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Feasibility Study of Gamma CT based on Compton kinematics

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1. Introduction

During a decommissioning process, the radioactive waste can be classified as a self-disposal waste, which does not need costly process, if we can identify and remove the hot spots in the waste. To take out the hot spots from the low-level waste, there is a need to estimate the location and activity of the spots and now we are developing a large-area Compton camera (LACC) for this purpose.

For the image reconstruction and activity estimation of the hot spots, the exponential attenuation of the gamma-rays inside the waste drum has to be considered. The industrial gamma Computed Tomography (CT) system, which uses a heavy mechanical collimator, has been used to obtain the attenuation map. In the scenario using a Compton camera, however, it is inefficient to use an additional mechanical collimator only for the acquisition of the attenuation map.

To resolve this issue, we suggest a new methodology to apply the electronic collimation based on Compton kinematics to gamma CT instead of mechanical collimation. With the Compton-kinematics-based gamma CT methodology, briefly the Compton gamma CT, we can use the LACC not only for the imaging of the internal hot spots but also for the production of the attenuation map in the waste drum, without any additional equipment. In this paper, we studied the feasibility of the Compton gamma CT system by using Geant4, Monte Carlo simulation toolkit.

2. Materials and methods

2.1 Gamma CT based on Compton kinematics

A Compton gamma CT system consists of an external gamma-ray source and two position-sensitive detectors. The data acquisition procedure of the Compton gamma CT is as follows:

1) For the coincident events, the list-mode data is recorded for each detector. The list-mode data has the form of (P, E), which represent the interaction position and deposited energy in the detector, respectively.
2) The geometric scattering angle θ_g is calculated by two vectors, v_1 and v_2, which are calculated by (P_s-P_1) and (P_1-P_2), respectively. P_s, P_1, and P_2 denote the source position and the interaction positions in the scatter and the absorber detectors, respectively. The θ_g is then calculated by Eq. (1).

$$\cos\theta_g = \frac{v_1 \cdot v_2}{|v_1||v_2|} \quad (1)$$

3) The kinematic scattering angle θ_e is calculated by Compton kinematics:

$$\cos\theta_e = 1 - \frac{m_e c^2}{(E - E_1)} + \frac{m_e c^2}{E} \quad (2)$$

where E_1 and E are the energy deposited in the scatter detector and the energy of the external gamma-ray source, respectively.

4) Then, we can calculate the scattering angle difference (SAD), as follows.

$$\mathrm{SAD} = \theta_e - \theta_g \quad (3)$$

5) To select only the unscattered events, the SAD window is applied to the coincided events. The list-mode data of the scatter detector, which satisfies the SAD window, is used to reconstruct the CT image. The rest procedure for the reconstruction of CT image follows the conventional gamma CT method.

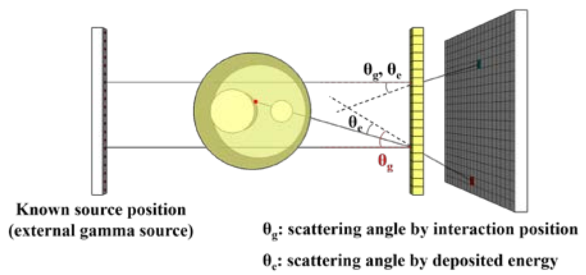


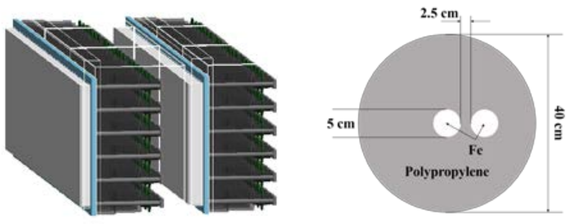
Fig. 1. Schematics of gamma CT method based on Compton kinematics.

As shown in Fig. 1, the θ_g and θ_e will be almost identical and the SAD distribution will be distributed near 0° for the unscattered photons from the external sources, but not for the scattered events or other events. Hence, with a suitable SAD window, the image quality will be improved based on Compton kinematics.

2.2 Feasibility study for Large-Area Compton camera system to Gamma CT

Geant4 (version 10.03) [1] was used to model the LACC, and to estimate the feasibility of the LACC for gamma CT. The LACC consists of two scintillation detectors; the scintillation detectors were composed of a monolithic NaI(Tl) crystal plane (Scintitech, MA, USA) coupled to an array of square-type photo-multipliers (PMTs). A NaI(Tl) crystal had an area of 105 cm (W) ×

27 cm (H) which corresponds to an area of the three-head LACC system (Fig. 2(a)). Thicknesses of NaI(Tl) crystals were 2 cm for the scatter detector and 3 cm for the absorber detector, respectively. The scatter-absorber detector distance was 25 cm.



(a) (b)

Fig. 2. Large-area Compton camera system (a) and standard phantom (b) modeled using Geant4.

The standard phantom for industrial gamma CT (Fig. 2(b)) [2] was modeled in Geant4. The 40-cm-diameter cylindrical phantom is made of polypropylene with two holes filled with Fe (ρ = 7.8 g/cm^3). The diameter of two holes is 5 cm. The distance between the phantom and the scatter detector is 10 cm.

Two gamma-ray sources were assumed; the first source was the external gamma source placed at 60 cm distance from the surface of the phantom and the other source was the inner source placed at the center of the phantom. Both sources have the energy of 1.33 MeV. The simulation was carried out with and without the inner gamma source in the waste drum. The strengths of the external source and the inner source were assumed to be 20 mCi and 0.1 mCi, respectively. The projection data was acquired at the 360 angular positions over 360^o. The acquisition time for each projection was assumed to 1 second.

