A Novel Method for the Image Quality assessment of PET Scanners by Monte Carlo simulations: Effect of the scintillator

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Abstract. The aim of the present study was to propose a comprehensive method for PET scanners image quality assessment, by the simulation of a thin layer chromatography (TLC) flood source with a previous validated Monte-Carlo (MC) model. The model was developed by using the GATE MC package and reconstructed images were obtained using the STIR software, with cluster computing. The PET scanner simulated was the GE Discovery-ST. The TLC source was immersed in 18F-FDG bath solution (1MBq) in order to assess image quality. The influence of different scintillating crystals on PET scanner’s image quality, in terms of the MTF, the NNPS and the DQE, was investigated. Images were reconstructed by the commonly used FBP2D, FPB3DRP and the OSMAPosl (15 subsets, 3 iterations) reprojection algorithms. The PET scanner configuration, incorporating LuAP crystals, provided the optimum MTF values in both 2D and 3DFBP whereas the corresponding configuration with BGO crystals was found with the higher MTF values after OSMAPosl. The scanner incorporating BGO crystals were also found with the lowest noise levels and the highest DQE values after all image reconstruction algorithms. The plane source can be also useful for the experimental image quality assessment of PET and SPECT scanners in clinical practice.

1. Introduction
Positron Emission Tomography (PET) scanners have been an essential imaging modality for various medicine disciplines. Their imaging performance is affected by various factors all of which contribute to the decreased PET resolution and image degradation [1]. The Detective Quantum Efficiency (DQE) is a figure of merit which is accepted as the best single objective indicator of overall image quality, for comparison between various imaging detector technologies [2]. DQE combines spatial resolution through the Modulation Transfer Function (MTF) and image noise through the Normalized Noise Power Spectrum (NNPS), to provide a measure of the Signal to Noise ratio (SNR) transfer through the imaging system, as a function of spatial frequency. Several studies have been carried out concerning PET image quality. However, in the majority of them, resolution was assessed from point sources in terms of the Point Spread Function (PSF) and consequently from the Full width at Half Maximum...
(FWHM) [3]. Only in a few studies resolution was assessed in terms of the MTF calculated from the PSF method [4]-[5]. MTF can be also assessed from a line source through the estimation of the Line Spread Function (LSF). The use of the LSF method for determining the MTF in tomographic imagers was initially introduced by Boone [6] who applied this method for CT scanners evaluation. Fountos et al. [7] recently introduced a similar method for Single Photon Emission Computed Tomography (SPECT) scanners to obtain the MTF through the LSF method. The concept of DQE was previously approached by various methods for PET scanners [8]. According to our knowledge the overall imaging quality performance has never been assessed in terms of the spatial frequency dependent DQE for PET scanners. The aim of this study was to extend a previous validated Monte Carlo (MC) model [9] for the complete characterization and the further improvement of the image quality in PET scanners. This novel image quality method was tested by investigating the effect of crystal material on PET scanner performance. To this aim, DQE was estimated by the simulation of a Thin Layer Chromatography (TLC) plane source filled with 18F-FDG. The Geant4 Application for Tomographic Emission (GATE) was used in combination with the Software for Tomographic Image Reconstruction (STIR) [10]. Various GATE studies have been published on implementing STIR reconstruction for large commercial PET scanners [1], [10]-[12]. None of these, however, simulated the GE Discovery-ST scanner in order to fully characterise the image quality of PET in terms of DQE. Furthermore, the influence of the replacement of the BGO crystals with various crystal materials on the image quality of the scanner was also investigated. The simulation of the plane source phantom provides an accurate model that is useful to fully characterize the performance of nuclear medicine imaging systems.

2. Materials and methods

2.1. Geometry of the modeled PET scanner

The GE Discovery ST PET/CT incorporates BGO [13], [14] crystals with dimensions of 6.3x6.3x30 mm [9]. The crystals were assembled into blocks of 6x6 crystals. Each block was coupled to a Photomultiplier Tube (PMT) consisting of four square channels, and is assembled in modules consisting of 8 blocks (2x4) each. The detector ring is finally comprised of 35 modules, i.e. 280 crystal blocks, or 24 rings of 420 crystals. The scanner is designed to acquire images in both 2D and 3D modes. The system was also simulated by replacing the BGO crystal arrays with YAlO3:Ce (YAP) [14], LuAP:Ce, LuYAP:Ce-70, LuYAP:Ce-80 [14]-[16], Lu2SiO5:Ce (LSO) [17]-[19], and Gd2SiO5:Ce (GSO) [20], [21] crystals.

2.2. Preparation of the MTF test object

The plane source was implemented by a layer of Silica gel on Aluminium (Al) foil substrates (Figure 1). The dimensions of the TLC plate were 5x10 cm² and it was immersed in 18F-FDG bath solution (1 MBq). The MTF test object was simulated within a phantom, consisting of two semi-cylindrical polyethylene blocks with 20 cm diameter and 70 cm length. Plane source images were acquired from STIR, after reconstruction with the commonly used FBP2D, the FPB3DRP and the MLE-OSMAPOSL reprojection algorithms [10].

2.3. Modulation transfer function (MTF) and Normalized noise power spectrum (NNPS)

Image quality was assessed in terms of the MTF that was obtained, by using the LSF method [7]. To estimate noise, NNPS data were obtained at the same activity concentration as that of the MTF from the coronal images [22].

2.4. Detective Quantum Efficiency (DQE)

Detective Quantum Efficiency (DQE) is calculated by comparing the SNR at the detector output with that at the detector input as a function of spatial frequency [2]. DQE is dependent on radiation exposure, spatial frequency, MTF, NNPS and detector material. High DQE values indicate that less radiation is needed to achieve identical image quality. The DQE of the PET scanner was calculated...
from the MTF, NNPS, and the incoming SNR squared (defined as the plane source phantom activity (counts/mm²) incident on the detectors) by using (1) [22]:

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DQE(u) = \frac{MTF^2(u)}{(SNR^2(u) \cdot NNPS(u))}
\]  

(1)

Figure 1. Block scheme of the DQE procedure.

3. Results and discussion

3.1. DQE

Figures 2 and 3 show DQE results obtained from the FBP2D, FBP3DRP and OSMAPOSL reconstruction algorithms, for the PET scanner configurations incorporating successively all the crystals under investigation. The curves correspond to the combined MTF and NNPS results from both the transverse and coronal reconstructed slices. The behavior of the DQE was influenced by both MTF and NNPS. DQE values of the PET configuration incorporating BGO crystals were found higher after FBP3DRP and OSMAPOSL image reconstruction algorithms examined in this study. DQE values of the LuYAP where found higher after FBP2D.
Figure 2. Comparison between the DQEs obtained from the plane source reconstructed images with the FBP2D (left) and the FBP3DRP (right) for various crystals.

Figure 3. Comparison between the DQEs obtained from the plane source reconstructed images with the OSMAPOSL (15 subsets, 3 iterations) for various crystals.

4. Conclusion
A novel image quality method for PET scanners was implemented with GATE Monte Carlo methods. PET images were obtained from STIR through the simulation of a novel thin 18F-FDG plane source. Image quality was assessed from the reconstructed images, by the estimation of the spatial frequency dependent DQE of the plane source reconstructed images. The influence of the detector material on the image quality of a PET scanner was also investigated. The method modelled and simulated in this study was used for the image quality assessment and optimisation, but it can be also useful for the further development of PET and SPECT scanners though GATE simulations.

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