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Near-Field High-Energy Spectroscopic Gamma Imaging Using a Rotation Modulation Collimator

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Abstract

Certain trace elements are vital to the body and elemental imbalances can be indicators of certain diseases including cancer and liver diseases. Neutron Stimulated Emission Computed Tomography (NSECT) is being developed as spectroscopic imaging technique to non-invasively and non-destructively measure and image elemental concentrations within the body. A region of interest is illuminated via a high-energy beam of neutrons that scatter inelastically with elemental nuclei within the body. The excited nuclei then relax by emitting characteristic gamma rays. Acquiring the gamma spectrum in a tomographic manner allows not only the identification of elements, but also the formation of images representing spatial distributions of specific elements. We are developing a high-energy position-sensitive gamma camera that allows full illumination of the entire region of interest. Because current scintillation crystal based position-sensitive gamma cameras operate in too low of an energy range, we are adapting high-energy gamma imaging techniques used in space-based imaging. A High Purity Germanium (HPGe) detector provides high-resolution energy spectra while a rotating modulation collimator (RMC) placed in front of the detector modulates the incoming signal to provide spatial information. The purpose of this manuscript is to describe the near-field RMC geometry, which varies greatly from the infinite-focus space-based applications, and how it modulates the incident gamma flux. A simple geometric model is presented and then used to reconstruct two-dimensional planar images of both simulated point sources and extended sources.

Keywords

Biomedical imaging; Gamma-ray spectroscopy; Neutrons; Nuclear Imaging

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1. Introduction

Elemental imbalances in the body can be symptoms or causes of certain diseases. Several studies have shown that trace element concentrations in human tissue may allow differentiation between malignant and benign tissue in the breast [1; 2; 3; 4; 5], prostate gland [6] and brain [1; 2; 7]. In addition, various liver diseases are caused by an overload of iron or copper including Hemochromatosis and Wilson's Disease [1; 8; 9; 10; 11; 12; 13]. Current methods for measuring elemental levels are invasive and are not compatible with *in vivo* methods [1; 3; 8; 9; 10; 11; 14; 15; 16; 17; 18].

Neutron Stimulated Emission Computed Tomography (NSECT) is being developed as a diagnostic tool to non-invasively and non-destructively measure, quantify and image elemental concentrations *in vivo* [19]. NSECT is a spectroscopic imaging technique whereby the region-of-interest (ROI) is illuminated with a beam of high-energy (3 – 5 MeV) neutrons. These neutrons scatter inelastically with elemental nuclei within the body causing the nuclei to become excited and emit characteristic gamma radiation as they relax back to ground state. One of our current challenges is to acquire these gamma rays in a manner that facilitates tomographic image reconstruction while maintaining a very high energy resolution.

In order to accurately identify elements, the energy spectrum must be as detailed as possible. Typical scintillation crystals have an energy resolution 5%–12% full width half-maximum (FWHM) [20]. Room-temperature semi-conductors have an energy resolution of approximately 2.5% FWHM [21]. At equivalent energies, single crystal High Purity Germanium (HPGe) semi-conductor detectors have an energy resolution of approximately 1% FWHM [20]. The HPGe detectors maintain their superior energy resolution over the energy range of interest making them the ideal choice for use with NSECT spectroscopy. Unfortunately, the detectors are monolithic 7 cm diameter crystals; thereby, they provide no spatial information.

Previously we have generated NSECT images using the first generation CT approach of scanning phantoms via a thin neutron beam at many different angles [22]. Although effective, the approach does not scale well. Specifically, as the beam narrows it is difficult to maintain adequate neutron flux. One would expect that scanning a 2 cm × 2 cm object with four 1 cm × 1 cm beams should result in the same number of neutrons passing through the object as with one 2 cm × 2 cm beam. But, with our current beam source, this is not the case. The tandem accelerator generates a wide beam that is then collimated down into a narrow beam, making it difficult to effectively tune the beam. Consequently, particles in the beam that have angular tracks are lost; in practice, the neutron flux does not scale linearly with beam size. Additionally, it is not time efficient to scan the sample with a small beam at many different positions. A possible solution is to illuminate the entire sample at once and image with a position sensitive gamma camera. Unfortunately, current scintillation crystal gamma cameras operate only in the lowest part of the NSECT energy range, which is ~300 keV – 2 MeV. They are limited in both detection efficiency and spatial resolution by collimator properties and crystal characteristics.

