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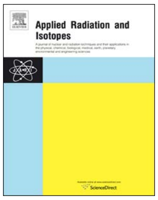

Geometrical parameters and scattered radiation effects on the extrinsic sensitivity and counting efficiency of a rectangular gamma camera

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ABSTRACT

A point source is used to investigate the effect of water phantom thickness and source-to-detector distance (SDD) on the sensitivity and counting efficiency of a rectangular detector gamma camera. The increase in water thickness resulted in an increase in scatter fraction, a decrease in sensitivity, and counting efficiency. The increase in SDD resulted in a decrease in sensitivity and an increase in counting efficiency. An SDD of 0.79 ± 0.02 m is found to provide a good compromise for acceptable sensitivity and reasonable counting efficiency.

1. Introduction

Gamma cameras commonly used in medical imaging have a limited energy resolution. In order to detect a sufficient number of photons, a broad photo-peak window is usually used, resulting in the detection of scattered photons. In several situations, scattering can account for more than half of the counts detected within the photo-peak window (Floyd et al., 1988). This causes degradation in image resolution and disturbs the results of quality assurance (QA) tests (Deloar et al., 2003; Holstensson et al., 2010; Bugby et al., 2014; Bhatia et al., 2015). The effect of scattered photons on planar nuclear medicine imaging (Nguyen et al., 2011; Frey et al., 2012) and Single Photon Emission Computed Tomography (SPECT) imaging (Deloar et al., 2003; Patton and Turkington, 2008; Seo et al., 2008; Holly et al., 2010; Khalil M., 2011) have been studied through experimental and Monte Carlo simulations.

The extrinsic sensitivity and counting efficiency are two important QA parameters. The reported values of counting efficiency and sensitivity vary as these parameters are dependent on the type of phantom and source-detector geometry (Aguiar and Galiano, 2004; Rodrigues and Galiano, 2007; Elshemey et al., 2013). The extrinsic sensitivity of a gamma-camera is the number of total counts collected, with a collimator attached to the gamma camera, within the photo-peak window divided by the value of the source activity (Santos et al., 2008). It depends mainly on the characteristics of the crystal of the camera and the associated photomultiplier tubes, as well as on the energy resolution of the camera and the collimator configuration (Elshemey et al., 2013; Bugby et al., 2014; Yamamoto et al., 2014; Bhatia et al., 2015). The counting efficiency is the count rate recorded by the detector divided by that theoretically striking the detector surface with a collimator in place (Rodrigues and Galiano, 2007; Elshemey et al., 2013). Early and Sodee (1995) and Gouda et al. (2015) presented measurements of extrinsic sensitivity and counting efficiency for a point source at different source-to-detector distance (SDDs). Rodrigues and Galiano (2007), Santos et al. (2008), Radu et al. (2009), Elshemey et al. (2013) and Ortiz-Ramírez (2015) reported similar measurements for a flood source.

In a similar study, Elshemey et al. (2013) presented a calculation of extrinsic counting efficiency and extrinsic sensitivity of a circular flood source (a ^{99m}Tc source homogeneously distributed in a circular water container in order to mimic the human body tissue) and a rectangular detector. Although this geometry imitates real conditions for gamma camera optimization, the employment of a point source instead of a flood source may have several advantages. Using a point source reduces the time required for rotational uniformity testing as detectors of a multiple detector gamma camera can be evaluated at the same time (Kappadath et al., 2009). It minimizes the absorbed dose and contamination to the personnel filling different phantoms (Jonson et al., 1992). It enables quantitative analysis of scattered photons for the purpose of scatter correction (Kojima et al., 1991) and minimizes the possibility of damage to collimators and detection systems (Kappadath et al., 2009).

