Published in final edited form as:

IEEE Trans Nucl Sci. 2009 ; 56(3): 687–693. doi:10.1109/TNS.2009.2019110.

A Backprojection-Based Parameter Estimation Technique for Skew-Slit Collimation

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Abstract

To estimate geometric parameters in a skew-slit single photon emission computed tomography (SPECT) scan, a simple method is presented that uses a single point source and a backprojection process. The method employs one point source placed sufficiently far from the axis of rotation but in the field of view. A skew-slit geometry is considered where the estimated parameters include the focal lengths of both opaque planes and the location of multiple transaxial slits and a single axial slit. Computer simulations show that view-angle independent parameters can be uniquely estimated. Three experimental scans were performed, and the view-angle independent parameters were accurately estimated. Tilt, sagging, and mechanical shifts result in parameters that change depending on the view angle in the experimental scans. These view-angle dependent parameters were estimated using the single point-source technique, but reconstructed phantom images showed some error in the estimation of the view-angle dependent parameters.

Index Terms

Acquisition geometry; computed tomography; parameter estimation; pinhole; skew-slit; SPECT

I. Introduction

Using cone-beam geometry with pinhole collimation, high-resolution images of small objects can be created. Image reconstruction is highly accurate if all geometric parameters are exactly known; however, it is impossible to know the exact parameter values because each experimental scan can have a completely different geometry.

To accurately estimate such geometries, it has been customary to scan point sources of isotope. Usually, the methods use mean-square-error minimization in which the measured image is compared with a pseudo image. Unfortunately, this can result in multiple, ambiguous solutions [1]. Multiple point sources in different locations are added to eliminate

the ambiguity of the different solutions [2]–[5]. In practice, some methods use phantoms consisting of multiple point sources [2]–[4]. Another method requires a specific mechanical setup where the point source is moved in careful shifts in a two-dimensional plane [5]. These methods can be subject to physical or human measurement error because of their complexity. Additionally, when the viewing area is small to achieve high magnification, the multiple sources must be closer together to fit in the viewing area. This can result in errors because of the required sensitivity. Likewise, these techniques are each specialized for a certain collimator geometry, and they may not be necessary for newer collimator designs.

Recently, a skew-slit collimator has been designed, simulated, built, and tested in which multiple slits are used in place of pinholes [6], [7]. The principal advantage of the multiple skew-slit system is the ability to choose and adjust both the axial and transaxial cone angles independently. For any pinhole or multiple pinhole system, these cone angles are the same. To increase magnification in a pinhole system, the cone angle is increased, and the resolution and sensitivity are consequently improved. However, for a circular scanning orbit, data-insufficiency artifacts become much worse for increasing cone angles. The multiple skew-slit system provides high resolution and sensitivity by using a very large transaxial angle, and it minimizes the data-insufficiency artifacts by using a small axial cone angle. To maximize the detector collection efficiency, three transaxial (horizontal) slits and one axial slit (vertical) are used (Fig. 1). The slit widths determine image resolution, and the transaxial resolution and axial resolution are controlled separately by adjusting the width of the axial and transaxial slit openings, respectively. If the system efficiency is mainly determined by the detector usage, the efficiency of the multiple skew-slit collimator is comparable to a multiple pinhole system. Physically, the slits on the skew-slit collimator are tungsten, and the housing is made of lead. Section II describes the collimator geometry in more detail.

This paper is not intended to compare the multiple skew-slit system to a multiple pinhole or any other system. Instead, the backprojection calibration technique is considered in terms of the skew-slit system. In principle, the theory behind the backprojection-based parameter estimation is not limited to a single system.

Instead of considering new phantoms or mathematics to apply to the design, a single, randomly-placed point source provides enough information to gather the acquisition geometry. By backprojecting the point-source projection data while varying individual parameter values, each parameter value can be accurately estimated by selecting the best backprojected image of the point source. Each of the backprojected images has a maximum pixel value, and the most accurate parameters are those used to backproject the image with the highest maximum value. This method is very simple because it only requires a single, randomly-placed point source and a backprojector.

