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Effect of detector parameters on the image quality of Compton camera for ^{99m}Tc

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Abstract

The Compton camera has a bright future as a medical imaging device considering its compactness, low patient dose, multiple-radioisotope tracing capability, inherent three dimensional (3D) imaging capability at a fixed position, etc. Currently, however, the image resolution of the Compton camera is not sufficient for medical imaging. In this study, we investigated the influence of various detector parameters on the image quality of the Compton camera for ^{99m}Tc with GEANT4. Our result shows that the segmentation of the detectors significantly affects the image resolution of the Compton camera. The energy discrimination of the detectors was found to significantly affect both the sensitivity and spatial resolution. The use of a higher energy gamma source (e.g., ^{18}F emitting 511 keV photons), however, will significantly improve the spatial resolution of the Compton camera. It will also minimize the effect of the detector energy resolution.

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Keywords: Compton camera; Medical imaging; Detector simulation; Monte carlo; GEANT4; Image resolution

1. Introduction

The Compton camera is a very promising medical imaging device when we consider its compactness (i.e., table-top size), low patient dose, multiple radioisotope tracing capability, inherent 3D imaging capability at a fixed position, etc. The application of the Compton camera to medical imaging has been studied by many researchers since 1970s [1–4]. Currently, however, the resolution of the Compton camera is not sufficient for medical imaging applications, which require ~5 mm (= FWHM) resolution. This study investigates the effect of various parameters of the Compton camera on the image quality (resolution and sensitivity) for ^{99m}Tc, which is the most popular radioisotope in nuclear medicine [5]. The Compton camera was simulated with the Monte Carlo particle transport simulation toolkit, GEANT4 [6].

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2. Methods

The Compton camera (Fig. 1) is composed of two plane-type position-sensitive detectors: a double-sided silicon strip detector (DSSD, $5 \times 5 \times 0.15\,cm^3$) as scatterer and a 25-segmented germanium detector (25-SEGD, $5 \times 5 \times 2\,cm^3$) as absorber. The distance between the scatterer and absorber is 5 cm. The Compton camera was modeled by the GEANT4 simulation toolkit considering various detector parameters. Fig. 2 shows the Compton camera as simulated with GEANT4.

This study investigated the effect of various detector parameters such as Doppler energy broadening, detector energy resolution, detector (electrode) segmentation, and energy discrimination by Monte Carlo simulation. The Penelope physics model was used in GEANT4 to accurately model the Compton scattering including atomic-binding effect and Doppler energy broadening. The energy resolution of the scatterer and absorber was simulated based on the measured data, assuming Gaussian

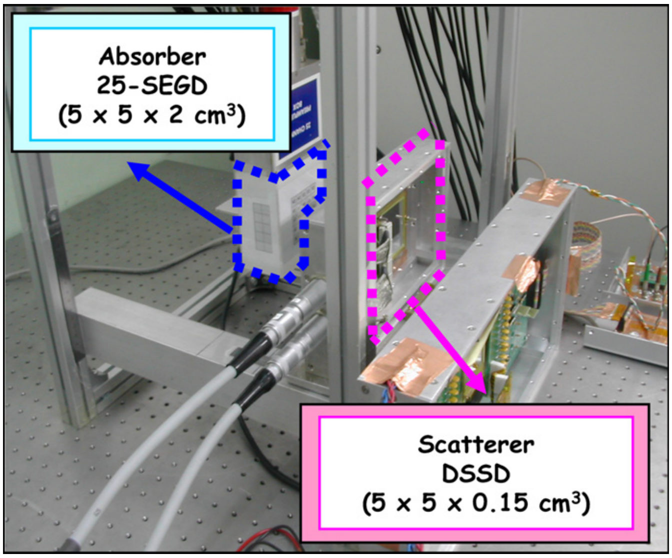

Fig. 1. The Compton camera is considered in this study. The Compton camera is composed of a double-sided strip silicon detector (DSSD, $5 \times 5 \times 0.15\,\mathrm{cm}^3$) and a 25-segmented germanium detector (25-SEGD, $5 \times 5 \times 2\,\mathrm{cm}^3$).

