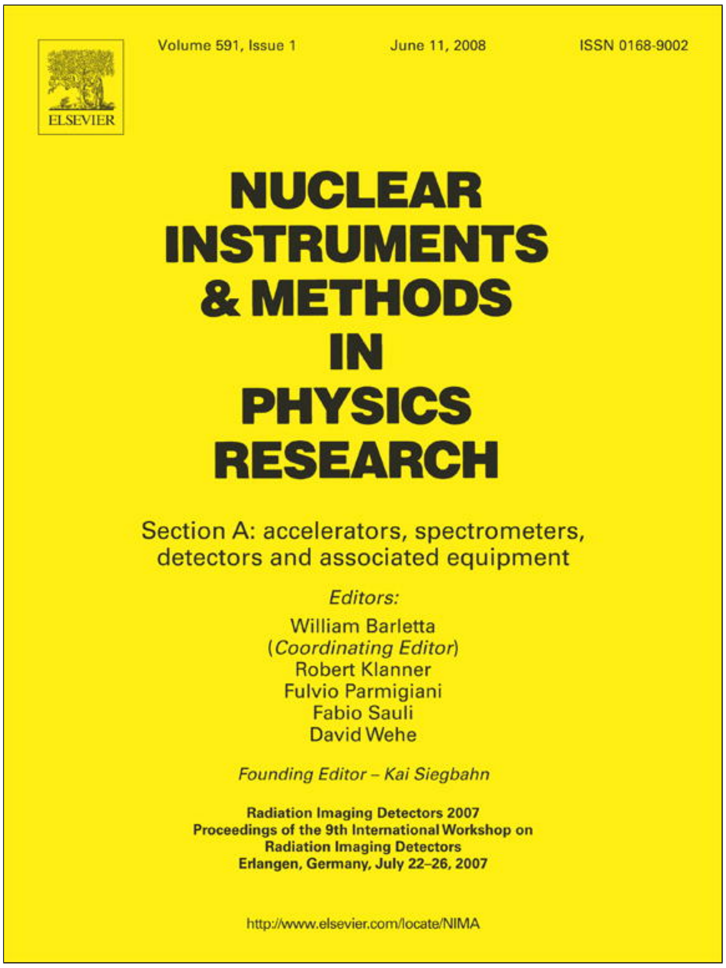

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Performance evaluation of a table-top Compton camera for various detector parameters

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Abstract

A prototype table-top Compton camera, composed of two small plane-type position-sensitive semiconductor detectors, is under development. The objective of this study was to find the optimal imaging conditions for the Compton camera in order to maximize its performance in terms of imaging resolution and imaging sensitivity. To that end, the performance of the Compton camera was simulated varying several detector parameters (i.e., the photon energy of the source, the geometrical configuration of the component detectors, and the interaction position resolution of the absorber detector), using the GEANT4 detector simulation toolkit. The Compton camera was found to show its highest performance for the photon energy of 364.5 keV (^{131}I), but also showed a relatively high performance for 511 keV (^{18}F) and 662 keV (^{137}Cs). The Compton camera showed its highest performance also when the scatterer and absorber detectors were positioned in parallel, separated by 10 cm. Finally, it was found significantly beneficial to the imaging resolution to increase the interaction position resolution of the absorber detector to $0.3 \times 0.3\,\text{cm}^2$ in the planar direction and to 0.5 cm in the axial direction.

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Keywords: Compton camera; Medical imaging; Position-sensitive detector; Monte Carlo; GEANT4

1. Introduction

The Compton camera is a very promising gamma-ray imaging device, especially in the field of nuclear medicine and molecular imaging [1–4]. The Compton camera has many advantages over conventional gamma-ray imaging devices, these advantages include 3D imaging capability from a fixed position, almost no limitation on the photon energy of the gamma sources, simultaneous multiple radioisotope tracing capability, and, in principle, high imaging resolution and sensitivity. Currently under development is a table-top Compton camera composed of small plane-type position-sensitive semiconductor detectors. The current version of the Compton camera, however, does not show sufficient imaging resolution and sensitivity for medical imaging applications. The objective of the present study was to find the optimal imaging conditions for the table-top Compton camera in order to maximize its performance in terms of imaging resolution and imaging sensitivity. To that end, different imaging conditions were simulated using the GEANT4 detector simulation toolkit [5].

