

Effect of position resolution on LoR discrimination for a dual-head Compton camera

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Abstract

With the current increase in effective germanium semiconductor detection technology, a positron emission tomography system comprising two opposing HPGe detectors is under development. This type of detection offers not only improvement to some aspects of PET, but also the ability to record single-photon information in the detection process. This information can be used in stand-alone imaging, and also as an additional information source in the PET process. Discrimination based on this single-photon information was proposed; however, the effectiveness of this discrimination is dependent on the resolution of the single-photon information. Simulations of the detection system, in which the positional resolution of the interaction information is variable, was conducted. The single-photon information has then been used in the PET imaging process and its effect on image improvement shown. Much like mechanical collimation, electronic collimation may be used to remove false LoRs from an image, at the expense of efficiency. Moreover, unlike mechanical collimation, this trade off may be dynamically adjusted post data acquisition.

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1. Introduction

With the advent of spatially sensitive semiconductor detection devices, we now have the ability to gain high spatial and spectral information about photon interactions in the detection volume. The SmartPET utilises high-purity germanium orthogonal strip detection devices in a dual-head PET configuration [1]. Spatial and spectral resolutions eliminate the depth of interaction problem inherent in scintillation counters, and also help discriminate against *in vivo* scattered photons in the data set. There is a disadvantage due to the low photoelectric cross-sections of HPGe devices when compared with their scintillating

counterparts, as the total photon energy is often not deposited in the detector.

However, HPGe devices offer such high resolutions that more than one energy deposit can be associated with the path of a single photon during multiple scatters. Such associations allow the imaging of single-photon sources [2]. This process of electronic collimation of single photons will be referred to as Compton Collimation (CC).

While it is understood that CC techniques may be used in the discrimination of some incorrect LoRs from a PET acquisition [3–5], this ability relies on the single-photon information. In the SmartPET this information will come from pulse shape analysis, the complexity of which depends on the resolution desired. Thus it is important to determine how much better the LoR information and final image resolution is for a given decrease in spatial uncertainty.

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2. Incorrect LoRs

In the acquisition of a PET data set, a number of elements can interfere with the integrity of the recorded data, above and beyond detection concerns. Even given perfectly resolved interactions, there is still the possibility of acquiring incorrect LoRs in the final information. This is due to three main effects:

1. randomly coincident LoR endpoints,
2. LoRs detected after intra-object scattering, and
3. confusion as to the primary event in an interaction sequence.

Removal of false LoRs has long been an issue in conventional PET, and mechanical collimation is often utilised to reduce incorrect LoRs from both random and scattering sources. Here electronic collimation is used to the same effect.

The spatial resolution of the interaction detections affects the uncertainty in the cone surface derived from the Compton information [2]. This, in turn, affects the ability to determine whether the associated LoR is adjacent (the condition of LoR validity) to the cone surface. In order to determine the effect of the spatial resolution on the ability to effectively remove false LoRs from the final data set, Receiver Operating Characteristic (ROC) curves have been utilised. The validation is a binary detection task, whereby the angular deviation of the LoR from the cone surface is used as a true/false threshold. As the spatial resolution is lowered, the Area Under the ROC Curve (AUC) is reduced. Therefore, we can quantify the binary detection task as a function of spatial resolution.

3. Discrimination technique

Some of the events that are detected as LoRs will have associated cone surfaces if individual photon interactions are recovered from the detection information. While image reconstruction from cone surfaces alone is an advantage of such a system, we will focus on the use of coincident acquisition for more conventional PET reconstruction through LoRs (denoted $\vec{\delta}$).

As stated, some of these LoRs will not be truly representative of the source location. That is, the annihilation location will not lie on the LoR (or near it, in the case of positron range and non co-linearity problems). In these cases, the cone surface can be used to determine the veracity of the LoR [4] in order to remove untrustworthy data from the data set.

Compton scattering in each HPGe volume results in multiple interactions ($\mathbf{x}_n = (\vec{x}_n, E_n)$), composing interaction sequences ($\mathbf{I}_m = (\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_n)$), of a single incident photon. Each interaction is composed of a spatial location, and an energy deposit, while the detector response, or interaction sequence, will be given by multiple interaction events (x and E are position and energy, while n and m refer to the interaction number and the detector element in

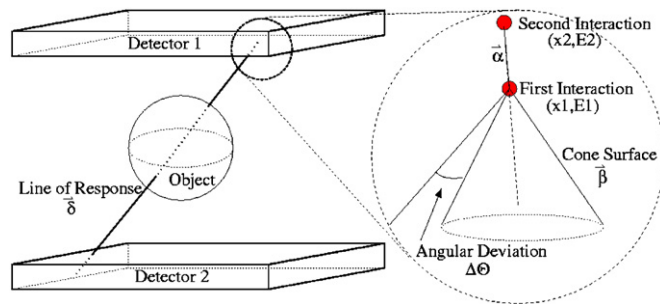


Fig. 1. The SmartPET design. Angular Deviation is shown between associated cone surface and line of response. First and second interaction locations, which define the cone surface are shown.

which the sequence is detected). If more than two interactions in a sequence are resolved, single-photon collimation is possible. In order that a LoR be formed, two interaction sequences must be acquired simultaneously in opposing detectors.