Previously, the focal length of cone-beam geometry has been proven to only affect the magnification of the reconstructed image [1]. One point source provides multiple, ambiguous solutions for the focal length. With skew-slit geometry, three or more transaxial slits provide enough information to resolve this ambiguity. Computer simulations and experimental scans show that the technique is robust for parameter that do not change

depending of the view angle, but the parameters that change due to shifting during the experiments are not estimated with the same accuracy.

II. Overview of Skew-Slit Geometry

Fig. 2 shows the skew-slit geometry and coordinate system used in the following simulations and reconstruction. The z axis is the axis of rotation, the y axis is parallel to the detector plane, and the x axis is perpendicular to the detector plane. The origin of the coordinate system is at the center of the imaging system.

The two focal lengths are named F_1 and F_2 . F_1 refers to the distance between the axis of rotation and the axial slit. F_2 refers to the distance between the axis of rotation and the transaxial slits. The z -axis location of the transaxial slits is described by the parameters S_1 , S_2 , and S_3 . The offset of the collimator and detector in the y -direction is described by the parameter τ_y . The parameter τ_z describes the offset of the collimator and detector in the z -direction. Electronic shift parameters, E_z and E_y , were added to describe electronic shifts in the transaxial and axial directions, respectively. Table I summarizes these parameters.

Initial manual measurements of the physical collimator suggested that the distance between the two opaque planes that contain the slits is approximately 9 cm. The transaxial slits are spaced approximately 3 cm apart. These parameters are only approximately known because mechanical measurements cannot easily be made with sub-millimeter accuracy.

Additionally, the skew-slit collimator has some adjustable parameters such as the distance between slits and the F_2 focal length. It is not feasible to accurately measure these parameters mechanically for each individual scan. It should also be noted that for a real system, F_1 , τ_y , and τ_z vary during the scan due to mechanical shifting and sagging.

III. Theory

Projection data is backprojected for each angle of a scan of a point source, and the backprojected image describes the location and size of the original point source (Fig. 3). In the backprojected image, there is a maximum value that should represent the location of the center of the point source. When incorrect geometric imaging parameters are used, the beams created by the backprojection do not intersect at one point, and the maximum value is significantly lower (Fig. 3(b)). Thus, the exact geometric parameters will produce the highest maximum value in the backprojected image.

Ideally, the maximum value would be given by the exact geometric parameters, but the accuracy of the given maximum values depends on the resolution of the reconstructed image. Finite resolution of the image can cause some slight variation in the results. In the event of a local maximum, the backprojected image can be examined to verify that the rays converge to a single point. Also, many local minima are avoided by knowing approximate values a priori.

Still, with cone-beam geometry, it has been proven that multiple point-sources are necessary for accurate estimation of all parameters. More importantly, the focal length (the distance between the axis of rotation and the focal point of the cone) is just a magnification factor in

the reconstruction. This problem is remedied by using multiple transaxial slits in the scan of the single point source. These multiple slits produce multiple projections of the same point source on the detector. Fig. 4 shows simulated superimposed images from the detector using three transaxial slits. Note that this data is equivalent to having three distinct sources located on a straight line parallel to the axis of rotation in cone-beam or pinhole collimation [4] and is very similar to the elliptical projections in [8].

Fig. 5 shows the detector and collimator in two different positions to demonstrate how parameter variations affect the quality of the backprojected images. Backprojected rays are represented that connect the data on the detector through the slits to the backprojected image array. The backprojected beams do not intersect at a single point if the focal length is incorrect, resulting in a lower maximum value.

With this method, there is very little difficulty with experimental setup because a quick scan of a point source in any location in the field of view will yield sufficient data. Still, the point source must be placed sufficiently far from the axis of rotation to yield unique projection data. This process is relatively simple in comparison to other calibration techniques [2]–[5] and can immediately precede or follow a more detailed scan with no change in the acquisition geometry. Effort and possible sources of human error are greatly minimized. A 3D image of the backprojection shows if the backprojected beams actually intersect, providing visual verification of the results.

Any method may be used to maximize the backprojection function, but maximization methods that respond well to a greater number of simultaneously changing variables are preferred. For simplicity, the parameters of the simulations and the phantom experiment in this research were found by performing an iterative line search. This is done by choosing an acceptable range of parameter values and varying each individually. When a maximum value was found for each parameter in that range, the range was decreased around the parameter that gave the previous maximum value. As the search range was decreased around an individual parameter, the next parameter was searched. This estimation process was iterated until the estimated parameters were stabilized.

