CIS: A GUI-BASED SOFTWARE SYSTEM FOR MONTE CARLO SIMULATION OF COMPTON CAMERA

RADIATION MEASUREMENTS AND INSTRUMENTATION

KEYWORDS: *Compton camera, GEANT4, graphical user interface*

SE HYUNG LEE *Hanyang University, Department of Nuclear Engineering 17 Haengdang-dong, Seongdong-gu, Seoul 133-791, Korea* and *University of Ulsan, College of Medicine, Asan Medical Center Department of Radiation Oncology, 388-1 Pungnap-2dong, Songpa-gu Seoul 138-736, Korea*

HEE SEO and JIN HYUNG PARK *Hanyang University Department of Nuclear Engineering, 17 Haengdang-dong, Seongdong-gu Seoul 133-791, Korea*

SUNG HO PARK *University of Ulsan, College of Medicine Asan Medical Center, Department of Radiation Oncology, 388-1 Pungnap-2dong Songpa-gu, Seoul 138-736, Korea*

JAE SUNG LEE *Seoul National University, Department of Nuclear Medicine and Interdisciplinary Program in Radiation Applied Life Science 28 Yeongeon-dong Jongno-gu, Seoul 110-744, Korea*

JU HAHN LEE and CHUN SIK LEE *Chung-Ang University, Department of Physics 221 Heukseok-dong, Dongjak-gu, Seoul 156-756, Korea*

CHAN HYEONG KIM* *Hanyang University, Department of Nuclear Engineering 17 Haengdang-dong, Seongdong-gu, Seoul 133-791, Korea*

Received April 17, 2008
Accepted for Publication February 20, 2009

In the present study, a Compton camera simulator based on the GEANT4 detector simulation tool kit and MATLAB™, and designated the Compton Imaging Simulator (CIS), was developed. The software system encompasses a simulator, an image-reconstruction algorithm, and a data analysis tool. The computational time to obtain a sufficient number of Compton scattered data was dramatically reduced using the source-biasing and exponential transform techniques. Also, a four-dimensional Monte Carlo simulation capability was incorporated. A comparison of the simulation results with the experimental results shows that the CIS accurately simulates the Compton camera.

I. INTRODUCTION

Compared with conventional gamma-ray imaging devices, the Compton camera has several advantages, including high imaging sensitivity, a multitracing functionality, and the capability of three-dimensional (3-D) imaging from a fixed position. Even though the Compton camera concept was introduced many years ago,[1,2] the development of high-resolution Compton cameras for medical applications became possible only very recently. Currently, several different types of Compton cameras are being developed by many different research groups.[3–6]

*E-mail: chkim@hanyang.ac.kr

In developing a high-performance Compton camera, detector simulation plays a crucial role owing to several facts:

1. The experimental approach is usually very time-consuming and costly.

2. The effects of the various detector parameters on the performance of the Compton camera can be simulated very accurately for all possible conditions, which usually is not possible in an actual experiment.

3. Simulated data, with and without noise, are necessary for the development of advanced image-reconstruction algorithms.

The GEANT4 object-oriented detector simulation tool kit[7,8] is usually used to model a Compton camera. In order to use that tool kit, however, the user must define and implement several classes in C++ because GEANT4 provides only a tool kit, not an executable application. Therefore, in using GEANT4, significant error-prone hard coding and facilities in Monte Carlo techniques and C++ programming are also required.

To address these problems and, thereby, facilitate the simulation of Compton cameras, the present study developed a Monte Carlo–based, user-friendly Compton camera simulator in the form of a graphical user interface (GUI) and designated the Compton Imaging Simulator (CIS). The simulator was developed based on the GEANT4 tool kit and MATLAB™ and was tested against an experiment result for a point source.

II. MATERIALS AND METHODS

GEANT4 is a general-purpose Monte Carlo radiation transport simulation tool kit widely used in many fields including high-energy particle physics, astrophysics, radiation detector development, radiation shielding, medical physics, and others. In GEANT4, particle interactions are simulated very accurately for photon energies down to a few hundred electron volts in the low-energy electromagnetic physics package. The Doppler energy broadening effect, which significantly affects the imaging resolution of a Compton camera for low-energy photon sources, is simulated in the Penelope physics model, and it also can be modeled in the low-energy electromagnetic physics package after the GEANT4 9.2 version. Furthermore, GEANT4 also has the capability of four-dimensional (4-D) Monte Carlo simulation, in which the source, phantom, and detector geometries are continuously moving.

