Optimization of Scatter Correction Method in Samarium-153 Single-photon Emission Computed Tomography using Triple-Energy Window: A Monte Carlo Simulation Study

Abstract

Purpose: In single-photon emission computed tomography imaging, the presence of scatter degrades image quality. The goal of this study is to optimize the main- and sub-energy windows for triple-energy window (TEW) method using Monte Carlo simulations. Materials and Methods: The comparison is based on the Monte Carlo simulation data with the results estimated using TEW method. Siemens Symbia gamma-camera equipped with low-energy high-resolution collimator was simulated for Sm-153 point source located in seven positions in a water cylindrical phantom. Three different main-energy window widths (10%, 15%, and 20%) and three different sub-energy window widths (2, 4, and 6 keV) were evaluated. We compared the true scatter fraction determined by SIMIND and scatter fraction estimated using TEW scatter correction method at each position. In order to evaluate the image quality, we used the full width at half maximum (FWHM) computed on the PSF and image contrast using Jaszczak phantom. Results: The scatter fraction using TEW method is similar to the true scatter fraction for 20% of the main-energy window and 6 keV sub-energy windows. For these windows, the results show that the contrast and resolution were improved. Conclusion: TEW method could be a useful scatter correction method to remove the scatter event in the image for Sm-153 imaging.

Keywords: Monte Carlo, samarium-153, scatter fraction, simulating medical imaging nuclear detectors, single-photon emission computed tomography, triple-energy window

Introduction

In nuclear medicine, samarium-153 (Sm-153) isotope is a potential choice because it emits both medium-energy $\beta$ - particles ($E_{\beta} \max = 0.80 \text{MeV}$) with a short half-life (46.7 h) and gamma-photons suitable for imaging at 103 keV. The physical characteristics of Sm-153 allow to be considered as an excellent radiotherapeutic and diagnostic image agent.\[^1,2\] Previous works\[^2-4\] demonstrated that the isotope chelated to ethylenediaminetetramethylene phosphonate is an effective treatment of bone metastases by the excellent biolocalization. Moreover, Sm-153 is potentially suitable as an alternative to $90Y$ in liver cancer treatment with advantage of gamma-radiation for imaging.\[^5\] Images obtained additionally permit be a rapid diagnostic of the therapeutic isotope. In Sm-153 single-photon emission computed tomography (SPECT) imaging with a gamma-camera, the presence of scatter introduces significant uncertainty in quantification of activity distribution. The scattered and primary photons cannot be determined experimentally. While, with the help of Monte Carlo simulation, it is possible to track the photons originating from the source that ultimately deposits its complete energy inside the crystal. It is increasingly used in nuclear medicine to develop new imaging parameters, scatter correction methods, and reconstruction algorithms. We have used Monte Carlo simulating medical imaging nuclear detectors (SIMIND) to accurately assess the contribution of scattered photons in the photopeak window. The quantification of gamma-camera imaging is improved after the correction of scattered radiation. Previous works\[^6-17\] were used triple-energy window (TEW) scatter correction to

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eliminate the detected scattered counts inside energy window. In order to quantify emission from the isotope Sm-153 using a gamma-camera accurately, however, it is important to correct the scattered photons which degrade image quality. We can reduce the counts of scattered photons in a photopeak energy window using TEW method, which is a simple method to use in clinical study for SPECT imaging. However, there are to date no study of measurements of the scatter fraction of Sm-153 as a function of the energy windows, in order to determine the optimal main- and sub-energy window for Sm-153 SPECT imaging. In this study, we assessed the fraction of scattered photons and determined the optimal main- and sub-energy windows for TEW scatter correction method for Sm-153 by means of Monte Carlo simulation.

**Materials and Methods**

**Detection system description**

In this study, we simulated Siemens Medical System Symbia equipped with low energy high resolution [Table 1]. The images were acquired by a single-head SPECT system (Symbia) based on 103 keV peak. The dimension of detector surface was 59.1 cm × 44.5 cm and having 2.54 cm NaI (Tl) crystal thickness. A water-filled cylinder phantom (diameter: 22 cm, length: 32 cm) was placed at 12 cm from the detector surface. We used the SIMIND Monte Carlo program to acquired data from Sm-153 point sources of 0.05-cm diameter located in different seven positions at the center of the cylinder phantom and offset by ± 5 cm in the X, Y, and Z directions relative to the center. Moreover, the Jaszczak phantom consists of six spheres with different diameters (31.8, 25.4, 15.9, 19.1, 12.7, and 9.5 mm) which are used to evaluate the image contrast. Figure 1 illustrates the SIMIND simulation for each point source.

