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Performance Comparison of Imaging Modality of Hybrid Gamma Imaging System Using Monte Carlo Simulation

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1. Introduction

A hybrid gamma imaging system is a device to detect the distribution of radioactive material which emits gamma ray. The system achieves high sensitivity and high imaging resolution on broad energy range of gamma ray, by combining mechanical collimation from coded aperture imaging and electronic collimation from Compton imaging. Considering the circumstances that gamma imaging is required, such as nuclear facility decommissioning or radioactive accident, the broad dynamic range of the system is a big advantage since such sites contain numerous isotopes emitting gamma ray with various energy.

The hybrid gamma imaging system usually utilizes different imaging method according to the energy of the incident gamma ray. On high or low energy range, either Compton imaging or coded aperture imaging is used since a photon with such energy tends to make an effective event on either collimation method. On the other hand, on the intermediate energy range, the hybrid imaging is used because high sensitivity and high resolution can be achieved by utilizing the events from both collimation methods. The energy range that hybrid imaging has the merit may depend on a geometry of the imaging system.

We are developing a large area hybrid gamma imaging system featuring maximized sensitivity, based on large scintillation detectors. On a large scale system, the energy ranges suitable for each collimation methods may differ from those of other existing small systems. Hence, in this research, the energy ranges for each imaging modalities of the large area hybrid gamma imaging system are determined by comparing imaging performances of three imaging methods using Monte Carlo simulation.

2. Materials and Methods

2.1 System Configuration

The geometry of the large area hybrid gamma imaging system was designed based on our previous researches on the optimization of large area Compton camera [1] and large area coded aperture gamma imaging system [2]. The system is composed of two large monolithic scintillation detector modules [3] and a coded aperture mask.

The first detector head is composed of a monolithic NaI(Tl) crystal with a size of 27 cm (W) × 27 cm (H) × 2 cm (T), coupled with 6 × 6 photomultiplier tubes (PMTs) array. The second detector head is similar to the first detector except that the thickness of the crystal is 3 cm. The coded aperture mask is a tungsten collimator with a size of 27 cm (W) × 27 cm (H) × 0.6 cm (T). On the collimator, holes are arranged in accordance with a modified uniformly redundant array (MURA) pattern. The pattern is composed of a 37 × 37 array, which is a 2 × 2 mosaic of a MURA pattern with rank 19. The mask is placed 6 cm apart from the surface of the first detector. The distance between the first detector and the second detector is 25 cm.

2.2 Monte Carlo Simulation

Geant4 (version 10.03.p03) was used for simulation of the hybrid imaging system. The properties of each detector such as energy resolution and spatial resolution were experimentally measured and were applied in the simulation. A background radiation field was also considered by using the background model from our previous research.

A virtual point source with an activity of 10 µCi was placed at 1 m apart from the front surface of the first detector. In order to assess a relation between gamma ray energy and the performances of the imaging methods, 13 cases with different gamma ray energy were simulated: 50, 100, 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, and 2000 keV. For each case, a measurement for 1 minute was repeatedly simulated for 10 times for statistical analysis.

2.3 Image Reconstruction and Assessment

The data from the simulation result were processed with an in-house program on MATLAB (R2018b). The recorded events were sorted and reconstructed in accordance with 3 imaging methods. For the coded aperture imaging, only events that a gamma ray was fully absorbed in the first detector were selected as effective events. For the Compton imaging, coincidence events that a gamma ray interacted with both detectors were selected. The effective events for the coded aperture imaging and the Compton imaging were combined and utilized to the hybrid imaging. The image reconstruction was conducted using a maximum likelihood expectation maximization (MLEM) algorithm for each imaging modality.

The images from different imaging modalities were evaluated and compared using resolution-variance analysis [4]. The resolution-variance analysis is a method to account for a trade-off relation of resolution and noise of the image. The resolution and the variance of the images were calculated for each EM iteration, then plotted as curves. For the resolution-variance analysis, a full width half maximum (FWHM) was used for the resolution term, and standard deviation of the maximum intensity values of 10 images was used for the variance term.

3. Results and Discussion

3.1 Visual Inspection

The performance of the imaging methods was first inspected visually. The images from the simulation of 800 keV gamma ray are displayed in Fig. 1 as the MLEM iteration numbers and the imaging method: the rows correspond to the iteration number of 1, 10 and 100, and the columns correspond to the coded aperture imaging, the Compton imaging, and the hybrid imaging, respectively. The Compton image converged quickly, as shown in Fig 1-(e), but it showed a noisy background on high iteration number (Fig. 1-(h)). On the other hand, less background noise was observed in the coded aperture image and the hybrid image even after many iterations.