To maintain adequate spatial resolution, single crystal cameras require a relatively thin crystal to reduce the spread of scintillation light. Increasing crystal thickness to improve detection efficiency would degrade spatial resolution. Additionally, collimation of high energy photons is a challenge and while special collimators have been designed for 511 keV use, septal penetration is a problem. This inability to effectively collimate high-energy gamma rays increases with gamma energy, compromising spatial resolution and system efficiency [23; 24].

To overcome high-energy collimation design limitations with Anger Cameras several groups have proposed using rotating parallel slit collimators in conjunction with standard position sensitive scintillation crystals. The proposed design should be more efficient at high-energies due to a wider acceptance angle and higher efficiency; thereby alleviating some of the design compromise between spatial resolution and system efficiency [24; 25; 26; 27; 28; 29].

While creative collimation solutions may exist to overcome spatial resolution problems with typical gamma cameras, the larger problem is energy resolution. Therefore, we have chosen to use the monolithic HPGe detectors and develop methods to reconstruct images through gamma collimation. Our current focus is to develop a camera that provides adequate two-dimensional (2D) planar images and then progress toward 3D images using tomographic techniques.

Currently, the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) captures and images gamma rays over an energy range (3 keV – 17 MeV) encompassing NSECT's range. Nine HPGe detectors provide spectral information, while rotating modulation collimators (RMC) placed in front of each detector provide spatial information. RMCs consist of two parallel-slat collimators offset from one another and placed in front of the HPGe's to modulate the incoming signal by rotating in unison about the z-axis. Counting the number of incident gammas at each collimator rotation angle allows for reconstruction of 2D planar images [30; 31; 32; 33]. It is important to note that images can be reconstructed even in the presence of septal penetration. The collimators only need to provide attenuation sufficient enough to modulate the incident gamma flux through a 180° collimator rotation. Within the 180° rotational symmetry of the system, the modulation profile is unique to a gamma source's location in space [30; 31; 32; 33; 34]. We propose to adapt this technology for use in the near field (< 50 cm) to provide an imaging solution for high-energy gamma rays.

Previously, we reported on geometric modeling of the RMC behavior [35] using an infinite focus model developed by Schnopper, et al. [34] and Hurford, et al. [30] (equation (1) below). F_{im} describes the probability of detecting a signal from a point source located at position, m , when the collimator is at angle, θ_i :

$$F_{im} = \frac{1}{4} \left[1 + \frac{8}{\pi} \cos \left(\frac{2\pi \tan^{-1} \left(\frac{r_m}{SID} \right) \cos(\theta_i - \theta_m)}{\tan^{-1} \left(\frac{pitch}{separation} \right)} \right) \right] \quad (1)$$

where r_m is the radius of the point source from the axis of rotation on the imaging plane, SID is z-distance between the imaging plane and the detector, θ_m is the angular position of the point source on the imaging plane, $pitch$ is the slat and slot width added together, and $separation$ is the distance between the two collimators. See Figure 2 for a detailed depiction of system dimensions.

Using (1) above we demonstrated near field simulation and reconstruction of images. Additionally, we showed that the inverse problem has a solution [35]. However, after building and testing a prototype collimator [36], we discovered the above model does not accurately reflect the behavior of the RMC in the near-field environment. Many assumptions that are valid for a focus of infinity (as is assumed in space-based imaging) are no longer valid in the near field. The biggest dilemma is that we cannot assume that the incoming gamma rays are parallel. The model becomes invalid in the near field when the angular pitch of the collimator ($\tan^{-1}(pitch/separation)$) becomes much less than the angular distance between the source and the detector ($\tan^{-1}(r_m/SID)$). When this occurs, there is a rapid fluctuation in the value of the cosine expression in (1) over a 180° collimator rotation (see Figure 1), causing F_{im} to no longer accurately reflect the observed near-field behavior [36].

