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Geometric Characterization of Multi-Axis Multi-Pinhole SPECT

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Abstract

A geometric model and calibration process are developed for SPECT imaging with multiple pinholes and multiple mechanical axes. Unlike the typical situation where pinhole collimators are mounted directly to rotating gamma ray detectors, this geometric model allows for independent rotation of the detectors and pinholes, for the case where the pinhole collimator is physically detached from the detectors. This geometric model is applied to a prototype small animal SPECT device with a total of 22 pinholes and which uses dual clinical SPECT detectors. All free parameters in the model are estimated from a calibration scan of point sources and without the need for a precision point source phantom. For a full calibration of this device, a scan of four point sources with 360° rotation is suitable for estimating all 95 free parameters of the geometric model. After a full calibration, a rapid calibration scan of two point sources with 180° rotation is suitable for estimating the subset of 22 parameters associated with repositioning the collimation device relative to the detectors. The high accuracy of the calibration process is validated experimentally. Residual differences between predicted and measured coordinates are normally distributed with 0.8 mm full width at half maximum and are estimated to contribute 0.12 mm root mean square to the reconstructed spatial resolution. Since this error is small compared to other contributions arising from the pinhole diameter and the detector, the accuracy of the calibration is sufficient for high resolution small animal SPECT imaging.

Keywords

calibration; SPECT; high-resolution imaging; pinhole; small animal

I. INTRODUCTION

A. Pinhole SPECT calibration

Pinhole SPECT is a well demonstrated technique for high resolution molecular imaging of small animals.¹⁻³ In order to preserve spatial resolution and to avoid artifacts, accurate calibration of the system geometry is essential. Errors from geometric calibration impact the accuracy of the system matrix in image reconstruction and contribute directly to a loss of spatial resolution. For small animal imaging, where the goal is often to image structures of millimeter size or smaller, the calibration should be accurate to a small fraction of a millimeter.

The optimal method for calibration depends on the scanner design. Some scanners with fixed geometry are best calibrated by stepping and scanning a point source in the field of view and by directly measuring, storing, and interpolating the system matrix elements.^{4,5} Most scanners, however, require motion of the detectors and pinholes to properly sample the image volume and instead utilize a geometric model to compute the system matrix elements. As a result, a substantial amount of effort has gone into modeling and calibrating the cone-beam geometry associated with pinhole collimation.⁶⁻¹³ Bequé *et al* have shown that there are seven geometric parameters associated with a single rotating detector-pinhole pair.¹⁰ To properly estimate these seven parameters, a scan of three non-collinear point sources with known relative distances is used. More recently, the detector-pinhole geometry has been described in terms of homogeneous coordinates,¹³ though the underlying geometric model is equivalent.

To improve the quality of small animal SPECT images, much design effort has been directed towards increasing the count sensitivity of scanners by means other than increasing the pinhole diameter at the expense of spatial resolution. Adding detectors is an obvious though costly way to increase sensitivity. For multi-detector scanners, the calibration involves estimating the seven geometric parameters of each detector-pinhole pair. Another way to increase sensitivity is to utilize more than one pinhole per detector, in either an overlapping or a non-overlapping configuration.¹⁴⁻¹⁷ Adding pinholes requires knowledge of their precise coordinates relative to the detectors and thus adds more parameters to be calibrated. In order to improve the sampling of the image volume and reduce artifacts, some scanners incorporate mechanical motion of the bed to achieve helical sampling¹⁸ or to distribute a focused field of view over a larger volume¹⁹. The bed's motion must be known with respect to the image volume and further complicates the system calibration.

B. Detached collimation devices

A lower cost alternative to developing specialized high resolution detectors for small animal SPECT is to use standard clinical gamma camera detectors, which are more widely available.^{14,20-26} With a sufficient pinhole magnification factor, high resolution and good image quality can be achieved using gamma camera detectors. The conventional design is to mount a pinhole collimator directly onto the rotating gamma camera. However, this requires custom collimator attachments that are specific to each gamma camera model and adds cost for design and fabrication.

An interesting alternative is to build an independent collimation device that does not physically attach to the gamma camera detectors and instead is placed directly onto the patient bed. In its most simple configuration, the device consists of a lead box with pinhole apertures and a turntable to rotate the animal being imaged.¹⁷ The gamma camera detectors are stationary and have the clinical parallel-hole collimators removed. The detached device does not require custom mechanical fixtures or custom re-engineering, further reducing the cost and complexity and allowing the same device to be used with virtually any clinical SPECT scanner model without modifications.

