Published in final edited form as:

IEEE Trans Nucl Sci. ; 61(2): 888–893. doi:10.1109/TNS.2014.2304887.

Modeling of Pixelated Detector in SPECT Pinhole Reconstruction

Bing Feng [Member IEEE] and

Siemens Molecular Imaging, Siemens Preclinical Solutions, Knoxville, TN 37932 USA (telephone: 865-218-2418)

Gengsheng L. Zeng [Fellow IEEE]

Department of Engineering, Weber State University, Ogden, UT 84408 USA (telephone: 801-626-6864)

Bing Feng: feng.bing@siemens.com; Gengsheng L. Zeng: larryzeng@weber.edu

Abstract

A challenge for the pixelated detector is that the detector response of a gamma-ray photon varies with the incident angle and the incident location within a crystal. The normalization map obtained by measuring the flood of a point-source at a large distance can lead to artifacts in reconstructed images. In this work, we investigated a method of generating normalization maps by ray-tracing through the pixelated detector based on the imaging geometry and the photo-peak energy for the specific isotope. The normalization is defined for each pinhole as the normalized detector response for a point-source placed at the focal point of the pinhole. Ray-tracing is used to generate the ideal flood image for a point-source. Each crystal pitch area on the back of the detector is divided into 60×60 sub-pixels. Lines are obtained by connecting between a point-source and the centers of sub-pixels inside each crystal pitch area. For each line ray-tracing starts from the entrance point at the detector face and ends at the center of a sub-pixel on the back of the detector. Only the attenuation by NaI(Tl) crystals along each ray is assumed to contribute directly to the flood image. The attenuation by the silica (SiO_2) reflector is also included in the ray-tracing. To calculate the normalization for a pinhole, we need to calculate the ideal flood for a point-source at 360 mm distance (where the point-source was placed for the regular flood measurement) and the ideal flood image for the point-source at the pinhole focal point, together with the flood measurement at 360 mm distance. The normalizations are incorporated in the iterative OSEM reconstruction as a component of the projection matrix. Applications to single-pinhole and multi-pinhole imaging showed that this method greatly reduced the reconstruction artifacts.

I. Introduction

For small animal pinhole SPECT imaging, pixelated detectors can be used to achieve high intrinsic resolution [1–3]. For example, the SPECT detector on the Siemens Inveon Multi-Modality platform [4] provides 2 mm intrinsic resolution, which consists of 68×68 10 mm-thick NaI(Tl) crystals, each with $2 \text{ mm} \times 2 \text{ mm}$ area on a 2.2 mm pitch, encapsulated by a thin aluminum entrance window. A challenge for the pixelated detector is that the detector response of a gamma-ray photon varies with the incident angle and the incident location within a crystal. The normalization map obtained by measuring the flood of a point-source at

a large distance (360 mm on Siemens Inveon systems) can lead to artifacts in the normalized projection data (Figs. 1 and 2) and in reconstructed images. The reason for the artifacts is that since the object is much closer (typically 120 mm to 135 mm from the detector) during imaging, photons reach to the detector at angles much different from angles in normalization measurement. We developed a method of generating normalization maps by scanning a large uniform cylindrical object in standard tomography mode (with the collimator on) [5]. This method worked well for single pinhole collimators with Tc-99m, but not so well for multi-pinhole collimators due to the averaged effects of the normalization over all pinholes. It also showed degraded performance with single pinhole collimators for medium-to-high energy photon emitters such as I-131, due to the severe scatter in the measurements of cylinder.

A different remedy for this problem is to put a point-source at the pinhole location and measure the flood. Normalization maps generated by a point-source at pinhole locations generally work much better than the normalization maps obtained by a point-source at 360 mm. However, due to the inter- and intra-scanners geometrical variations caused by the manufacture and the exchangeable pinhole collimators, on some scanners with different geometric parameters from those when the normalization measurements were performed, we can still see artifacts in reconstructed images, because the imaging geometry was different from when the normalization was measured. Another challenge for this approach is to generate normalization maps for a multi-pinhole collimator.

In this work, we investigated a method of generating normalization maps by ray-tracing through the pixelated detector based on the imaging geometry and the photo-peak energy for the specific isotope. The normalization is defined for each pinhole as the normalized detector response for a point-source placed at the focal point of the pinhole, and incorporated in the iterative reconstruction [6]. Compared to the prior methods, the proposed method uses accurate geometry in calculations and provides a more accurate approach of estimating the intrinsic crystal efficiencies, and does not involve additional measurements other than the conventional point-source flood at 360 mm.

