How Gamma Camera's Head-Tilts Affect Image Quality of a Nuclear Scintigram?

Hojjat Mahani [1,2], Alireza Kamali-Asl [3,*], Mohammad Reza Ay [2,4]

1. Radiation Application Research School, Nuclear Science and Technology Research Institute, Tehran, Iran.
2. Research Center for Molecular and Cellular Imaging, Tehran University of Medical Sciences, Tehran, Iran.
3. Radiation Medicine Engineering Department, Shahid Beheshti University, Tehran, Iran.
4. Department of Medical Physics and Biomedical Engineering, Tehran University of Medical Sciences, Tehran, Iran.

Received: July 26 2014
Accepted: October 01 2014

A B S T R A C T

Purpose: Mechanical calibration of camera plays an important role in nuclear imaging to acquire a more qualified and quantized scintigram. The objective of this work was to quantitatively evaluate planar resolution and sensitivity of a tilted Anger camera using a Monte Carlo simulation.

Methods: For this purpose, spatial resolution and system sensitivity of a tilted-head, LEHR collimated gamma-camera were evaluated using Monte Carlo simulation. To do so, tilt-angle of camera's head was considered to vary from -10 to 10 degrees from the baseline. The Monte Carlo simulated data were validated by means of a comparison with experimental data. In addition, the performance of the system was analyzed both in spatial and frequency domains.

Results: Spatial resolution, in terms of FWHM, for simulated and measured point-spread functions (PSFs), at the rest-position has a value of 7.22 mm and 7.43 mm, respectively. The results also show that the spatial resolution monotonically increases as the absolute value of tilt angles increases, up to a degradation factor of 2.02 for a typical scintillation-camera. System sensitivity exhibits a constant behavior for all tilt-angles with a maximum statistical fluctuation of 2%.

Conclusion: While a head tilt has no effect on the sensitivity of the camera, it can result in a poor and spatially variable planar spatial resolution and contrast of the images provided by the tilted-scanner.

Keywords:

Spatial Resolution,
Image Quality,
Tilted-Head,
Gamma-Camera,
Monte Carlo Simulation.

1. Introduction

Nuclear medicine imaging plays an increasingly pivotal role in biomedical research [1]. SPECT will definitely maintain an exclusive standing in clinical diagnosis, assessment of response to treatment, and delivery of targeted therapies [2].

Thus far, there are a number of studies evaluating performance of scintillation-cameras using Monte Carlo simulations [3-6]. Staelens et al. in 2003, modeled a gamma-camera with Geant4 Application in Tomographic Emission (GATE) [3]. Assie and his colleagues overviewed GATE with four examples of its validation against real data, including SPECT and PET systems, in 2004 [4]. They evaluated spatial resolution, sensitivity, and some correction techniques. In 2009, Mikeli and his co-workers also studied a gamma-camera using GATE [5]. They worked on simulation of a collimator with different hole diameters using a point-source study. Peterson and Furenlid, in 2011, reviewed SPECT detectors [6]. They discussed key performance properties of SPECT cameras.

Alignment and geometrical calibration of the camera (or head) are of great consideration to obtain a high quality nuclear image [7]. In clinical routine, some

*** Corresponding Author:**
Alireza Kamali-Asl, PhD
Radiation Medicine Engineering Department, Shahid Beheshti University, Tehran, Iran.
Tel:+98 21 29904227 / Fax: +98 21 22431780
E-mail: a_r_kamali@yahoo.com, a_kamali@sbu.ac.ir

mechanical malfunctions such as the instrumentation fatigue, the earth summit, and perhaps any error in gearing system of the camera can cause the loss of calibration. Subsequently, several effects tend to be appeared, result in a tilt of the head from the baseline, yielding a change in source-to-collimator distances (SCDs) for different virtual points in the field-of-view (FOV) based on their relative positions.

The collimator mainly determines spatial resolution and sensitivity of the imaging systems [8]. However, with conventional SPECT imaging, the SCD can highly affect spatial resolution of the images, and is of great importance. Increasing the SCD can lead to a loss in spatial resolution and thereby degradation in the image while has no effect on signal-to-noise ratio (SNR) of the data [8]. In clinical nuclear medicine imaging, one should make every effort to set the head(s) as close as possible to the patient to improve spatial resolution of the camera [9].