Although the mechanics are simplified, one drawback of a detached device is that the calibration is unique each time that the device is placed on the bed in preparation for imaging. One approach is to acquire a separate calibration scan each time prior to imaging. More conveniently, a real-time calibration may be performed, where point sources with different gamma ray energy are imaged along with the emission data.¹⁷ For example, ¹⁵³Gd point sources may be imaged along with ^{99m}Tc-labeled radiopharmaceutical in the animal while acquiring data in dual energy windows. The geometric calibration is determined from the point source data, which is then applied to the reconstruction of the emission data. The underlying geometry of this design, with a rotating animal and with stationary pinholes and detectors, is identical to that of the case of mounted collimators where the detector-pinhole pair rotates around the animal, and thus the geometric model of Bequé *et al*¹⁰ still applies.

C. Multi-axis multi-pinhole collimation

For optimal physiologic conditions during imaging, the ideal geometry is for the animal to be in a configuration that is horizontal and stationary instead of vertical and rotating.²⁷ In order to achieve this configuration with a detached collimation device, the pinholes and the detectors may be rotated independently around the animal. A photograph of a prototype device using this approach is shown in Fig. 1. Since the pinhole collimator and the detectors are not attached, there are two independent axes of rotation that must be represented in the geometric model. Linear motion of the animal bed also is included, defining a third geometric axis.

In this paper, a new geometric model for independently rotating pinholes and detectors is developed and validated. The theoretical basis for this model is derived first and leads to a description of a forward projector and backprojector to be used for calibration and image reconstruction. The model is easily generalized to multiple detectors and multiple pinholes per detector. This geometric model is applied to experimental data of point sources imaged using a prototype detached small animal SPECT device with 22 pinhole apertures and two gamma camera detectors. Procedures are described for a “full calibration” of the entire set of geometric parameters and for a “rapid calibration” of a limited parameter set that is appropriate for real-time calibration. A complete characterization of the device performance and image quality with phantom and animal studies is outside the scope of this investigation. Here, the focus is on the calibration of this unique geometry and on the accuracy of the calibration, with the goal of demonstrating its feasibility for high resolution small animal SPECT.

II. THEORY

A. Geometry definition

A schematic of the system geometry for the independently rotating pinholes and detectors is shown in Fig. 2. The coordinate system (x,y,z) defines the image volume. A particular source voxel in this space located at $r_S=(x_S,y_S,z_S)$ projects through a pinhole located at $r_P=(x_P,y_P,z_P)$ and intersects the detector at the point $r_I=(x_I,y_I,z_I)$. The intersection point r_I is detected by the gamma camera at coordinates (X,Y) in the projection data. The electronic center of the detector, which is the origin of the coordinate system (X,Y) , is located at $r_D=(x_D,y_D,z_D)$ with respect to the image volume. The detector is assumed to be a plane with normal vector n_D . The collimator cylinder and the detector rotate about separate axes, as shown in Fig. 2, with rotation angles ϕ_P and θ_D , respectively. The z -axis of the image volume is chosen such that it coincides with the axis of rotation of the cylindrical collimator. The detector's axis of rotation does not coincide with the cylinder's axis of rotation. Although only one pinhole, one detector, and one source are shown in Fig. 2, there may be several pinholes i , several detectors j , and several point sources k , with the location of each described by vectors $r_{P,i}$, $r_{D,j}$, and $r_{S,k}$, respectively. It is assumed that all pinholes are mounted to the same collimator and rotate about the same axis, and that all detectors are mounted to a common gantry and rotate about the same axis.

To derive a description of the detector geometry, a first step is to start in the reference frame D with respect to the detector's axis of rotation. A coordinate system $(x^{(D)},y^{(D)},z^{(D)})$ is defined in this frame, with origin at the point $dr=(dx,dy,dz)$ and with axial coordinate $z^{(D)}$ along the detector's axis of rotation. In this reference frame, there are six parameters (three translational and three rotational) that describe the location and orientation of the detector. Following the nomenclature of Bequé *et al.*,¹⁰ the orientation of the detector is described in terms of an axial tilt angle Φ , an in-plane twist angle ψ , and a rotation angle Θ . The angle Θ is expressed as $\Theta=\theta_D+\Theta_0$, the sum of the rotation angle θ_D reported by the motion control device and the detector's actual offset Θ_0 from this angle.

