Published in final edited form as:

IEEE Trans Nucl Sci. 2002 ; 2: 1258–1262. doi:10.1109/NSSMIC.2002.1239548.

Feasibility Study of Compton Scattering Enhanced Multiple Pinhole Imager for Nuclear Medicine

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Abstract

This paper presents a feasibility study of a Compton scattering enhanced (CSE) multiple pinhole imaging system for gamma rays with energy of 140keV or higher. This system consists of a multiple-pinhole collimator, a position sensitive scintillation detector as used in standard Gamma camera, and a Silicon pad detector array, inserted between the collimator and the scintillation detector. The problem of multiplexing, normally associated with multiple pinhole system, is reduced by using the extra information from the detected Compton scattering events. In order to compensate for the sensitivity loss, due to the low probability of detecting Compton scattered events, the proposed detector is designed to collect both Compton scattering and Non-Compton events. It has been shown that with properly selected pinhole spacing, the proposed detector design leads to an improved image quality.

Keywords

Compton scattering enhancement; multiple pinhole

I. Introduction

Parallel hole and pinhole are by far the most often used collimation methods for nuclear medicine applications, although fanbeam and conebeam collimators are also applied [1][2]. These collimators have the advantage of being non-multiplexing and therefore every detected gamma ray defines a unique angular region, within which the gamma ray was generated or scattered. However, this uniqueness of information is achieved at the cost of losing all photons that do not fall into those possible paths defined by the collimator. Several mechanical collimators involving certain degrees of multiplexing have been studied in the past. The idea of using combined mechanical and electronic collimations was previously proposed by Uritani et al [3]. In this paper, we present an alternative detector configuration based on the similar principle. It consists of a multiple pinhole collimator placed in front of a less optimised Compton camera. The choice of using multiple pinhole collimator offers a wide range of freedom in selecting the open fraction of the collimator and spatial coding scheme for different applications. The proposed imager is designed to collect events both Compton scattered between the two detectors and interact with either the first or the second detector only. Therefore, the raw sensitivity is not limited by the relatively low probability of

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detecting an incoming photon through Compton scattering. To evaluate the detector performance, we used the variance-resolution trade-off curve calculated based on the Maximum *a priori* (MAP) reconstruction methods [4][5].

II. The Detector Concept

The proposed detector system is essentially the combination of a Gamma camera using a multiple pinhole collimator and a Silicon scattering detector inserted between the Anger camera and the collimator, as shown in Fig. 1. The extra information from Compton scattering not only enables one to say that the detected photon is from one of the pinholes in the collimator, but also assigns a different probability for each pinhole. The proposed detector system also makes use of those events that interact with either the first or the second detector only. The data containing both Compton scattered and non-Compton scattered events is used in list-mode image reconstruction. For simplicity, we will use the term “CSE detector” for the proposed design and “MPH detector” for standard multiple pinhole detector.

III. Methods For Comparisons

A. Detector Simulation and Image Reconstruction

The basic detector and source configurations used in this study are shown in Table I. In order to study the effect of the amount of multiplexing on the detector performance, 5 different multiple pinhole configurations were simulated, with 9, 25, 49, 121 and 225 pinholes respectively. The corresponding pinhole distances were 3.0, 2.0, 1.5, 1.0 and 0.6cm. The multiple pinholes were placed in square patterns. The actual pinhole positions were randomized by a small amount (1~2mm) around the grid points to reduce the possible artifacts, which may arise as a result of sampling the object at some discrete spatial frequencies. Two such detectors were placed above and below the object. The object simulated was assigned an activity distribution as shown in Fig. 2. It contains four hot or cold spheres, superimposed on a continuous background.

B. Variance-Resolution Trade-off

Fessler and Rogers proposed an approach that analyses the mean, variance and spatial resolution properties of images estimated through optimising an implicitly defined object function, such as the Penalized Likelihood or Maximum *a priori* (MAP) estimators [6][7]. This method was used in developing a pre-conditioner for Conjugate Gradient PET image reconstruction [8]. Qi et al further explored this idea by adopting this pre-conditioner as an approximation of the inverse of the Hessian matrix and developed a closed form approximation for resolution and variance[9][10].