Both tomographic (3D) and planar resolution (2D) of SPECT images may suffer from a tilted condition; however, this work is focused on the 2D case. To the best of the authors' knowledge, there is no study investigating this effect on gamma-cameras. Therefore, the principal aim of this study was to quantitatively analyze the system resolution and sensitivity of a tilted-camera in both spatial and frequency domains. In other words, the goal was to address the following challenge "how spatial resolution changes when if the head tilts from its standard alignment?"

2. Materiels and Methods

2.1. The Scanner

In this study, a low-energy, high-resolution (LEHR) parallel-hole collimated Symbia SPECT-CT system (Siemens Medical Solutions, USA) was modeled and also utilized [10]. This work is solely focused on SPECT subsystem. Moreover, some specifications of the subsystem are summarized in Table 1.

Table 1. Symbia SPECT subsystem specifications

Parameter	Value
Intrinsic spatial resolution (mm)	3.9
Hole diameter (hexagonal-type)(mm)	1.11
Septal thickness (mm)	0.16
Hole length (mm)	24.05
Crystal thickness (mm)	9.525

2.2. Tilted-Camera Geometry

Rotation of the head around the baseline (i.e. the table direction) is one the most frequent events as a result of the camera's out-of-calibration. Tilted-camera geometry is illustrated in Figure 1. The three point-like sources, and their locations (y= -20.4 cm, y = 0 cm, and y = 20.4 cm) are also depicted. These point-source locations were determined such that cover the entire axial FOV and also all of them still remain in the FOV, for the maximum tilt. The axial direction was assumed to lie on y-axis; θ denotes the tilt-angle about the camera's baseline, and axial length of the camera, L, was nearly 54 cm.

At the rest-position (i.e., tilt-angle = 0°), all sources are located at a distance of 10 cm from the collimator's face. Assuming that the head rotates θ degrees about its center, the left source sees a shorter SCD while the right one senses a greater SCD. The middle sees also a lower SCD for a tilt shown in Figure 1. Since the geometry is symmetric, all mentioned events have been reversed for negative tilt-angles. In clinical considerations, the tilt-angle cannot exceed ±10 degrees.

SNR of a scintigram is mostly determined by the system sensitivity. Although a tilt of the head has a considerable effect on spatial resolution, in theory such a tilt has no effect on the sensitivity of the camera because the sensitivity of parallel-hole collimators is always independent of the SCD. This is true for all tilt-angles, provided that flood source (used in the sensitivity calculations) completely remains in the FOV. It should be noted that positive tilt-angles refer to clockwise rotations.

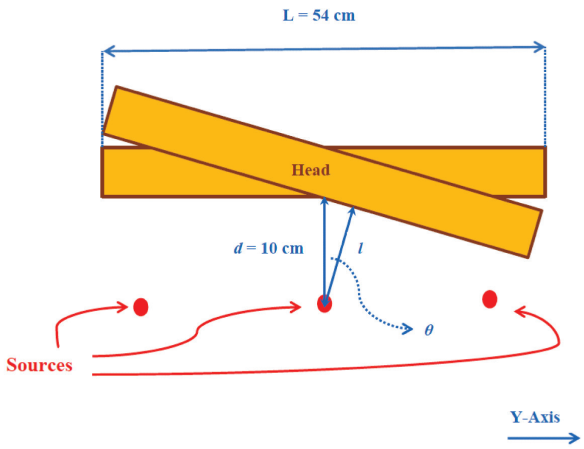


Figure 1. Geometry of a tilted-camera, along with three point-source locations over the FOV for evaluating variation of spatial resolution. Note that the head is rotated clockwise (a positive tilt-angle).

2.3. Simulation Study

There has been an enormous increase and interest in the use of Monte Carlo techniques, in all aspects of nuclear imaging including planar imaging [11]. Monte Carlo N-Particle version 4C (MCNP4C) was performed to assess camera's performance under various tilted-camera conditions. In order to evaluate system resolution using MC simulation, intrinsic- and energy-resolution of the NaI(Tl) crystal were also taken into account for an accurate simulation.

MC simulations allowed us to investigate some tilted-geometry conditions which are practically impossible due to difficulties in implementing such conditions in clinical practice, and the lack of options of the device being investigated. In addition, to speed up the MC simulations, a variance reduction technique, by ignoring tracking of secondary electrons, was also implemented.

