other systems. The NECR is much better at low activity concentration. For example, the NECR of the DRX PET scanner is about twice that of the DLS at lower activity concentrations. In the tissues that there is not high blood flow and metabolism, and therefore low activity concentration, a relative high NECR in the low radioactivity concentration is very important for detection of small tumors.

V. CONCLUSION

The obtained results demonstrate that all four PET cameras possess high NECR, low scatter fraction and acceptable sensitivity. However, there were some differences in their performances as we have especially assessed by the NECR concept.

The GE Discovery PET/CT camera, DRX, was seen to outperform the other three scanners in terms of overall NECR performance. This was due to having the highest true count performance, while having the lowest scatter fraction and an average random rate performance.

Aside from the DRX, the DSTE was seen to outperform the DST and DLS scanners in terms of NECR better than the other cameras.

Having successfully simulated the aforementioned four scanners, our research goal is to use the Monte Carlo simulation technique to better understand system performance, particularly with regards to resolution degrading phenomenon, and as such to arrive at powerful, accurate and feasible reconstruction algorithms with better knowledge of the systems at hand.

As for future work, we intend to work on improving image reconstruction algorithms including the resolution recovery concept. In fact, the understanding of the systems performance will lead to better algorithms and comparative image reconstruction resulted in significantly sharper images.

REFERENCES