Experimental Performance Evaluation of Large-area Hybrid Gamma Imaging System (LAHGIS)

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1. Introduction

Hybrid gamma imaging [1] is one of the promising gamma imaging methods for the fields where imaging radiation source is required over a broad energy range. Hybrid gamma imaging achieves high sensitivity and imaging resolution over a broad energy range by combining mechanical collimation (e.g. coded aperture imaging) and electronic collimation (e.g. Compton imaging), otherwise the imaging performance highly depends on gamma energy of the source when either collimation methods is used alone.

A recently developed Compton camera, named Large-area Compton Camera (LACC) [2], features high imaging sensitivity and 3-D imaging capability by using large-area scintillation detectors rather than small detectors that most of recent Compton cameras adopt for hand-held portability. However, like most of other Compton cameras, it is only practical for gamma rays with energies higher than a few hundred keV due to its electronic collimation principal; at lower energies, there is large uncertainty on energy measurement and the probability that a photon undergoes Compton scattering in a detector and reaches the other is low. Hybrid imaging is one of the available methods that solve the energy dependency of the LACC.

In the present study, we developed a high-sensitivity hybrid gamma imaging device, named Large-area Hybrid Gamma Imaging System (LAHGIS), by adopting hybrid imaging based on the LACC. The performance of the system was assessed through a series of experiments acquiring images of gamma-ray sources with several conditions.

2. Materials and Methods

The LAHGIS is composed of two large-area scintillation detectors [3], a coded aperture mask, a dedicated signal processing system, and a personal computer, as shown in Fig. 1. Each detector consists of a monolithic NaI(Tl) scintillator crystal of which size is 27 × 27 cm^2, coupled with 36 square array of photo-multiplier tubes (PMTs). The thickness of the crystal is 2 and 3 cm, respectively for the front and back detector. For the coded aperture mask, tungsten blocks (0.73 × 0.73 × 0.6 cm^3) are assembled in a plastic frame according to 2 × 2 mosaic of rank 19 modified uniformly redundant array (MURA) pattern. The mask is fixed in front of the front detector with a 6 cm distance so that the coded aperture provides a field of view of 130°.

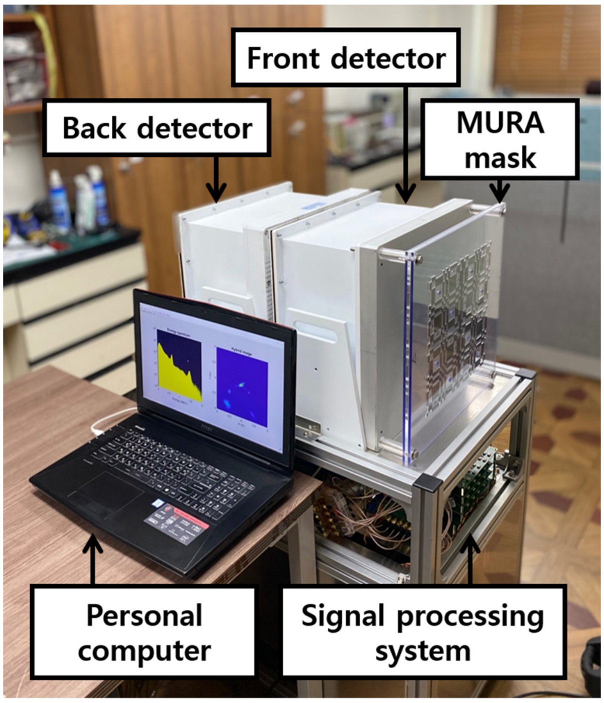

Fig. 1. Developed LAHGIS composed of two NaI(Tl) scintillation detectors, a MURA mask, a signal processing system and a personal computer.

Additional detail of the mask design of the LAHGIS can be found elsewhere [4].

The signals from the detectors are processed with an in-house signal processing system based on multiplexer and field programmable gate array (FPGA). The events are recorded according to the trigger logic: events for coded aperture imaging are acquired when a single trigger occurs on the first detector, events for Compton imaging are recorded when both detectors make trigger signals in the coincidence time window of 200 ns.

Images were reconstructed using a maximum-likelihood estimation-maximization (ML-EM) algorithm for hybrid imaging [1]. Sensitivity images and system matrixes were calculated for each collimation method, considering the probability of the effective events including attenuation from the mask, solid angle, and interaction probability in the detectors. An image space was set as a plane on the given source distance with 300 × 300 pixels, and the iteration number was set as 30. Data acquisition and image reconstruction were conducted on a personal computer (Intel Core i7-6700 CPU) with a dedicated program based on MATLAB (version 2018b).

