Towards the Experimental Assessment of the DQE in SPECT Scanners

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Abstract. The purpose of this work was to introduce the Detective Quantum Efficiency (DQE) in single photon emission computed tomography (SPECT) systems using a flood source. A Tc-99m-based flood source ($E_{\gamma}=140$ keV) consisting of a radiopharmaceutical solution of dithiothreitol (DTT, $10^{-3}$ M)/Tc-99m(III)-DMSA, 40 mCi/40 ml bound to the grains of an Agfa MammoRay HDR Medical X-ray film) was prepared in laboratory. The source was placed between two PMMA blocks and images were obtained by using the brain tomographic acquisition protocol (DatScan-brain). The Modulation Transfer Function (MTF) was evaluated using the Iterative 2D algorithm. All imaging experiments were performed in a Siemens e-Cam gamma camera. The Normalized Noise Power spectra (NNPS) were obtained from the sagittal views of the source. The higher MTF values were obtained for the Flash Iterative 2D with 24 iterations and 20 subsets. The noise levels of the SPECT reconstructed images, in terms of the NNPS, were found to increase as the number of iterations increase. The behavior of the DQE was influenced by both MTF and NNPS. As the number of iterations was increased, higher MTF values were obtained, however with a parallel, increase of magnitude in image noise, as depicted from the NNPS results. DQE values, which were influenced by both MTF and NNPS, were found higher when the number of iterations results in resolution saturation. The method presented here is novel and easy to implement, requiring materials commonly found in clinical practice and can be useful in the quality control of SPECT scanners.

Keywords: SPECT; DQE; MTF; NNPS; LSF; film; flood source

1. Introduction

The Detective Quantum Efficiency (DQE) has been defined as the efficiency of a system to transfer the Signal to Noise Ratio (SNR) through the imaging chain [1,2]. In this sense DQE has been generally accepted as the most appropriate objective indicator of overall image quality, suitable for comparison between various imaging systems [3]. 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 transfer through the imaging system, from its input to its output, as a function of spatial frequency [4, 5]. The use of the line spread function (LSF) method for determining the MTF in tomographic imagers was initially introduced by Boone who applied this method for CT scanner evaluation [6]. Fountos et al. introduced a similar method for single photon emission computed tomography (SPECT) scanners by immersing an Agfa MammoRay HDR Medical X-ray film in a solution of dithiothreitol (DTT)/Tc-99m(III)-DMSA to obtain the MTF through the LSF method [7]. This method averages data from a significantly larger number of samples (line profiles) instead of using a point, resulting in a less prone to noise technique [8,9]. The flood source can be prepared by using materials easily accessible in clinical practise (i.e. films, radiopharmaceuticals and PMMA plates) and can be used in quality control procedures of nuclear medicine imaging systems, as well as, in the comparison of different SPECT systems and protocols [10-12].
2. Materials and Methods

2.1 Preparation of a film-based flood source for the MTF and NNPS measurements

For the purposes of the present study the optimum flood source, determined in a previous study [7], was used for the DQE determination, by immersing the Agfa MammoRay HDR Medical X-ray film (Agfa-Gevaert, Mortsl, Belgium), which was used as substrate, in $^{99m}\text{Tc}$-DMSA (III) (Technescan DMSA, Mallinckrodt BV, Petten, Holland). The film was placed between two methyl-methacrylate (PMMA) slabs and positioned in a dual-head Siemens e-Cam $\gamma$-camera (Erlangen, Germany). The film/radiopharmaceutical solution combination was prepared by using 40 mCi/40ml of the $^{99m}\text{Tc}$-DMSA (III) solution and a 3x3cm piece of the Agfa MammoRay HDR Medical X-ray film. The flood source obtained this way exhibits an activity of 44.4 MBq. The obtained planar images were obtained with a matrix of 256x256 and 500 kcounts. Images of the $^{99m}\text{Tc}$-DMSA(III) radiopharmaceutical solution and the Agfa MammoRay HDR Medical X-ray film combination were obtained by using the brain SPECT imaging protocol of the Siemens e-Cam $\gamma$-camera.

2.2 MTF

The MTF was obtained by using the LSF method, for the brain SPECT imaging protocol, after application of Iterative OSEM Flash 2D on the thin flood images, without any filtering. The Iterative reconstruction software (Siemens Medical Systems, Inc., Hoffman Estates, Il., USA) was installed in the E-Soft system. The standard first-order Chang attenuation correction was applied to reconstructed slices [13].

2.2.1. LSF

In the LSF method, the thin flood source was positioned at angles ranging from $2^\circ$ to $8^\circ$ to the horizontal or vertical axes respectively. This technique was followed in order to avoid aliasing effects, as described in the Fujita technique [14]. Considering angles greater than $8^\circ$, the dimensions of the vertical LSFs will be different from those of the true LSFs by more than 1%, and geometrical corrections should then be applied [7]. The final LSF was obtained by averaging all line LSF profiles after angle correction. The average LSF was fitted using four different functions: a Gaussian, a sum of two Gaussians, a Lorentzian and a hybrid (sum) of a Gaussian and a Lorentzian functions. Fourier transformation and subsequent normalization were then applied on the final LSF to compute the MTF [7,8].

