# AID – A Novel Method for Improving the Imaging Resolution of a Table-Top Compton Camera

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***Abstract*—A Compton camera is usually composed of a scatterer detector and an absorber detector. The interaction position resolution of the absorber detector is the critical or limiting detector parameter that most seriously affects the imaging resolution of the table-top Compton camera currently under development in our group. Currently, it is assumed that all interactions occur at the centers of the detector segments of the absorber detector (25-segmented germanium detector), which is a simple but obviously not the best practice, considering that the interaction depths of the photons in the absorber detector, especially of low-energy photons, are not distributed uniformly. More photons have interaction in the front region of the detector due to the limited penetrating depth of the photons. Therefore, the present study developed a novel, "average interaction depth (AID)" method, which improves the imaging resolution of Compton camera by additionally considering the average interaction depth of the incident photon in the absorber detector. Simulations with Geant4 showed that the imaging resolution of the Compton camera can be significantly improved by using the AID method. For example, the resolution for a 511 keV $\gamma$ point source was improved from 9.9 mm to 7.6 mm in full width at half maximum (FWHM). For a 364 keV $\gamma$ point source, the improvement was even more significant from 11.4 mm to 7.2 mm.**

***Index Terms*—Absorber, Compton camera, Geant4, interaction depth.**

## I. Introduction

THE Compton camera, which, in principle, can provide both high imaging resolution and sensitivity, is considered to be a very promising imaging device in the field of nuclear medicine and molecular imaging [1]–[4]. The Compton camera has been used in astrophysics as a gamma-ray telescope [5], and has also been considered to be a promising option for the localization of high-energy gamma sources in homeland security applications [6]. The advantages of the Compton camera over conventional gamma-ray imaging devices include portability, 3-D imaging capability from a fixed position, wide energy range applicability, simultaneous multiple radioisotope tracing capability, and others. Fig. 1 illustrates the operative principle behind the Compton camera with its scatterer and absorber detectors.

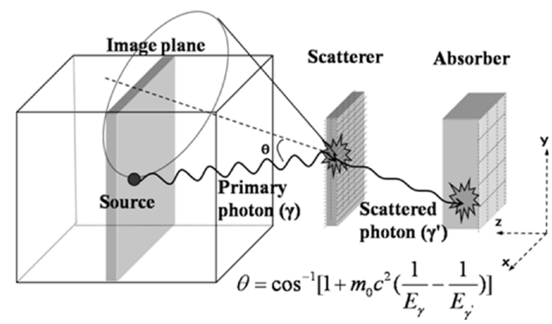


Fig. 1. Principle of a Compton camera. The Compton scattering angle $\theta$ is the opening angle of the cone. The line joining two interaction positions in each detector is the axis of the cone, and the interaction position in the scatterer detector is the apex of the cone. The intersection of many of these cones indicates the source location. In this study, the image plane has a dimension of 20 cm $\times$ 20 cm and a pixel size of 0.1 cm $\times$ 0.1 cm. The source-to-scatterer distances (SSDs) of 6, 10, 15, and 20 cm for each point source were studied, and the image plane in each case was placed at the corresponding source distance.

The imaging resolution is affected by several parameters such as the source energy, the energy resolutions and the interaction position resolutions of the component detectors, and the degree of Doppler energy broadening of the Compton scattering in the scatterer detector [7]. For the table-top Compton camera, currently under development in our group, the interaction position resolution of the absorber detector (25-segmented germanium detector) is the detector parameter that most seriously limits the imaging resolution [8]. Currently, it is assumed that all interactions occur at the centers of the 25 detector segments of the absorber detector. It is a simple but obviously not the best choice, considering that the interaction depths of the photons in the absorber detector are not distributed uniformly. That is, the photons, especially the low-energy photons, tend to have interactions in the portion of the detector volume closer to the source due to the limited penetrating depth of the photons.

The objective of this study was to develop a new, "average interaction depth (AID)" method, which improves the imaging resolution of the Compton camera by additionally considering the interaction depth of the photon in the absorber detector. In this method, the interaction depth of the incident photon is not measured, but estimated from the simulated interaction-depth data for the same photon energy in the same germanium detector, in order to improve the imaging resolution.