IV. Computer Simulations

Three computer simulations were performed in which the parameters were estimated from simulated projection data. The skew-slit geometry from Fig. 2 was used in the simulations. The acceptance angle of the slits in simulation was 180° , and the slit openings were infinitely small. A low-pass filter was applied to the projection data for smoothing purposes. The simulated projection data were stored as 128×128 pixel images, and the backprojected image was stored as a $128 \times 128 \times 128$ voxel 3D image. Higher resolution could be used for any situation that requires the additional accuracy. All length units described for the simulations refer to detector pixel size and backprojection array voxel size, which are the same. More specifically, each of the six sides of the 3D voxels in the backprojected image array was identical to the size of a detector pixel. A circular orbit was used, and the axis of rotation was assumed to be constant throughout the scan. The detector was rotated for 10 views over the full 360° orbit.

For each of the three simulations, the size and location of the source were varied. For the first simulation, a spherical point source of diameter 1.6 was placed on the x-axis at $\{x, y, z\} = \{5, 0, 0\}$. As described earlier, a range of possible parameter values was selected for each parameter, and an iterative line search was performed until the parameters were stabilized. Table II lists each parameter, the range of values that were searched, the actual value of each parameter, and the estimated values for the first simulation. Any possible parameters not listed in the table were assumed to be constant. As can be seen from the estimated values, the focal lengths were accurately estimated, and the τ_y values and slit values were estimated with minimal error. The accuracy of the backprojected image was also verified visually by viewing the backprojected array, and all backprojected beams crossed at a single, focused point.

Table III and Table IV show the results for the second and third simulations that were performed. It was observed that the size of the point source was arbitrary. The accuracy of the estimated parameters from simulation 3 compare with the parameters from simulation 2 despite the source having a diameter of 6 pixel units. The size of the source was observed to affect only the speed and sensitivity of the maximization process and not the estimated values. In the backprojected array of a large sphere, for example, there is a maximum voxel value at the center of the sphere, and the backprojected image is maximized when all parameters are correct. A final simulation was performed in which the source was simulated on the axis of rotation, and the parameters were not accurately estimated. Also, simulations conducted with only one transaxial slit and one axial slit did not produce unambiguous solutions due to insufficient data.

V. Experimental Data

A. Point Source Scans

Three point source experiments were performed using the prototype skew-slit collimator on a Philips' IRIX SPECT camera. The collimator was attached to detector #1 of the three-detector system, and detectors #2 and #3 were not used. The detector array had a size of 256×256 , and the backprojected image array had a size of $256 \times 256 \times 256$.

The point source was made of a small drop of Tc-99m in a capillary tube. The inner diameter of the tube was 1 mm. The activity of the Tc-99m was approximately 80 μCi . Three distinct scans were performed, each with the point source positioned at a different location. The total duration of each experimental scan was 9 minutes, and each scan had 60 views over the full 360° circular orbit. The geometry of the system was not changed from one experimental scan to another. Fig. 6 shows the experimental superimposed projection data (as in Fig. 4).

A total of 30 parameters were estimated in the experimental scan, and these parameters are described in Table V. Several parameters were added to describe mechanical and electronic shifts. Two parameters, E_z and E_ϕ , were added to the estimation algorithm to describe potential electronic shifts in the transaxial and axial directions, respectively. Besides the added shift parameters, the focal lengths were based on the IRIX system readout for the axis of rotation. It was assumed that the system data was accurate, and the F_1 focal length still

described the distance between the axis-of-rotation and the axial slit. The F_2 focal length was described by the difference between the axial and transaxial slits, $F_2 - F_1$.

Examination of the projection data showed 8 noticeable shifts over the 360° scan. These shifts were most likely due to camera sagging and tilt, and they are best described by angular-dependent F_1 , τ_y , and τ_z parameters. It is not claimed, however, that these are a comprehensive set of parameter for the skew-slit system. Because the projection data showed significant camera shifting occurring every 45° , the three variable parameters were each split into a set of 8 parameters to describe the shifting. A full set of 60 values for each of these variables would result in a total of 186 values to estimate and would take far too much computational time. It was also observed that due to correlation between the parameters, the optimization often “converges” to a local maximum if too many parameters are used.