2. Methods

The table-top Compton camera is composed of two plane-type position-sensitive semiconductor detectors: a double-sided silicon strip detector (DSSD, $5 \times 5 \times 0.15\,\text{cm}^3$, 16×16 strips) as the scatterer detector and a 25-segmented germanium detector (25-SEGD, $5 \times 5 \times 2\,\text{cm}^3$, 5×5 segments) as the absorber detector (Fig. 1) [6]. The Compton camera was simulated with the GEANT4 detector simulation toolkit. In the simulation,

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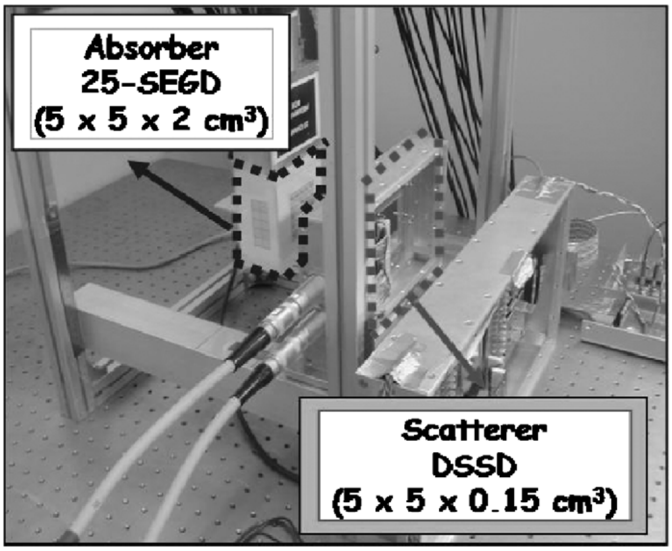

Fig. 1. Table-top Compton camera.

the energy resolution assumed 4 keV on scatterer detector and 1–2 keV on absorber detector depending on the deposited energy of the photon in the absorber detector, interaction position resolution, and energy discrimination levels of the component detectors were all modeled. Doppler energy broadening was included by implementing the Penelope physics model. To reduce computation time, the 'exponential transform' technique, which artificially increases the interaction probability of an incident photon in the scatterer detector, was implemented.

In this study, the performance of the table-top Compton camera was determined as a function of the photon energy of the source and the geometrical configuration of the component detectors. The performance of the Compton camera for the photon energies of 140, 364.5, 511, 662, and 1332 keV, which represent ^{99m}Tc, ^{131}I, ^{18}F, ^{137}Cs, and ^{60}Co, respectively, was calculated. The considered geometrical configuration variables of the component detectors were the inter-detector distances (IDDs) of 3, 6, 10, 15, and 20 cm and inter-detector angles (IDAs) of 0°, 30°, 45°, 60° and 90°. Considering that the imaging resolution is limited mainly by poor interaction position resolution of the absorber detector [7], the Compton camera's imaging resolution was evaluated also as a function of the interaction position resolution of the absorber detector.

3. Results and discussion

Fig. 2 shows the imaging sensitivity, imaging resolution, and figure-of-merit (FOM) [2] of the table-top Compton camera as a function of the photon energy of the source. The simulated photon source was a point source located 6 cm in front of the camera. The imaging sensitivity of the Compton camera is the maximum for the photon energy of 364.5 keV. For 140 keV, the imaging sensitivity is very low, mainly because most of the photon energies deposited in the scatterer detector are very small and thus easily discriminated by the energy discrimination level of the scatterer detector (20 keV). Above 364.5 keV, the imaging sensitivity decreases as the photon energy increases, due simply to the decline of the interaction probability for higher-energy photons. Fig. 2 also shows that the imaging resolution of the Compton camera does not significantly improve for photon energies greater than 364.5 keV, mainly because the effect of Doppler energy broadening is significant only when the photon energy is very small [8]. The slight increase of the imaging resolution over 364.5 keV seems related to the energy resolution characteristics of the component detectors. Overall, the table-top Compton camera shows its highest performance (highest FOM) for the photon energy of 364.5 keV, but also shows relatively high performances for 511 and 662 keV.

