Tomographic Imaging by a Si/CdTe Compton Camera for $^{111}$In and $^{131}$I Radionuclides

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Abstract—Tomographic imaging with radionuclides commonly used in nuclear medicine, such as $^{111}$In (171 and 245 keV) and $^{131}$I (364 keV), is in high demand for medical applications and small animal imaging. The Si/CdTe Compton camera with its high angular and high energy resolutions is an especially promising detector to extend the energy coverage for imaging to the range that covers gamma-ray emitted from these radionuclides. Here, we take the first steps towards short-distance imaging by conducting experiments using three-dimensional phantoms composed of multiple sphere-like solutions of $^{111}$In and $^{131}$I with a diameter of 2.7 mm, placed at a distance of 41 mm. Using simple back-projection methods, the positions of the sources are reproduced with a spatial resolution of 11.5 mm and 9.0 mm (FWHM) for $^{111}$In and $^{131}$I, respectively. We found that a LMM-EM method gives a better resolution of 4.0 mm and 2.7 mm (FWHM). We resolve source positions of a tetrahedron structure with a source-to-source separation of 28 mm. These findings demonstrate that Compton Cameras have the potential of close-distance imaging of radioisotopes distributions in the energy range below 400 keV.

Index Terms—Compton camera, CdTe, Si, semiconductor, double-sided strip detector, 3D imaging

I. INTRODUCTION

The Compton camera is a type of gamma-ray detector which utilizes Compton scattering in the detector. The direction of an incident gamma-ray is determined by solving the Compton scattering equation. It is regarded as one of the most promising detectors to observe gamma rays with energies from several tens of keV to several MeV, where Compton interaction is the dominant process of photon interactions. Unlike most other types of gamma-ray detectors, the Compton camera requires no collimators to determine the directions of an incident gamma-ray. Therefore, it has the potential to achieve a high detection efficiency and a wide field of view at the same time. One of the promising applications of Compton cameras is in medical imaging, which achieves this by means of detecting gamma-rays emitted from radionuclides [1], [2], [3].

A key detector parameter for medical imaging is the angular resolution, because it determines the accuracy of the location of gamma-ray emitting sources. Moreover, since the angular resolution also plays a factor in the amount of background contamination, it is important to have high angular resolution to increase the signal to background ratio. The angular resolution of a Compton camera is determined from the energy and positional resolutions of the detector. In addition, the resolution is also limited by the finite momentum distribution of the bound atomic electrons in the detector material of the scattering part of the camera. This is called the Doppler-broadening effect and is a dominant factor affecting the angular resolution of a Compton camera below a few hundred keV [4], [5].

In using Compton cameras to observe commonly used radionuclides, such as $^{111}$In and $^{131}$I, that emit low-energy gamma-rays below $\sim$400 keV and widely used in pre-clinical and clinical imaging, we have to ensure a sufficient angular resolution comparable with (or better than) those of the existing detectors, notably SPECT and PET. For this purpose, we have been developing multi-layered Si/CdTe Compton cameras (Si/CdTe CCs) [6], [7], [8]. Owing to their good performance in energy and positional resolutions, and the use of Si as the scattering material, which reduces the Doppler broadening effect, the Si/CdTe CCs have achieved a high angular resolution and provide high sensitivity of detecting sources [6], [7], [8]. In previous results, we obtained an angular resolution of 17 degrees FWHM (full width at half maximum) at 81 keV and 10 degrees FWHM at 122 keV. The angular resolution improves for higher incident energies, such as at 511 keV where the resolution is measured to be 2.5 degrees FWHM [8]. Si/CdTe CCs have a typical energy resolution of $\sim$4-5 keV (FWHM), which allows us to resolve multiple lines emitted from sample containing a mixture of radioisotopes [8].