A ^{99m}Tc-disk source (as a flood source) of 1 cm diameter at a 10 cm distance from the collimator's face was used for sensitivity calculation and was solely investigated by MC simulation. A 20% energy-window centered at the photopeak was then applied to the all detected photons. For resolution and sensitivity evaluation, a cutoff energy of 100 keV was set so that all photons with lower energy than this threshold were terminated. Having simulated the PSFs, the 2D scintigrams were represented in a 128 × 256 image-matrix, and 2.1 mm pixel-size, as for our experiments.

2.4. Experimental Study and Validation

The experiments were conducted with imaging parameters as in the MC simulation, using Symbia T2 SPECT-CT system (Siemens Medical Solutions, USA). Three point-like sources were filled with 10 mCi Tc-99m as point sources, and were placed at three specific different locations within the FOV, and the planar data were acquired with a 300-second acquisition time. The images were then provided in DICOM format (128 × 256 matrix-size, and pixel-size of 2.1 mm). Prior to acquiring useful data, the system was calibrated in geometry, and position using a multiple-head registration (MHR) phantom. The MHR phantom is a dedicated Symbia SPECT-CT scanners phantom and consists of a plane containing five point-like sources arranged on the plane [12]. Also, the MC simulated results were validated against the experiments for the rest-position.

2.5. Assessment Strategy

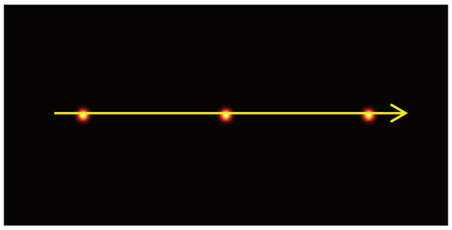
A degradation factor, ratio of FWHM of the broader PSF to the narrower one in the same scintigram, was defined as a key parameter in order to assess the tilt effect. In an ideal case, such a factor is equal to unity. However, in a tilted-head condition, this quantity is greater than unity. This quantity also shows how the spatial resolution is position-dependent on the scintigram, i.e. a higher factor originates from an image with more non-uniform spatial resolution. By taking the Fourier transform of the PSFs, and deriving radial modulation-transfer-functions (MTFs) [13], performance of the tilted-scanner can be alternatively analyzed in the Fourier domain. MTF is an important tool in the interpretation of an imager because it simultaneously brings together spatial resolution and image contrast. In the frequency domain, one would expect that all MTFs coincide in the case of rest-position, and diverge for the tilted-geometries.

In addition, the ratio of sensitivity of the tilted scanner to the rest-position was used as a factor indicating changes in the sensitivity of the imager for different tilt-angles. In an ideal scanner, a ratio of unity over all tilt-angles is expected.

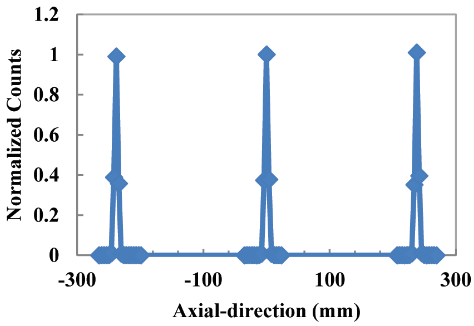
3. Results

3.1. Spatial Resolution Analysis

Figures 2(a) and 2(b) show the MC simulated planar image for three point sources as described in Section 2.2, along with their profiles through the arrow, respectively, for the rest-position condition.



(a)



(b)

Figure 2. (a) Simulated 2D PSFs for three point-sources; **(b)** Profiles of the PSFs through the arrow for the rest-position condition, all profiles are normalized to unity.

Comparison of the MC data against the measured PSFs are highlighted in Figure 3. The validation is only performed for the rest-position using three 10 mCi Tc-99m point-sources, and 300 seconds data-acquisition time.

Two-dimensional MC simulated PSFs, and their profiles through the arrow are shown in Figures 4(a) and 4(b), respectively, for the maximum tilt case.