The location of the intersection point $r_I^{(D)}$ in this reference frame D , in terms of the detected coordinates (X,Y) and using the sign conventions in Fig. 2, is expressed as:

$$r_I^{(D)} = R_z(\theta_D + \Theta_0) R_y(\Phi) R_x(\Psi) \begin{pmatrix} R \\ X + U \\ -(Y + V) \end{pmatrix} \quad (1)$$

where R is the detector orbit radius and U and V are linear in-plane offsets of the detector's electronic center, and $\mathcal{R}_x(\psi)$, $\mathcal{R}_y(\Phi)$, and $\mathcal{R}_z(\Theta)$ are the rotational operators:

$$R_x(\Psi) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\Psi & -\sin\Psi \\ 0 & \sin\Psi & \cos\Psi \end{pmatrix} \quad (2)$$

$$R_y(\Phi) = \begin{pmatrix} \cos\Phi & 0 & -\sin\Phi \\ 0 & 1 & 0 \\ \sin\Phi & 0 & \cos\Phi \end{pmatrix} \quad (3)$$

$$R_z(\Theta) = \begin{pmatrix} \cos\Theta & \sin\Theta & 0 \\ -\sin\Theta & \cos\Theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (4)$$

Thus in reference frame D , the six parameters R , U , V , Θ_0 , Φ , and ψ specify the location and orientation of the detector.

In order to describe the interaction point r_I with respect to the image coordinate system (x,y,z) as shown in Fig. 2, an additional transformation must be applied to $r_I^{(D)}$ to account for the independent axes of rotation. Six new parameters are required. The vector $dr=(dx,dy,dz)$ describes the translational shift between the two axes of rotation, and three angles α , β , and γ describe rotations with respect to the x , y , and z axes. The interaction point r_I in the image volume reference frame is:

$$r_I = R_z(\gamma) R_y(\beta) R_x(\alpha) r_I^{(D)} + \begin{pmatrix} dx \\ dy \\ dz \end{pmatrix} \quad (5)$$

$$R_x(\alpha) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{pmatrix} \quad (6)$$

$$R_y(\beta) = \begin{pmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{pmatrix} \quad (7)$$

$$R_z(\gamma) = \begin{pmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (8)$$

The location of the detector's electronic center r_D is found simply by substituting $X=Y=0$ in Eq (1) and substituting this result into Eq (5).

In addition to the interaction point, the detector's normal vector n_D and the unit vectors n_X and n_Y defining the (X,Y) coordinates must be known. Using the sign conventions in Fig. 2, these vectors are computed as:

$$n_D = R_z(\gamma) R_y(\beta) R_x(\alpha) R_z(\Theta) R_y(\Phi) R_x(\Psi) \begin{pmatrix} -1 \\ 0 \\ 0 \end{pmatrix} \quad (9)$$

$$n_X = R_z(\gamma) R_y(\beta) R_x(\alpha) R_z(\Theta) R_y(\Phi) R_x(\Psi) \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \quad (10)$$

$$n_y = R_z(\gamma) R_y(\beta) R_x(\alpha) R_z(\Theta) R_y(\Phi) R_x(\Psi) \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix} \quad (11)$$

Note that for the special case where $dx=dy=dz=0$ and $\alpha=\beta=\gamma=0$, the geometric model reduces to the conventional case of a single rotation axis where the pinholes are mounted to the detector.

The pinhole location r_p and the point source location r_s are defined with respect to the image volume reference frame. The pinhole location is expressed naturally in terms of cylindrical coordinates:

$$r_p = \begin{pmatrix} \rho_p \cos \varphi \\ \rho_p \sin \varphi \\ z_p \end{pmatrix} \quad (12)$$

where ρ_p and z_p are the pinhole's radial and axial coordinates, and where $\varphi = \phi_p + \phi_0$ is the sum of the rotation angle ϕ_p of the cylindrical collimator and the initial offset angle ϕ_0 of the pinhole. The point source location relative to the detector and collimator is affected by linear motion of the bed:

$$r_s = \begin{pmatrix} x_s \\ y_s \\ z_s \end{pmatrix} + tB \begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix} \quad (13)$$

where B is the linear displacement of the bed and b_x , b_y , and b_z are the directional vectors in the x , y , and z directions. The parameter b_z is equal to $\sqrt{1 - (b_x^2 + b_y^2)}$ and is not an independent parameter to be calibrated. The parameter t sets the distance scale of the bed motion with respect to the rest of the system geometry and has an ideal value of unity. Estimating the scale parameter t accounts for possible inconsistency between the absolute coordinates (X, Y) reported by the detector and the absolute bed position reported by the motion controller.