In our previous work, we reported the results of 3D imaging of a mouse using a Si/CdTe Compton Camera in 2013 [1]. Recently, Kataoka et al. (2018) [2] presented their results of tomographic imaging of mice obtained with a GAGG-scintillator-based Compton Camera. However, these experiments focused on gamma-rays with energies above 300 keV. In order to utilize a Compton camera in an energy range that covers both 171 keV and 245 keV for the two major gamma-ray line emissions emitted from $^{111}$In, we need to investigate the performance at these low energy range. When used in small animal imaging, e.g., mice and rats, three-dimensional imaging
capability at short distances (~ few cm) is crucial, and hence evaluation of the performance is also one of the focal points of this work.

The primarily motivation for developing methods that can extract medical information from the output data generated by Compton camera systems is driven by the potential of developing novel medical imaging systems. The list-mode maximum-likelihood expectation maximization (LM-MLEM) is the often used method to reconstruct images from event-based (list mode) data. However, previous LM-MLEM based experiments were restricted to imaging using high energy gamma rays or limited to imaging sources located at much greater distances compared to the imaging distances considered in this work. Also, most of the past simulation studies of imaging algorithms assumed a simple detector response function.

In this paper, we measure the performance of a Si/CdTe Compton camera at short-distance tomographic imaging of radionuclide targets in the energy range of 171 keV to 364 keV.

In this work, we measure the performance of a Si/CdTe Compton camera at short-distance tomographic imaging of radionuclide targets in the energy range of 171 keV to 364 keV. In Section IV, we perform tomographic imaging, point source radioisotopes and measure some fundamental limitations. Also, most of the past simulation studies of imaging algorithms assumed a simple detector response function.

In and 131I, and evaluate the spatial resolution of the targets placed at a distance of ~41 mm. Finally, we conclude our result in Section V.

II. SI/CDETE COMPTON CAMERA

The Si/CdTe CC used in our experiments consists of 2 scattering layers made of silicon double-sided strip detectors (Si-DSDs) and 3 absorption layers made of CdTe double-sided strip detectors (CdTe-DSDs). These detectors are stacked with a pitch of 4 mm. Table I summarizes the specifications of the detectors. Each layer has a detection area of 32 mm × 32 mm with a positional resolution of 250 µm. Each Si-DSD and CdTe-DSDs are 500 µm and 750 µm thick, respectively. The CdTe-DSD has an Al/CdTe/Pt configuration, which is based on the high-resolution CdTe-diode detector technology. The detectors were operated at a temperature of ~20°C, and a bias voltage of 250 V was applied.

The low-noise analog ASICs of the Si-DSD and CdTe-DSDs digitize the pulse heights in reading the signals from each strip. To begin with, the triggers from the Si layers and the CdTe layers are ORed independently and become triggers at the scattering part (Si) and the absorbing part (CdTe). When two triggers are detected within a 600 nanoseconds time window, the signals from all layers are taken as a candidate of Compton scattering events in the camera. If the signals are spread over adjacent strips, those data are merged to extract the position and the deposited energy, corresponds to each interaction. Further information about the CdTe-DSDs and its data processing are found in [17], [18]. Hereafter, the reconstructed energy and position, which corresponds to the data of one interaction, is referred as a hit.

As summarized in Table I, the measured FWHM energy resolutions for a Si-DSD and CdTe-DSD are 5.5% at 31 keV and 1.9% at 356 keV, respectively. In practice, the energy is determined as the sum of the energies of a signal hits from a Si-DSD and a CdTe-DSD. The resolution is found to be 4.1 keV at 171 keV and 5.0 keV at 245 keV. The maximum counting rate of the system is about 1 kcps.

Silicon is used as the scattering medium in Compton cameras because Doppler-broadening effect, which degrades the angular resolution, is relatively small compared to other material. Appendix A summarizes our study of the Doppler-broadening effects in silicon and we considered a detector with a different scattering medium besides silicon.

We place the front detector of the camera at a distance of 41 mm away from the vertical axis of the target stage (see Fig.1). The target is mounted on a rotary stage and measurements of the target can be performed from arbitrary angles.

III. ANALYSIS METHOD

Before conducting tomographic imaging, we investigated the angular and spatial resolutions of the Si/CdTe CC, comparing the experimental results with Monte Carlo simulations for a single point source.