The purpose of this manuscript is to explain the near-field RMC geometry by developing a geometric model that predicts how the RMC will modulate the incoming gamma flux. This model is then used to determine the informational limits of the system by generating 2D reconstructions of 2D images. The above tasks will be accomplished assuming an ideal model in which the collimators are perfectly attenuating and all gamma sources are located on a single plane parallel to the detector face. This manuscript is organized as follows. The methods section explains the near-field geometry, defines a geometric model, and outlines the reconstruction method and its application to reconstruct both point and extended sources. The results section demonstrates how the geometric model predicts modulation behavior and then presents the reconstructed images. Finally the discussion section describes the benefits and limitations of the model as well as providing a discussion regarding the reconstructed images.

2. Methods

2.1 Near Field Geometric Model

The layout and dimensions of the RMC / detector unit (hereafter referred to as “camera”) are shown in (Figure 2). The x,y,z coordinate system is centered at the middle of the detector face, with the x,y plane covering the detector face and the z -axis defining the axis of rotation. The z -distance between the imaging plane and the detector face is referred to as the ‘SID’ and the z -distance between the two collimators is referred to as the ‘separation’. Each collimator slat is defined by its ‘slat width’, ‘slat height’ and separated by a ‘slot width’. The ‘collimator angle’ is the angle between the collimator slats and the x -axis. As the RMC rotates, the collimators modulate the number of gamma rays that reach the detector. The gamma ray sources are located on the imaging plane, which is parallel to the front face of the detector.

Figure 3 depicts the modulation profile obtained from a simulation of a gamma ray point source as well as the collimator views that obtain this profile. The solid line was generated by the geometric model (9) explained later in this manuscript. The dashed line was from a GEANT4 Monte Carlo simulation of a gamma point source interacting with the RMC and detector. More information on GEANT4 simulations of NSECT can be found in [36; 37]. The profile is a simple peak, with the maximum value obtained when the vertical slats of the collimator are aligned with the angular location of the point source (where θ_C equals θ_m). Beneath the profiles are the corresponding collimator views as seen from the perspective of the point source that created these profiles. The top inset depicts the point source's location on the imaging plane. The z-axis is pointed out of the page. Typical RMC dimensions are: slat width and slot width 0.5 – 4 mm, slat height 1 – 4 cm; separation 5 – 20 cm; SID 10 – 50 cm. Note that the separation is the distance between the center-point of the two collimators. The parameters used in both simulations were: slat width 0.5 mm, slot width 1 mm, slat height 1.5 cm, separation 20 cm, SID 50 cm, and r_m 6 cm.

The near-field modulation behavior is as follows.

First, let us assume a point source located on the axis of rotation, with the collimator slats oriented vertically. Gamma rays can pass through the entire length of the collimator in the vertical direction, but only a certain distance, $2l$, in the horizontal direction. The parameter l is calculated as shown below (2). Essentially, l is the distance dictated by the geometric angle of acceptance defined by the collimator's slots and slats.

$$l = SID \frac{\text{slot width}}{\text{slat height}} \quad (2)$$

This distance, $2l$, and the vertical distance, $2v$, define a rectangle of acceptance (ROA).

Figure 4 illustrates the model geometry. The top picture shows the front-on view of the collimator, as seen from the perspective of a point source, with the rectangle of acceptance drawn on top of it. The bottom picture shows the point source, collimators (light color indicates slots, dark color indicates slats) and HPGe detector as seen from the side. The geometric acceptance angle dictates the distance in the horizontal direction, l , that the rays can pass through the collimator. In a non-ideal model, the distance $2l$ would be affected by high-energy gamma rays penetrating the slats.

As the collimators rotate, this ROA continues to have the same area, and rotates like a propeller pinned to the collimator. The same area of the detector is visible to the point source at all collimator angles. Thus, no modulation occurs for point sources located along the axis of rotation.

Let us also assume that the length of the ROA extends to infinity in the vertical direction, $2v$, but remains fixed at $2l$ in the horizontal direction. As the collimator rotates, the ROA sweeps out an area of acceptance in space. An off-axis point source will only be able to “see” the detector when it is inside the ROA. The farther away the point source is (in terms of radial distance on the imaging plane), the less time it will remain inside the ROA because each angular step translates into a larger arc. The above concept is illustrated in Figure 5A, which

shows the rectangle of acceptance sweeping out an area of acceptance in space. At 0° points A and B are inside the rectangle, at 20° only point B is inside and at 45° both points are outside.