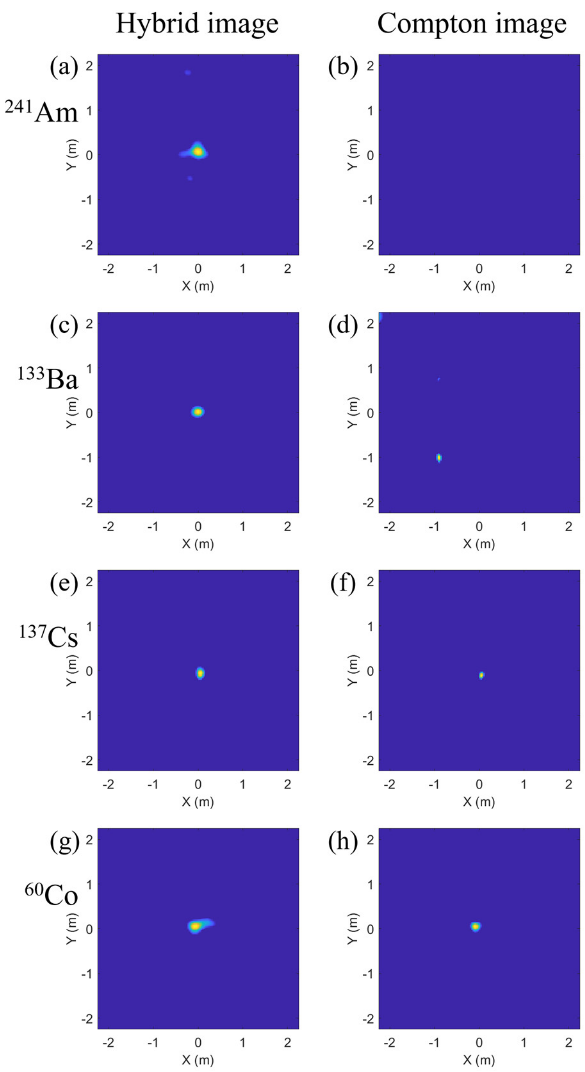

Fig. 2. Reconstructed images of the sources with different gamma energies: (a, b) 59.5 keV of ^{241}Am, (c, d) 356 keV of ^{133}Ba, (e, f) 662 keV of ^{137}Cs, and (g, h) 1170 and 1330 keV of ^{60}Co; hybrid images (left) and Compton images (right).

3. Results and Discussion

The experimental condition was established to investigate the performance of the LAHGIS as the energy the gamma ray. Source was placed at 3 m from the system, and the data were recorded for 1 minute. Four sources were used in the experiment: ^{241}Am (59.5 keV, 11.0 μCi), ^{133}Ba (356 keV, 31.7 μCi), ^{137}Cs (662 keV, 18.7 μCi), and ^{60}Co (1170 and 1330 keV, 7.7 μCi).

Each of the four sources was imaged with an energy window according to the gamma energy of the source: 45–75 keV for ^{241}Am, 319–393 keV for ^{133}Ba, 612–712 keV for ^{137}Cs, and 1100–1390 keV for ^{60}Co. The reconstructed images are shown in Fig. 2; images of the sources reconstructed using only coincidence events (i.e. Compton images) are also shown along with the images using both single and coincidence events (i.e. hybrid images) for comparison.

As shown in the left column of Fig. 2, all four sources were clearly imaged with hybrid imaging, with biases less than 9 cm (=3 pixels). On the contrary, when only coincidence events were used, the sources with low gamma energy (^{241}Am and ^{133}Ba) were not recognized on the images (Fig. 2(b, d)), while the sources with high gamma energy (^{137}Cs and ^{60}Co) were shown as very sharp images (Fig. 2(f, h)). For the low gamma energy sources, it is due to the low probability of coincidence event occurrence (0 event for ^{241}Am and 70 events for ^{133}Ba) and the large relative error following the energy measurement on such a low energy range (~10 % for 356 keV of ^{133}Ba). For the high gamma energy sources, one of the possible reasons for the sharp images is that the number of effective coincidence events was insufficient for many ML-EM iterations. From the hybrid images acquired with the LAHGIS, the imaging resolutions were evaluated as followings: 8.9° for ^{241}Am, 6.0° for ^{133}Ba, 8.0° for ^{137}Cs, and 8.5° for ^{60}Co. The imaging resolution showed little dependency on the gamma energy within the energy range considered in the present study.

4. Conclusion

In the present study, a hybrid gamma imaging system with high sensitivity, named LAHGIS, was developed based on the large-area scintillation detectors of the LACC. The performance of the LAHGIS was tested for the sources with different gamma energies. The results showed that the low-energy sources were successfully imaged which was difficult when Compton imaging was used alone. The imaging resolution was 7.9±1.1°, and the relationship between imaging resolution and gamma energy was insignificant within the energy range invested in the present study (59.5–1330 keV). Other factors that possibly affect the performance of the system, such as source positon and activity, will be studied in future work.

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