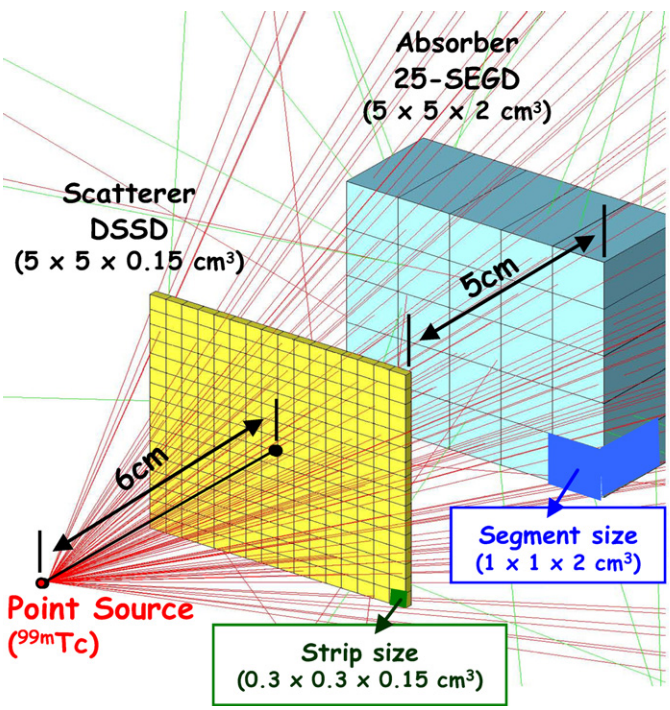

Fig. 2. GEANT4 simulation of the Compton camera.

distribution of the full-energy peak in the energy spectrum. The discrimination levels, which are applied to discriminate the electronic noise signals, were simulated at 20 and 10 keV for the scatterer and absorber, respectively. Detector segmentation (16×16 strips in the scatterer and 5×5 segments in the absorber) was modeled by using the 'G4PVReplica' class in the GEANT4 toolkit [7].

The time, position, and energy of an interaction event are obtained by the 'G4VSteppingVerbose' class in GEANT4. Time and energy information is used to simulate the coincidence counting and energy gating (140 ± 10 keV), respectively. The effective events, which satisfy the coincidence and energy gating, are applied to the simple backprojection algorithm to reconstruct the Compton camera image [8]. The interaction positions and deposited energies in the scatterer and absorber determine the position of the original photon within a conical ambiguity [9].

3. Results and discussion

The simulation model of the Compton camera was first verified by comparing the simulation results with those from the MCNPX model. There was a good agreement between the results from the GEANT4 and MCNPX models; both models showed the image resolution of 0.375 mm (= FWHM) for the ideal detector case for the ^{99m}Tc point source at 6 cm from the scatterer. The simulated sensitivity of the Compton camera was also very reasonable when compared with the MCNPX result.

Fig. 3 shows the two dimensional (2D) images of the Compton camera for the ^{99m}Tc point source for the equal number of effective events (= 10,000). The ^{99m}Tc point source is located at 6 cm from the scatterer. In this study, the 'ideal' detector is defined as a detector, which can determine the interaction location and deposit energy of an interaction very accurately (i.e., without any uncertainty). For the ideal detector, the image resolution of the Compton camera was very high, i.e., FWHM = 0.375 mm (case (a) in Fig. 3). The sensitivity of the Compton camera was also very high ($\sim 1.43 \times 10^{-4}$).