If CC information is available, Compton kinematics allow the construction of a cone surface (shown in Fig. 1) with a given axis ($\vec{\alpha} = \vec{x}_1 - \vec{x}_2$) and half angle, θ given by

$$\theta_{\text{measured}} = \cos^{-1} \left[1 + m_e c^2 \left(\frac{1}{E_0} - \frac{1}{E_0 - E_1} \right) \right],$$

where E_0 is the incident energy and, for the CC scenario, the detection uncertainty is defined by $\Delta \mathbf{I}_m = \Delta \theta$.

The accuracy of the cone surface ($\Delta \theta$) is dependent on the resolution of the interactions and the magnitude of the scattering axis [2]. Ignoring for the moment the scattering axis, the cone-surface ambiguity arises from spectral and spatial (the subject of this investigation) uncertainty. Spectral uncertainty arises from two sources, these being the intrinsic spectral resolution of the detector and, in the case of Compton scattering, Doppler broadening. HPGe has an intrinsic spectral resolution of 1%, which is a small contribution to angular resolution when compared to spatial resolution and Doppler broadening. However, in systems with poor spectral resolution it can become the dominant contributor to the uncertainty in the resultant cone-surface half-angle. This is of particular importance at extreme scattering angles [6]. Doppler broadening occurs due to scattering from a bound electron, rather than one at rest. This gives rise to an electron momentum distribution that manifests as a possible discrepancy between the measured energy deposit, and the photon scattering angle. Doppler broadening may be calculated from Compton profiles, but in this case the G4LECS addition [7] to the Geant4 Toolkit was used.

In a PET scenario, given coincident detections, if either sequence has $n \geq 2$, the adjoining LoR should lie adjacent to an associated cone surface. From Fig. 1, given infinite precision data

$$\hat{\alpha} \cdot \hat{\delta} = \cos(\theta_{\text{LoR}})$$

$$|\theta_{\text{LoR}} - \theta_{\text{measured}}| = \Delta \theta.$$

A validation test may be applied to any LoR, where there is at least one associated cone surface. Each LoR can then undergo a binary detection test, the ability of which is dependent on the magnitude of $\Delta\theta$, and will use a threshold on acceptable values of $\Delta\Theta$ that are considered true.

LoRs derived from randomly coincident photons are likely to fail the test. If an incident energy of 511 keV is assumed, and not correct (as is the case in intra-object scatter) then the LoR is also likely to fail the test. Finally, if the primary scatter event is confused, $\Delta\Theta$ should be smaller for the correct ordering. Hence, the three problems stated in Part 2 might be reduced using this discrimination technique.

ROC curves can then be constructed, using $\Delta\Theta$ as the threshold value, and the area under them calculated. This provides a measure of the ability to remove false LoRs, and can be calculated as a function of system spatial resolution, measured as Full-Width at Half-Maximum (FWHM). In the analysis, spectral resolution is affected only by Doppler broadening, while spatial resolution has been blurred with a Gaussian function.

4. Data simulation

Co-linear 511 keV photons were simulated using the Geant4 Toolkit [8]. The emitting object was a dual-source system (10:1 strength ratio) situated between two HPGe detection volumes of dimension 60×60 mm (face) \times 20 mm (depth) separated by 60 mm. The sources were separated by 6 mm parallel to the detector face. A second data set was simulated that included an Al scattering cylinder of radius 25 mm and depth 100 mm along the source separation axis.

The first three interactions in each detection volume were recorded for processing and analysis. The data were separated into three parts:

1. data without intra-object scatter but with a 50% random fraction,
2. data without intra-object scatter but with disordered photon interaction information, and
3. data with intra-object scattering but with no random fraction or correctly ordered photon information.

The ROC curves were calculated for the data with 50% random LoRs, while a percentage success was used to determine the interaction ordering. From the data with random and scatter LoRs, independent images of the system were reconstructed from the LoRs passing the test for three threshold levels of $\Delta\Theta$ and a spatial resolution of 0.5 mm.