B. Calibration parameters

Thus there are many parameters in this geometric model that must be calibrated. These are:

- For each detector: R , U , V , Θ_0 , Φ , Ψ
- For each pinhole: ρ_p , ϕ_0 , z_p
- For the independent axes of rotation: dx , dy , dz , α , β , γ
- For each point source: x_s , y_s , z_s
- For the linear bed displacement: b_x , b_y , t

The dependent variables are the detected coordinates X and Y . The independent variables are the rotation angle ϕ_p of the cylindrical collimator, the gantry angle θ_D of the detectors, and the displacement B of the bed motion. The angles ϕ_p and θ_D are set by two separate motion controllers and are not necessarily equal. For the acquisition sequence used here, where the collimator rotation is programmed to match the detector rotation, a common rotation angle θ is used for both.

It is important to recognize that there is redundancy in the definition of the geometric model, unless four of the parameters are fixed. Although the z -axis of the image coordinate system is specified to be along the rotation axis of the cylindrical collimator, the direction of the x -axis and the location of the origin ($z=0$) are not yet specified. The x -axis and origin may be defined by selecting one pinhole as a reference and fixing its parameters ϕ_0 and z_p to be zero. Similarly,

the $x^{(D)}$ -axis and origin ($z^{(D)}=0$) of the detectors' gantry coordinate system must be specified. This is accomplished by selecting one detector as a reference and fixing its parameters Θ_0 and V to be zero.

Thus for a scanner with N_D detectors, N_P pinholes per detector, and N_S point sources used for calibration, the number of independent parameters M associated with the system calibration is:

$$M = (6 + 3N_P) N_D + 3N_S + 5 \quad (14)$$

For a system with multiple detectors and several pinholes per detector, there are a rather large number of calibration parameters. The experiments described below utilize two detectors, eleven pinholes per detector, and four point sources, resulting in a total of 95 independent parameters for the geometric model.

C. Projection and backprojection

The equations derived above are the basis of the projection and backprojection operators necessary for calibration and subsequent image reconstruction. Projection involves computing the detected X and Y coordinates given the location r_s of a source voxel in the image volume. This requires knowledge of the locations of the pinhole and the electronic center of the detector, along with the directional vectors associated with the detector. The pinhole location r_p is calculated using Eq. (12). The location r_D of the detector's electronic center is calculated using Eq. (5), after setting $X=0$ and $Y=0$. The directional vectors n_D , n_X , and n_Y are calculated using Eqs. (9), (10), and (11). The interaction point r_I is the intersection of the ray between r_s and r_p with the plane defined by r_D and n_D and is expressed as:

$$r_I = r_s + \frac{(r_D - r_s) \cdot n_D}{(r_p - r_s) \cdot n_D} (r_p - r_s) \quad (15)$$

where “ $\cdot$ ” denotes the vector dot product. The detected X and Y coordinates are then computed as follows:

$$X = (r_I - r_D) \cdot n_X \quad (16)$$

$$Y = (r_I - r_D) \cdot n_Y \quad (17)$$

The X and Y coordinates are binned according to the detector's intrinsic pixel size and matrix dimensions. As discussed below, the detector's pixel size indirectly sets the absolute distance scale of the entire system calibration.