II. Methods

We have developed a method to numerically calculate the PSF for a pinhole system in order to improve image resolution over a sensitivity-function-based method [6]. The method calculates the probability of photon penetration through the pinhole edges using a ray-tracing approach. To calculate the transmission by the collimator plate along each ray, we trace the ray through the collimator by analytical calculations. However, an ideal detector was assumed in the previous work, which absorbs all the photons irradiating its surface. In this work, we extended the previous method to include the modeling of the detector response for photons passing through each pinhole, to correct for the “dark cross” artifacts. In brief, we could write the projection matrix which relates a voxel in object to a data point in projection space as

$$P = N_d P_{ideal}, \quad (1)$$

where P_{ideal} is the projection matrix derived for the ideal detector, which models the PSF and attenuation [6–7], and N_d is a matrix that describes the true normalized detector responses at each detector crystal (pixel), which we called normalization. Since N_d depends on the incident angles of the photons, N_d is calculated for each pinhole in the case of a multi-pinhole collimator. In the following sections we will describe the ray-tracing method used to calculate the normalization N_d and experiments that evaluate our method.

A. Generation of the Ideal Flood Image for a Point Source by Ray-Tracing

The pixelated SPECT detector on the Siemens Inveon SPECT system contains 68×68 NaI(Tl) crystals. Each crystal has the dimensions of $2 \text{ mm} \times 2 \text{ mm} \times 10 \text{ mm}$, arranged in $2.2 \text{ mm} \times 2.2 \text{ mm}$ 2D pitch, with the gaps filled by Silica glass (SiO_2). Each crystal pitch area on the back of the detector is divided into 60×60 sub-pixels (Fig. 3). Lines are obtained by connecting between a point-source and the centers of sub-pixels inside each crystal pitch area. The solid angle that a sub-pixel subtends at the point-source is taken as the incoming photon flux shined on the sub-pixel. For each line ray-tracing starts from the entrance point at the detector face and ends at the center of a sub-pixel on the back of the detector. The step size for ray-tracing is chosen as the same size of the sub-pixel ($2.2 \text{ mm} / 60$). At every increment the new ending point is calculated and judgment is made on (1) which crystal pitch area the ray is currently in, (2) whether it is in the NaI(Tl) region or the SiO_2 region. Once transition from one region to another occurs, ray-tracing will go backward by one step and will restart tracing by $1/10$ step-size to refine the calculation of the line-integral inside each region. Only the attenuation by NaI(Tl) crystals along each ray is assumed to contribute directly to the flood image. No scattering is modeled, except the line attenuation coefficients [8] used in attenuation calculation include scattering components (Table 1). The attenuation by the silica (SiO_2) reflector is also included in the ray-tracing. Summing rays over all sub-pixels and over all crystals gives the flood image for the point-source. In above calculations, since ideal crystal efficiencies are assumed, the flood image calculated responds to the ideal flood image.

B. Calculation of the Normalization for Each Pinhole

As mentioned before, the normalization in (1) is defined for each pinhole as the true normalized detector response for photons passing through the pinhole, including the effects of the crystal efficiencies. We could calculate the ideal flood image for a point-source placed at the focal point of the pinhole (in absence of the collimator) as described in Section A. Scaled by the incoming flux strength image (68×68), the ideal flood image became the normalized detector response for the detector with ideal crystal efficiencies.

To estimate the crystal efficiencies, we generated another ideal flood image for a point-source at 360 mm distance, where the point-source was placed for the flood measurement as a routine process. We could write the measured flood image F_{real} as the multiplication of the ideal flood image F_{ideal} and the crystal efficiencies C_{eff} :

$$F_{real} = F_{ideal} C_{eff}. \quad (2)$$

The crystal efficiencies C_{eff} can be obtained by dividing the flood measurement by the calculated ideal flood with the point-source at the same place. Since the ideal flood image F_{ideal} calculated by the ray-tracing method was based on the actual imaging geometry, we would expect that the crystal efficiencies C_{eff} calculated by (2) approximated the intrinsic crystal efficiencies which were independent of the point-source location and only dependent on electrical settings for the detector. Once the crystal efficiencies were known, we could calculate the normalization for the pinhole by (2) from the normalized ideal flood image for the pinhole. The normalizations were incorporated in the iterative OSEM reconstruction as a component of the projection matrix as in (1).