We collected 50 million photons during the simulation. The images had a 0.34 cm pixel size and 128 × 128 matrix size. Figure 2 shows photon energies and intensities of Sm-153 radionuclide decay.

**Monte Carlo simulation**

The Monte Carlo simulation SIMIND code describes a SPECT camera.[17] The SIMIND program has two main programs: CHANGE, which defines the system parameters, and SIMIND, which executes the simulation. Moreover, using CHANGE program, we can introduce the desired parameters of system. SIMIND accurately simulates all interactions of photons inside the collimator.[18] At the end of simulation, SIMIND provides the value of geometric, penetration, scatter, and X-ray component and image in separate files. We imported binary images created by SIMIND in ImageJ software (Bethesda, Maryland, USA).[19] The validation of the SIMIND program for SPECT imaging has been verified for different gamma-camera according to the previous studies.[20-24]

**Triple-energy window method**

The TEW method estimates the counts of the scattered photons in the main photopeak window from the counts acquired in two sub-windows on both sides of this window. At each pixel in planer image, the counts of scattered photons are subtracted from the total counts in photopeak window to obtain the count of primary photons. If the measured count is not enough, we can enlarge the width of the sub-windows.

In this study, we used the main-energy window widths (10%, 15%, and 20%) centered on 103 keV and sub-energy window widths (2, 4, and 6 keV) [Table 2].

The true scattered photon fractions for the main-energy window calculated by SIMIND were compared with the scattered photon fraction assumed from TEW scatter correction method. The counts of scattered photons and counts of primary photons were calculated by relationships below [14,15]:

\[
C_{scat} = \left(\frac{C_{left}}{W_s} + \frac{C_{right}}{W_s}\right) \times \frac{W_m}{2}
\]

(1)

| Table 1: Collimator specifications |
|-----------------------------------|
| Landmark | LEHR collimator                  |
| Geometric of hole | Hexagonal                        |
| Length of hole (cm) | 5.970                            |
| Septal thickness (cm) | 0.016                            |
| Diameter of hole (cm) | 0.111                            |
| LEHR: Low energy high resolution |

Figure 1: The different point source locations used in the simulating medical imaging nuclear detectors

Figure 2: Energies and intensities of gamma-rays emitted from the samarium-153 sources
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The simulated energy spectrum is shown in Figure 3. The counts acquired in different windows are shown in Table 3.

Table 3: The counts acquired in different windows

| Range (keV)    | Counts |
|---------------|--------|
| 93-113        | 11500  |
| 113-115       | 386    |
| 91-93         | 1270   |
| 113-117       | 656    |
| 89-93         | 2480   |
| 113-119       | 822    |
| 87-93         | 3600   |
| 95-111        | 9660   |
| 111-113       | 544    |
| 93-95         | 1330   |
| 111-115       | 930    |
| 91-95         | 2600   |
| 111-117       | 1200   |
| 89-95         | 3810   |
| 98-108        | 6430   |
| 108-110       | 818    |
| 96-98         | 1400   |
| 108-112       | 1440   |
| 94-98         | 2790   |
| 108-114       | 1900   |
| 92-98         | 4060   |

\[ C_p = C_{\text{left}} - C_{\text{sca}} \]  \hspace{1cm} (2)

where \( C_{\text{left}} \): counts in lower sub-energy window; \( C_{\text{right}} \): counts in upper sub-energy window; \( W_s \): width of sub-energy window; \( W_m \): width of main window; \( C_{\text{tot}} \): counts in main window; \( C_{\text{sca}} \): scatter counts; and \( C_p \): primary counts. The scatter-to-total ratio (scatter fraction) was calculated as Eq. (3):

\[ S / T = \frac{C_{\text{sca}}}{C_{\text{tot}}} \times 100\% \]  \hspace{1cm} (3)

The quality of the Sm-153 SPECT image was quantitatively evaluated using the image contrast assessment. Contrast was calculated by the following formula using Eq. (4):

\[ \text{Contrast} = \frac{M_s - M_b}{M_s M_b} \]  \hspace{1cm} (4)

where \( M_s \) and \( M_b \) are the mean pixel values of the activity of spheres and the activity of background as noise, respectively.