While the parameters in Table V may not represent a full skew-slit and gantry system characterization, they were chosen based on computational time after careful examination of the projection data. These parameters have the most significant effect on the reconstructed images. More parameters will be added as deemed necessary based on experimental data.

The backprojection process was identical to the simulation data except that the size of the backprojected array was reduced to $15 \times 15 \times 15$ after the first backprojection to save computation time; here, the voxel size remained 2.33 mm cubed, but the unused areas of the array were cropped. Then, the $15 \times 15 \times 15$ voxel section was moved within the original $256 \times 256 \times 256$ array such that the maximum voxel value from the previous iteration was always at the center of the reduced array. The search interval for each parameter changed dynamically. In the first 10 iterations, the interval was $\pm 10\%$ of the default value. It was reduced to $\pm 1\%$ in the next 10 iterations and to $\pm 0.1\%$ for the final iterations. The total computation time was approximately 30 minutes on a workstation with a 2 GHz Dual Core AMD Opteron Processor 270.

The three point source estimation experiments yielded values that are shown in Table VI. The electronic shift parameters did not change from their default values, and the other parameters did vary slightly from scan to scan. Still, because the experiments were performed consecutively without any changes to the collimator or gantry, the parameters should all be the same.

B. Phantom Reconstruction With Estimated Values

An Ultra-Micro Hot-Spot Phantom model ECT/HOT/UMMP was used for the phantom study (Fig. 7). The phantom was filled with 22.5 mCi (0.8325 GBq) of Tc-99m and was scanned on an IRIX SPECT system. The phantom had 6 sections of hollow channels with diameters 2.4, 2.0, 1.7 1.35, 1.0, and 0.75 mm. The detector array had a size of 256×256 , and the image array had a size of $256 \times 256 \times 256$. The phantom was scanned at 180 views over 360° for 90 minutes. The pixel size in the detector array was 2.3 mm, and the voxel size in the backprojection array was 0.16 mm.

The phantom scan was performed immediately before the three point-source scans in the previous section. To illustrate the effectiveness of the point source experiments, 5 separate reconstructions of this scan were performed. In the first reconstruction, the default parameter values (hand measured) from Table V were used. In the next three reconstructions, the parameters found using the three point source experiments from above were used. In the final reconstruction, the results from the point source experiment #1 were used, but the $\tau_y(1, \dots, 8)$ parameter was adjusted manually to give better results. The OSEM algorithm was used to reconstruct the images (5 iterations with 15 subsets and 12 views in each subset).

Fig. 8 shows the 5 reconstructed images. When the parameters are left at their default values, the reconstructed image has very few discernable features (Fig. 8(a)). Each of the three reconstructions that used the point source estimation technique was a significant improvement from the first reconstruction, but there was some inconsistency with artifacts and blurring of channels (Fig. 8(b)–(d)). With the hand-adjusted τ_y parameter, sub-millimeter spatial resolution was achieved. The smallest channels of diameter 0.75 mm can be seen in Fig. 8(e).

VI. Conclusion and Discussion

A very simple method to find the geometric parameters of a multiple-skew-slit collimated SPECT experiment was presented. Using a single point source, the parameters were accurately estimated for computer-generated data in 3 separate experiments. The simulations also demonstrated that the source did need to be placed away from the axis of rotation for an unambiguous solution. Voxel-driven backprojections provided sufficient data to accurately estimate parameter values. In the three experimental point source scans, only the parameters that are independent of the view angle were estimated with acceptable accuracy. Sub-millimeter spatial resolution was achieved using the skew-slit collimator and the single point-source parameter-estimation technique only after the $\tau_y(1, \dots, 8)$ parameter was adjusted manually.

The three transaxial slits create three separate projections of the point source on the detector, imitating a pinhole geometry in which three separate point sources are placed on a straight line parallel to the axis of rotation. It has previously been proven that multiple point sources are necessary to accurately estimate the parameters of a single pinhole system; however, with multiple slits, only one point source is required. Also, much like Bequé *et al.* [4], the performance of this method is evaluated for image reconstruction accuracy only, allowing correlated errors that do not significantly reduce the accuracy of the reconstructed image.