Backprojection is simpler to derive and is basically the tracing of a ray originating at a specific location in the detector coordinate system through the image volume. Since the X and Y coordinates are known, the interaction point r_I is computed directly using Eqs. (1) through (8). Backprojection originates from this point, in the direction defined by the difference vector $(r_p - r_I)$. Various ray-tracing algorithms then may be used to implement the backprojection operation.²⁸⁻³⁰

III. EXPERIMENTS

A. Prototype device

A prototype small animal SPECT device has been constructed and is used here to test the geometric model and calibration process. A photograph of this device in operation with a dual-detector clinical SPECT scanner is shown in Fig. 1. The device consists of a lead cylindrical collimator of 9 mm thickness mounted horizontally to a rotary stage (Model RV80PP, Newport Corporation, Irvine, CA) and a linear stage (Model ILS250PP, Newport Corporation) that

moves an animal bed horizontally within the cylinder. The rotary and linear stages have specified absolute accuracies of 0.01° (corresponding to 0.005 mm uncertainty in pinhole location) and 0.005 mm, respectively, and contribute negligible error. The cylinder contains a total of 22 tungsten pinhole inserts with 0.9 mm diameter apertures. The pinhole apertures are located at 30 mm radius and all aim toward the central axis with slight focusing in the axial direction. The pinhole pattern is designed to project overlapping images onto the detector while fully utilizing the entire detector area. An aluminum base connects the components together into a single portable device, with the cylinder cantilevered outward such that the base does not attenuate the gamma rays projected through the pinholes.

The entire device is placed directly on the patient table of a standard dual-detector SPECT scanner (e.cam, Siemens Medical Solutions, Hoffman Estates, IL). The clinical parallel-hole collimators are removed from the gamma camera detectors. No custom mechanical fixtures are used to position the device precisely with respect to the detectors. The operator visually aligns the rotation axes and positions the cylindrical collimator in the center of the scanner field of view. The rotary and linear stages are connected to a programmable motion controller (Model ESP300, Newport Corporation), which is placed on the patient table or on a cart adjacent to the patient table.

B. Data acquisition

The SPECT scanner is configured to acquire a step-wise rotation sequence. Depending on the type of calibration, either 64 steps and 360° gantry rotation for a “full calibration” or 32 steps and 180° gantry rotation for a “rapid calibration” are acquired at 60 seconds per step. Here, the rotation angle refers to the actual rotation of each detector as opposed to the total angular coverage of both detectors. (For example, a 180° rotation for this dual detector scanner means that the entire 360° range is covered by at least one detector.) The device’s motion controller is programmed to rotate the cylindrical collimator with the same rotation sequence and timing as the SPECT scanner. Since the SPECT scanner and the device have independent motion controllers, they must be synchronized with a reasonable degree of accuracy. After initializing the scanner and the device motion controller, they are both manually triggered at the same time (to within about one second). To facilitate synchronization, the SPECT scanner is configured to acquire data while the detectors are rotating (“acquire during step” mode). By including the camera step motion in the total time per projection, the timing is better defined and more easily matched by the device’s motion controller. Although there is some data blurring caused by camera and collimator motion during acquisition and by timing errors from manual synchronization, the time associated with blurring is much smaller than the step time, and the effect on the data quality is minimal.

The two types of acquisitions, for “full calibration” and “rapid calibration”, differ in gantry rotation range (360° vs 180°) and point source configuration. The goal of a full calibration is to completely calibrate the device without assuming that any of the independent geometric parameters are known exactly. For a full calibration, four ^{153}Gd or ^{57}Co point sources (Model MMS04, Isotope Products Laboratories, Valencia, CA) of nominal activity 1.8 MBq (50 μCi) and 7.4 MBq (200 μCi), respectively, are taped to the outside of a hollow 30 mm diameter cylinder and scanned over a full 360° rotation. A 20 mm shift of the bed position is included halfway through the acquisition.

The goal of a rapid calibration is to calibrate only the parameters affected by a repositioning of the device with respect to the SPECT scanner, while assuming that the other parameters are constant since the prior full calibration. This is similar to the approach used by Cardi *et al* to calibrate a pinhole SPECT insert placed within a commercial small animal PET scanner.³¹ For that insert, a total of six parameters were used to characterize the relative geometry between SPECT insert and the PET detectors. This corresponds with the parameters (dx,dy,dz) and

(α, β, γ) for the geometric model presented here to describe the detector reference frame relative to the pinhole collimator. Because the PET detectors were in a fixed full-ring configuration and because the cylinder did not rotate, the calibration of their SPECT insert did not require other parameters and was done using a single point source.