This simplistic model is binary, as either the point source sees the detector or it does not. The resulting modulation profile would be a square wave, with cutoffs at zero once the point source is outside the ROA. However, this is not the case in a more realistic model, where once a source is located inside the rectangle of acceptance, the modulation profile begins to increase from baseline, reaching its maximum when the angle of the collimator (θ_c) is equal to the angle of the point source (θ_m).

For such a profile to occur, let us assume that the axis of rotation of the ROA is pinned to the point source, instead of to the center of the collimator. This is akin to rotating the point source and leaving the camera fixed, instead of rotating the collimator and leaving the point source fixed (Figure 5A vs. Figure 5B). This alternate view depicted in Figure 5B shows the area of the detector the point source can “see” as the ROA rotates about the point source. Figure 5C shows the geometry determining the area of the detector face “seen” when the collimator is aligned with the point source (maximum area). Finally, Figure 5D shows the model geometry as the ROA rotates.

The number of gammas detected from the point source is proportional to the area of the detector face that is covered by the ROA and can be calculated in the following manner:

$$\theta = |\theta_m - \theta_c| \quad (3)$$

$$q = r_m \sin \theta \quad (4)$$

$$\alpha = \begin{cases} 2\cos^{-1}[(q+l)/r] & \text{if } (q+l) \leq r \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

$$\beta = \begin{cases} 2\cos^{-1}[(l-q)/r] & \text{if } |l-q| \leq r \\ 0 & \text{if } (l-q) > r \\ 2\pi & \text{if } (l-q) < -r \end{cases} \quad (6)$$

$$A_{im} = \pi r^2 - \frac{1}{2} r^2 (\alpha - \sin \alpha) - \frac{1}{2} r^2 (\beta - \sin \beta) \quad (7)$$

Note: area of a semicircle defined by angle ϕ and radius r , is defined: $\frac{1}{2} r^2 (\phi - \sin \phi)$

$$r_s = \sqrt{SID^2 + r_m^2} \quad (8)$$

$$S_{im} \approx \frac{F_{im}}{4\pi r_s^2} \quad (9)$$

In (9) S_{im} is the approximate probability of detecting a signal from a point source located at pixel, m (which is defined in the imaging plane by radius, r_m , and angle, θ_m when the collimator is at angle θ_c). It is the solid angle corresponding to the visible amount of detector area (A_{im}) within the sphere of point source activity ($4\pi r_s^2$). A_{im} is equal to the area of detector face (defined by radius r) minus the area of semicircle A minus the area of semicircle B . θ is the relative angle between the point source and the RMC; q is the distance between the centerline of the rectangle of acceptance and center of the detector; α and β are the angles that define the semicircles A and B (see Figure 5C and Figure 5D).

Analyzing the above equations, when l is greater than the radius of the detector, r , plus the quantity q , S_{im} will be the same value for all collimator angles. This would happen with either a large collimator pitch or a point source located very close to the axis of rotation. At the other extreme, S_{im} , would approach a delta function as l approaches zero and q becomes large, which would happen for a small collimator pitch or a source very far from the axis of rotation. Figure 3 shows a modulation profile (dashed line) obtained with the proposed geometric model (9) for a point source located at pixel m on the imaging plane by determining S_{im} at each collimator angle θ_i .

It is also important to note that the above equations do not take into account the separation between the collimators or their alignment, nor does it account for aliasing of the point sources. Our belief is that when dealing with such high-energy gamma rays septal penetration will cause these parameters to have little impact on the overall geometric behavior of the system.

2.2 Image Reconstruction

2.2.1 MLEM Algorithm—We have been using the maximum likelihood expectation maximization (MLEM) algorithm to reconstruct NSECT images. MLEM is well suited for high-noise, low-count systems such as NSECT because it accounts for the Poisson nature of photon counting. MLEM converges to an undesirable high-frequency solution however [38]; to prevent this, the algorithm was capped at 20 iterations for all reconstructions presented in this manuscript. This number was chosen because it appeared to be a good trade off between maximum signal identification and minimum noise.