The angular resolution of the Compton camera is defined as the FWHM of the Angular Resolution Measure (ARM), which is the difference between the scattering angles, ∆θ ≡ θK − θG, where θK is calculated using the energies of the scattered electron and scattered photon and θG is calculated using the measured momentum directions of the incident and scattered photons.

To evaluate the angular resolution of the Si/CdTe CC for various energies, we conducted experiments in each of which one of 133Ba, 22Na point sources and a 10 µL droplet of 111In were placed at a distance of 41 mm from the detector. The procedure of obtaining the ARM distributions is described in the following sub-sections.
energies below 0.5 MeV, a photon will likely Compton scatter once through the silicon scattering plate used here. After filtering by energy thresholds, we select the events which have two hits, one at the Si-DSD and the other at the CdTe-DSD. This was applied to both experimental and simulation data. The energy scatter plot between the Si- and CdTe-DSDs for $^{111}$In data is shown on the left in Fig. 2.

We then select an event comprising of a hit from the Si-DSD and the CdTe-DSD. This definition of an event was also applied to simulated data. The scatter plot of the energy between Si- and CdTe-DSD for $^{111}$In is shown on the left in Fig. 3. The green shaded regions are where the events and fluorescence K emissions following the decay of $^{111}$In are found, whose energy in Si-DSD is 23-27 keV. However, we are able to remove the fluorescence K events during data processing. Then, we extract the events in which the hits in a Si-DSD and a CdTe-DSD are emerged due to a scattering and an absorption. We check that the measured energies satisfy the Compton equation,

$$\cos \theta = 1 - \frac{m_e c^2}{E} \left( \frac{1}{\gamma^2} - \frac{1}{\gamma} \right),$$

(1)

where $\gamma$ is the sum of the detected energies and $\gamma/\gamma$ is the energy detected from the CdTe-DSD; $m_e$ and $c$ are the electron rest mass and the light velocity, respectively. We excluded the events when $|\cos \theta| > 1$ and interpret that the hit in the Si-DSD corresponds to the scattering interaction and the hit in the CdTe-DSD corresponds to the absorption. This is valid for gamma-rays with an energy below $m_e c^2/2$. Using these events, we obtained the spectrum of the energy sum in the Si-DSD and the CdTe-DSD (right panel of Fig. 3). Note that some of the events that the scattering for gamma-rays with an energy of 350 keV take place in the CdTe-DSD in which could also satisfy the condition of $|\cos \theta| > 1$. However, we confirmed that the number of these events is less than 1% of the total events, and they are negligible in this analysis.

The energy windows were set to 168–174 keV and 242–248 keV for the two primary lines of $^{111}$In from which the energy sum was calculated to analyses the ARM distribution and in the image reconstruction process. The semiconductor detectors have sufficiently high energy resolutions so that the events consisting of summed peaks at the 194 keV and 268 keV can be completely distinguished from 171 keV and 245 keV peaks. The energy windows for the other sources were set to 362–368 keV for $^{131}$I, 353–359 keV for $^{133}$Ba, and 508–514 keV for $^{22}$Na.

The ARM for certain energy bands was evaluated by calculating the difference between the two scattering angles; $\theta_K$ was calculated from the energies of Compton scattering and photo absorption, and $\theta_G$ from the positions of the two hits and the source. Fig. 3 shows ARM's distributions at the peak energies, the angular resolution at each energy was determined at FWHM.

B. Estimation using Monte-Carlo simulations

In this section, we study how the detector parameters, i.e., the position and energy resolutions, affect the angular resolution of the Si/CdTe CC. We developed the Geant4 simulation codes to simulate our experimental setting with an isotropically-emitting gamma-ray source placed at similar distances as in our experiments. In the simulations, the two effects caused by the finite resolution in the position and energy are treated separately;

(a) For the effect due to position resolution, we define mesh grids with the same pitch as the detector strip in a scattering volume and use the center position of the corresponding pixels instead of the precise positions of the hits. In this setup, we use a stacking pitch of 4 mm as the distance between the scattering and absorbing layers. (b) For the effect due to energy resolution, we model the detector’s energy response using the experimental data and apply this model to the simulation data. The detail of the model function is described in Appendix.