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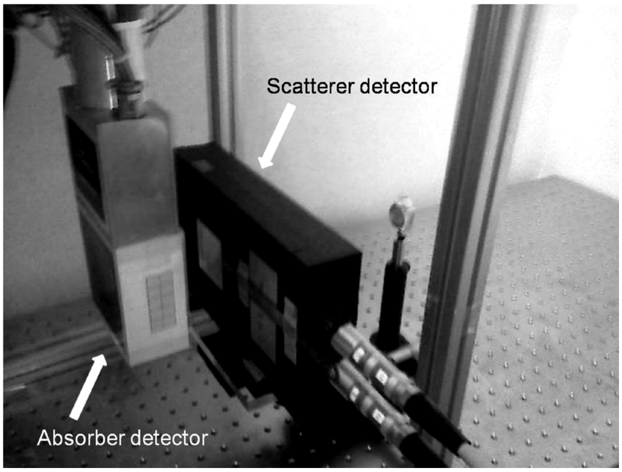


Fig. 2. Table-top Compton camera which consists of a double-sided silicon strip detector as a scatterer detector and a 25-segmented germanium detector as an absorber detector. The dimensions of the scatterer and absorber detectors are 5 cm × 5 cm × 1.5 cm and 5 cm × 5 cm × 2 cm, respectively.

## II. Material and Methods

The table-top Compton camera considered in this study consists of two planar-type position-sensitive semiconductor detectors: a double-sided silicon strip detector (DSSD, 50 mm × 50 mm × 1.5 mm), manufactured by Micron Semiconductor, as the scatterer detector, and a 25-segmented germanium detector (SEGD, 50 mm × 50 mm × 20 mm) manufactured by Eurisys-Canberra, as the absorber detector (Fig. 2). The detailed configuration of the Compton camera can be found elsewhere [9].

Because the scatterer detector has a total of 16 strips on each side, and is only 1.5 mm thick, the scattering position can be determined very accurately. The segmentation of the absorber detector is, however, relatively coarse ($5 \times 5$ segments) in the planar direction, the detector is as much as 20 mm thick, and thus the interaction position of an incident photon in the absorber detector cannot be determined accurately. The spatial resolutions of the scatterer and absorber detectors are about $3 \times 3 \times 1.5\ \mathrm{mm}^3$ and $10 \times 10 \times 20\ \mathrm{mm}^3$, respectively. Also, as already stated, the use of the central points of the detector segments of the absorber detector as the interaction locations, though convenient, is not the best practice. In the present study, therefore, the average depth of the interaction locations in the absorber detector, instead of the depth at the central point ($= 10\ \mathrm{mm}$), was used as the interaction depth in order to improve the imaging resolution of Compton camera for 364 keV and 511 keV point sources.

The Geant4 detector simulation toolkit [10] was used to calculate the distribution of the interaction points in the absorber detector for each source-to-scatterer distance (SSD) and source energy. More than $1.5 \times 10^5$ effective events, which meet the requirement of the energy gate and coincidence detection, were simulated and analyzed for each case to find the relationship between the average depth of the interaction points and the deposited energy in the absorber detector. Note that the deposited energy in the absorber detector is essentially equal to the incident photon energy for a full-energy absorption in the absorber detector. If a photon has multiple interactions in a single segment of the absorber detector, it was assumed that the total energy deposited in the segment was deposited at the first interaction point in the segment.

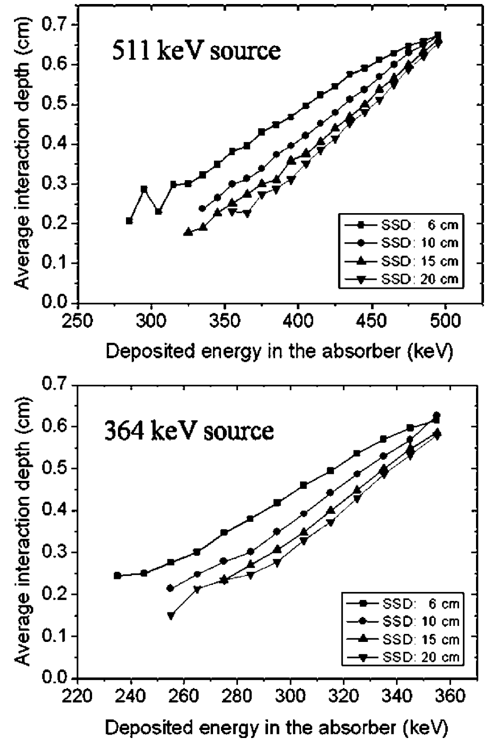


Fig. 3. Average depth of interaction points in the absorber detector as a function of the energy deposited in the absorber detector for 511 keV (top) and 364 keV (bottom) point source at 6, 10, 15, and 20 cm from the scatterer detector.

