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Feasibility study on Compton imaging for visualization of flow patterns using radiotracers

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ABSTRACT: The radiotracer technique could be used in studies on multiphase flow systems by three-dimensional visualization of flow patterns, and, relatedly, there have been attempts to develop an industrial-purpose single photon emission computed tomography (SPECT) system. Compton cameras also have a great potential for industrial applications, due specifically to their inherent three-dimensional imaging capability, multi-tracing capability, and higher imaging sensitivity than imaging devices based on mechanical collimation. In the present study, the feasibility of Compton imaging for visualization of detailed flow patterns was determined using a Geant4 Monte Carlo simulation toolkit. The Compton camera considered is a double-scattering type consisting of three gamma-ray detectors: two double-sided silicon strip detectors (DSSDs) as scatterer detectors and one NaI(Tl) scintillation detector as an absorber detector. The results showed that the three-dimensional source distributions can be determined with the Compton camera under various source conditions, including a point source at the center, and two cylinderial volume sources of different dimensions or energies.

KEYWORDS: Compton imaging; Inspection with gamma rays

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Contents

1 Introduction

Visualization of flow patterns in an industrial process unit allows for detection of flow maldistributions in a multiphase system as well as for effective design and optimization of an industrial process. For the purposes of visualization, there have been attempts to develop an industrial single photon emission computed tomography (SPECT) system to visualize complicated flow patterns using gamma radiotracers [1, 2]. Compton cameras [3] also have great potential for industrial applications, owing to (1) an inherent three-dimensional imaging capability without object rotation; (2) a higher imaging sensitivity and wider field-of-view compared with imaging devices based on mechanical collimation; (3) a capability of tracing multiple radioisotopes at the same time; and (4) a higher imaging resolution for higher-energy gamma ray sources. These advantages mean that a Compton camera can operate in a very limited space while providing reasonable performance. In the present study, the feasibility of Compton imaging for visualization of detailed flow patterns was evaluated with a Geant4 detector simulation toolkit [4, 5].

2 Simulation geometries

The Compton camera considered in the present study, a double-scattering type and recently developed as a prototype system, consists of three gamma-ray detectors: two double-sided silicon strip detectors (DSSDs) as scatterer detectors and one NaI(Tl) scintillation detector as an absorber detector [6, 7]. Provided that the deposited energies in the component detectors and the tracks of the scattered photons can be accurately determined, the gamma-ray source can be three-dimensionally localized from three or more conical surfaces. The vertex and axis of each conical surface is determined by the interaction locations in each of the scatterer detectors, while the half-angles of the cones are calculated, according to Compton kinematics, with the energy of the source photon (or as the sum of the deposited energies in all of the component detectors) along with the deposited energy in the first scatterer detector. The DSSDs are 10 cm $\times$ 10 cm $\times$ 0.05 cm in size, with 128 strips on each side. The interaction position resolution is, therefore, 760 μm $\times$ 760 μm $\times$ 500 μm. The trajectory of a scattered photon can be determined accurately by measuring the two interaction locations within the two high-spatial-resolution scatterer detectors, in which case high

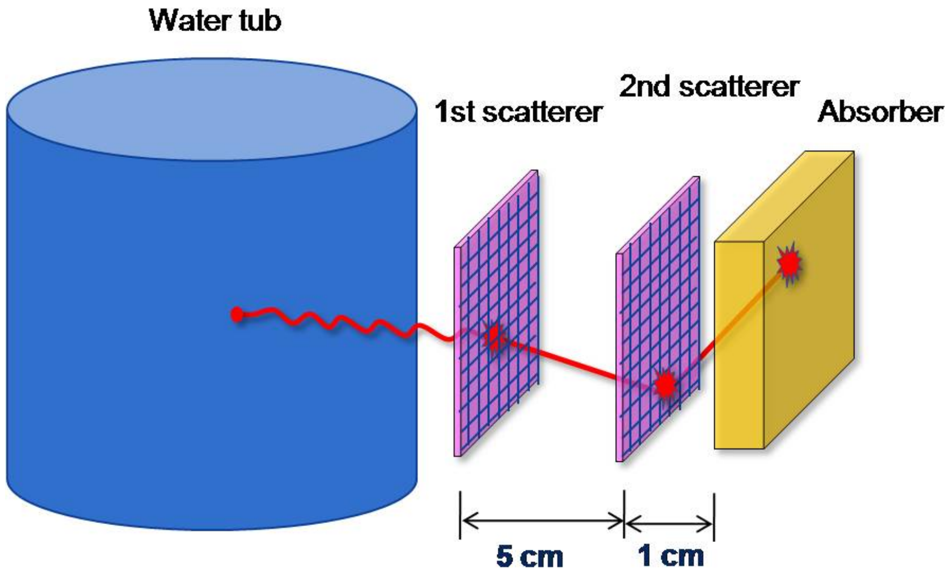

Figure 1. Simulation geometry. The double-scattering Compton camera used in the simulations consists of double-sided silicon strip detectors (DSSDs) as scatterers and an NaI(Tl) scintillation detector as an absorber.