Since the distance between the source and the camera is short, the size of the source is not negligible and its non-zero size has an effect on the angular resolution. In the simulations, we set the size of the source to the same as that used in the experiments (1 mm radius). We also modeled the geometry of the 2 Si-DSDs, 3 CdTe-DSDs plates, the aluminum detector box, and detector boards modeled using SiO$_2$. The simulation records the position and energy information due to Compton scattering and photo absorption.

The energy dependence of the angular resolution was obtained for both the experimental and simulation data as shown in Fig. 4. In the simulations, we assumed the same geometry as that of the experiment and calculated the ARMs (case 1). We also simulated (case 2) where only the Doppler-broadening effect was considered for the detector with the infinitely good energy and positional resolutions and an infinitely small point source was assumed (dotted curve in Fig. 4, (3) same as (2) but with a source with a size of 1 mm in radius (dashed curve), (4) where no Doppler-broadening effect, only the position resolution of the detector was taken into account (solid curve with square markers). (5) is similar to (4) in the energy resolution, instead of position, was taken into account (solid curve with downward-pointing open triangle markers).

The result of the main simulation (i.e., case 1) was found to be in good agreement with experiments. We also found that using a scattering material with a small Doppler-broadening
effect and a high energy resolution is important, because it significantly affects the angular resolution below 300 keV. In addition, the simulation result (3) implies that the effect of the source size is also a significant factor for short-distance imaging. The effect of the positional resolution is nearly constant with respect to gamma-ray energy, although a slight increase as a function of the energy is observed. This is presumably because the uncertainty in the position of the Compton-cone axis is larger in forward scattering. If the positional resolution was 2 mm, as an example, instead of 250 µm, this effect would be multiplied by six fold.

C. Spatial resolution on the target plane

The spatial resolution of the Compton camera, which is a key parameter of the performance of a camera, was evaluated using the following reconstruction method. We define the spatial resolution of the Si/CdTe CC as the FWHM of the point spread function (PSF). The PSF is a function of the radial distance $r$ from the point source and is calculated as the integrated pixel value per area for the annulus region from $r$ to $r + dr$, where $dr$ is 0.5 mm.

We reconstructed the image by superposing multiple Compton cones onto a 2-dimensional plane at the position of the target source, parallel to the detector plane. We refer to this method as the simple back-projection (SBP). Specifically, we used the method described in [19], [20] to deal with a non-zero thickness of the cone surface due to the limited position and energy resolutions. The pixel value at $\vec{X}$ is given by

$$V(\vec{X}) = |\vec{L}|^{-2} \exp \left[ -\frac{1}{2} \left( \frac{\vec{X}}{\sigma} \right)^2 \right].$$

(2)

where

$$\sigma = |\vec{L}| \tan(\Delta \theta)$$

(3)

and $\vec{L}$ is the closest position on the cone surface to the pixel position $\vec{X}$, $x$ is $|\vec{X} - \vec{L}|$, which is the distance between $\vec{X}$ and $\vec{L}$, and $\Delta \theta$ is the smoothing factor in the back-projection image. In principle, $\Delta \theta$ can be negligibly small if the number of events is large enough, but in practice a very small value of $\Delta \theta$ often results in artifacts in the image. In this work, we set $\Delta \theta$ to 0.5 degrees, the smallest value with which significant artifacts do not appear. In order to shorten the computation time, the pixels whose distances from the cone surface were larger than 3$\sigma$ were ignored.

Fig. 5(a) shows an image of 245 keV from $^{111}$In made with the SBP method, overlaid with the circle to indicate the FWHM of the PSF. Fig. 5(b) shows the energy dependence of the PSF obtained from the experimental data. The measured FWHMs of the PSF were 7.8, 6.8, and 6.0 mm at 171, 245, and 356 keV, respectively. We confirmed that the obtained results were consistent with those of the simulations.