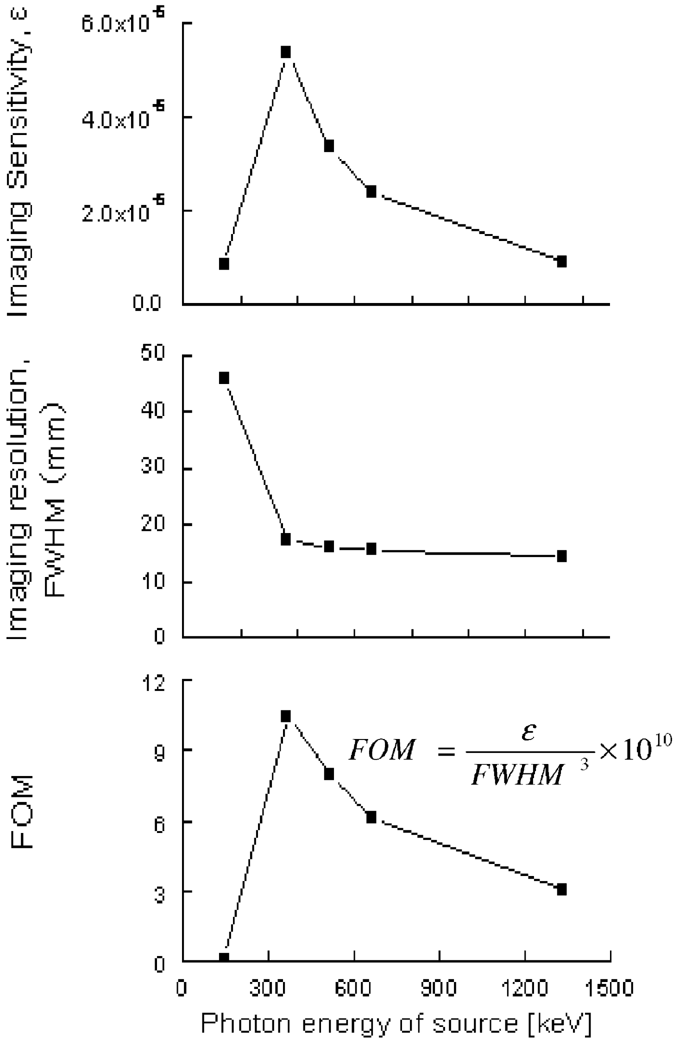

Fig. 2. Variation of the imaging sensitivity, imaging resolution, and figure-of-merit (FOM) of table-top Compton camera as a function of photon energy of source.

Fig. 3 shows the performance of the table-top Compton camera as functions of the IDD and IDA for an ^{18}F point source 6 cm in front of the Compton camera. With increasing IDD, the effect of the interaction position resolution of the component detectors on the imaging

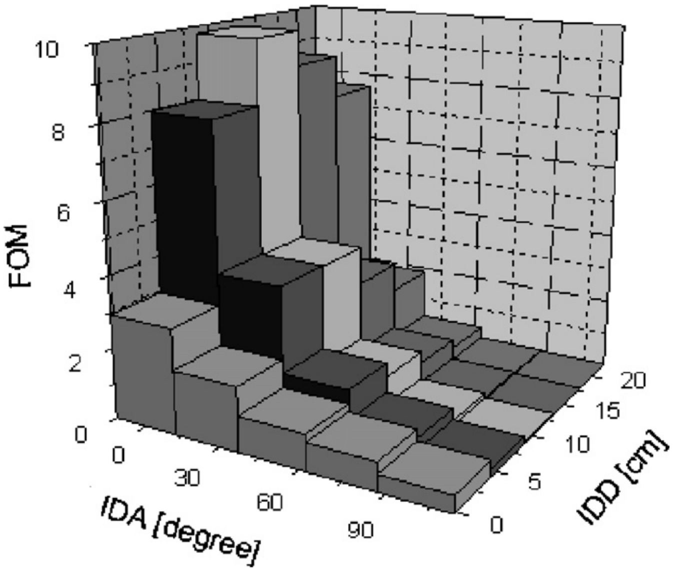

Fig. 3. Performance (i.e., figure-of-merit, FOM) of table-top Compton camera as functions of inter-detector distance (IDD) and inter-detector angle (IDA).