Results

The simulated energy spectrum is shown in Figure 3. The counts acquired in different windows are shown in Table 3.

As shown in Figure 4, it is clear that the geometric component is large and remains constant with increase in photopeak window. Table 4 shows the comparison of true scatter fraction (%) and scatter fraction estimated.
by TEW scatter correction method at each position. The scatter fraction depended on the source position in cylindrical phantom. The results showed that, for 20% of the main-energy window and 6 keV sub-energy window of Sm-153, the scatter fraction estimated by TEW is similar to the true scatter fraction determined by SIMIND.

Figure 5 demonstrates the images for Sm-153 point source at seven positions. The calculated vertical and horizontal full width at half maximum (FWHM) on the images is shown in Table 5. It shows that, for each position, the TEW method is decreasing the FWHM.

Figure 6 shows the reconstructed images of simulated Jaszczak phantom SPECT before and after scatter correction. It noted that the contrast of the six spheres was improved with 20% of the main-energy window and 6 keV sub-energy windows for TEW, as shown in Figure 7. Therefore, 6 keV sub-window with a 20% main-energy was possible energy windows setting for the TEW method in Sm-153.

**Discussion**

A previous study has assessed the TEW method for Sm-153 SPECT data. But until now, no study has compared the fraction of scattered photons of Sm-153 with varying main- and sub-energy windows for the implementation of the TEW method. The scattered photons are a major factor degrade resolution image and image contrast. The resolution is mostly expressed as the FWHM of the Point Spread Function (PSF). A smaller FWHM implies

![Figure 6: The reconstructed images of simulated Jaszczak: (a) without the triple-energy window image, (b) Scatter image, (c) with the triple-energy window image](image-url)

![Figure 7: Calculated contrast of six hot spheres (S1, S2, S3, S4, S5, and S6) with different diameters (31.8, 25.4, 15.9, 19.1, 12.7, and 9.5 mm, respectively) with triple-energy window (using 20% of the main-energy window and 6 keV sub-energy windows) and without triple-energy window](image-url)

**Table 4: Comparison of simulated scatter fraction (%) and scatter fraction estimated using triple-energy window scatter correction method for different main- and sub-windows**

| Window width (%) | Position (x, y, z) | Simulation (Sca/Tot) | TEW (Sca/Tot) | Difference (%) |
|------------------|---------------------|----------------------|---------------|----------------|
|                  |                     | 2 keV | 4 keV | 6 keV | 2 keV | 4 keV | 6 keV |                  |
| 20               | (0, 0, 0)           | 48.80 | 72.00 | 68.00 | 64.00 | 32.22 | 28.24 | 23.75 |
|                  | (−5, 0, 0)          | 49.00 | 70.00 | 66.00 | 62.00 | 30.00 | 25.76 | 20.97 |
|                  | (5, 0, 0)           | 48.00 | 71.00 | 66.00 | 62.00 | 32.39 | 27.27 | 22.58 |
|                  | (0, −5, 0)          | 57.00 | 72.00 | 67.00 | 64.00 | 20.83 | 14.93 | 10.94 |
|                  | (0, 5, 0)           | 37.00 | 68.00 | 63.00 | 59.00 | 45.59 | 41.27 | 37.29 |
|                  | (0, 0, −5)          | 46.00 | 69.00 | 66.00 | 63.00 | 33.33 | 30.30 | 26.98 |
|                  | (0, 0, 5)           | 46.00 | 71.00 | 66.00 | 62.00 | 35.21 | 30.30 | 25.81 |
| 15               | (0, 0, 0)           | 47.00 | 78.00 | 73.00 | 69.00 | 39.74 | 35.62 | 31.88 |
|                  | (−5, 0, 0)          | 46.00 | 77.00 | 72.00 | 68.00 | 40.26 | 36.11 | 32.35 |
|                  | (5, 0, 0)           | 46.00 | 77.00 | 73.00 | 68.00 | 40.26 | 36.99 | 32.35 |
|                  | (0, −5, 0)          | 56.00 | 79.00 | 74.00 | 69.00 | 29.11 | 24.32 | 18.84 |
|                  | (0, 5, 0)           | 35.00 | 75.00 | 70.00 | 65.00 | 53.33 | 50.00 | 46.15 |
|                  | (0, 0, −5)          | 45.00 | 75.00 | 71.00 | 67.00 | 40.00 | 36.62 | 32.84 |
|                  | (0, 0, 5)           | 45.00 | 76.00 | 71.00 | 67.00 | 40.79 | 36.62 | 32.84 |
| 10               | (0, 0, 0)           | 45.00 | 86.00 | 82.00 | 77.00 | 47.67 | 45.12 | 41.56 |
|                  | (−5, 0, 0)          | 44.00 | 86.00 | 82.00 | 78.00 | 48.84 | 46.34 | 43.59 |
|                  | (5, 0, 0)           | 44.00 | 89.00 | 83.00 | 78.00 | 50.56 | 46.99 | 43.59 |
|                  | (0, −5, 0)          | 54.00 | 92.00 | 87.00 | 82.00 | 41.30 | 37.93 | 34.15 |
|                  | (0, 5, 0)           | 33.00 | 86.00 | 81.00 | 76.00 | 61.63 | 59.26 | 56.58 |
|                  | (0, 0, −5)          | 42.00 | 88.00 | 83.00 | 77.00 | 52.27 | 49.40 | 45.45 |
|                  | (0, 0, 5)           | 42.00 | 88.00 | 83.00 | 78.00 | 52.27 | 49.40 | 46.15 |