To reconstruct the Compton scatter image, the list-mode expectation maximization (LM-EM) algorithm was used [11], which is assumed to be more suitable for Compton camera image reconstruction than the conventional EM method, considering that the number of events is much smaller than the number of possible detection bins. The iteration was performed 5 times using $1.0 \times 10^4$ Compton-scattered events.

A total of eight source conditions, that is, 511 keV ($^{18}$F) and 364 keV ($^{131}$I) $\gamma$ point sources as well as the SSDs of 6, 10, 15, and 20 cm for each point source, were simulated in the present study. The distance from the scatterer detector to the absorber detector was fixed at 6 cm. The imaging resolution of the Compton camera was evaluated in full width at half maximum (FWHM) of the cross-sectional profile through the peak for the 2-dimensional Compton scatter image of the point source.

Background events were not included in this simulation study considering that the Compton imaging, which employs both coincidence counting and energy gating, are not very sensitive to these.

## III. Results

Fig. 3 shows the average depth of the interaction locations in the absorber detector as a function of the energy deposited in the absorber detector for different photon energies (511 keV and 364 keV) and different SSDs ($= 6, 10, 15,\ \mathrm{and}\ 20\ \mathrm{cm}$).

TABLE I
CALCULATED CURVE FITTING PARAMETERS FOR DIFFERENT SOURCE CONDITIONS.

| Source energy | Source-to-scatterer distance (SSD) | Curve fitting parameters | | | |
|---|---|---|---|---|---|
| | | a | b | c | b |
| 364 keV | 6 cm | 6.34 | -0.068 | $2.40 \times 10^{-4}$ | $-2.68 \times 10^{-7}$ |
| | 10 cm | 3.61 | -0.037 | $1.25 \times 10^{-4}$ | $-1.24 \times 10^{-7}$ |
| | 15 cm | 12.5 | -0.123 | $3.98 \times 10^{-4}$ | $-4.13 \times 10^{-7}$ |
| | 20 cm | 1.04 | -0.010 | $2.92 \times 10^{-5}$ | $-1.27 \times 10^{-8}$ |
| 511 keV | 6 cm | 1.26 | -0.012 | $3.72 \times 10^{-5}$ | $-3.28 \times 10^{-8}$ |
| | 10 cm | 1.34 | -0.012 | $3.44 \times 10^{-5}$ | $-2.69 \times 10^{-8}$ |
| | 15 cm | 0.50 | -0.005 | $1.62 \times 10^{-5}$ | $-1.03 \times 10^{-8}$ |
| | 20 cm | 4.72 | -0.035 | $8.53 \times 10^{-5}$ | $-6.30 \times 10^{-8}$ |

The results show that the average interaction depth (AID) of the incident photons monotonically increases with the increase of the deposited energy, which is due to the fact that higher-energy photons have higher penetrating depth. For the same deposited energy in the absorber detector, the AID is smaller for the larger SSDs, which is mainly due to the relatively high discrimination level of the scatterer detector (20 keV). This is the case because the angular coverage of the incident photons to the scatterer detector becomes narrower, approaching the normal direction, with the increase of the SSD, which then results in the increase of the average incident angle of the scattered photons on the absorber detector. This happens because a photon must deposit a relatively large amount of energy in the scatterer detector and correspondingly scatter at a relatively large angle in order to overcome the energy discrimination level of the scatterer detector and be registered as an effective event. If the scattering angle is small, then, the photon will deposit only a small amount of energy to the scatterer detector and simply be ignored by the energy discrimination mechanism. Therefore, the increase of the SSD results in the increase of the average incident angle of the scattered photons on the absorber detector, which then results in the decrease of the interaction depth in the absorber detector.

The relationship between the AID and the deposited energy ($=$ the incident photon energy) in the absorber detector was fitted by simple third order polynomial least-squares regression fitting on the Geant4-simulated data as follows:

$$AID = a + bE + cE^2 + dE^3 \tag{1}$$

where the AID is in cm, E is the energy deposited in the absorber detector in keV, and a, b, c, and d are the fitting parameters, the calculated values of which are given in Table I.