The GUI environment was designed with MATLAB™, which has many useful image processing and 3-D visualization functionalities as well as GUI construction tools. The GUI was then connected with Cygwin, which is commonly used for GEANT4 simulation in a Microsoft Windows environment.

The List-Mode Expectation Maximization (LM-EM) algorithm,[9–11] an iterative method that, compared with the simple back-projection method, significantly improves imaging resolution, was incorporated into the CIS in order to reconstruct the Compton image. Gaussian fitting was used to evaluate the resolution of the Compton image with respect to the full-width at half-maximum (FWHM) of the reconstructed image.

The exponential transform technique, which artificially increases the probability of Compton scattering in the scatterer detector, and the source-biasing technique, which imposes a limit on the direction of the primary photons from the source, were used in the CIS to enhance the simulation speed. Finally, in order to simulate wobbling or moving detectors during measurement, a 4-D Monte Carlo simulation capability was also incorporated.

III. RESULTS

Figure 1 shows the input window of the CIS. The window consists of four input categories. The first category receives the source-related information including the source photon energy, source shape, source dimensions, position, and source-biasing angle. The second category receives the phantom-related information including the phantom shape, dimensions, material composition, and position. The third category receives the scatterer and absorber detector parameters that determine the performance of a Compton camera. The third category also receives the dimensions, positions, material compositions, discrimination levels, energy resolutions, and spatial resolutions of the component detectors as well as their geometrical configurations of interdetector distance and interdetector angle.

The fourth category receives all other optional information. For example, an ideal Compton camera, which determines the interaction positions and deposited energies in the component detectors with no uncertainty and/or is not affected by the Doppler energy broadening effect, can be modeled through this category. The noise-free data obtained from an ideal detector simulation are usually used in developing advanced image-reconstruction algorithms. The 4-D Monte Carlo simulations in which the detector geometry continuously changes during simulation can be also modeled through this category.

The user can visually check the geometries of the source, phantom, and detectors through the provided image, which is simultaneously updated when the input parameter is changed, on the CIS (Fig. 2). This will contribute to reduce possible user errors in the geometry implementation.

After all of the input-window parameters are defined, the simulation can be initiated by clicking the "Run"

