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 SImulating Medical Imaging Nuclear Detectors (SIMIND) code for samarium-153 (Sm-153) imaging. **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 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 resolution and contrast 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*

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Introduction

In nuclear medicine, samarium-153 (Sm-153) isotope is a potential choice because it emits both medium-energy β - *particles* (E_β max = 0.80MeV) 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 ethylenediamine tetramethylene 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 signifcant uncertainty in quantifcation 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.

Table 1: Collimator specifications

	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

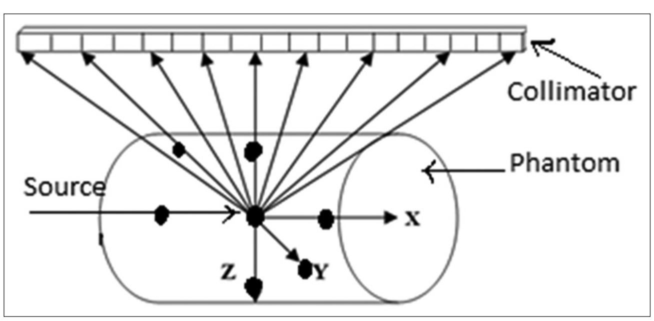

Figure 1: The different point source locations used in the simulating medical imaging nuclear detectors

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]:

$$C_{sca} = \left(\frac{C_{left}}{W_s} + \frac{C_{right}}{W_s}\right) \times \frac{W_m}{2} \quad (1)$$

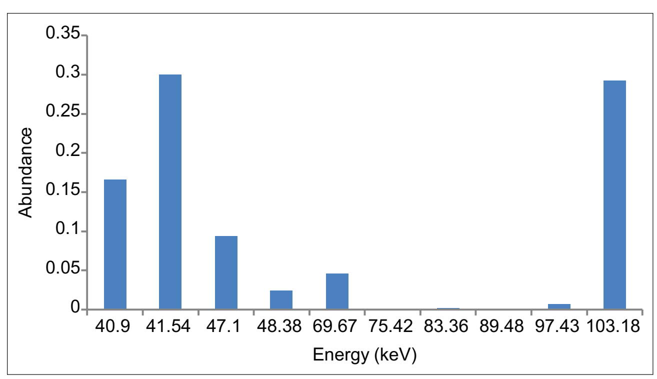

Figure 2: Energies and intensities of gamma-rays emitted from the samarium-153 sources

Table 2: Photopeak windows and sub-windows used in the simulation

Photopeak windows Sub-windows	20% (93-113 keV)	15% (95-111 keV)	10% (98-108 keV)
2 keV	91-93 and 113-115 keV	93-95 and 111-113 keV	96-98 and 108-110 keV
4 keV	89-93 and 113-117 keV	91-95 and 111-115 keV	94-98 and 108-112 keV
6 keV	87-93 and 113-119 keV	89-95 and 111-117 keV	92-98 and 108-114 keV

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

$$C_P = C_{tot} - C_{sca} \quad (2)$$

where C_{left}: counts in lower sub-energy window; C_{right}: counts in upper sub-energy window; Ws: width of sub-energy window; Wm: width of main window; C_{tot}: counts in main window; C_{sca}: scatter counts; and C_p: primary counts. The scatter-to-total ratio (scatter fraction) was calculated as Eq. (3):[6]

$$S/T = \frac{C_{sca}}{C_{tot}} \times 100\% \quad (3)$$

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):

$$Contrast = \frac{M_s - M_b}{M_{s+}M_b} \quad (4)$$

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.