C. Applications to Single-Pinhole and Multi-Pinhole Imaging

Test data were acquired for a 30 mm diameter syringe filled with Tc-99m solution on a Siemens Inveon Multi-Modality scanner with single-pinhole (1-MGP-1.0) and five-pinhole (5-MWB-1.0) collimators, respectively (neither on the same day nor with the same syringe). A routine normalization was acquired with Tc-99m point-source at 360 mm distance. For the single-pinhole study, the projection data summed over all views were checked for the dark cross artifacts (Fig. 2) before and after applied the conventional normalization and the normalization by the proposed method, respectively. The test data were reconstructed by the proposed method which models the pixelated detector in the projection matrix. For comparison, the data were normalized by the normalization maps obtained by point-source at 360 mm distance and reconstructed by the OSEM with the same number of iterations and subsets.

III. Results

The ideal flood images were generated by ray-tracing for a Tc-99m point-source at 360 mm distance (the routine normalization measurement location) and 95 mm distance (pinhole focal point for 1-MGP-1.0 collimator) and shown in Fig. 4. There was a “cross” of lower intensities in each flood image which was consistent with the “dark cross” shown in the projection data in Fig. 2. Also consistent with measurements, the “dark cross” in the 95 mm case was much deeper than in the 360 mm case. It was verified through simulations that center of the cross moved together the in-plane location of the point-source, as shown in the measurements. The projection data acquired by the single-pinhole collimator were summed over all angular views, and normalized by the conventional point-source normalization and the proposed normalization. In Fig. 5, after applying the proposed normalization, the “dark cross” disappeared, but it remained on the projection data normalized by the conventional normalization.

The reconstructed images for single-pinhole (Fig. 6) and five-pinhole (Fig. 8) showed obvious “dark stripe” artifacts for the conventional normalization method, but much less obvious artifacts for the proposed method. The count-profile averaged over the selected axial range was shown in Fig. 7 for the single-pinhole collimator and in Fig. 9 for the five-pinhole collimator. In the both cases, the proposed method reduced the dip in the middle, especially for the single-pinhole case, where a large reduction was shown. For the five-pinhole collimator, the dip was originally small with the conventional point-source

normalization, which was because only the center pinhole contributed to the dip and it was out-weighted by the other pinholes.

IV. Discussions

The “dark cross” pattern in the projection data caused a “dark stripe”, instead of a “dark cross”, in the reconstructed images. This was because the in-plane “dark stripe” smeared into a range of transverse image slices in reconstruction, unlike the axial “dark stripe” which was reinforced at back-projection for every angle.

The normalized detector response in (1) for a crystal could be a kernel to describe the responses in the neighboring crystals, instead a single term (zero-order approximation). We compared this approach and found it worked similarly but was much slower in reconstruction (due to convolution with the kernel) than the adopted single-term approach.

As a simple ray-tracing method which models average attenuation (absorption) of photons by the pixelated detector, our method successfully reproduced the “dark cross” pattern in the flood image (Fig. 4) for 140 keV photons, and reduced the “dark stripe” artifacts for the single-pinhole and five-pinhole collimators (Figs. 6–9). Since no explicit modeling of scatter was included in the ray-tracing, our method needs further evaluation for the SPECT isotopes with high energy photons, such as I-131 (364 keV). We could expect some scatter estimation techniques may be needed to deal with the increased inter-crystal scattering. We would prefer simple methods based on Klein-Nishina formula [9] or scattering kernels [10] than the Monte-Carlo simulations [11], because the latter are computationally much more expensive.

V. Conclusion

We developed a method of generating normalization maps by ray-tracing for pixelated pinhole SPECT detector. Preliminary results with Tc-99m show that it greatly reduced the reconstruction artifacts.

References

1. Wojcik R, Majewski S, Steinbach D, Weisenberger AG. High Spatial resolution Gamma Imaging Detector Based on 5" Diameter R3292 Hamamatsu PSPMT. *IEEE Trans Nucl Sci.* 1998; 45:487–491.
2. Schramm N, Wirrwar A, Sonnenberg F, Halling H. Compact high resolution detector for small animal SPECT. *IEEE Trans Nucl Sci.* 2000; 47:1163–1167.
3. Qi, YJ.; Tsui, BMW.; Wang, Y.; Yoder, B.; Wojcik, R.; Majewski, S. Performance characteristics of a new modular camera based on pixelated crystal for high-resolution pinhole SPECT with comparison to a standard camera with continuous crystal; *IEEE Nucl Sci Symposium Conference Record*; 2004. p. 2325-2329.
4. Austin, DW.; Paulus, MJ.; Gleason, SS.; Mintzer, RA.; Siegel, SB.; Figueroa, SD.; Hoffman, TJ.; Wall, JS. Design and performance of a new SPECT detector for multimodality small animal imaging platforms. *IEEE Nucl. Sci. Symposium Conference Record*; 2006. p. 3008-3011.
5. Feng, B.; Austin, DW. Generation of normalization maps for pixelated pinhole SPECT detectors by scanning a uniform cylinder phantom. *IEEE Nucl. Sci. Symposium Conference Record*; 2012. p. 2932-2933.