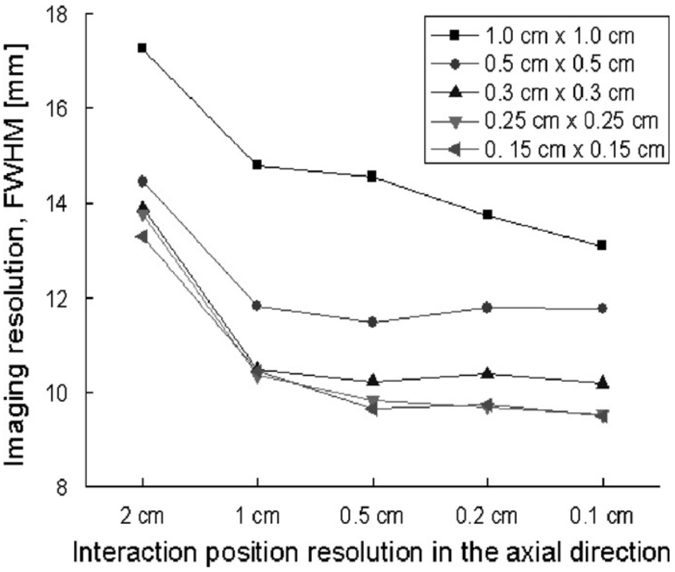

Fig. 4. Variation of imaging resolution of table-top Compton camera as a function of interaction position resolution of absorber detector.

resolution decreases, resulting in improved imaging resolution. On the other hand, the imaging sensitivity decreases with increasing IDD, because the covered solid angle decreases. The highest performance (highest FOM) in the cases considered in this study was found when the IDD was 10 cm. The result also indicates that the table-top Compton camera shows its highest performance when the IDA is 0° for all of the IDDs considered in this study. This is mainly because (1) the imaging sensitivity of the Compton camera decreases with increasing IDA as a result of the annihilation photons from the ^{18}F source, which is positron emitter, having a relatively high quantum energy (511 keV)

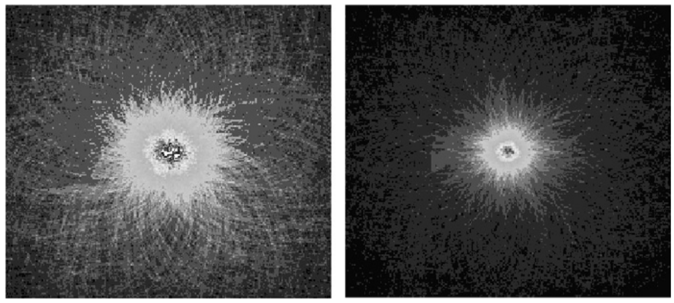

Fig. 5. Reconstructed images from table-top Compton camera. Left: Current system with position interaction resolution of absorber detector $= 1 \times 1\,\text{cm}^2$ (planar direction) and 2 cm (axial direction). Right: A system with position interaction resolution of absorber detector $= 0.3 \times 0.3\,\text{cm}^2$ (planar direction) and 0.5 cm (axial direction).

and thus tending to scatter in the forward direction, and (2) the scattering angle uncertainty increases with increasing IDA according to the kinematics relationships of Compton scattering. In summary, the Compton camera shows its highest performance when the scatterer and absorber detectors are positioned in parallel, separated by 10 cm.

Fig. 4 shows the variation of the imaging resolution as a function of the interaction position resolution of the absorber detector for an ^{18}F point source 6 cm in front of the Compton camera. The interaction position resolution of the current absorber detector is $1 \times 1\,\text{cm}^2$ in the planar direction and 2 cm in the axial direction. The result shows that it is significantly beneficial to the imaging resolution of the Compton camera to increase the interaction position resolution to $0.3 \times 0.3\,\text{cm}^2$ in the planar direction and to 0.5 cm in the axial direction: thereby, the imaging resolution is enhanced from 17.2 to 10.2 mm FWHM (Fig. 5).

4. Conclusions

The performance of the table-top Compton camera was evaluated as a function of various detector parameters in order to find the optimal imaging conditions. The Compton camera showed its highest performance for the photon energy of 364.5 keV (^{131}I), but also showed a relatively high performance for 511 keV (^{18}F) and 662 keV (^{137}Cs). The Compton camera showed its highest performance when the scatterer and absorber detectors are positioned in parallel and separated by 10 cm. It was found significantly beneficial to the imaging resolution of the Compton camera to increase the interaction position resolution to $0.3 \times 0.3\,\text{cm}^2$ in the planar direction and to 0.5 cm in the axial direction: thereby, the imaging resolution was enhanced from 17.2 to 10.2 mm FWHM. This resolution is not very high, but will be appreciably enhanced by employing the expectation-maximization (EM) algorithm, currently under development for the table-top Compton camera.

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