The details of the development leading to this method can be found in the references cited above. Here we briefly restate some of the key steps. Given a measured data set $\mathbf{y}$, the log-likelihood of an estimator $\mathbf{x}$, of the underlying object is

$$L(\mathbf{y} \mid \mathbf{x}) = \sum_i y_i \log \frac{\bar{y}_i}{\bar{y}} \quad (1)$$

where $\mathbf{x} \in \mathbb{R}^n$ is the unknown image and $\mathbf{y} \in \mathbb{R}^m$ is the measured data. The mean of the data is related to the image $\mathbf{x}$ through transformation

$$\bar{\mathbf{y}} = \mathbf{P}\mathbf{x} + \mathbf{r} \quad (2)$$

where $\mathbf{P}$ is the detector response function and $\mathbf{r}$ is the mean contribution from object scattering events and background radiation. The MAP estimate is achieved by maximizing an object function

$$\Phi(\mathbf{x}, \mathbf{y}) = \mathbf{L}(\mathbf{y} \mid \mathbf{x}) + \beta \mathbf{R}(\mathbf{x}) \quad (3)$$

For simplicity, we only used the quadratic roughness penalty with the form

$$R(\mathbf{x}) = \sum_j \frac{1}{2} \sum_i w_{ij} \phi(x_j - x_i) \quad (4)$$

where w_{ij} is the weighting factor that takes into account the 26 neighbours and

$$\phi(t) = t^2/2 \quad (5)$$

So that the MAP estimator is defined as

$$\hat{\mathbf{x}} = \arg \max_{\mathbf{x}} \Phi(\mathbf{x}, \mathbf{y}) \quad (6)$$

For a non-linear estimator, one can use the local impulse response (LIR) as a measure of the spatial resolution property. For the j th voxel it is defined as

$$l^j(\hat{\mathbf{x}}) = \lim_{\delta \rightarrow 0} \frac{E(\mathbf{y}(\mathbf{x} + \delta \mathbf{e}_j)) - E(\mathbf{y}(\mathbf{x}))}{\delta} = \frac{\partial}{\partial x_j} \hat{\mathbf{x}}(\mathbf{y}(\mathbf{x})) \quad (7)$$

Using the first order Taylor expansion and chain rule, one can approximate the local impulse response by its linearized representation:

$$l^j \approx \frac{\partial}{\partial x_j} \hat{\mathbf{x}}(\mathbf{y}(\mathbf{x})) \approx [\mathbf{F} + \beta \mathbf{R}(\hat{\mathbf{x}})]^{-1} \mathbf{F} \mathbf{e}_j \quad (8)$$

where $\mathbf{F} = \mathbf{P}'\mathbf{D}[1/y_i]\mathbf{P}$ is the Fisher information matrix (FIM). Similarly, the covariance of MAP reconstruction can be approximated as [6]

$$\text{Cov}(\hat{\mathbf{x}}) \approx [\mathbf{F} + \beta\mathbf{R}]^{-1}\mathbf{F}[\mathbf{F} + \beta\mathbf{R}]^{-1} \quad (9)$$

For the detector geometry and the 3-D source object used in this study, calculating the FIM (or even a column of FIM) is a very challenging task. To make the calculation computationally practical, we need to make further simplification by assuming the system is “locally shift-invariant” [8]. One can bring the diagonal matrix sandwiched between $\mathbf{P}'$ and $\mathbf{P}$ outside so that

$$\mathbf{F} = \mathbf{P}'\mathbf{D}\left[1/\bar{y}_i\right]\mathbf{P} \approx \mathbf{D}_k\mathbf{P}'\mathbf{P}\mathbf{D}_k \quad (10)$$

and similarly

$$\beta\mathbf{R}(\hat{\mathbf{x}}) = \beta\mathbf{D}_k\mathbf{D}_\eta\mathbf{C}'\mathbf{C}\mathbf{D}_\eta\mathbf{D}_k \quad (11)$$