For the prototype multi-axis small animal SPECT device investigated here, the rapid calibration involves many more degrees of freedom and allows the calibration to be acquired in real time along with the emission data. Since the gamma camera detectors are not fixed and are routinely reconfigured with different orbital radii, the rapid calibration must account for the variable detector geometry as well as the relative orientation of the pinhole collimator. For a rapid calibration, two point sources are taped to either the animal bed or to the exterior of a cylinder containing the animal or phantom to be imaged. The rapid calibration scan is acquired over a 180° rotation in 32 minutes and is suitable for real-time calibration. In either case of full or rapid calibration, a precision point source phantom is not used to define the relative source locations. Instead, the sources are placed at approximately known positions which are later used to seed the analysis algorithm.

IV. DATA ANALYSIS

A. Pre-processing

The projection data (Fig. 3) consist of a set of “dot images” that trace orbits as a function of the rotation angle of the pinholes and detectors. Each dot corresponds to the projection of a specific point source through a specific pinhole onto the detector. With four point sources and with eleven pinholes per detector, there could be up to 44 dot images per projection, but only a fraction of the projected rays actually intersect with the detector and produce dot images. The number of counts per dot image varies greatly, depending mainly on the distance between the point source and pinhole and on the angle of incidence to the pinhole.

The projection data are pre-processed before performing the geometric calibration. First, the dots are identified by an automated algorithm, and each dot's centroid is determined by least squares fit to a two-dimensional Gaussian function. The true point spread function (PSF) is not exactly Gaussian because of depth-of-interaction effects in the scintillation crystal (9.5 mm thick). A first-order model is used to account for the centroid shift related to the mean depth-of-interaction. The two-dimensional Gaussian fit is a reasonable approximation in determining the centroid of the dot, though a more advanced PSF model may improve the accuracy of dot localization. Some residual uncertainty related to depth-of-interaction remains and contributes to the residues of the geometric calibration, but as seen below, the residues are negligible relative to the detector's intrinsic resolution.

The next task is to sort the dots by assigning the correct point source and pinhole associated with each dot. Initial estimates of the geometry (pinhole locations, detector orbit radius) and of the point source locations are used to predict the dot locations. Then the software algorithm automatically determines the closest dot to each predicted location and assigns the corresponding point source and pinhole to this dot. Many source-pinhole pairs do not result in a dot, and these are flagged accordingly by the software. A user interface displays the projections with dots color-coded by point source to allow the operator to verify success of the dot-sorting algorithm, although the algorithm has been found to be robust and does not require user intervention.

B. Parameter estimation

With the dots properly located and identified, the next task is to determine the best estimates of the geometric parameters for the device-scanner system. The processed data consist of measured X and Y coordinates as a function of rotation angle, for each detector, pinhole, and

source. Parameter estimation is performed by least squares minimization of the difference between the measured and projected dot locations using the Levenberg-Marquardt algorithm.³² “Missing” dots associated with source-pinhole pairs not intersecting with the detector and also significant outliers are flagged and excluded from the least squares estimation.

For a full calibration using this prototype hardware, a total of 95 geometric parameters are estimated. As described above, there are six parameters associated with each detector, three for each pinhole, three for each point source, six to describe the gantry coordinate system, three to describe the bed motion, minus four to define the two coordinate systems. Four parameters defining the coordinate axes (Θ_0 and V for one detector, and ϕ_0 and z_p for one pinhole) are fixed to be zero and are thereby excluded from the parameter estimation.

For a rapid calibration, it is assumed that the pinhole locations and bed motion direction are constant since the previous full calibration. Under this assumption, there are $(3N_p N_D - 2)$ new “known” parameters associated the pinhole locations and also 3 new “known” parameters associated with the bed motion. The total number of free parameters M' for a rapid calibration becomes:

$$M' = 6N_D + 3N_s + 4 \quad (18)$$

Since only two point sources are used, there are only 22 free parameters for a rapid calibration for this prototype device. The parameter estimation uses the same least squares algorithm as for full calibration, except that all pinhole locations and bed motion parameters are held constant at their values determined during the prior full calibration.

V. RESULTS

A. Full calibration

Full calibration is successfully achieved using four point sources with 360° rotation and 20 mm bed motion shift. The data pre-processing algorithm successfully locates and identifies the large number of dot images resulting from the multiple pinholes and point sources. Fig. 3 shows a typical projection image, illustrating that the dot images are well separated and easily resolved and suggesting that the algorithm still would be successful if more pinholes were used. The least squares fit to the 95 free geometric parameters converges unambiguously.