For the case with the inner source, the feasibility of Compton gamma CT was studied. We compared the CT image of the LACC with that of conventional gamma CT system based on electronic collimation. For the comparison, the conventional gamma CT system was modeled assuming that the system was composed of 36 × 10 scintillation detectors, each of which is comprised of a 1"×1" cylindrical NaI(Tl) crystal coupled to a cylindrical PMT. For the case with the inner source, we confirmed the ability of blocking the scattered events with the SAD window of Compton gamma CT.

The energy resolution and spatial resolution of the detectors were applied in the simulation based on experimental results, that is, 9% (@662 keV) and 10 mm FWHM [3]. The energy resolution of 9% (@662 keV) was also applied to the cylindrical NaI(Tl) detector in the conventional gamma CT simulation. The G4EMLivermorePhysics physics library was used. The filtered back projection (FBP) was used to reconstruct the CT image with the Ram-Lak filter. We used MATLAB to obtain CT images.

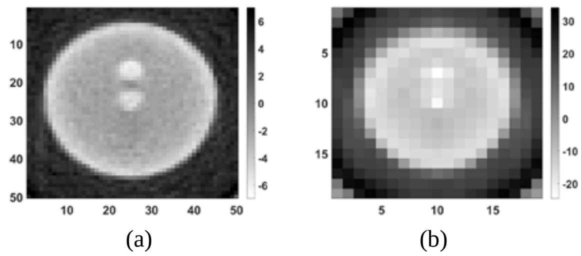
3. Results

The CT images without the inner source were obtained with the LACC and the conventional gamma CT as shown in Fig. 3. The energy window of 1.2–1.4 MeV was used for the conventional CT system, and the SAD window of −5° to +5° was used for the LACC. The reconstructed image space was discretized on a 50 × 50 grid for the CT image of the LACC, and a 19 × 19 grid for the image of the conventional gamma CT system.

Fig. 3 shows that the CT image obtained by the LACC has good image quality compared to that of the conventional gamma CT system. The CT image of the conventional system seems to be somewhat worsened due to lack of spatial resolution in the detector. Intrinsic efficiencies were evaluated to 1.28% for LACC and 1.43% for the conventional system. Though the conventional system has a slightly high intrinsic efficiency compared to LACC, there is little difference in efficiency. From the result, it was confirmed that it is capable to obtain CT image of the waste drum using the LACC without additional mechanical collimator.

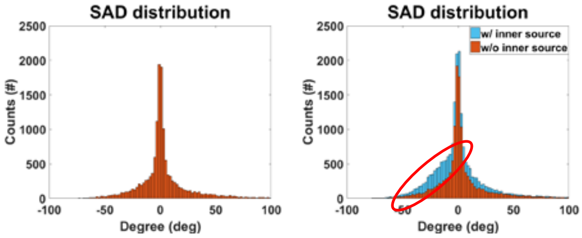
The SAD distributions with and without the inner source were compared as shown in Fig. 4. Fig. 4(a) indicates that the SAD distribution, without the inner source in the waste drum, is conversed on about 0^o. The SAD distribution with the inner source is seemed to be somewhat broaden and not be conversed on 0° (Fig. 4(b)). Hence, it is important to block the events, which the red circle line indicates in Fig. 4(b). For this, we used the SAD window of −5° to +5° in the process of CT image reconstruction.

We obtained the CT images with and without the inner source in the standard phantom (Fig. 5). It was shown that the use of the SAD window in the Compton gamma CT substantially enhances image quality by blocking the effect of the other gamma-ray source which would worsen the image quality.



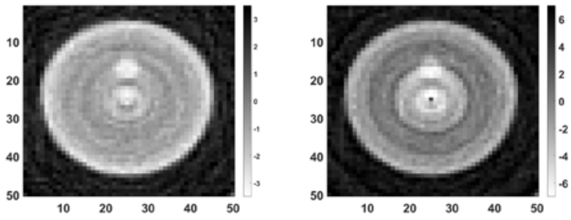
(a) (b)

Fig. 3. Obtained CT images with LACC (a) and conventional gamma CT system (b).



(a) (b)

Fig. 4. Obtained SAD distribution without inner source (a) and with inner source (b).



(a) (b)

Fig. 5. Obtained CT images with SAD window (a) and without SAD window (b) for condition of inner source existing in waste drum.

The LACC seems to have the ability to get the attenuation map of the waste drum without any additional equipment. It is also possible to use the scatter and the absorber detector alone as a gamma CT system based on electronic collimation. This could be an option to increase the efficiency of the LACC as gamma CT. In addition, the size of detectors is recommended to be larger because it is important to reduce the number of projection positions for gamma CT. For this reason, The LACC will have the strength to obtain the attenuation map in the waste drum.

4. Conclusions

In the present study, we proposed a new gamma CT method based on Compton kinematics and estimated the feasibility of the LACC for gamma CT. The results show that Compton gamma CT is able to block the scattered events and other gamma events effectively. It was confirmed that the LACC can be used to obtain the attenuation map in the waste drum using. Although a small-sized Compton camera systems could be applicable for this approach, they will suffer from small field-of-view and low efficiency. In this case, it is inevitable to translocate the Compton camera in order to get sufficient projection data for a number of projection positions, in that the area of the detectors is limited to cover the waste drum. A remarkable feature of this work is that the LACC can obtain the hot spot image, as well as attenuation map distribution in the waste drum, not requiring additional equipment. Attenuation map in the waste drum will provide an accurate system matrix, which enable us to get high-quality hot spot images and to estimate activity in the waste drum as well. In the near future, using Monte Carlo simulation, we will confirm the feasibility of the LACC system to localize the hot spot distribution and to get the attenuation map simultaneously in the waste drum.

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