where $\mathbf{D}_k = \mathbf{D}[K_j]$ with

$$K_j = \sqrt{\frac{\sum_i P_{ij}^2 / \bar{y}_i}{\sum_i P_{ij}^2}} \quad (12)$$

and $\mathbf{D}_\eta = \mathbf{D}[\eta_j]$ with

$$\eta_j = \sqrt{\frac{\beta \sum_k c_{kj}^2 \ddot{\phi}([C\hat{\mathbf{x}} - \mathbf{m}])}{k_j \sum_j c_{kj}^2}} \quad (13)$$

where $\ddot{\phi}(t) = d^2 / dt^2 \phi(t)$. Substituting (10) and (11) into (8), one gets the approximation for the local impulse response

$$l^j \approx [\mathbf{P}'\mathbf{P} + \eta_j^{-2}\mathbf{C}'\mathbf{C}]^{-1}\mathbf{P}'\mathbf{P}e_j \quad (14)$$

Using the locally shift-invariant approximation, the eigenvalues, λ_i and μ_i , of the block-circulant representations of $\mathbf{P}'\mathbf{P}$ and $\mathbf{C}'\mathbf{C}$ can be derived using the 3-D Fourier transform. This property was used to develop closed form expressions for the LIR and variance of MAP reconstruction [9]

$$l^j(\hat{x}) = \mathbf{Q}' \mathbf{D} \left[\frac{\lambda_i}{\lambda_i + \eta_j^2(\hat{x}) \mu_i} \right] \mathbf{Q} e_j \quad (15)$$

$$\text{Var}_j(\hat{x}) \approx \frac{k_j^{-2}}{N} \sum_i \frac{\lambda_i}{(\lambda_i + \eta_j^2(\hat{x}) \mu_i)^2} \quad (16)$$

where $\mathbf{Q}$ and $\mathbf{Q}'$ are the unitary 3-D discrete Fourier transform operator and its transpose. The j th element of the LIR is defined as Contrast Recovery Coefficient (CRC).

IV Results

A. Reconstructions in 3-D

Fig. 3 shows the back-projected probability distribution across each of the 16 slices of the source object for a detected Compton scattering event. It is easily seen that the angular ambiguity is greatly reduced by adding the Compton scattering information. This was translated into an improved image quality as shown in Fig. 4-6. The list-mode MAP algorithm with quadratic penalty function (as shown in Eq. 4 and 5) was used for these reconstructions. All three data sets contained the same number of counts. Using the Compton scattering information significantly reduced the variance at the same value of CRC. It also helped to achieve a better reconstruction in the cold region. This should improve the accuracy of quantifying the activity concentration within a preset region-of-interest (ROI). When comparing the detector performances based on the same measuring time, the detector, using only Compton scattered events, suffered from the low sensitivity and produced the highest standard deviation at the same CRC (resolution). This can be improved if one also makes use of the non-Compton events. These results are shown in Table II.

B. Resolution-Variance Trade-Off

To further evaluate the proposed detector design, we compared the image quality using the variance-resolution trade-off curve achieved at the image centre. This study took the following steps. First, we compared the relative detector performance as a function of the amount of multiplexing in the data, with collimators having different pinhole configurations. Second, based on the results achieved, we compared the “best” CSE detector (amongst the detectors compared) with the “best” standard MPH detector to show the benefit of combining Compton aperture with mechanical collimation. Finally, we briefly discussed results from resolution-variance trade-off study and highlighted the limitations of this approach.

The effect of the amount of multiplexing on the CSE detector performance was studied using the five multiple pinhole configurations (see Section II). Standard deviations as a function of resolution (CRC) were derived using (15) and (16). The collected data sets were

normalized to the same measuring time and shown in Fig. 7 and 8. For the standard MPH detector, the best variance-resolution (CRC) was achieved with the 25pinhole collimator, given the same measuring time. The difference between detectors using the 25 pinhole and 9 pinhole collimators is very small. This indicates that a collimator with relatively small amount of multiplexing is preferred if no extra information is available. When Compton information is added, a larger open fraction on the collimator provided images with the lowest variance. The best variance-CRC (resolution) trade-off was achieved with the 121pinhole collimator.