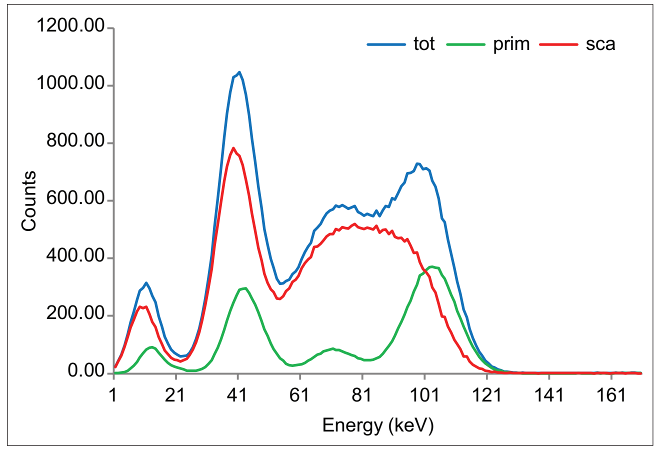

Figure 3: The simulated photon spectrum emitted by the samarium-153

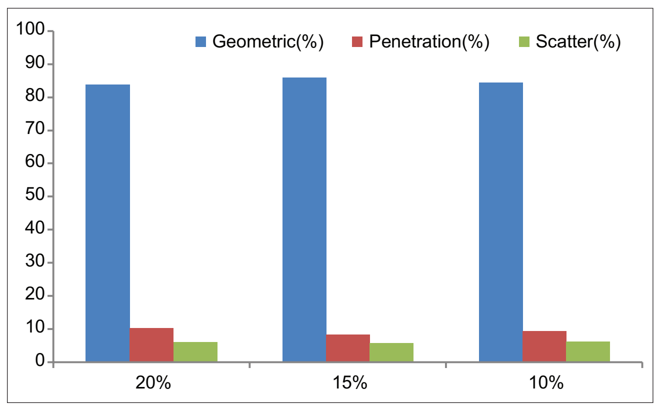

Figure 4: The variation of geometric, penetration, and scatter component with energy window widths

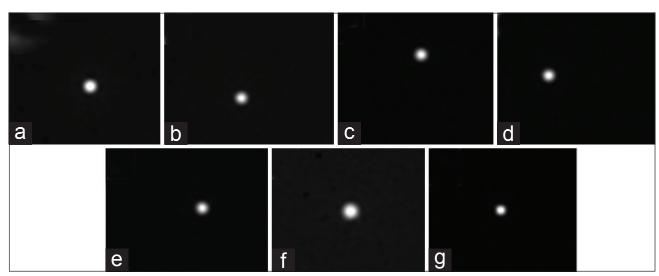

Figure 5: Images for Sm-153 point source at each position in water cylindrical phantom (a) center of water. (b) Point source offset from center to X-axis (−5 cm). (c) Point source offset from center to X-axis (+5 cm). (d) Point source offset from center to Y-axis (−5 cm). (e) Point source offset from center to Y-axis (+5 cm). (f) Point source offset from center to Z-axis (−5 cm). (g) Point source offset from center to Z-axis (+5 cm)

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.

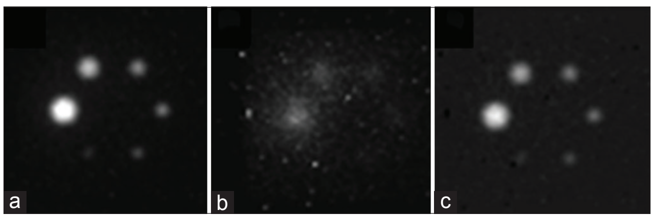

Figure 6: The reconstructed images of simulated Jaszczak: (a) without the triple-energy window image, (b) Scatter image, (c) with the triple-energy window image

Discussion

A previous study[12] 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.[25-27] The resolution is mostly expressed as the FWHM of the Point Spread Function (PSF). A smaller FWHM implies

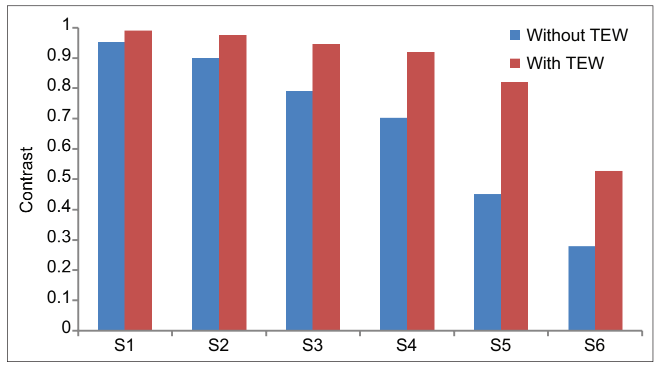

Figure 7: Calculated contrast of six hot spheres (S_1, S_2, S_3, S_4, S_5, and S_6) with different diameters (31.8, 25.4, 15.9, 19.1, 12.7, and 9.5 mm, respectively) with triple-energy window (using 20% of the main-energy window and 6 keV sub-energy windows) and without triple-energy window

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

Table 5: Full width at half maximum of the point source images of Figure 3

Source position (x, y, z)	Without TEW		With TEW	
	X FWHM (mm)	Y FWHM(mm)	X FWHM (mm)	Y FWHM (mm)
(0, 0, 0)	9.73	9.51	7.47	7.47
(−5, 0, 0)	9.65	9.42	7.95	7.24
(5, 0, 0)	9.62	9.51	7.08	7.21
(0, −5, 0)	9.47	9.29	7.00	7.24
(0, 5, 0)	9.60	9.29	7.52	7.79
(0, 0, −5)	12.19	11.98	8.90	8.52
(0, 0, 5)	7.68	7.46	6.67	5.10

FWHM: Full width at half maximum, TEW: Triple-energy window, FWHM: Full width at half maximum

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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Nil.

Conflicts of interest

There are no conflicts of interest.

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