The Doppler energy broadening significantly affected the image resolution of the Compton camera (FWHM = 7.99 mm, case (b)). This effect, however, will be negligible for high-energy photon sources (e.g., a few hundred keV or more). The image resolution was significantly affected by the energy resolution of the Compton camera (FWHM = 8.74 mm, case (c)). The image resolution was seriously deteriorated by the segmentation of the detector (FWHM = 16.5 mm, case (d)). To improve the resolution of the Compton camera, the absorber should be replaced with a more sophisticated detector such as a double-sided strip germanium detector (DSGD) or a stack of double-sided strip silicon detectors (DSSD). The overall image resolution, considering the above three parameters (Doppler energy broadening, detector energy resolution, and detector segmentation), was 20.3 mm (= FWHM, case (e)).

Finally, as we included the energy discrimination of the scatterer and absorber in the simulation, the resolution of the Compton camera became very poor (FWHM = 36.4 mm, case (f)). This is mainly due to the fact that the small ellipses at the imaging plane, which are generated when the deposit energy in the scatterer is small, are

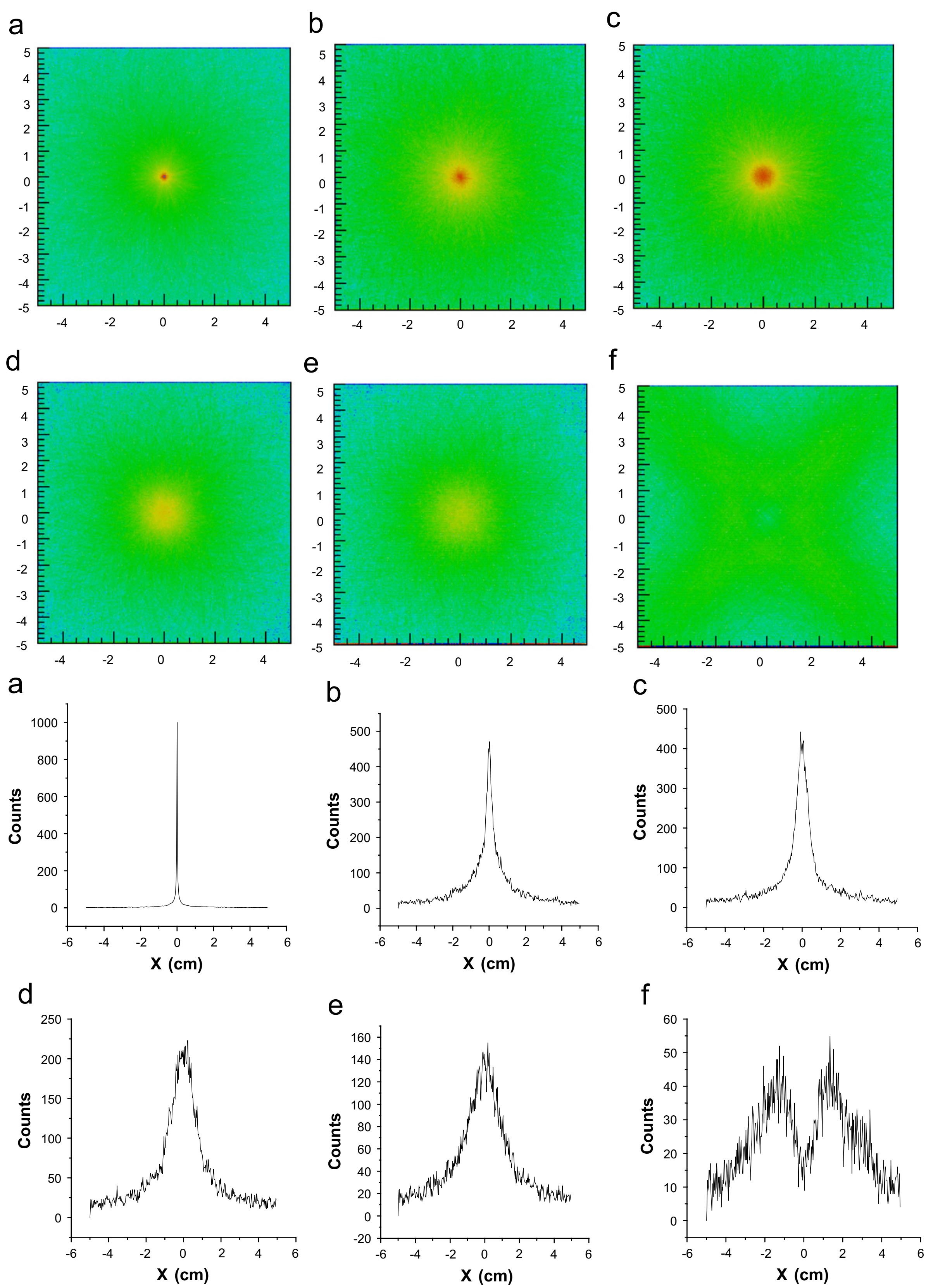

Fig. 3. The 2D simulated images from the Compton camera for ^{99m}Tc point source at 6 cm: (a) ideal detector, (b) detector with Doppler energy broadening, (c) detector with energy resolution, (d) detector with electrode segmentation, (e) combination of (a)–(d), and (f) Combination of (a)–(d) and detector energy discrimination. The plots are generated for the equal number of effective events (= 10,000).

rejected by the energy discrimination of the scatterer. The sensitivity is also significantly affected by the energy discrimination (~1/100). This is due to the fact that the deposited energy in the scatterer is very small (<30 keV) for most cases. This problem will be negligible for a high-energy gamma source (e.g., ^{18}F emitting 511 keV annihilation photons).

4. Conclusion