imaging resolution can be acheived. The NaI(Tl) scintillation detector is 10 cm $\times$ 10 cm $\times$ 5 cm in size, and is used, as the absorber detector, to determine the energy of double-scattered photons. The absorber detector in this type of Compton camera, in fact, is used only for energy gating, which is a selection condition to be an "effective event" (that is, the sum of the deposited energies in the three component detectors should match the source energy within a given margin). In the present study, all of the performance-related parameters were considered in the Monte Carlo simulations, including the details of the detector geometry, the energy resolutions of the component detectors, the discrimination level in energy measurement, and Doppler broadening in the Compton scattering process [8]. In the simulations, gamma sources were placed in a cylindrical acryl tub (15 cm diameter $\times$ 30 cm height) filled with water. Three source conditions were considered: (1) a point source of 511 or 1332 keV located at the center of the water tub, (2) two cylindrical volume sources of 511 keV having different dimensions and opposite directionalities, each located 5 cm from the center, and (3) two cylindrical volume sources of 511 and 1332 keV vertically connected with each other. The dimensions of the volume sources were 3 cm (D) $\times$ 10 cm (H) and 5 cm (D) $\times$ 10 cm (H) under condition (2), and 3 cm (D) $\times$ 5 cm (H) under condition (3). The Compton images were reconstructed using the maximum-likelihood expectation-maximization (ML-EM) algorithm [9, 10]. Figure 1 shows a schematic of the simulation geometry for a centered point source.

3 Results and discussion

Figure 2 shows the reconstructed Compton images and their profiles along the central axis (y=0). The imaging resolutions for the point source, obtained from Gaussian fitting to the profiles, were 11.2 and 6.2 mm FWHM for the energies of 511 and 1332 keV, respectively. Clearly, that the Compton camera could effectively image the point source located at the center of the water tub. In

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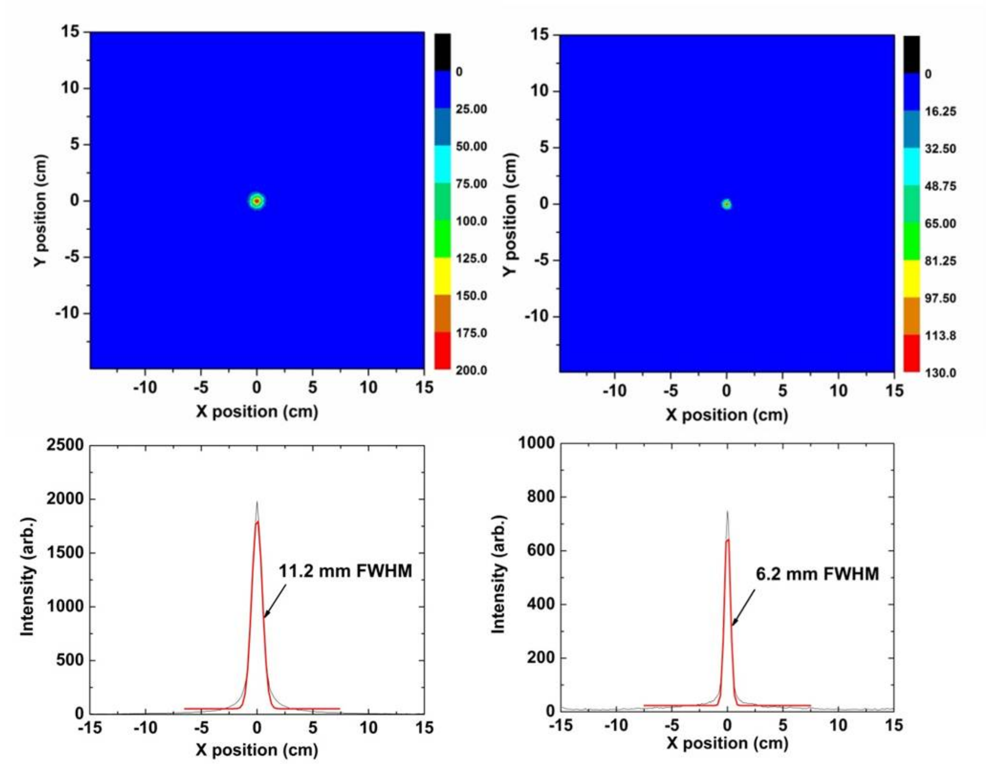

Figure 2. Reconstructed Compton images and their profiles for 511 (left) and 1332 keV (right) point source.