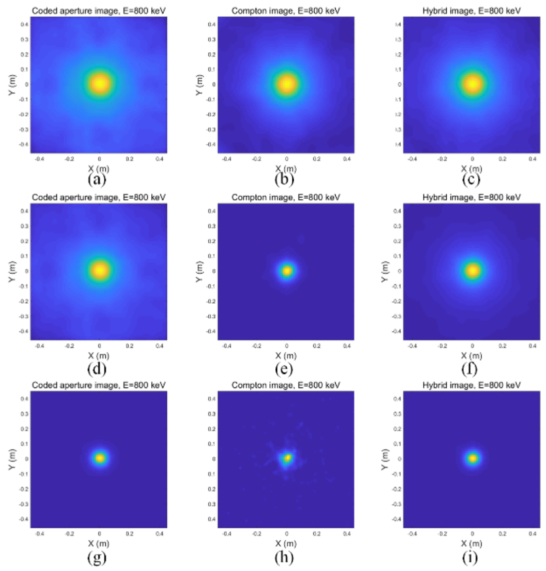

Fig. 1. Reconstructed images of 800 keV gamma ray point source: after 1, 10, and 100 MLEM iterations (top row to bottom row) for coded aperture imaging, Compton imaging, and hybrid imaging (left column to right column)

3.2 Resolution-variance Analysis

The resolution and the variance are on a trade-off relation in the EM image reconstruction. The resolution-variance analysis was conducted to account for such a relation. Considering a plot of resolution versus variance, a method of which curve is close to the origin has better performance.

The resolution-variance curves of some cases are displayed in Fig. 2 and Fig. 3. On the energy range lower than 200 keV, a photon tends to be absorbed in the first detector, rather than to be scattered and to reach the second detector. Thus, on this energy range, the effective event for the Compton imaging occurred so rarely to reconstruct an image. When the energy of a photon was in the range of 400 – 600 keV, it was possible to acquire the Compton images, but the resolution and the noise were worse than those of the coded aperture imaging and the hybrid imaging, which showed similar performance, as shown in Fig. 2.

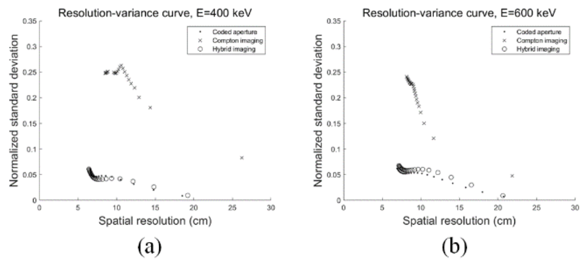

Fig. 2. Comparison of the resolution-variance curve from three imaging modalities at lower energies: (a) 400 keV, (b) 600 keV.

When the energy of the gamma ray was increased above 1000 keV, as shown in fig. 3, the performance of the coded aperture imaging worsened, while those of Compton imaging and hybrid imaging improved. The hybrid imaging was beneficial to other methods on the energy range of 1000 – 1800 keV. When the energy of the gamma ray was 2000 keV or higher, the Compton imaging showed better performance than the others.

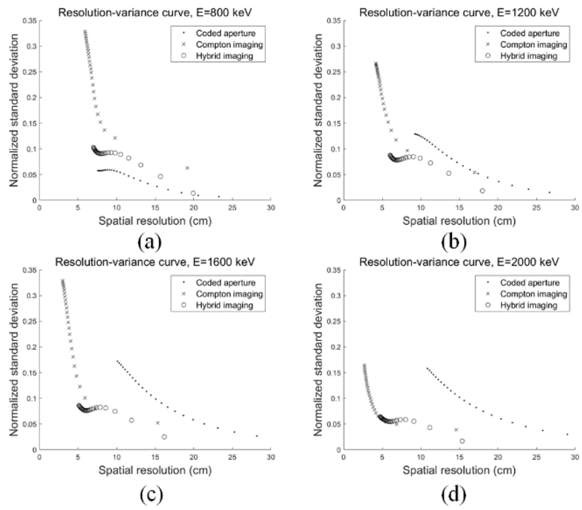

Fig. 3. Comparison of the resolution-variance curve from three imaging modalities at several gamma energies. (a) 800 keV, (b) 1200 keV, (c) 1600 keV, and (d) 2000 keV.

4. Conclusion

We compared the performance of three imaging methods of the large area hybrid gamma imaging system on various gamma energy with Monte Carlo simulation. The coded aperture imaging was appropriate for lower energy than 1000 keV. The hybrid imaging was beneficial on the range of 1000 – 2000 keV. For higher energy than 2000 keV, the Compton imaging showed the best performance. These results may be affected by circumstances such as measurement time or activity of a source, etc. Also, the comparison in this paper was limited in resolution and variance of the image. Other indicators such as sensitivity should be considered in a certain condition. In the future, the performance of the system will be assessed further with various methods in various circumstances.

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