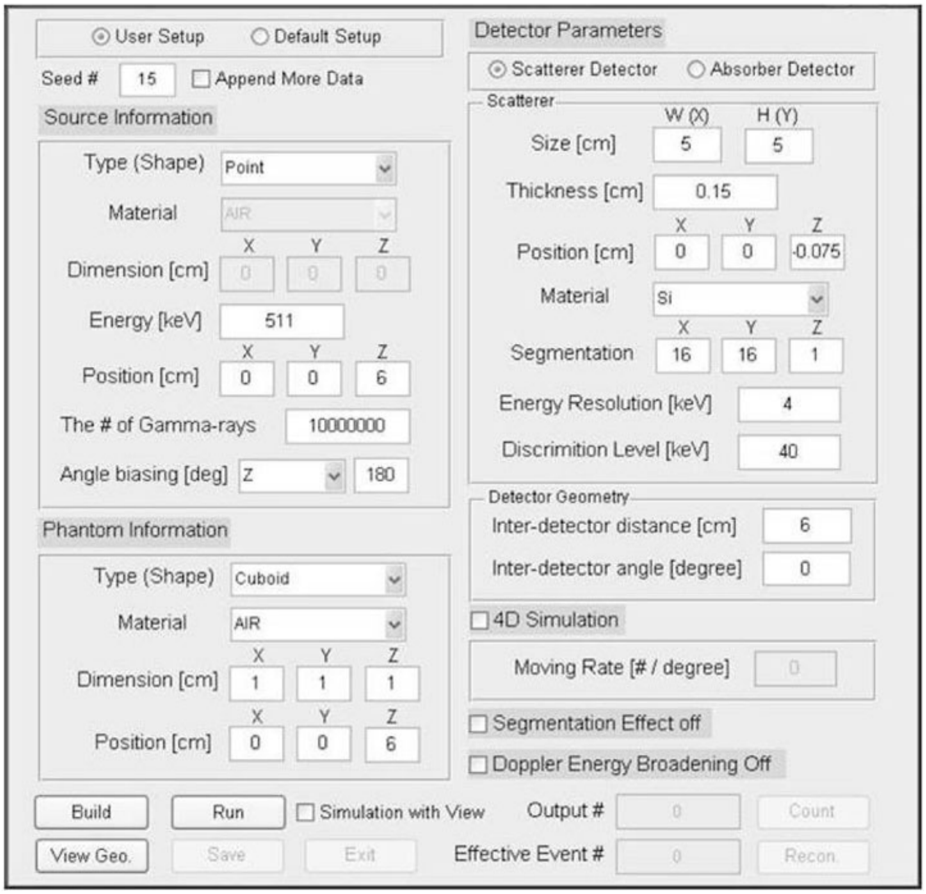

Fig. 1. Input window of CIS.

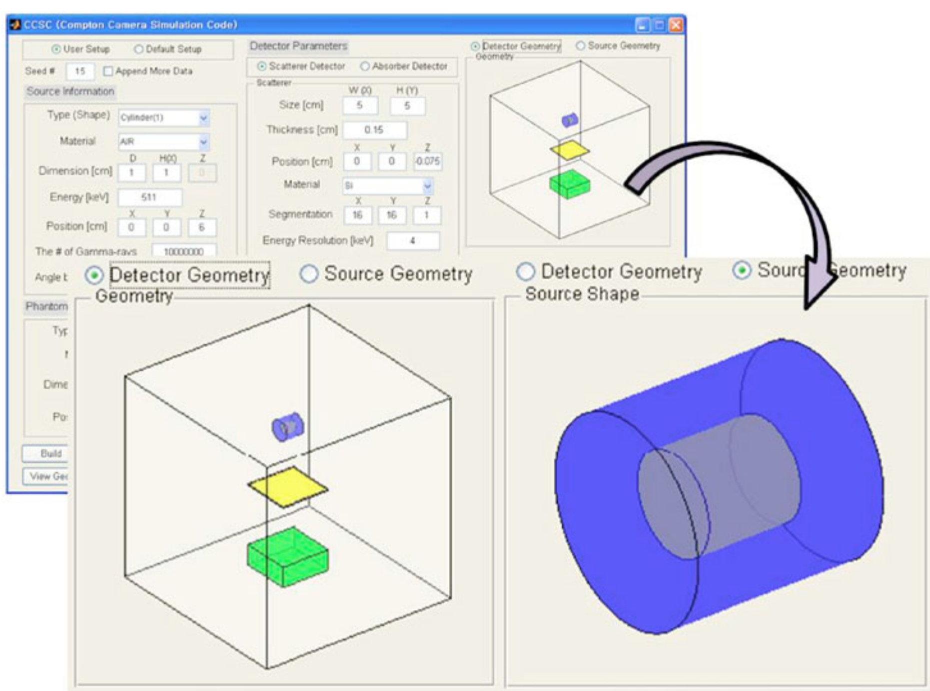

Fig. 2. The 3-D visualization of source, phantom, and component detector geometries in CIS.

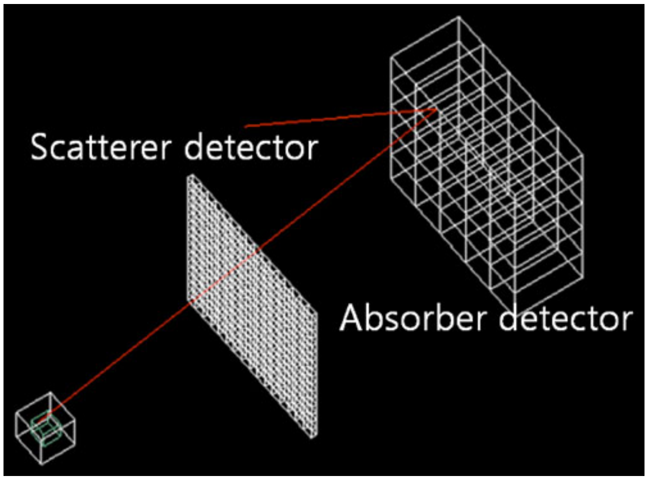

Fig. 3. The 3-D visualization of GEANT4 simulation geometry and particle track by OpenGL.