**TEW**: Triple-energy window
the better quality of the image. The FWHM and contrast were utilized to assess the effect of the processing method on image quality. The choice of optimal energy window in TEW method has a key role which appears the lowest scatter fraction. We have determined the optimal windows that it displays the similar scatter fraction calculated by means of simulation and TEW method. Different scatter fractions were obtained for each source location. There was a smaller difference with 20% main-energy window and 6 keV secondary energy window. By looking at Table 4, it is obvious that the calculated spatial resolution was improved with TEW method. As shown in Figure 5, the 20% main-energy window with 6 keV sub-energy windows produces a better contrast when using the TEW correction. The simplicity of this method makes it feasible in a clinical study. However, the estimation of scattered photons cannot be determined experimentally; with the help of Monte Carlo simulation, accurate assessment of the scattered photon fractions inside photopeak window can be made.

**Conclusion**

In this study, we used the Monte Carlo SIMIND code with TEW scatter correction method to correct the scatter events detected in photopeak window for Sm-153. The results indicate that it is better to use a 20% main photopeak window with 6 keV sub-windows when TEW method is applied.

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**Conflicts of interest**

There are no conflicts of interest.

**References**

1. Yeong CH, Abdullah BJ, Ng KH, Chung LY, Goh KL, Sarji SA, et al. Production and first use of 153SmCl3-ion exchange resin capsule formulation for assessing gastrointestinal motility. Appl Radiat Isot 2012;70:450-5.
2. Iagaru AH, Mittra E, Colletti PM, Jadvar H. Bone-targeted imaging and radionuclide therapy in prostate cancer. J Nucl Med 2016;57:19S-24S.
3. Naseri Z, Jalilian AR, Kharat AN, Bahrami-Samani A, Ghannadi-Maragheh M. Production, quality control and biological evaluation of 153Sm-TTHMP as a possible bone palliation agent. Iran J Nucl Med. 2011;19:60-8.
4. Kathiresan RK, Begum B, Rangarajan. Comparison of Tc-99m MDP and Sm-153 EDTMP bone scan. Indian J Nucl Med 2011;26:163-4.
5. Hashikin NA, Yeong CH, Abdullah BJ, Ng KH, Chung LY, Dahalan R et al. Neutron activated samarium-153 microparticles for transarterial radioembolization of liver tumour with post procedure imaging capabilities. PLoS One 2015;10:e0138106.
6. Lee YS, Kim JS, Kim KM, Lim SM, Kim HJ. Determination of energy windows for the triple energy window scatter correction method in I-131 on a Siemens SYMBIA gamma camera: A GATE simulation study. J Inst 2015;15:10:1-8.
7. Takayama T, Ichihara T, Motomura N, Ogawa K. Determination of energy window width and position for scintigraphic imaging using different energy resolution detection with the “triple energy window (TEW) Scatter Compensation Method IEEE. Kaku Igaku 1998;35:51-9.
8. Changizi V, Takavar A, Babakhani A, Sohrabi M. Scatter correction for heart SPECT images using TEW method. J Appl Clin Med Phys 2008;9:136-40.
9. Dewaraja YK, Li J, Koral K. Quantitative 131I SPECT with triple energy window Compton scatter correction. IEEE Trans Nucl Sci 1998;45:3109-14.