The MLEM algorithm depends on a probability matrix, P , which is a 2D matrix that contains the probability that the counts at each collimator angle, θ_c , originated at each pixel, m . The algorithm for iteration $n+1$ is given by:

$$p_m^{n+1} = \frac{p_m^n}{\sum_{\theta_c=1}^C P_{m\theta_c}} \sum_{\theta_c=1}^C \frac{P_{m\theta_c} obs_{\theta_c}}{\sum_{m=1}^M P_{m\theta_c} p_m^n} \quad (10)$$

where p^n is the initial estimate of the reconstructed image (which can be simply set to a constant positive number) for each of M total pixels and obs_{θ} is the observation matrix (modulation profile) obtained at each angle θ_c for C total angles [35].

For the experiments presented in this study, multiple camera views (i.e., cameras placed at multiple locations relative to the source) were combined to create a single image using the following extension of the MLEM algorithm above (10).

$$p_m^{n+1} = \frac{P_m^n}{\sum_{\text{camera}=1}^{\text{cameras}} \sum_{\theta_c=1}^C P_{\text{camera}, m \theta_c}} \sum_{\text{camera}=1}^{\text{cameras}} \sum_{\theta_c=1}^C \frac{P_{\text{camera}, m \theta_c} \text{obs}_{\text{camera}, \theta_c}}{\sum_{m=1}^M P_{\text{camera}, m \theta_c} p_m^n} \quad (11)$$

Here a separate probability matrix, P , and observation matrix, obs , are obtained for each camera view and then used to create a single reconstructed image.

Of note in this algorithm is that the number of reconstructed image pixels is not explicitly dictated by the number of camera angles or cameras, as any combination of the three is mathematically acceptable. But, care must be taken in choosing the number of cameras, camera angles and image pixels, so that the system is acceptable in terms of amount of information used to recreate the image. In this study, all reconstructed images were chosen to be 25×25 (625 total) pixels. To determine the impact of the number of camera angles and the number of cameras: two different numbers of camera angles were tried (i.e. 180 and 600), as well as camera arrangements of one, four and nine.

2.2.2 Image simulation and reconstruction procedure—The following procedure was implemented to generate reconstructed images. First, a 2D 25×25 pixel “true image” was generated by placing gamma ray sources (pixels valued at 1000) on a background field of zeros. Second, a probability matrix was generated by calculating S_{im} from (9) for each pixel at each collimator angle. Third, a 1D observation matrix was generated by multiplying the true image by the probability matrix. Finally, the observation matrix and corresponding probability matrix were fed into the MLEM algorithm (10) for reconstruction (note: in this instance P in (10) and (11) is equal to S from (9)). To generate multiple camera views of the same true image, the above process was modified in the following manner. Steps two and three were repeated for all camera locations and then all observation and probability matrices were combined in step four (utilizing (11)).

A Matlab [39] script was developed to generate a probability matrix based on the geometric model outlined above in (9), where S_{im} was determined for each pixel at each collimator angle. User selectable dimensions included: collimator slot width, slat height, collimator separation (separation), distance to the imaging plane (SID), number of collimator angular steps, the number and size of the pixels in the imaging plane and the center of the imaging plane relative to the axis of collimator. It is important to note that the axis of collimator rotation always defines the (0,0) x,y point of the imaging plane.

2.2.3 Point Source Simulations and Reconstructions—Point sources were reconstructed at multiple locations within the imaging plane utilizing the following imaging parameters: slot width 0.1 cm, slat height 4.0 cm, separation 5.0 cm, SID 10.0 cm, and pixel width 0.5 cm. Two values of collimator angular steps were attempted: 180 and 600. Four camera views were used, located 12.73 cm from the axis of rotation at 45° , 135° , 225° , and 315° . The locations of these cameras are shown in Figure 6A.

2.2.4 Extended Source Simulations and Reconstructions—An extended source phantom consisting of three circles (see Figure 6B) was tested using the following parameters: slot width 0.1 cm, slat height 4.0 cm, separation 5.0 cm, SID 10.0 cm, collimator angular steps 180, pixels 625, and pixel width 1.0 cm and 1.5 cm. Nine camera views were used, including one centered on the axis of rotation. For the 1.5 cm pixels, the center of the imaging plane was located a radius of 22.36 cm from the axis-of-rotation at 26.6°, 63.4°, 116.6°, 153.4°, 206.6°, 243.4°, 296.6°, and 333.4°. For the 1.0 cm pixels, the center of the imaging plane was located a radius of 18.02 cm from the axis-of-rotation at 33.7°, 56.3°, 123.7°, 146.3°, 213.7°, 236.3°, 303.6°, and 326.3°. These camera locations were identified through trial and error on preliminary reconstructed images and are placed uniformly around the phantom (see Figure 6B for a depiction of camera layout). These positions may appear to be severe; however, it should be noted that while these positions worked the best, others worked rather well. While the precise position of the cameras must be known to generate probability matrices, these exact positions are not necessary to image objects and it should not be necessary to change camera positions to image different objects.