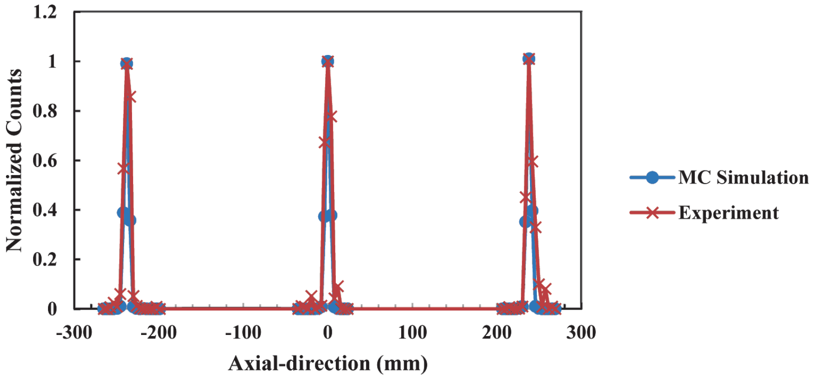
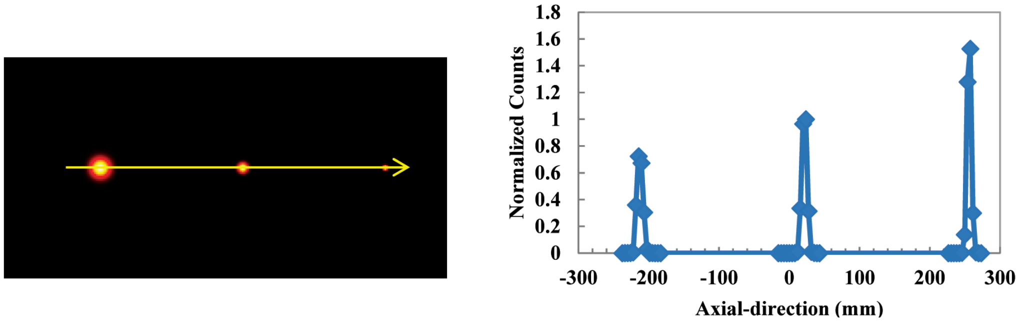


Figure 3. Comparison between MC simulated PSFs and measured PSFs provided by the Symbia T2 SPECT-CT system, for the rest-position, all profiles are normalized to unity.



(a) (b)

Figure 4. (a) Simulated 2D PSFs for three point-sources; **(b)** Profiles of the PSFs through the arrow for the maximum-tilt condition, all profiles are normalized to the central PSF.

Figure 5 gives the degradation factor over all tilt-angles. As absolute value of the tilt-angle increases, the factor increases and refers to spatial resolution degradation on the image.

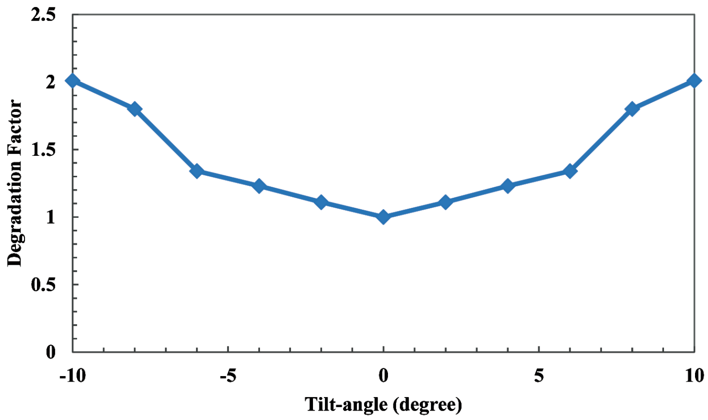
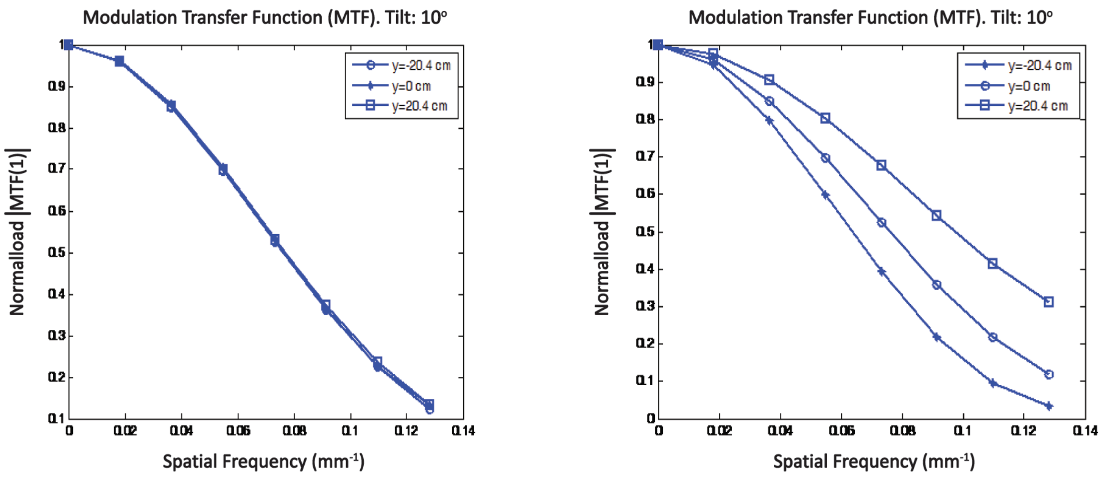