Monte Carlo simulations were performed with the GEANT4 simulation toolkit to investigate the effect of various detector parameters on the image quality of the Compton camera. The result shows that the image resolution of the Compton camera is very poor (= 36.4 mm FWHM) for ^{99m}Tc, which emits very low-energy photons (= 140 keV). The Doppler energy broadening significantly affects the image resolution of the Compton camera. The energy discrimination of the detectors was found to significantly affect both the sensitivity and image resolution. The use of a higher energy gamma source such as ^{18}F emitting 511 keV annihilation photons, however, will significantly improve the image resolution of the Compton camera, nearly eliminating the effect of the energy discrimination and Doppler energy broadening. The use of a high-energy photon source will also reduce the effect of the energy resolution of the detectors. The segmentation of the detectors (especially, the 25-SEGD absorber) significantly affects the image resolution of the Compton camera. The segmentation of the absorber should be reduced down to a few mm or less in order to achieve the image resolution of 5 mm, which is required in medical imaging. In conclusion, we believe the achievement of a 5 mm resolution Compton camera is possible by selecting a high-energy photon source such as ^{18}F and carefully optimizing the above parameters.

Acknowledgments

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References

[1] R.W. Todd, J.M. Nightingale, D.B. Everett, Nature 251 (1974) 132.
[2] Manbir Singh, Med. Phys. 10 (4) (1983).
[3] J.W. LeBlanc, N.H. Clinthorne, C. Hua, et al., IEEE Trans. Nucl. Sci. NS-45 (1998) 943.
[4] Y.F. Yang, Y. Gono, S. Motomura, S. Enomoto, Y. Yano, IEEE Trans. Nucl. Sci. NS-48 (2001) 656.
[5] Andreh Studen, Compton camera with position-sensitive silicon detectors, Ph.D. Dissertation, University of Ljubljana, 2005.
[6] S. Agostinelli, et al., Nucl. Instr. and Meth. A 506 (2003) 250.
[7] GEANT4 Collaboration, Physics Reference Manual [Online], available at http://wwwasd.web.cern.ch/wwwasd/geant4/geant4.html.
[8] J.H. Lee, Applications of position-sensitive semiconductor detectors: Compton polarimeter and Compton camera, Ph.D. Dissertation, Chung-Ang University, 2004.
[9] Chia-ho Hua, Compton imaging system development and performance assessment, Ph.D. Dissertation, University of Michigan, 2000.