To evaluate the effect of measurement noise on the reconstruction process, the extended sources experiment was repeated with Gaussian noise added to the observation matrices in a way that approximated Poisson noise. The true signal at each observation angle was multiplied by a number between -1 and 1. The probability of choosing such number was based on the Gaussian distribution $\sim(0,2)$. The reconstruction algorithm generated images using the noisy observation matrices and the clean probability matrices.

3. Results

3.1 Expected Geometric Behavior

The modulation profiles predicted by the geometric model highlight several trends, which are depicted in Figure 7. Moving the point source further away in the z-direction will increase the area of detector that the point source can see, but this is negated by the decrease in solid angle (see Figure 7A and Figure 7B) resulting in a modulation profile with a smaller peak when the source is farther away. Additionally, by keeping the angular location (θ_m) the same but changing the radial distance (r_m) of the source from the axis of rotation, the modulation profile becomes thinner as the radius increases (Figure 7C). When the radius is kept the same but the angular location of the source is changed, the modulation profile shape remains the same, but the location of peak changes to correspond with θ_m (Figure 7D).

3.2 Image Reconstruction

3.2.1 Additional Sources of Information: More Cameras and More RMC Angles

—The MLEM algorithm successfully reconstructed images only when using multiple camera views. The bottom row in Figure 8 depicts four reconstructed images of a single point source obtained at different camera locations (the image planes can be seen in Figure 6A). These images are unclear, and no “point” is clearly identifiable. The “true” image of the point source is shown in Figure 9A.

The top row in Figure 8 depicts the observation matrices obtained for the same point source as viewed by four different cameras. The modulation profiles for each point source varied depending on the source's location relative to the origin; therefore, they each contain unique information and by combining the information from several cameras successful image reconstruction is achieved (see Figure 9).

Increasing the number of camera angles from 180 to 600 had no effect on individual or combined reconstructions. Figure 9 is a comparison of reconstructions (utilizing four camera views) of the same point source between the 180 angle (Figure 9D) and 600 angle (Figure 9C) systems. The reconstructions are identical. After consideration, this surprising finding is acceptable and explained in the discussion section.

3.2.2 Point Sources—Adequate point source reconstructions were obtained throughout the entire $12.5\text{ cm} \times 12.5\text{ cm}$ field of view by using four camera views (see Figure 9).

3.2.3 Extended Sources—Reconstructing the extended source required nine cameras, because using cameras located only at the four corners of the imaging plane was not enough. Instead eight cameras were placed in a ring about the imaging plane and a ninth was placed at the origin in order for the reconstructed image to be reasonable (Figure 6B). Figure 10 depicts the same 25×25 pixel image reconstructed with the 9 camera views with $1\text{ cm} \times 1\text{ cm}$ and $1.5\text{ cm} \times 1.5\text{ cm}$ pixels. The 1.5 cm^2 pixel image was clearer than the 1.0 cm^2 pixel image. This was expected due to the properties of the imaging system and reconstruction algorithm and is explained further in the discussion. Note both images come from the same true 25×25 pixel image. The difference is that resolution is achieved by ‘imaging’ the true image with a probability matrix determined by either a $1\text{ cm} \times 1\text{ cm}$ pixel grid or a $1.5\text{ cm} \times 1.5\text{ cm}$ pixel grid.

Reconstruction of the noisy extended source was successful. Figure 11 shows a non-noisy (Figure 11A) observation matrix and its noisy equivalent (Figure 11B). Figure 11C shows a 1.5 cm pixel reconstructed image obtained with 9 noisy observation matrices. Reconstruction of noisy data does appear feasible.