While this research does not include all possible parameters for the skew-slit system, it can be seen that the backprojection process accurately estimates all view-angle independent parameters. The view-angle dependent parameters are estimated with small errors. In theory, there is no limit to the number of parameters that can be estimated. Time and convergence to a local minimum, however, become factors when estimating large numbers of parameters.

The three experimental point source estimations resulted in detrimental image artifacts and blurring. This is mainly due to the high magnification of the system and the limited

information available from a point source scan. Noise in the projection data results in small errors in the estimated parameters (Table VI). While small, these errors are visibly detrimental when the parameters are used to reconstruct an image that is magnified by about 14 $\times$. Unlike computer simulations, the pixel with the maximum value in the projected image is not exactly at the center of the projected source. For future implementation, image processing of the projected images may be performed before the backprojection process to decrease the parameter sensitivity. This may also reduce the likelihood of encountering a local minimum and also allow more variance in the initial parameter estimates.

Also, the point-source technique struggled to effectively estimate angular-dependent parameters such as mechanical shifts and F_1 . This is partially due to the time and computational resources necessary to estimate a large number of parameters. Still, much of the shifting occurs in the x-direction, and a small point source does not provide complete information to estimate small changes in parameters such as F_1 . Future experiments will be performed with larger sources that will have visible changes in magnification for such shifts. Additional strategies to improve the robustness of the technique are under investigation.

Because simultaneous, multiple-parameter estimation can be time-consuming, a maximization/minimization method such as the Nelder-Mead simplex method can be used to find the multiple parameters simultaneously [9]. In addition, a scan could be performed in which the point sources are included with the original phantom/subject scan. This would eliminate any inconsistencies caused by separate phantom and point source scans. The ultimate goal is to calibrate the collimator geometry using patient data, which would be accomplished by maximizing a concentrated area of the scan data instead of a separate point source [10]. In theory, a larger source or even the object being scanned would provide more information on magnification and view-angle dependent parameters.

Acknowledgments

This work was supported in part by the Margolis Foundation and the National Institutes of Health (NIH) under Grant R21 EB006830.

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Fig. 1. Demonstration of the multi-skew-slit geometry that incorporates three slits orthogonal to the axis of rotation.

Fig. 2. Skew slit geometry containing two separate focal lengths. The x -axis is orthogonal to the detector plane, and the y -axis is parallel to the detector plane. The z -axis is the axis of rotation.

Fig. 3. Backprojected images using voxel-driven backprojection: (a) using exact parameter values creating an absolute maximum. (b) Using a small error in τ_y , resulting in a much lower maximum value.

Fig. 4. Simulated superimposed projection data of a single point source viewed from 10 different angles using three transaxial slits.

Fig. 5.

Theory for the use of multiple slits to estimate focal lengths using a single point source. (a) Backprojected rays from the detector intercept at the correct location when the focal length is the correct length. (b) When the focal length is too small, the backprojected rays intercept at three separate locations, causing a smaller maximum value.

(Scan 1)

(Scan 2)

(Scan 3)

Fig. 6.

The separate projection data sets of a single point source viewed from 60 different angles. In each scan, the source was placed in a different location. The prototype skew-slit collimator with one axial and three transaxial slits was used.

Fig. 7.
The Ultra-Micro Hot-Spot Phantom model ECT/HOT/UMMP used in the phantom study.

Fig. 8. 2D slices of a reconstructed image array from an Ultra-Micro Hot-Spot Phantom model ECT/HOT/UMMP scan using several different parameter sets. (a) Using default (hand-measured) parameter values. (b) Using parameters estimated from first point-source scan. (c) Using parameters estimated from second point-source scan. (d) Using parameters estimated from third point-source scan. (e) Using manually-adjusted τ_y values for best image results.