2.3 NNPS

To estimate noise, NNPS data were obtained at the same activity concentration as that of the MTF from the sagittal images, using the following method. A sub-image was first extracted from the sagittal plane images. The sub-image was chosen in the centre of the coronal plane, where the pixel values are different from the background. Half overlapping ROIs were then taken from the sub-images. The mean pixel value of each ROI was calculated and subtracted from each pixel of the ROI. Thus a new image corresponding to signal variations remained. The squared modulus of the 2D Fast Fourier Transform (FFT) of each ROI was calculated and added to the NPS ensemble. This was repeated for all the ROIs taken from each image. Finally, the NNPS was calculated by dividing with the squared mean value of the sub-image and afterwards the ensemble average was obtained [2,9].

2.4 DQE

DQE has been defined as $\text{DQE} = \frac{\text{SNR}_{\text{out}}^2}{\text{SNR}_{\text{in}}^2}$ [2]. According to this, $\text{SNR}_{\text{out}}$ and $\text{SNR}_{\text{in}}$ are the output and input signal to noise ratios respectively. In the present study $\text{SNR}_{\text{out}}$ was expressed in terms of MTF and NNPS and thus it is a function of spatial frequency, while $\text{SNR}_{\text{in}}$ was expressed
through radiation intensity. The DQE of the PET scanner was calculated from the MTF, NNPS, and incoming $SNR_{in}^2$ by using equation (1):

$$DQE(u) = \frac{MTF^2(u)}{SNR_{in}^2 \cdot NNPS(u)}$$  \hspace{1cm} (1)

$SNR_{in}^2$ was defined as the activity (in counts/mm$^2$), of the plane source phantom, incident on the detectors. The number of photons incident on the detectors was calculated through the determination of the solid angle ratio and was found equal to 25473.72/mm$^2$ [15]. Since the spatial frequency sampling steps of MTF and NNPS are generally not the same, NNPS was linearly interpolated at the frequency sampling points of MTF and then DQE was calculated at these points.

3. Results and Discussion

Figure 1a shows MTF results, obtained from SPECT images, in transverse plane, using the brain protocol. In figure 1a the curve showing the highest MTF values was obtained for the Iterative Flash 2D reconstruction method with 24 iterations and 20 subsets for the brain protocol.

Figure 1b shows NNPS results obtained from the Flash 2D iterative SPECT images for the brain protocol. The curves, shown in figure 1b correspond to sagittal reconstructed slices in which both the number of subsets and iterations were increased. A first point to note is that variation on the NNPS curves is attributed to the restricted amount of pixel data that can be extracted from a Nuclear Medicine image. In every case the noise levels of the SPECT reconstructed images, in terms of the NNPS, were found to increase as the number of iterations increase. The maximum noise levels were attributed to the 20 iterations and 20 subsets reconstructed image with a value of 0.04 mm$^2$ at 0.066 cycles/mm. Figure 2 shows DQE curves from both the transverse and the sagittal reconstructed slices, for various iterations and subsets combinations. The behavior of the DQE was influenced by both MTF and NNPS. As the number of iterations was increased, higher MTF values were obtained.
however with a parallel, increase of magnitude in image noise, as depicted from the NNPS results. This ratio results in a reduction of the image signal to noise ratio with the increase of the number of iterations. Figure 2 shows that the higher SNR can be obtained when the number of iterations results in resolution saturation. A further increase in iterations, does not improve resolution, whereas the increase in image noise leads in DQE reduction. In particular, the maximum DQE value (0.055 at 0.008 cycles/mm) was obtained for the 24 iterations/20 subsets image in figure 2, however as the spatial frequencies increase, images obtained with fewer number of iterations (for example the 12 iterations/20 subsets image in which resolution was already saturated) shows higher DQE values.

4. Conclusions
Image quality characterisation of a SPECT scanner was achieved through the estimation of the MTF, the NNPS and the DQE of a thin flood source, which was prepared in our laboratory, by immersing an Agfa MammoRay HDR Medical X-ray film into $^{99m}$Tc (III)-DMSA-DTT radiopharmaceutical solution. The influence of iterative image reconstruction on the flood source images was investigated by using various iterations and subsets. Image quality in terms of MTF was found to improve by increasing the number of iterations (number of image updates). The corresponding reconstructed image noise levels, in terms of the NNPS, were found to increase with both number of iterations and subsets. DQE values, which were influenced by both MTF and NNPS, were found higher when the number of iterations results in resolution saturation. The method presented in this work can be used for the routine $\gamma$-camera quality control.

5. References
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