4. Discussion

To adequately visualize NSECT data a high-energy gamma camera is necessary. Herein we described the adaptation of a space-based imaging technology for use in the near field. Due to the inability of the far-field model to explain near-field behavior, we developed and presented a geometric model of the RMC that explains how modulation profiles are generated. We then used the geometric model to generate simple reconstructed images.

Our results clearly show that the model's behavior closely resembles that of the Monte Carlo simulation (Figure 3) [36]. The geometric model verifies that modulation profiles are unique to a source's location in space, as they will shift peak location with a change in θ_m and change shape with a change in radius, r_m (Figure 7). It also predicts that the number of counts overall will decrease when the distance between the source and detector (SID) increases. This is expected due to a decrease in solid angle.

The geometric model is an idealized model and not a prediction of absolute modulation profile shape. It addresses only the basic pattern of modulation by only accounting for the distance from the source to the detector, the source's location on the imaging plane and slot width and slat height. A more definitive model would take into account all RMC design parameters including the slat width, the distance between the collimators, the collimator alignment and high-energy gamma ray penetration of the collimator slats. However, the proposed model is only presented to give a basic view of RMC functionality in the near-field. Taking into account all the other variables will not change the overall modulation profile behavior as the peak number of counts will occur where predicted by the model, and the basic modulation profile curve will remain the same. The largest expected difference between a modulation profile predicted by this model and one generated by an actual RMC will be caused by penetration of the slats by the high-energy gamma rays. This penetration will cause the "floor" of the modulation profile to rise while the peak counts will remain essentially the same. Thus, as the gamma energy increases, the peak in the modulation profile will sink (relatively) into the background noise. Due to the limitations stated above, this model should not be used to determine the dimensions of a functional RMC, as the largest design challenge will be to determine an RMC design that provides enough stoppage so that the modulation profile peak remains visible above the background. We believe that a suitable RMC design can be found that provides adequate stoppage of gamma rays and allows the peak to maintain visibility, although clearly this would become increasingly challenging for higher photon energies.

The model presented herein can be used to verify results obtained from more complex simulations or from experiments conducted in the lab, as well as to verify the feasibility of reconstructing images using a probability matrix, which is necessary in order to reconstruct 2D images from one dimensional data (here, data counts at each collimator angle).

In this near-field model the modulation profiles for each pixel are simple curves and do not vary much between neighboring pixels. There is, therefore, insufficient information regarding source locations. Reconstructing images in this type of system is difficult and this is apparent in the single-camera reconstructions shown in Figure 8.

Two steps were implemented to overcome this information shortcoming; (i) reconstructing using observation matrices with information from more collimator angles and (ii) reconstructing using information from multiple camera views, such as might come from a single camera placed sequentially at different locations, or multiple cameras used simultaneously. Both steps added more information to the system, but only the latter was successful in improving reconstructed image quality. We will elaborate on this finding.

It was hoped that increasing the number of collimator angles would improve image quality. The system is under-sampled when using data from 180 collimator angles to reconstruct 625 pixels. But increasing the number of collimator angles to 600 yielded no improvement. A possible explanation is the simplicity of the modulation profiles over the entire imaging plane. Using more angles results in a more finely sampled modulation profile, but does not add extra information, as the profiles are smooth curves. If the individual modulation profiles were highly sinusoidal or variable, more finely sampling the data by increasing the

number of angular steps would most likely result in better reconstruction image quality, because the probability matrices and observation matrices would contain more distinct information.

The fact that all of the available information can be represented by a limited number of angles means the modulation profiles are inherently limited information, and a different set of measurements are required for an adequately sampled system. One such set of measurements is multiple camera views, which is our second solution to the information shortcoming.