Although there are gamma cameras with rectangular detectors that are routinely quality controlled using point sources (Hutton et al., 2011; Frey et al., 2012; Islamian et al., 2012; Case and Bateman, 2013; D'Arienzo et al., 2016; Inoue et al., 2016; Scuffham et al., 2016; Wagner et al., 2016), several important pieces of information are still missing. There are no available calculations of the counting efficiency

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for such geometry. No recommendation has been reported for the optimal thickness of the phantom to be used for the quality control of a gamma camera using a point source. There is no available comparison between point and flood sources in terms of the extrinsic sensitivity and counting efficiency for a gamma camera with a rectangular detector. Moreover, since the increase in extrinsic sensitivity is accompanied by a decrease in counting efficiency, a compromise needs to be found.

The present work aims at providing convincing answers for these questions by using a point source (^{99m}Tc), a water phantom container and a gamma camera with a rectangular detector to acquire energy spectra and calculate the scatter fraction, extrinsic sensitivity and counting efficiency of the camera in different scattering conditions (thicknesses of 0, 50, 100, 150 and 200 mm and source-to-detector distances of 0.5, 0.7, 0.9 and 1.1 m).

2. Experiment and calculations

A dual-head gamma camera (two movable detector heads, Symbia SPECT/ CT, Siemens, Germany) with a 9.9 mm thick NaI(TI) scintillator crystal detector, equipped with a parallel-hole, collimator was used in the present work. Measurements were carried out using a lead collimator with 9×10^{4} hexagonal holes (hole length of 24.05 mm, septal thickness of 0.2 mm, and hole diameter across the flats of 1.45 mm), a 543×395 mm rectangular camera and photomultiplier tubes (53 of diameter of 76 mm and 6 of diameter of 51 mm). The summation of all 59 photomultiplier tube signals was used to provide the total count recorded by the camera. A 1 keV/channel energy spectrum was recorded, since the detector has an energy resolution of 9.9% full width at half maximum (FWHM) at 140 keV. The dead time was 1.25 s (at source strength of $0.197 \pm 3.7\times10^{-4}$ GBq), while the background correction was 1000 counts (for a counting period of 60 s).

In order to emulate the thickness of a water phantom in the direction of the gamma camera, a home-made acrylic cylindrical, vertically scaled phantom container was used for measurements (with a diameter of 0.32 m, a height of 0.25 m and a wall thickness of 25 mm), as was done by Elshemey et al. (2013). The container was filled with water representing a phantom of an imaged material. A syringe (inner diameter of 4.35 mm, volume of 44.35 mm^{3}), filled with $0.197 \pm 3.7\times10^{-4}$ GBq of ^{99m}Tc was used as the radiation source. This volume of ^{99m}Tc solution inside the syringe represents practically a point source, as long as the distance between the source and the point of interest is at least 10 times the largest dimension of the source (Sherer et al., 2014). The source was first placed at a distance of 0.25 m from the head of the gamma camera underneath an empty phantom container. The energy spectrum was then acquired. The same steps were repeated for the phantom's container filled with different levels of water (50, 100, 150 and 200 mm) as scattering media. All data were corrected for the decay of ^{99m}Tc (Podgorsak, 2010).

The energy spectra were acquired for different source thicknesses in order to determine the variation of scatter contribution with source thickness. This was carried out using only one head of the dual-head gamma camera. The scattered fraction was calculated from the energy spectrum. In the first step, the number of counts, $T\left(H\right)$, as a function of layer thickness H, was calculated using (Kojima et al., 1991; Elshemey et al., 2013):

$$T\left(H\right) = S\left(H\right) + D\left(H\right) \tag{1}$$

where $S\left(H\right)$ is the number of counts for scattered photons and $D\left(H\right)$ is the number of counts for non-scattered photons, both taken in the energy range used in imaging of ^{99m}Tc, from 133 keV (140 keV −5.0%) up to 153 keV (140 keV +10%), based on the asymmetrical scattered correction method by Kojima et al., 1992.