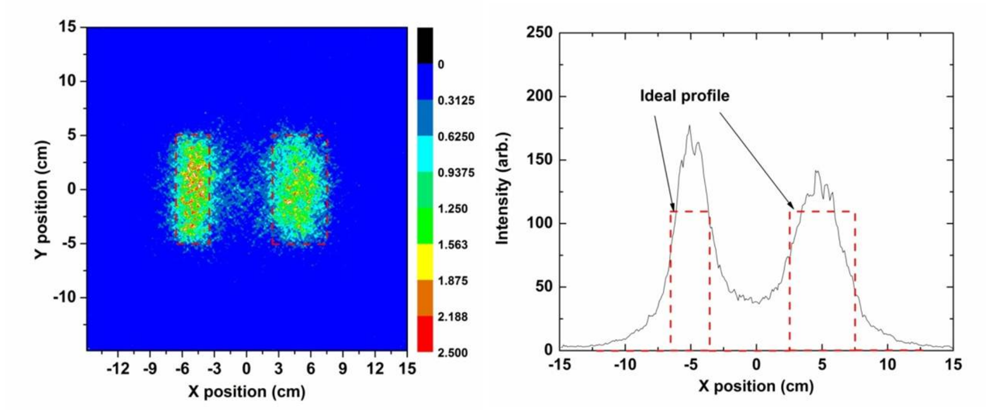

Figure 3. Reconstructed Compton image (left) and its profile (right). The red lines on the profile show the actual source dimensions and locations.

Compton imaging, most events that undergo Compton scattering inside a phantom are not recorded as an effective event, due to the sum-energy gate mentioned earlier; hence, the source location can easily be determined in three-dimensional space, even when the source is deeply located. The imaging sensitivity, however, is lower than that in the case of a shallow source. Figure 3 shows the reconstructed Compton image and its profile along the central axis (y=0) under source condition (2), that is, two volume sources of different dimensions. The red lines shown in the profile

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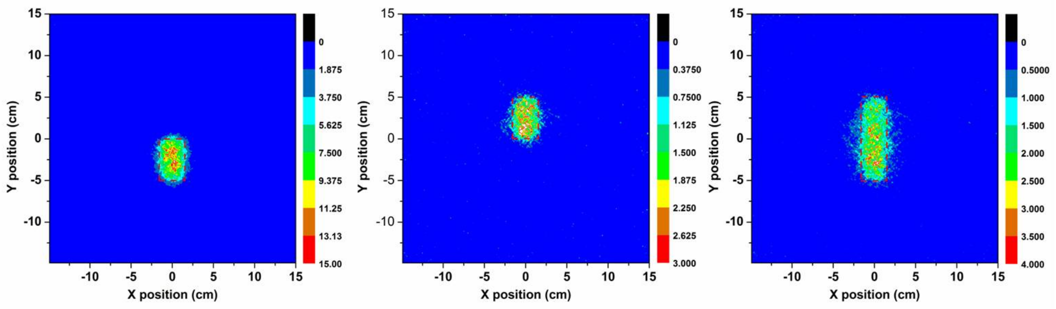

Figure 4. Reconstructed Compton images for source energies of 511 keV (left), 1332 keV (middle), and both (right). The red lines show the actual source dimensions and locations.

represent the actual source regions of the cylindrical volume sources. The result clearly shows that the sources were successfully identified in the reconstructed image; this indicates that Compton imaging can be used effectively, in industrial applications, for visualization of gamma radioisotope distributions in water tub. Figure 4 shows the Compton images under source condition (3). The images confirm that volume sources of different energies can be imaged separately by single measurement with the Compton camera.

Imaging sensitivity is one of the most important parameters in this application. In Compton imaging, it is defined as the ratio of the number of recorded effective events to the number of gamma rays emitted from the source. The calculated imaging sensitivities in the present study were on the order of 10^{-6} for the three source conditions. Therefore, if 27 DSSD detectors (in $3 \times 3 \times 3$ configuration) are used for each of the scatterer detectors, the imaging sensitivity will be about 10^{-3}. Because the number of effective events required for a Compton image typically is about 10^4, a total of 10^7 primary gamma rays will be sufficient for determination of the source distribution. If data is obtained for 5 s, the required source activity would be 2×10^6 Bq (=54 μCi), assuming one photon per each disintegration. In this light, it is expected that with the data acquisition time of 5 s, the source distribution could be determined, provided that the source activity in the field-of-view maintains a few tens of μCi.

4 Conclusions

In the present study, the feasibility of double-scattering-type Compton imaging for visualization of flow patterns was determined by Monte Carlo simulations that predicted the camera's imaging performance for gamma sources in a water tub. A tomographic imaging device using gamma radiotracers can play an important role in industrial applications by detecting flow maldistributions in a multiphase system. Visualization of flow patterns also can be used to design and optimize industrial processes. The Compton camera represents a promising industrial applicability, because it can be used in a very limited space while providing three-dimensional images from a fixed position with reasonable imaging resolution. In addition, there is almost no limitation on the gamma-ray energy injected into the industrial process. The multi-tracing capability of the Compton camera is useful also for characterizing a mixing reactor, specifically by injecting different kinds of radioisotopes for each fluid.

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