5. Analysis and discussion

In Fig. 2 it is shown that, without any other processing, as the spatial resolution is decreased the AUC is similarly reduced, and the gradient of the curve becomes progressively shallower. At an AUC of 0.5 the test is as useful as

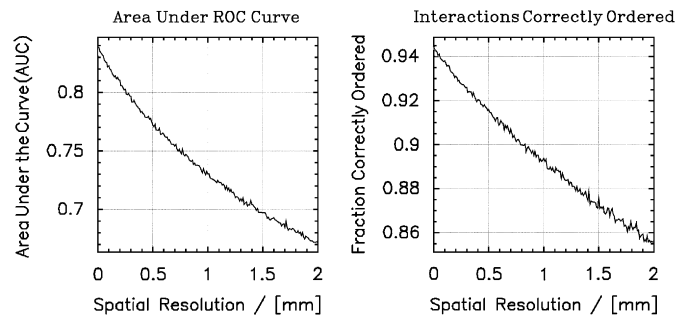


Fig. 2. AUC (left) and percentage success (right) as a function of spatial resolution for data with no intra-object scattering.

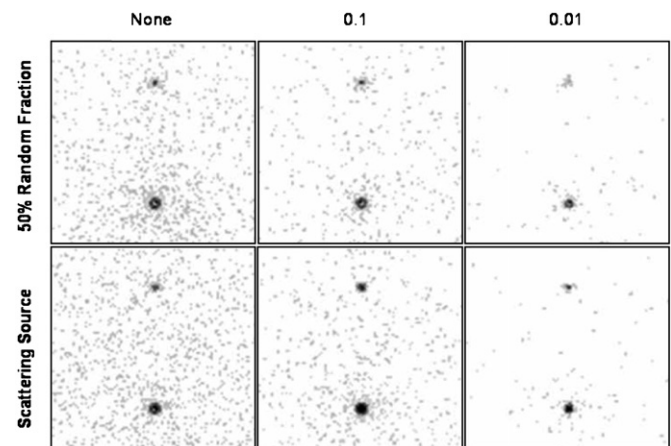


Fig. 3. Central image reconstruction slice for the random and scatter LoRs. The threshold values used are none (left), 0.1 (middle), and 0.01 (right).

random assignment. At a spatial resolution of 2.0 mm we have not yet reached this level, but the test is becoming much less effective. It should be noted that the non-unity AUC for perfect spatial resolution is due to Doppler broadening affecting the cone surface.

However, it should also be noted that points on the ROC curve are calculated by changing the threshold used. The desired level of discrimination can be chosen judiciously to suit the situation.

To give an indication as to the effect of this technique, two images were reconstructed (from the random and scatter data) over three threshold values. Because there were only two point sources in zero background, the points were well defined in the central image, even with scattering and random events included. However, using a log scale, the scattered events in the image slice are easily identifiable. Their partial removal is evident in Fig. 3. The areas in the peaks were summed and it was found that the 10:1 ratio was maintained for all but the scattering data at a 0.01 threshold level—here, a 14:1 ratio was determined. However, the test does come at a cost in efficiency of true LoRs. For the random data, the count in the main (lower) peak for 0.1 and 0.01 threshold cases was reduced to 55% and

13%, respectively, of that in the no-threshold case. In the scatter data these fractions were 72% and 17%.

These images indicate that in a high-scattering environment, or where the random fraction in the final data set is high, this technique is efficient at reducing the number of incorrect LoRs in the image. In this sense, it is similar to septa currently used in PET to remove scattered events by partial mechanical collimation. However, unlike mechanical collimation, the threshold level may be chosen to suit the imaging conditions. If the discrimination is conducted offline, no data is lost, so that the full set can still be used in the reconstruction if maximum efficiency is desired.

As the threshold is raised, lower quality LoRs are sacrificed in favour of high-quality ones but at the expense of the amount of data. In the case of point sources this may be a sensible option, as shown in Fig. 3. Here an angular threshold of 0.01 may be used to remove extraneous information without degradation of the reconstructed image. However, in a situation involving a more disperse object, the optimum threshold may be less obvious. The chosen value will depend upon the object being imaged and the exact information required. For example, the threshold may be increased to allow more events into the image to accurately reconstruct the distribution. In an extreme case of low statistics, or a very distributed source, a threshold may not even be applied. The value of the technique is that it may be applied post-acquisition, to accommodate both the object under investigation and the number of LoRs required in the investigation.

6. Conclusion

In environments where maximising the signal-to-noise ratio is of great importance, LoR discrimination is most useful. Here, it has been shown that the incorrect LoRs may be removed from the final image, at the cost of detection efficiency. The collimating discrimination can, however, be conducted post-acquisition and the threshold chosen to maximise image resolution depending on application.

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