The accuracy of the calibration process needs to be assessed in order to determine its suitability for high resolution small animal SPECT. A starting point is the covariance matrix that results from the least squares estimation. The diagonal elements represent the statistical variances of the fitted parameters based on the measured data. The off-diagonal elements represent the statistical covariances between the parameters. With such a large number of degrees of freedom, a full understanding of the propagation of errors on spatial resolution is complex and is better served by experimental measurement of the residues in the projected dot coordinates (see below).

Nonetheless, the uncertainties in the parameters as derived from the covariance matrix are valuable for understanding the goodness of fit and validity of the geometric model. Large uncertainties would signify that the corresponding parameters are redundant or irrelevant to the measured data, or that the data sampling is insufficient to allow accurate estimation of these parameters. Verifying that the uncertainties are reasonably small instills a high level of confidence in the geometric model and data sampling. Typical uncertainties for a full calibration are summarized in Table I. The uncertainties are small, below 0.1 mm for distances and below 0.5 milliradian for angles. It should be noted that these values originating from the covariance matrix do not represent true confidence intervals because of correlation between parameters and non-statistical uncertainties from other sources.³²

A more reliable assessment of the accuracy is to characterize the residues, that is, the differences between the measured and estimated coordinates of the projected dot images. Unlike the covariance matrix, the residues reflect all sources of uncertainty associated with the system calibration. The desired characteristics of the residues are that they be small in comparison to the detector resolution and that they be unstructured (dominated by random fluctuations). If these goals are met, then the geometric calibration does not add significant error in comparison to the other sources of error.

The residues for a typical full calibration with four point sources are histogrammed in Fig. 4. The distribution is approximately Gaussian with 0.8 mm full width at half maximum (FWHM). The variance of this distribution reflects contributions from gamma camera nonlinearity (vendor specification <0.2 mm differential and <0.7 mm absolute), from statistical errors in dot localization, from parallax errors due to depth-of-interaction effects in the detectors, from mechanical jitter during rotation, and from other uncertainties related to the calibration model. Most importantly, the total variance of 0.8 mm FWHM is much smaller than the gamma camera's intrinsic spatial resolution (vendor specification of 3.9 mm FWHM), and therefore the reconstructed spatial resolution is not significantly affected by the geometric calibration. The magnification factor of 7 from pinhole collimation further reduces the effect of these uncertainties in reconstructed images.

B. Rapid calibration

Rapid calibration is successfully achieved using two point sources and 180° rotation and without the need for bed motion to improve sampling. The pinhole locations and the bed motion direction vector are assumed constant since the time of the prior full calibration. By Eq. (18), for this prototype device there are 22 free parameters for a rapid calibration versus 95 for a full calibration. These include six each for the two detectors, six for the independent axes of rotation, three each for the locations of the two point sources, minus two to define the coordinate system in the detectors' reference frame. The least squares fit to the 22 geometric parameters converges unambiguously.

Other acquisition strategies for rapid calibration include the use of a 360° instead of 180° gantry rotation or the use of one point source instead of two point sources. A 360° rotation improves data sampling, but a 180° rotation is more desirable for faster calibration or for real time calibration, since the emission scan uses a 180° rotation. Using one point source instead of two is more attractive to implement but provides less sampling. Table II lists the calibration results for three cases: two point sources with 360° rotation, two point sources with 180° rotation, and one point source with 180° rotation. The uncertainties derived from the covariance matrix show modest differences between 180° versus 360° rotation with two point sources. The uncertainties are larger for 180° rotation, which is to be expected because the 360° rotation provides twice the sampling and an expected $1/\sqrt{2}$ reduction in statistical noise. However, for the case of one point source and 180° rotation, the uncertainties in many parameters are several times larger than for two point sources and 180° rotation, which cannot be explained by statistics alone. Incomplete data sampling explains the discrepancy, since it is more difficult to characterize an ellipse-like track with only 180° sampling. With two detectors, 180° gantry rotation, and two point sources on opposite sides of a cylinder, there is in effect 360° sampling by the combined detectors, and the rapid calibration is successful.