Figure 5. Degradation factor as function of tilt-angle, the degradation factor is defined as a ratio of FWHMs of the broader PSF to the FWHM of narrower one in the same image.

3.2. Spatial-Frequency Analysis

Radial MTFs for the rest and maximum-tilt conditions are shown in Figures 6(a) and 6(b), respectively. The MTFs were calculated by taking the 2D Fourier transform of the PSFs depicted in Figures 2 and 4.



(a) **(b)**

Figure 6. (a) MTFs of the scanner for the rest-position. **(b)** MTFs of the scanner for the maximum tilt, for three point-like sources.

3.3. System Sensitivity Analysis

System sensitivity was measured with a disk-source of 1 cm diameter. Figure 7 shows relative simulated system sensitivity across the tilt-angles. The sensitivity values are normalized to the value for the rest-position.

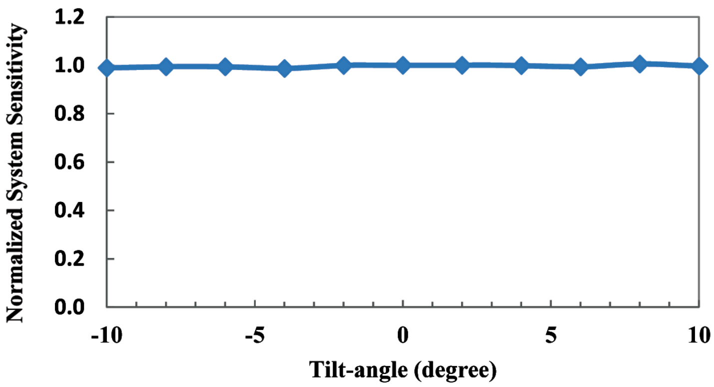


Figure 7. Sensitivity of the system as a function of tilt-angle, the values are normalized to sensitivity for the rest-position.

4. Discussion

In this study, we aimed to evaluate the performance of a gamma-camera under a tilted-condition using an MCNP Monte Carlo simulation by simulating PSFs of three point-like sources at different axial locations, and validating the results by means of comparison with the experimental data.

According to Figure 3, there is a good agreement between the MC simulated and measured PSFs. However, the measured PSFs are slightly noisier along with owing longer tails (Figure 3). Image resolution is about 7.22 mm and 7.43 mm for simulated and measured PSFs, respectively. As can be seen in Figure 4, the source closer to the head, exhibits a narrower PSF along with a higher amplitude. Moving the source toward the other side of the head, results in a broader and lower-amplitude PSF. Figure 4, also manifests a spatially non-uniform resolution across the FOV of the camera for a tilted condition. Spatial resolution at left-side of the head reaches a value of 8.52 mm, and at the same time decreases to 4.22 mm at the opposite side of the head, for maximum tilt (tilt-angle of 10 degrees). Note that because of the symmetric condition, the results are only presented for positive tilt-angles (clockwise rotations) (Figures 4 and 6(b)). It can be concluded from Figure 4 that such a head-tilt introduces translation of the peak-positions of the PSFs from their original locations on the projection image; this may also cause problems in accurate localization of the signal during the tomographic reconstructions as well.

Referring to Figure 5, the greater the tilt-angle, the higher the FWHM variation in the edge of the FOV and thereby the higher the non-uniformity of image resolution, demonstrating a shift-variant scintillation camera. Monotonically increasing the FWHM not only reveals degradation of image resolution, but also introduces a position-dependent spatial resolution, up to a degradation factor of 2.02 in the image for the maximum tilt. As can be seen in Figure 5, regardless of the direction of the head rotation, since the geometry is symmetric, the same value of the factor would be obtained for a corresponding negative tilt-angle. Spatially varying image resolution is more crucial for a more laterally-extended object (for example, whole-body scans) and lower SCD data acquisition. In addition, as can be understood from Figure 4, the contrast of the scintigrams provided by this imaging modality tends to be position-dependent across the image. In other words, a position (on the image) with poorer spatial resolution (in terms of FWHM) manifests a lower contrast as can also be seen in MTFs from Figure 5, and vice versa.