10. Fujioka H, Inoue T, Ishimaru Y, Akamune A, Murase K, Tanada S et al. Compton scatter correction using the triple energy window (TEW) method in conventional single photon emission computed tomography without TEW acquisition hardware. Ka Igaku 1997;34:251-8.
11. Ogawa K. Simulation study of triple-energy-window scatter correction in combined TI-201. Tc-99m SPECT. Ann Nucl Med 1994:8:277-81.
12. Asgari A, Ashoor M, Sohrabpour M, Shokrani P and Rezaei A. Evaluation of various energy windows at different radionuclides for scatter and attenuation correction in nuclear medicine. Ann Nucl Med 2015;29:375-83.
13. Kim KM, Varrone A, Watabe H, Shidahara M, Fujita M, Innis RB, et al. Contribution of scatter and attenuation compensation to SPECT images of nonuniformly distributed brain activities. J Nucl Med 2003;44:512-9.
14. Ogawa K, Harata Y, Ichihara T, Kubo A, Hashimoto S. A practical method for position-dependent Compton-scatter correction in single photon emission CT. IEEE Trans Med Imaging 1991;10:408-12.
15. Bong JK, Son HK, Lee JD, Kim HJ. Improved scatter correction for SPECT images: A Monte Carlo study. IEEE Trans Nucl Sci 2005;52:1263-70.
16. Bouzekaouei Y, Bentayeb F, Asmi H, Bonutti F. Determination of the energy windows for the triple energy window scatter
correction method in gadolinium-159 single photon emission computed tomography using Monte Carlo simulation. Iranian J Med Phys 2019.
17. Ljungberg M. The SIMIND Monte Carlo Program Home Page. Available from: https://www.msf.lu.se/research/the-simind-monte-carlo-program. [Last accessed on 2019 Nov 05].
18. Pandey AK, Sharma SK, Karunanithi S, Kumar P, Bal C, Kumar R. Characterization of parallel-hole collimator using Monte Carlo simulation Indian J Nucl Med 2015;30:128-34.
19. ImageJ Program. Available from: https://imagej.nih.gov/ij/download.html. [Last accessed on 2019 Nov 05].
20. Ejeh JE, van Staden JA, du Raan H. Validation of SIMIND Monte Carlo simulation software for modelling a siemens symbia T SPECT scintillation camera. IFMBE Proceedings 2018;573-6.
21. Toossi BM, Islamian PJ, Momennezhad M, Ljungberg M, Naseri SH. SIMIND Monte Carlo simulation of a single photon emission CT. J Med Phys 2010;35:42-7.
22. Azarm A, Islamian JP, Mahmoudian B, Gharepapagh E. The effect of parallel-hole collimator material on image and functional parameters in SPECT imaging: A SIMIND Monte Carlo study. World J Nucl Med 2015;14:160-4.
23. Vicente EM, Lodge MA, Rowe SP, Wahl RL, Frey EC. Simplifying volumes-of-interest (VOIs) definition in quantitative SPECT: Beyond manual definition of 3D whole-organ VOIs. Med Phys 2017;44:1707-17.
24. Rafati M, Rouhani H, Bitarafan-Rajabi A, Noori-Asl M, et al. Assessment of the scatter correction procedures in single photon emission computed tomography imaging using simulation and clinical study. J Cancer Res Ther 2017;13:936-942.
25. ALehyani SH. Application of single photon emission computed tomography (SPECT) parameters for bone scintigraphy. J King Saud Univ – Sci 2009;21:109-17.
26. Asl MN, Sadremontzar A, Bitarafan-Rajabi A. Evaluation of six scatter correction methods based on spectral analysis in (99m) Tc SPECT imaging using SIMIND Monte Carlo simulation J Med Phys 2013;38:189-97.
27. Dewaraja YK. Ljungberg M and Koral KF. Characterization of scatter and penetration using Monte Carlo simulation in 131I imaging. J Nucl Med 2000;41:123-30.