Hereafter, we use the FWHM of the PSF as the measure of the imaging capability rather than that of the ARM because the former is directly derived from the image.

IV. TOMOGRAPHIC IMAGING

A. Experiment with a 3-dimensional phantom

To evaluate the 3-dimensional imaging capability of a Si/CdTe CC, we prepared a phantom composed of 4 point sources arranged in a regular tetrahedron with side lengths of 28 mm (Fig. 6). Each point source in the phantom consists of a 10 µL droplet of liquid radiation source with activities of
74 kBq held in a micro tube. The diameter of the droplet is estimated to be 2.7 mm. The 4 sources had the same emission intensities within 0.2 %. The radionuclides used in the experiments were $^{111}$In and $^{131}$I, both of which are widely utilized in nuclear medicine.

We measured the phantom from 16 angles, rotating the phantom about the vertical $y$–axis by 22.5 degree increments in order to acquire a 3-dimensional image, refer to Fig. 1. The center of the phantom was placed at a short distance of 41 mm from the camera. The measurement time was set to 20 minutes for each measurement.

Fig. 3. Distributions of the ARM obtained from our experimental data. The angular resolutions are 6.1° at 171 keV, 5.0° at 245 keV, 4.0° at 356 keV, and 3.8° at 511 keV.

BWWM of PSF

Fig. 4. Energy dependence of the angular resolution of the Si/CdTe CC measured with (filled triangles) experiments and (open circles and solid line) simulations. Open squares and triangles show the contributions of the energy and positional resolutions, respectively, obtained with simulations. Dotted and dashed lines show the FWHM of the simulated ARM distribution for a spherical source with the infinitely small radius and 1-mm radius, respectively, obtained with the ideal detector having the infinitely good positional and energy resolutions, where only the initial electron momentum distribution is considered. See text for detail.

Fig. 5. (a) Image constructed from experimental data with the simple back-projection for 245-keV gamma rays emitted from $^{111}$In. The open circle indicates the FWHM of the point spread function. (b) Spatial resolution vs incident energy of the gamma rays.

B. Reconstruction of a 3-dimensional image

In this section, we reconstruct 3D images using the SBP method and an iterative estimation method.

Using the SBP method, a back-projection of Compton cones to a 3-dimensional imaging space is required. We used the back-projection method described in Section III-C to calculate the voxel values of 3-dimensional histograms and superimposed the multiple back-projected Compton cones on the 3-dimensional space of the Si/CdTe CC.

We converted the positional information of the data to offset the rotation angle of the phantom. This conversion makes the measurement of the phantom rotating with a pitch of 22.5 degrees in the experiment to be equivalent to measuring the fixed phantom from 16 angles of views.

In the simple back-projection method, the resulting image was blurred by the detector response, which was expected given that it is known to be difficult to estimate the actual distribution of gamma-ray sources using this method [21]. Thus, we also utilized the Maximum Likelihood Expectation Maximization (MLEM) method. The MLEM algorithm is an iterative method to find the source distribution that yields the highest likelihood from the data and it can recover the shape and size of the gamma-ray emitting sources.

Specifically, we adopted the list-mode MLEM (LM-MLEM) method described in [10], [11]. In this method, the image $\lambda^{(k+1)}$ after $k+1$-th iteration is calculated from the $k$-th image $\lambda^{(k)}$ according to the formula

$$\lambda^{(k+1)}_j = \frac{\lambda^{(k)}_j}{s_j} \sum_i t_{ij} \sum_k t_{ik} \lambda^{(k)}_k, \tag{4}$$

where $j$ represents the index of the voxel in the image space, $s_j$ is the probability that a photon emitted from the voxel $j$ can be detected and $t_{ij}$ is the probability that a gamma-ray emitted from the $j$-th voxel will be detected as event $i$. In this work, we use Eqs (2) and (3) to calculate this quantity. In this case, $\Delta \theta$ in Eq (3) should be the angular resolution of the Compton camera, and we set it to 2.0 degrees as a representative number taken from Fig. 5. In this study, we focused on the size and shape of the source reconstructed with the MLEM method, and simply assumed that $s_j = 1$ for all $j$. This is because the absolute value of $s_j$ simply determines the normalization of the reconstructed image and does not affect the shape or the size of the reconstructed image. Here we also assumed that...
all \( s_j \) have the same value, i.e., the detection probability was uniform across the image space.