Fig. 4 shows the improvement of the imaging resolution resulting from the use of the AID for the 511 keV (top) and 364 keV (bottom) $\gamma$ point sources. The SSD is 6 cm. For the 511 keV $\gamma$ point source, the imaging resolution was improved from 9.9 mm to 7.6 mm in FWHM, and for the 364 keV $\gamma$ point source, the improvement was more significant, from 11.4 mm to 7.2 mm.

For the higher-energy photon source (511 keV), the interaction points are rather uniformly distributed in the absorber detector and, therefore, the selection of the central depth ($= 10$ mm) of the absorber detector as the interaction depth might be a reasonable choice. For the lower-energy photon source (364 keV), however, the incident photons tend to interact in the shallow region of the absorber detector, and thus the use of the AID, instead of the central depth ($= 10$ mm), is more effective in improving the imaging resolution of the Compton camera. Thus, the AID method will be more effective for low-energy photon sources of clinical interest such as $^{99m}$Tc (140 keV), $^{123}$I (159 keV), and $^{111}$In (171 and 245 keV).

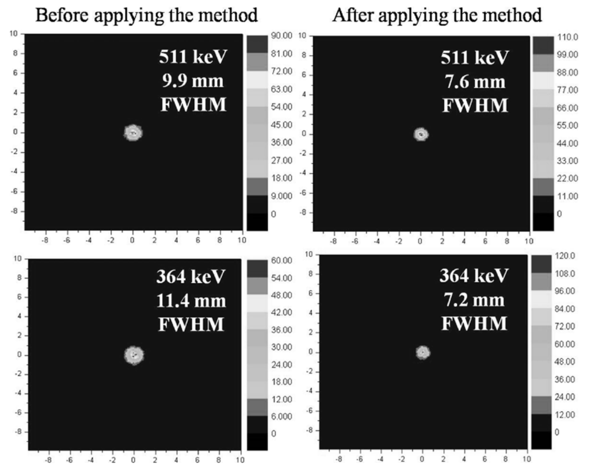


Fig. 4. Compton scatter image and imaging resolution of the table-top Compton camera before (left) and after (right) applying the average interaction depth (AID) method for 511 keV (top) and 364 keV (bottom) $\gamma$ point source at 6 cm from the scatterer detector.

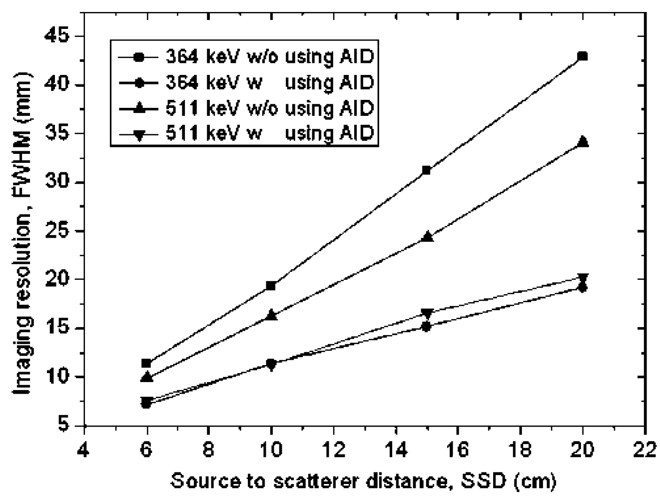


Fig. 5. Imaging resolution of the table-top Compton camera for eight source conditions (SSD $= 6, 10, 15,$ and $20$ cm, source energy of 364 keV and 511 keV) with and without using average interaction depth (AID) method.

Fig. 5 shows contrasting imaging resolutions of the table-top Compton camera, both having used and not having used the AID method for different source conditions in the image-reconstruction process. The result clearly shows that the AID method is more effective for the larger SSDs, in the cases of both the 511 keV and 364 keV photon energies.

The table-top Compton camera under development will be used to determine the location of radiation source, which does not require very high imaging resolution. In addition, the improvement achieved by the AID method is, indeed, enough considering that the spatial resolution of the absorber detector in the planar direction is very low. The use of very sophisticated electronics for more accurate determination of each interaction depth, therefore, is not really necessary in the present system and application.