As shown in Figure 6(a), in the case of rest-condition, all PSFs are the same, and consequently, the same frequency behaviors are manifested. For the maximum-tilt condition, the PSFs tend to be different in both FWHM and intensity, resulting in different MTFs. The broader PSF manifests faster decaying behavior and therefore lower contrast at all frequencies, as would be expected (Figure 6(b)).

As plotted in Figure 7, the sensitivity of the system exhibits no significant change over all tilt-angles. Maximum difference of this parameter is about 2% because of statistical fluctuations, since the efficiency of parallel-hole collimators remains, in theory, constant as SCD increases or decreases.

5. Conclusion

In cancer diagnostic, it is more usual to scan whole-body of the patient being imaged, especially in bone scans. Such scintigrams usually require large FOVs, and therefore a head-tilt can cause serious problems. Our findings highlighted that a head tilt can introduce a non-uniform degradation of spatial resolution as well as contrast in the resulted images. As the point source moves away from the center, the spatial resolution becomes increasingly non-uniform.

In summary, a tilt of the head results in a spatially non-uniform image resolution up to a degradation factor of 2.02. In other words, at a tilted-condition, the gamma-camera imaging system becomes non-stationary. According to the results, the head tilt imposes no significant effect on SNR of the image for parallel-hole collimated gamma-cameras.

In this study, we limited our work to a 2D case. The future works of this investigation will be to evaluate tomographic (3D) spatial resolution at a tilted-condition and possible effects of iterative reconstruction algorithms on image quality using a dedicated Monte Carlo toolkit, for example, GATE simulator, for a more accurate MC simulation.

References

[1] E.C. Frey, J.L Humm, and M. Ljungberg, "Accuracy and precision of radioactivity quantification in nuclear medicine images," Seminars in Nuclear Medicine, vol. 42, pp. 208-218, 2012.

[2] A. Rahmim and H. Zaidi, "PET versus SPECT: strengths, limitations and challenges." Nuclear Medicine Communications, vol. 29, pp. 193-207, 2008.

[3] S. Staelens et al., "Monte Carlo simulations of a scintillation camera using GATE: validation and application modeling," Physics in Medicine and Biology, vol. 48, pp. 3021-3042, 2003.

[4] K. Assie et al., "Monte Carlo simulation of PET and SPECT instrumentation using GATE." Nuclear Instruments and Methods in Physics Research A, vol. 527, pp. 180-189, 2004.

[5] M. Mikeli, D. Thanasas, and E. Stiliaris, "Collimator study of a gamma-camera system using GATE," IEEE Nuclear Science Symposium Conference Record, pp. 3931-3935, 2009.

[6] T.E. Peterson and L.R Furenlid, "SPECT detectors: the Anger camera and beyond," Physics in Medicine and Biology, vol. 56, pp. R145-R182, 2011.

[7] NEMA NU-1, Performance evaluation of scintillation camera: National Electrical Manufacturing Association, 2007.

[8] S.C. Moore, K. Kouris, and L. Cullum, "Collimator design for single photon emission tomography," European Journal of Nuclear Medicine, vol. 19, pp. 138-150, 1992.

[9] J.T. Bushberg, J.A Seibert, E.M Leidholdt, and J.M. Boone, The Essential Physics of Medical Imaging, Philadelphia: Williams and Wilkins Press, pp. 686-687, 2002.

[10] System specification, Symbia TruePoint SPECT-CT: Siemens Medical Solution, USA, 2005.

[11] H. Zaidi, "Relevance of accurate Monte Carlo modeling in nuclear medical imaging," Medical Physics, vol. 26, pp. 574-608, 2000.

[12] S.X. Wang and J. Fang, "Symbia Head Position Correction", US Patent, No. US20080315079A1, 2008.

[13] R.A. Powsner, M.R. Palmer, E.R. Powsner. Essential of Nuclear medicine Physics and Instrumentation, New York: John Wiley & Sons, pp. 175-176, 2013.