![3D Phantom](image)

**Fig. 6.** The phantom: each point source consists of a 10-\( \mu \)L droplet of liquid radionuclide, which is the light blue point at the bottom of the micro tube in the photo and is located at the vertices of a tetrahedron. Cross sections 1 and 2 are slices chosen for Figs. 8 and 9. The direction of the \( y \)-axis is the same as that in Fig. 1.

![3D Phantom](image)

**Fig. 7.** Simple back-projection image of the phantom visualized with the maximum intensity projection (MIP). This image is reconstructed from 8 projection angles of \(^{131}\)I data.

**TABLE II**

| # of views (Pitch of angles) | \( 2^\circ \) | \( 4^\circ \) | \( 8^\circ \) | \( 16^\circ \) |
|-----------------------------|--------------|-------------|-------------|-------------|
| \(^{111}\)In                | 36056        | 71038       | 141585      | 284790      |
| \(^{131}\)I                | 12764        | 24502       | 47481       | 94276       |

**V. RESULTS AND DISCUSSION**

We reconstructed a simple back-projection image using the events extracted with the selection criteria described in Section III-A. Figure 7 shows the reconstructed SBP image of a \(^{131}\)I phantom measured from 8 view angles, using the maximum intensity projection (MIP) method for visualization. The numbers of events selected from each data set for use in image reconstructions are listed in Table II.

The 3-dimensional structure of the phantom, which is a tetrahedron (see Fig. 7), was successfully reproduced, and the four point sources were clearly visible. The position of each point was determined as the center of the voxel, which is the position of the local maximum value, and the distances between them were found to be consistent with the expected configuration with deviations away from the true value of less than 1.5 mm. The spatial resolution of the 3-dimensional image was evaluated by means of the FWHM of a point in cross-sectional slices of the back-projection images. The panels in the left 2 columns in Figs. 8 and 9 show lateral cross-sectional slices (see Figs. 7 and 6) for \(^{111}\)In and \(^{131}\)I, respectively, which were reconstructed from the data measured from 2 (top row), 4, 8, and 16 angles. The lateral resolution was measured with the cross-sectional slices parallel to the \( x - z \) plane in Figs. 1 and 6. We measured the FWHMs of the distribution of the voxel values along the \( x \)- and \( z \)-axes of the sliced images of point sources of the two radionuclides. The larger and smaller ones are described as the lateral resolutions along the major and minor axis, respectively, in Table III and IV. The axial resolution was defined as the FWHM of the distribution of the voxel values along the \( y \)-axis.

For the images reconstructed from 16 projection angles, we obtained lateral resolutions of 11.5 and 9.0 mm for \(^{111}\)In and \(^{131}\)I, respectively. The axial resolutions were 6.1 and 4.4 mm, respectively. Table III summarizes the result.

**TABLE III**

**Spatial resolution of the SBP images**

| Resolution based on images for \(^{111}\)In (171 keV+245 keV) | Lateral resolution | Lateral resolution | Lateral resolution |
|---------------------------------------------------------------|-------------------|-------------------|-------------------|
| # of angles                                                   | Major axis (mm)   | Minor axis (mm)   | Axial resolution (mm) |
| 2                                                            | 20.3              | 8.1               | 7.7               |
| 4                                                            | 17.6              | 8.1               | 6.8               |
| 8                                                            | 11.4              | 7.6               | 6.1               |
| 16                                                           | 11.5              | 7.2               | 6.1               |

The lateral resolution columns show the FWHM of the point source along the \( x \)- and \( z \)-axes, whereas the axial resolution one shows that along the \( y \)-axis. See Fig. 6 for the definition of the axes.