TABLE I

Summary of Basic Geometric Parameters in Skew-Slit Geometry

Parameter	Description
F_1	Focal length describing the distance from the axial slit to the axis of rotation
F_2	Focal length describing the distance from the transaxial slits to the axis of rotation
S_1, S_2, S_3	Positions of slits 1, 2, and 3 with respect to $z = 0$.
τ_y	The location of the projection of the z -axis onto the detector with respect to the center of the detector ($y=0$)
τ_z	The location of the projection of the y -axis onto the detector with respect to the center of the detector ($z=0$)
E_z	Transaxial electronic shift
E_y	Axial electronic shift

TABLE II

Simulation Results for Source of Diameter 1.6 Centered at a Location of {5,0,0}

Parameter	Range Searched	Actual Value	Estimated Value
F_1	30 to 50	40.0000	39.9994
F_2	45 to 75	60.0000	60.0355
S_1	4 to 12	8.0000	8.2397
S_2	-4 to 4	0.0000	0.2387
S_3	-12 to -4	-8.0000	-7.7624
τ_y	-4 to 4	0.0000	-0.1240

TABLE III

Simulation Results for Source of Diameter 1.0 Centered at a Location of {5,5,0}

Parameter	Range Searched	Actual Value	Estimated Value
F_1	30 to 50	40.0000	40.1120
F_2	45 to 75	60.0000	59.7632
S_1	4 to 12	7.2222	7.2222
S_2	-4 to 4	0.2222	0.0754
S_3	-12 to -4	-7.7778	-7.6728
τ_y	-4 to 4	-0.5000	-0.5090

TABLE IVSimulation Results for Source of Diameter 6 Centered at a Location of $\{-5, -5, -5\}$

Parameter	Range Searched	Actual Value	Estimated Value
F_1	30 to 50	40.0000	39.9538
F_2	45 to 75	60.0000	59.8400
S_1	4 to 12	7.5556	7.5130
S_2	-4 to 4	-0.4444	-0.4444
S_3	-12 to -4	-7.4444	-7.4474
τ_y	-4 to 4	1.0000	1.0960

TABLE V

Summary of the Estimated Parameters in the Three Experimental Point Source Scans and Their Initial Default Values in the Estimation Process. (1 unit = 2.33 mm)

Parameter Name	Description	Initial Value
E_z	Transaxial electronic shift	0
E_y	Axial electronic shift	0
S_1, S_2, S_3	Positions of the three transaxial slits with respect to $z=0$ (as in Table 1)	12.9, 0, -12.9
F_2-F_1	The distance between the transaxial and axial slit planes	38.6
$F_1(1,...,8)$	The focal length between the axial slit and the axis of rotation	21.4
$\tau_y(1,...,8)$	The location of the projection of the axis of rotation on the detector with respect to the center of the detector ($y=0$)	0
$\tau_z(1,...,8)$	The location of the projection of the y-axis on the detector with respect to the center of the detector ($z=0$)	0

TABLE VI

Estimated Parameters From Three Experimental Point Source Scans. (1 unit = 2.33 mm)

Parameter	Point Source Experiment #1	Point Source Experiment #2	Point Source Experiment #3
E_z	0	0	0
E_y	0	0	0
S_1, S_2, S_3	16.3, 2.2, -12.3	16.1, 2.0, -12.3	16.2, 2.0, -12.7
F_2-F_1	40.5	40.2	40.6
$F_1(1,...,8)$	{13.1, 13.7, 12.7, 12.6, 11.9, 12.5, 13.0, 12.7}	{14.0, 13.3, 12.7, 12.6, 12.7, 12.4, 13.1, 12.7}	{13.1, 13.5, 12.8, 12.6, 12.0, 12.5, 13.0, 12.7}
$\tau_y(1,...,8)$	{0.14, 0.06, 0.00, 0.06, 0.10, 0.17, -0.05, 0.25}	{0.11, -0.04, -0.02, -0.01, 0.06, -0.04, 0.19, 0.11}	{0.01, -0.05, 0.08, 0.08, -0.08, 0.05, 0.03, 0.16}
$\tau_x(1,...,8)$	{-0.46, -0.43, -0.09, 0.26, 0.27, 0.58, 0.59, 0.57}	{-0.54, -0.54, -0.22, 0.06, 0.53, 0.78, 0.68, 0.63}	{-0.31, -0.48, -0.11, 0.12, 0.34, 0.50, 0.49, 0.38}