## IV. Conclusions

In the present study, the imaging resolution of the table-top Compton camera was improved by using the average depth of the interaction locations in the absorber detector, instead of simply assuming the depth at the center of the detector ($= 10\ \mathrm{mm}$) to be the interaction depth. The average interaction depth (AID) method was found to be very effective, especially for low-energy photon sources and for sources relatively separated from the scatterer detector. More sophisticated techniques based on detailed collection-time information of electrons and holes on the opposite sides of the detector can provide better interaction position resolution for each event [12]–[14], but the present study provides a simple but effective means of improving the imaging resolution of the Compton camera, without the need of any sophisticated electronic circuits and/or elaborate experiments.

## References


[1] R. W. Todd, J. M. Nightingale, and D. B. Everett, "A proposed $\gamma$ camera," *Nature*, vol. 251, pp. 132–134, 1974.

[2] M. Singh and D. Doria, "An electronically collimated gamma camera for SPECT," *Med. Phys.*, vol. 10, no. 4, pp. 421–435, 1983.

[3] J. Bernabeu *et al.*, "Development of a high efficiency and high resolution Compton probe for prostate imaging," *Nucl. Instrum. Methods Phys. Res. A*, vol. A527, pp. 58–61, 2004.

[4] S. Motomura, S. Enomoto, H. Haba, K. Igarashi, Y. Gono, and Y. Yano, "Gamma-ray Compton imaging of multitracer in biological samples using strip germanium telescope," *IEEE Trans. Nucl. Sci.*, vol. 54, no. 3, pp. 710–717, Jun. 2007.

[5] V. Schoenfelder *et al.*, "Instrument description and performance of the imaging gamma-ray telescope COMPTEL aboard the Compton gamma-ray observatory," *Astrophys. J. Suppl. Ser.*, vol. 86, pp. 657–692, 1993.

[6] A. S. Hoover, R. M. Kippen, J. P. Sullivan, M. W. Rawool-Sullivan, W. Baird, and E. B. Sorensen, "The LANL prototype Compton gamma-ray imager: Design and image reconstruction techniques," *IEEE Trans. Nucl. Sci.*, vol. 52, no. 6, pp. 3047–3053, Dec. 2005.

[7] A. Zoglauer and G. Kanbach, "Doppler broadening as a lower limit to the angular resolution of next generation Compton telescopes," *Proc. SPIE-Int. Soc. Opt. Eng.*, vol. 4851, pp. 1302–1309, 2003.

[8] S. H. An, H. Seo, J. H. Lee, C. S. Lee, J. S. Lee, and C. H. Kim, "Effect of detector parameters on the image quality of Compton camera for $^{99\mathrm{m}}\mathrm{Tc}$," *Nucl. Instrum. Methods Phys. Res. A*, vol. A571, pp. 251–254, 2007.

[9] J. H. Lee, N. Y. Kim, C. S. Lee, and Z. H. Jang, "Development of the multi-purpose gamma-ray detection system consisting of a double-sided silicon strip detector and a 25-segmented germanium detector," *Nucl. Phys. A*, vol. 758, pp. 150–153, 2005.

[10] S. Agostinelli *et al.*, "GEANT4-a simulation toolkit," *Nucl. Instrum. Methods Phys. Res. A*, vol. A506, pp. 250–303, 2003.

[11] S. J. Wilderman, N. H. Clinthorne, J. A. Fessler, and W. L. Rogers, "List-mode maximum likelihood reconstruction of Compton scatter camera images in nuclear medicine," in *Proc. IEEE Nuclear Science Symp. Conf. Rec.*, Toronto, ON, Canada, Nov. 8–14, 1998, vol. 3, pp. 1716–1720.

[12] M. Momayezi, W. K. Warburton, and R. Kroeger, "Position resolution in a Ge-strip detector," *Proc. SPIE-Int. Soc. Opt. Eng.*, vol. 3768, pp. 530–537, 1999.

[13] M. Amman and P. N. Luke, "Three-dimensional position sensing and field shaping in orthogonal-strip germanium detectors," *Nucl. Instrum. Methods Phys. Res. A*, vol. A452, pp. 155–166, 2000.

[14] E. A. Wulf *et al.*, "Depth measurement in a germanium strip detector," *IEEE Trans. Nucl. Sci.*, vol. 49, no. 4, pp. 1876–1880, Aug. 2002.