button, which will generate and compile the source files and execute the particle transport simulations. The trajectories of the particles under simulation, as well as the simulation geometry, can also be visualized using the OpenGL visualization driver (Fig. 3).

Finally, the calculated data generated from the Monte Carlo simulation are supplied to the LM-EM image-reconstruction algorithm, which will generate a Compton image. The imaging resolution (FWHM) is automatically calculated by Gaussian-fitting the reconstructed image. Examples of a reconstructed image, its profile, and analysis data are shown in Fig. 4.

Figure 5 shows the Compton images for a ^{131}I point source obtained by the CIS and from an actual experiment. The experiment was performed with a tabletop Compton camera consisting of a double-sided silicon strip detector (as the scatterer detector) and a 25-segmented germanium detector (as the absorber detector). It can be seen that the simulated image obtained from the CIS agrees well with the measured image. The imaging resolutions obtained from the CIS and the experiment were 6.9 mm FWHM and 6.6 mm FWHM, respectively. Figure 6 shows the Compton images for a plane source (disk type, diameter of 5 cm) and volume source (cylinder type, diameter of 3 cm and height of 10 cm) obtained from the CIS.

The computational time to obtain the sufficient number of Compton scattered data was dramatically reduced using the source-biasing and exponential transform techniques. For example, in case of the source biasing of 40 deg and the source energy of 511 keV, the computational time to obtain the same number of Compton scattered data was reduced by a factor of ~170, which, however, strongly depends on the simulation geometry and the source energy.

IV. CONCLUSIONS

In the present study, a GUI-based Compton camera simulator, the CIS, was developed based on the GEANT4 tool kit and MATLAB™. The simulator was found to be very accurate, efficient, and easy to use, providing 4-D Monte Carlo capabilities as well as additional image-reconstruction and image analysis capabilities. This

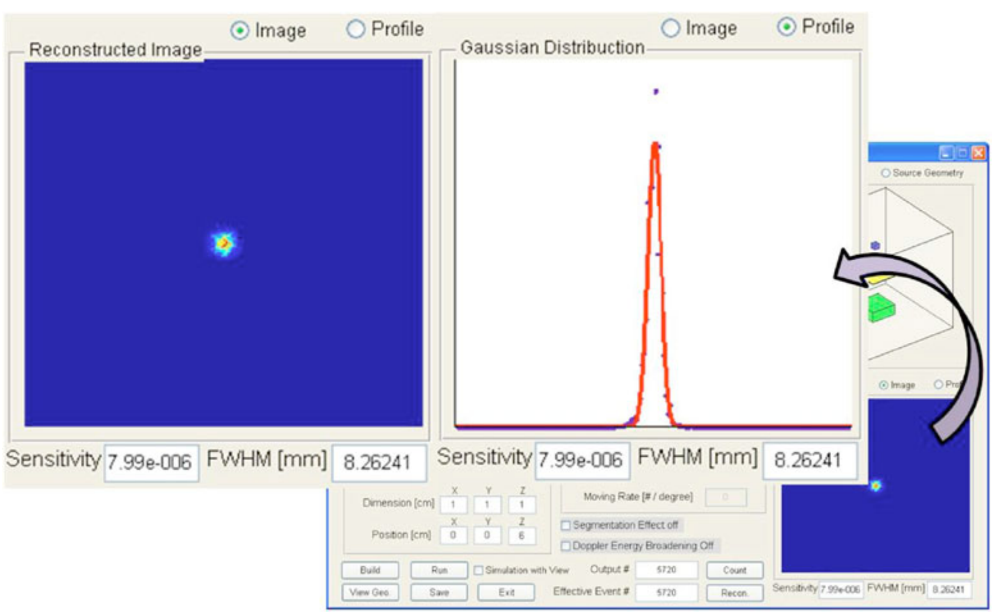

Fig. 4. Compton image, its profile, and analysis data for a point source.