The incorporation of multiple views into the reconstruction of a single image provides much more constraint on the final image than would be obtained from a single view, and therefore leads to a much better image. This is easiest to see for reconstruction of the point sources where adequate reconstruction was achieved for all point sources at all locations within the FOV by using a combination of four camera views (see Figure 9). The extended source was also successfully reconstructed, but more cameras and larger image sizes were necessary to achieve this (Figure 10 and Figure 11). Due to the image covering a large majority of the FOV, there is very little signal variation at each collimator angle, causing very indistinct observation matrices (see Figure 12). By adding more information from multiple cameras, the reconstruction algorithm has more data to work with, and can do a better job predicting which pixels generated the signals that caused the observation matrices. This finding is verified by the fact that reducing imaging size (by reducing true and reconstructed image pixel size) reduces image quality. Reducing image size results in less variation between modulation profiles for each pixel and each pixel's profile will more closely resemble its neighbors. This is shown in Figure 12, which depicts the observation matrices from four different camera views of the extended source. Note the greater variation in the observed data matrices shown in the top row that correspond to the image with 1.5 cm pixels as opposed to the bottom row from the image with 1.0 cm pixels. Therefore, the reconstruction algorithm has less information to work with, and will produce an image with reduced quality.

These experiments show that the system is information limited. The experiments conducted herein show that adding additional cameras provides more unique information than adding additional RMC interrogation angles. Further study is necessary to determine the optimal number of RMC angles and cameras, as well as, the minimum number of detected gamma events necessary to have an adequately sampled system. The geometric model presented herein is not a proper way to determine these system limits, and this type of calculation requires Monte Carlo simulations and/or lab experiments.

5. Conclusion

To summarize, we presented a geometric model to define how an RMC would modulate gammas in the near field. Using this model we reconstructed images of point and extended gamma sources. Due to the information limited modulation profile curves, in order to reconstruct images it is necessary to obtain observation matrices from multiple cameras located around the object.

This is a significant first step in developing a high-energy gamma camera for use with NSECT. Future work in this area involves the use of the prototype RMC camera, this geometric model and a Monte Carlo model to identify optimal RMC parameters.

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Schnopper and Hurford Prediction

Figure 1.

Schnopper and Hurford predicted near-field modulation profile for camera configuration (SID 50 cm, separation 20 cm, pitch 0.15 cm, r_m 6 cm and θ_m 90°).

Figure 2.
Layout and dimensions of detector and RMC. The top picture is a 3-D view, while the bottom is a side-view.

Figure 3. Simulated modulation profiles of a point source generated using the proposed geometric model (solid line) and a Monte Carlo simulation (dashed line). Beneath are the corresponding collimator views.

Figure 4.

Top: front view of collimator. Bottom: Side view of collimator depicting point source, collimators and detectors.

Figure 5.
Illustrations of the geometry of the rotating ROA.

Figure 6.

Locations of cameras. A) locations of four identical imaging planes around a central camera (4-cameras used for point-source reconstructions). B) locations of cameras around extended source. Darker cameras are for the 1.5 cm pixel image and lighter cameras are for the 1 cm pixel image. The 1 cm pixel image is shown on top of the 1.5 cm pixel image.

Figure 7.

Modulation profiles predicted by the geometry of the collimator. (A) The area of the detector seen by a source 40 and 50 cm away and (B) the matching solid angle seen by each source. Note how more area is seen by the SID 50 cm source, but less solid angle. (C) Shows the effect of keeping the angular location the same and changing the radius from 4 to 6 cm, while (D) shows the effect of keeping the radius the same and changing the angular location of the point source (71.5° - 108.5°).

Figure 8.

Individual observation matrices and reconstructions obtained for a single point source as seen by four different cameras at 180 angular steps. Plane at (x,y) refers to the imaging plane centered at that (x,y) location (see Fig 6A). Intensity is approximately the number of photons detected per 1000 emitted.

Figure 9.

Point source (A) true image, (B) horizontal profile of the reconstructed signal strength through the point. Reconstruction with 4 combined camera views utilizing (C) 600 angles and (D) 180 angles. The color bars indicate image intensity. A point source of intensity 1000 has a reconstructed intensity of approximately 60 in these images.

Figure 10.

Extended source (A) true image. Reconstruction with (B) 1.5 cm pixels and (C) 1 cm pixels.

Figure 11.

Observation matrix from a single camera view (A) no noise (B) noise added. (C) Reconstruction using 9 combined noisy observation matrices. Intensity is approximately the number of photons detected per 1000 emitted.

Figure 12.

Top row: Observation matrices obtained with 1.5 cm pixel widths. Bottom row: Observation matrices obtained with 1 cm pixel widths. Both are for four different image plane locations.

Note the greater variation for the 1.5 cm pixels as opposed to 1 cm pixels. Intensity is approximately the number of photons detected per 1000 emitted.