In absence of water, $S\left(H_o\right) \approx 0$, since the source radiation would interact only with air and the container's material before reaching the detector. Then, Eq. (1) yields $T\left(H_o\right) = D(H_o)$. otherwise $D\left(H\right)$ can be calculated as:

$$\begin{aligned} D\,(H) &= D\,(H_o)\, e^{-(\mu_w H+\mu_{acr}x+\mu_{air}[z-H-x])} \\ &= T\,(H_o)\, e^{-(\mu_w H+\mu_{acr}x+\mu_{air}[z-H-x])} \end{aligned} \tag{2}$$

where μ_w, μ_{acr} and μ_{air} are the liner attenuation coefficients of water, acrylic and air respectively, H is the water thickness, x is the phantom material thickness (2.5 mm×2, for phantom base + phantom lid), and z is the length of the air gap between point source and camera's aperture.

The scattered fraction is defined as the ratio of scattered to non-scattered counts, $S\,(H) = T\,(H) - D\,(H_o)$. The non-scattered photons are measured in absence of water H_o mm. (Kojima et al., 1991; Elshemey et al., 2013):

$$SF = \frac{S\,(H)}{D\,(H)} = \frac{T\,(H) - D\,(H)}{D\,(H)} = \frac{T\,(H)}{T\,(H_o)}\, e^{\,(\mu_w H+\mu_{acr}x+\mu_{air}[z-H-x])} - 1 \tag{3}$$

At 140 keV, the published linear attenuation coefficients of water μ_w acrylic μ_{acr} and air μ_{air} are 0.154, 0.178 and 3.844×10^{-6} cm^{-1}, respectively, (Kojima et al., 1991;Van Laere et al., 2000; Berger et al., 2010). The linear attenuation coefficient for air μ_{air} was calculated using linear interpolation from the tabulated data of Berger et al., 2010.

The acquisition time was 60 s at 15% energy window (140 keV −5% to +10%; 133–153 keV) (Kojima et al., 1991; Elshemey et al., 2013). The extrinsic sensitivity, S, was calculated using as (Rodrigues and Galiano, 2007; Santos et al., 2008; Elshemey et al., 2013):

$$S = \frac{N}{At} \tag{4}$$

where, N is the number of counts at the photo-peak recorded by the detector at 15% predefined energy window (140 keV −5% to +10%; 133–153 keV, Kojima et al., 1991) for acquisition time interval, t and source activity, A. Note that N is different from $T\,(H)$ in that it is calculated at a larger source to detector distance, from 0.5 m to 1.1 m (Elshemey et al., 2013).

The solid angle (Ω) of a point source at a distance d away from a detector facing the corner of a rectangular detector with area equal to ab is given by (Tsoulfanidis, 1983):

$$\Omega = \frac{1}{4\Pi} \arctan \frac{ab}{d\sqrt{a^2 + b^2 + d^2}} \tag{5}$$

where, a is the length and b is the width of rectangle, respectively. With the source placed underneath the center of a rectangular detector, the solid angle was calculated by dividing the rectangle into four equal smaller rectangles with the source facing each of the four smaller rectangles at the corner (i.e. at the mid-point between the four rectangles). The total solid angle was thus equal to the sum of the solid angles calculated for each of the smaller rectangles.

The extrinsic counting efficiency, ε, for 140 keV photons for a point source is given by (Agbemava et al., 2011; El-Khatib et al., 2014):

$$\varepsilon = \frac{N}{N_{th}} = \frac{N 4\Pi}{\Omega\, fAt} \tag{6}$$

where, N_{th} is the number of counts that theoretically strike the detector's surface in the same time interval, t, used for recording N. The point source activity was $0.197 \pm 3.7\times10^{-4}$ GBq; the half-life used for activity correction was 6.02 h (Mostafa et al., 2011) and photon emission probability $f =$ 89 % (R�sch, 2003). The number of counts, N, was measured three times at different water scattering layers for SDDs of 0.5, 0.7, 0.9 and 1.1 m. These distances are very helpful in calculating the counting efficiency of gamma camera (Rodrigues and Galiano, 2007). The mean values of the corresponding extrinsic sensitivity and counting efficiency were then calculated. The uncertainty is given by standard deviation from the mean.