6. Feng B, Chen M, Bai B, Smith AM, Austin DW, Mintzer RA, Osborne D, Gregor J. Modeling of the Point-Spread-Function by Numerical Calculations in Single-Pinhole and Multi-Pinhole SPECT Reconstruction. *IEEE Trans Nucl Sci.* 2010; 57:173–180.
7. Austin, DW.; Feng, B.; Mintzer, RA.; Chen, M.; Gregor, J.; Stuckey, AC.; Wall, JS. Validation of CT-based attenuation correction for multi-pinhole PSF reconstruction for small-animal SPECT. *IEEE Nucl. Sci. Symposium Conference Record*; 2010. p. 3339-3342.
8. <http://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html>
9. Klein, O.; Nishina, Y. On the scattering of radiation by free electrons according to Dirac's new relativistic quantum dynamics. In: Bethe, Hans A.; Guth, Alan H., editors. *The Oskar Klein Memorial Lectures, Vol. 2: Lectures*. World Scientific Publishing Co. Pte. Ltd; 1994. p. 113-139. Translated Reprints by Oskar Klein, Ed. Gösta Ekspong
10. Bai C, Zeng GL, Gullberg GT. A slice-by-slice blurring model and kernel evaluation using the Klein-Nishina formula for 3D scatter compensation in parallel and convergent beam SPECT. *Phys Med Biol.* 2000; 45:1275–1307. [PubMed: 10843105]
11. Lee S, Gregor J, Osborne D. Development and validation of a complete GATE model of the Siemens Inveon trimodal imaging platform. *Mol Imaging.* 2013; 12:1–13. [PubMed: 23962650]

Fig. 1.
The flood image measured with a point source on Inveon pixelated SPECT detector, showing a “dark cross” pattern. The “#-shaped” pattern was due to the 3×3 PMT array.

Fig. 2.

(Left) The raw projection data for a syringe filled with Tc-99m solution, acquired with a single pinhole collimator on Siemens Inveon SPECT system, summed over all angular views. (Right) Summed projection data normalized by the conventional point-source normalization. The “dark cross” pattern was shown on both. (Lower Row) A dip was shown on the count profile averaged over the selected axial range in each case, due to the “dark cross” pattern.

Fig. 3.

Ray-tracing through the pixelated SPECT detector to calculate the ideal flood image for a point-source. Each crystal pitch area contains active NaI(Tl) and gap SiO₂ regions, divided into 60×60 sub-pixels.

Fig. 4. The ideal Tc-99m flood images generated by ray-tracing for a point-source at 360 mm (Left) and 95 mm (Right) distances. A “dark cross” was shown on each image as expected.

Fig. 5.

The projection data for a syringe filled with Tc-99m solution, acquired with a single pinhole collimator on Siemens Inveon SPECT system, summed over all angular views. (Left) Normalized by the conventional point-source (Right) Normalized by the proposed normalization. (Lower Row) The count profile averaged over the selected axial range.

Fig. 6.

Reconstructed images of the test syringe for the single-pinhole acquisition with the conventional normalization map (Upper) and by our proposed method (Lower). Each row from left to right shows the transverse, coronal, and sagittal views.

Fig. 7.

The count-profiles for the single-pinhole images in Fig. 6, averaged over the selected axial range. Proposed method reduced the dip in the middle by a large degree.

Fig. 8.

Reconstructed images of the test syringe for the five-pinhole acquisition with the conventional normalization map (Upper) and by our proposed method (Lower). Each row from left to right shows the transverse, coronal, and sagittal views.

Fig. 9.

The count-profiles for the five-pinhole images in Fig. 8, averaged over the selected axial range. Proposed method reduced the dip in the middle.

Table 1

The attenuation coefficients of NaI and SiO₂ at 140 keV, used for calculation of the flood images.

Material	Total Mass Attenuation (cm ² /g)	Density (g/cm ³)	Total Linear Attenuation (cm ⁻¹)
NaI	0.7189	3.67	2.638
SiO ₂	0.1441	2.20	0.3175