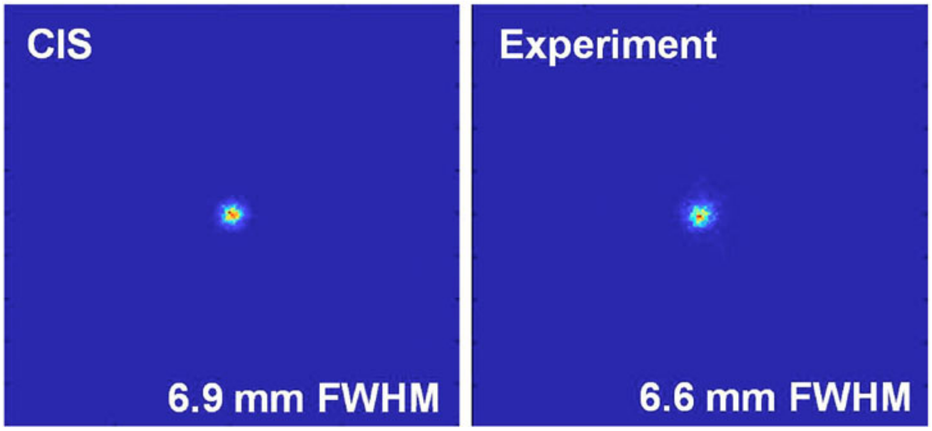

Fig. 5. Compton images obtained from CIS and experiment for same condition.

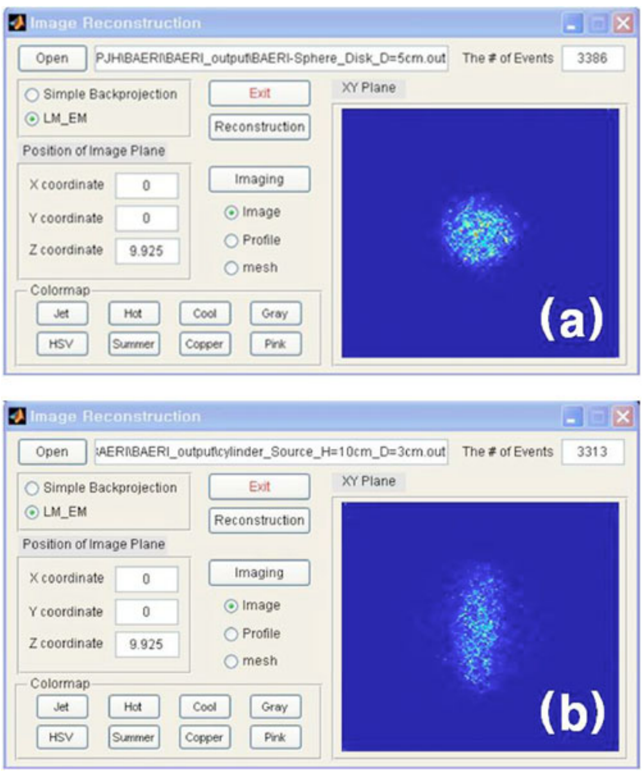

Fig. 6. Compton images for (a) a disk source (plane) and (b) cylinder source (volume) obtained from CIS.

simulator is believed to be especially useful for Compton camera optimization, in which typically a number of similar cases are simulated and only one or two parameters are changed. The CIS will be registered and distributed to the interested users in the near future after implementing some timing properties of the Compton camera system including the dead time and timing resolution of the component detectors, random coincidence events, etc.

ACKNOWLEDGMENTS

This work was supported by the Nuclear Research and Development Program in Korea through the Basic Atomic Energy Research Institute; the Basic Research Program; and the Korean Ministry of Knowledge Economy (2008-P-EP-HM-E-06-0000)/Sunkwang Atomic Energy Safety Co., Ltd.

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