To demonstrate the benefit of the proposed detector design, we compared the performances of the “best” CSE detector (using the 121pinhole collimator) with the “best” standard MPH detector using (the 25pinhole collimator). The results are shown in Fig. 9. It is easily seen that using Compton scattered events only gave the worst performance amongst the configurations in the sense that it results in the highest variance at the same CRC. This is due to the relatively low sensitivity of the proposed detector. This limitation can be greatly reduced if one also uses the non-Compton events. In practice, the sensitivity for Compton scattering events may also be improved by having thicker Si detector and better angular coverage for the scattered photons. These may further improve the performance of the proposed detector.

IV. Conclusions And Discussions

We presented a comparative study between the standard multiple pinhole detector and the Compton-Scattering-Enhanced multiple pinhole detector. The results achieved are summarised as following:

- The proposed CSE detector design results in an improved imaging performance compared with standard MPH detectors.
- It provides not only lower variance but also lower covariance in the image. This should be beneficial for both detection and quantification tasks.
- In order to compensate for the low probability of detecting Compton scattered events, one needs to use collimator with relatively large open fraction and make use of those non-Compton events.

V. Acknowledgement

The authors would like to thank Prof. Jeffrey Fessler for the very valuable discussions and suggestions.

VI. References

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Fig 1.
Schematic of the Compton scattering enhanced multiple pinhole imaging system

Fig. 2.
The phantom used in 3-D study

Fig. 3.
Back-projection of probability for a detected event. The detector used the 49pinhole collimator

Fig. 4.

Reconstructed image with 250k Compton scattered events. The CRC at the center is 0.3. The collimator used has 49 pinholes.

Fig. 5.

Reconstructed image with 250k events, including both Compton scattered and non-Compton scattered events. The CRC at the center is 0.3. The ratio of Compton scattered events used is determined based on the proposed detector design (see Table I for details).

Fig. 6.
Reconstructed image with 250k multiple pinhole events (with no Compton scattering information) events.

Fig. 7. Standard deviation as a function CRC for detector using standard MPH events (no Compton scattering information used at all). Five MPH configurations were used and curves are normalised to the same measuring time.

Fig. 8. Standard deviation as a function CRC for detector using 100% CSE events. Five MPH configurations were used and curves are normalised to the same measuring time.

Fig. 9.
Comparison between the “best” MPH and CSE detectors

Table I

PARAMETERS USED IN THE SIMULATION

	First Detector	Second Detector	Multiple Pinhole Aperture	Object
Total Size (mm)	250×250×20	400×400×6	250×250×5	96×96×48
Pixel Size (mm)	2.5×2.5×2.5mm	4×4×6	(Pinhole size) Ø1.5mm	3×3×3
No. of pixels	100×100×8 (8×10 ⁴)	10 ⁴	(No. of pinholes) 9 to 225	16×32×32 (16384)
Z-location (mm)	-50	-150	0	50~100
Material	Si	NaI(Tl)	Tungsten	Air
Energy Resolution	Elec. Noise (1keV) + Doppler Broadening	10% at 140keV	--	--
Energy threshold	2.5keV	20keV	--	--
Notes	1. Doppler Broadening is included.	1.Depth of interaction not included. 2.Resolution is equal to pixel size.	1.Aperture penetration is modeled. 2.Photons scattered in collimator ignored.	1. Object scattering and attenuation ignored. 2.Scattering in collimator ignored.

Table II

IMAGE PROPERTIES AT THE CENTRE OF THE RECONSTRUCTED IMAGES FOR DETECTORS USING THE 49 PINHOLE COLLIMATOR

	MPH only	CSE+MPH	CSE only
CRC	0.3	0.3	0.3
Norm. STD (Same Counts)	1.0	0.61	0.42
Norm. STD (Same Time)	1.0	0.78	1.19