The shape of each point source was somewhat distorted to an oval shape from the actual circular (or spherical in the three dimension) shape when the number of the observed angles was small, and the tendency was more pronounced with a smaller number of angles (Figs. 8 and 9). The distortion in the images is reflected in Table III as a large difference between the major- and minor-axis widths of a point source; the former is about 2.5 times larger than the latter for the 2-angle images. For the image of 8 angles, the difference between the major- and minor-axis widths is smaller than these widths. There is a tendency for the difference of the width to be smaller for increasing as the number of the observation angles increases. Given that the improvement of the width differences from the images of 8 angles to those of 16 angles is much smaller than the widths, observing in more than 8 projection angles does not improve the image quality very much. In the SBP image, the lateral resolutions were significantly worse than the axial ones; this is consistent with the fact that the region, created by superimposing multiple Compton cones, extends in the \( x - z \)
TABLE IV

SPATIAL RESOLUTIONS OF THE LM-MLEM IMAGES

Resolution based on images for $^{111}$In (171 keV+245 keV)

| # of angles | Lateral resolution | Axial resolution |
|-------------|--------------------|-----------------|
|             | Major width [mm]   | Minor width [mm]|
| 2           | 4.1                | 1.8             |
| 4           | 4.6                | 2.6             |
| 8           | 4.1                | 3.0             |
| 16          | 4.0                | 3.1             |
|             | 2.0                | 2.5             |
|             | 2.7                | 2.7             |

Resolution based on images for $^{131}$I (364 keV)

| # of angles | Lateral resolution | Axial resolution |
|-------------|--------------------|-----------------|
|             | Major width [mm]   | Minor width [mm]|
| 2           | 3.1                | 1.5             |
| 4           | 3.2                | 2.0             |
| 8           | 2.8                | 2.2             |
| 16          | 2.7                | 2.4             |
|             | 1.8                | 2.1             |
|             | 2.1                | 2.1             |

See Table III caption for the detailed description.

For images from 8 (third rows) and 16 (fourth rows) projection angles, distortions of the point sources were not visible anymore. Table IV tabulates the results. We obtained lateral resolutions to be 4.0 and 2.7 mm for the radiation sources $^{111}$In and $^{131}$I, respectively, for the images reconstructed from 16 projection angles. The axial resolutions were 2.7 and 2.1 mm, respectively.

In the image of the 8-angles and 16-angles, the spatial resolution ranges from 2.1–4.1 mm for gamma rays below 400 keV, the energy of which is low for imaging with Compton cameras. From the symmetry of the actual source shape, its major and minor widths are expected to be the same. We found that the difference between the major/minor widths was smaller in the MLEM than in the SBP method, the fact of which implies that the MLEM reproduces the true shape of the source better. It should be noted that the spatial resolution described here includes the source size. Therefore, our results imply that the Si/CdTe Compton camera has better performances in localization of sources.

We also calculated the source intensities of the reconstructed images. Specifically, we evaluated the uniformity of the intensity with the counts in ROIs (region of interest) set on each point source in the reconstructed images from 16 projection angles. The sizes of these ROIs are a sphere with a 10 mm diameter, which is large enough to cover the distributions of the point sources. The deviations from the averaged intensity the 4 point sources were calculated to be around 10% for both $^{111}$In and $^{131}$I. Similar results were obtained from the images of the LM-MLEM method.

In summary, we demonstrated that the Si/CdTe Compton camera can be used for the spatial resolution of the images.
camera gives the spatial resolution of 4.4–11.5 mm at a
distance of 41 mm from the detector surface in the SBP image.
The localization in the tetrahedron-shaped phantom is much
improved when we use the LM-MLEM method. The resultant
size of the sources in the reconstructed images range from
2.1–4.1 mm, compared to the actual size of the droplet of the
radioactive sources of 2.7 mm (Fig. 5). This performance is
attractive for the use in practical applications of imaging of
gamma-rays by using commonly-used radionuclides, such as
111In and 131I.

VI. Conclusions

We conducted a study of imaging capability of a Si/CdTe
CC using 3-dimensional phantoms with 111In and 131I
solutions. These radionuclides, which are often used in med-
ical imaging, emit low-energy gamma rays below 0.5 MeV.
Conventional Compton cameras are not designed to cover
such a low energy band with a spatial resolution better than
5 mm. The Si/CdTe CC has a good energy and positional
resolutions and its Doppler-broadening effect is smaller than
traditional Compton cameras based on scintillators such as
NaI(Tl). We demonstrated that tomographic imaging of a
Si/CdTe CC yields improved image quality. The SBP and
LM-MLEM algorithms were applied to a set of projection
data obtained from 16 different angles. Using simple back-
projection methods, the positions of the sources are reproduced
with a lateral resolution of 11.5 mm and 9.0 mm (FWHM)
for 111In and 131I, respectively. We found that a LM-MLEM
method gives better lateral resolutions of 4.0 mm and 2.7 mm
(FWHM) with 16 view angles. These numbers are reduced
to 2.7 mm and 2.1 mm, when we use the axial resolution.
We successfully separated the sources which are placed at
a distance of 28 mm in the tetrahedron structure of the phantom.
The results imply the potential of Compton Camera in the
energy range below 400 keV for observing targets placed close
to the camera.

Appendix

A. Estimation of the Doppler-broadening effects of silicon

We present our study of the Doppler-broadening effects
of silicon and other scatter materials in the detector. The
effect is represented as the angular resolution in this section.
We calculated the angular resolution, using the Geant4[22]
simulation toolkit, where we assumed a 100 m × 100 m × 100 m
cube for each material and recorded the energies and momenta
when gamma rays hit the material (Fig. [10]). Here, again the
angular resolution of the Compton camera is defined as the
FWHM of ARM. Silicon was found to show the best angular
resolution among the materials, which were about 50 and 70%
of those of CdZnTe and GAGG, respectively. Given the lowest
Doppler-broadening effect among the candidate materials, we
conclude that silicon is the most suitable scattering material.

B. Energy resolutions of the detectors in simulations

For the simulations used in this study, the energy resolution
of the detectors is determined as follows. The energy reso-

\[
\Delta E = \sqrt{\left(\Delta E_{\text{electronics}}\right)^2 + \left(\Delta E_{\text{statistics}}\right)^2} \tag{5}
\]

where

\[
\Delta E_{\text{statistics}} = 2.35\sqrt{FWE}\, W, \tag{6}
\]

and F is the Fano factor, E is the gamma-ray energy, and W is
the average ionization energy. The Fano factors for silicon and
CdTe are 0.11 and 0.13, respectively. The average ionization
energies are 3.6 eV and 4.5 eV, respectively. \(\Delta E_{\text{electronics}}\) is
measured to be 1.6 keV in both Si and CdTe. For CdTe-DSDs,
a term to represent the decrease in energy resolution caused
by the depth dependence of the charge collection efficiency
in the detectors is also needed. This is approximated using the
following linear function

\[
\Delta E_{\text{cdte}} = \sqrt{\left(\Delta E_{\text{electronics}}\right)^2 + \left(\Delta E_{\text{statistics}}\right)^2 + \alpha E} \tag{7}
\]

Fitting this to the experimental data yields \(\alpha = 0.008\).

Acknowledgment

This work was supported by JSPS KAKENHI Grant
Numbers 16H02170, 16H03966, 18H02700, J18H05463,
20K22355 and World Premier International Research Center
Initiative (WPI), MEXT, Japan. This work was supported
by a matching fund program of Centers for Inter-University
Collaboration from ISAS (Institute of Space and Astronautical
Science), JAXA (Japan Aerospace Exploration Agency). This
work was supported by JST Advanced Measurement and
Analysis program (2012-2014). The authors thank iMAGINE-
X Inc. for supporting data analysis of Compton cameras.

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