The accuracy of rapid calibration with two point sources and 180° rotation is characterized in terms of the residues. The residues histogram (Fig. 5) is similar to that of a full calibration, also having a FWHM of 0.8 mm. Although this indicates the degree of accuracy in projection space relative to other sources of error, it does not indicate its impact on reconstructed spatial resolution. One approach to evaluating its impact is to acquire and reconstruct data from a point

source. With a pair of ^{153}Gd point sources placed on the surface of a 30 mm diameter hollow cylinder and with a single ^{57}Co point source positioned at the center of the field of view, projection data are acquired using the rapid calibration protocol described above with 180° gantry rotation. After using the ^{153}Gd data to compute the geometric calibration, the ^{57}Co data are reconstructed using the iterative ordered subsets expectation maximization algorithm³³ and a Gaussian model of the point spread function.

Reconstructed images of the ^{57}Co point source are shown in Fig. 6. The reconstructed images do not exhibit any obvious errors or artifacts from geometric calibration. The transaxial and axial FWHM are measured here to be 1.1 and 0.8 mm respectively, with the difference mainly attributed to the physical dimensions of the point source. (The active element of the ^{57}Co point source is specified by the vendor to be a cylinder with 1.0 mm diameter and 0.5 mm axial height.) The spatial resolution R_0 of a pinhole imaging system is estimated as:³⁴

$$R_0 \approx \sqrt{\left(\frac{(a+b)}{a}d_e\right)^2 + \left(\frac{b}{a}R_i\right)^2} \quad (19)$$

where R_i is the detector's intrinsic resolution, d_e is the pinhole effective diameter, a is the pinhole-to-detector distance, and b is the object-to-pinhole distance. For this device at the center of the field of view ($R_i = 3.9$ mm, $d_e = 0.9$ mm, $a = 210$ mm, $b = 30$ mm), the expected spatial resolution is estimated to be 1.2 mm for the central pinhole. Parallax error from variable depth of interaction and camera nonlinearity also affect the spatial resolution, to a lesser extent. Nonetheless, the measured resolution is actually smaller than predicted above because of resolution recovery arising from the point spread function model in the reconstruction, and because non-central pinholes experience oblique angles of incidence (thus reducing the effective pinhole diameter) and larger magnification factors. From the FWHM measurement and the lack of artifacts in the point source images, one may conclude that the calibration accuracy is sub-millimeter and acceptable for small animal imaging. However, this assessment based on point source images has the limitations that it does not yield a quantitative estimate of the calibration error and that it applies only for a single location in the field of view.

Thus another approach is necessary in order to quantify the effect of rapid calibration on reconstructed images over the entire field of view. After already having performed a full 360° calibration on a prior day, two 180° rapid calibrations using two point sources are acquired sequentially without disturbing the apparatus. The two 180° acquisitions are scanned over different angular ranges (with start angles of 0° and 180°), and the point sources are shifted 20 mm to achieve different sampling. Analyzing these data leads to two independent sets of rapid calibration parameters. For each voxel in image space, the first calibration is used to project the point onto the detector, and then the second calibration is used to backproject the ray. The minimum distance between the backprojected ray and the voxel location gives an estimate of the reconstruction error resulting from the difference between the calibrations. Repeating the projection and backprojection over many voxels produces a distribution of reconstruction errors over the entire image volume. Fig. 7 shows a histogram of the reconstruction error derived from two independent rapid calibrations covering the entire image field of view for a mouse ($32 \text{ mm} \times 32 \text{ mm} \times 96 \text{ mm}$). The root mean square (RMS) of the reconstruction error over this volume is 0.12 mm. The 0.12 mm RMS error arising from rapid calibration is an order of magnitude smaller than the spatial resolution predicted by Eq. (19), confirming that the calibration accuracy does not significantly degrade the quality of reconstructed images.

C. Count statistics

An important consideration in calibration is attaining sufficient count statistics in order to localize the dot images in the projection data. For the case of a full calibration, the acquisition time may be lengthened if necessary to accumulate more counts, if the point sources have very

low activity. For a rapid calibration, there are practical limits to the acquisition time, and it is necessary to demonstrate acceptable results with a short scan time using commonly available point sources. This study uses a scan protocol appropriate for rapid calibration, namely dual detectors, 32 steps over 180°, and 60 seconds per step, for a total acquisition time of 32 minutes. A scan of two 7.4 MBq (200 μ Ci) ^{57}Co point sources using this relatively quick protocol leads to negligible reconstruction error (0.12 mm RMS) and demonstrates the success of rapid calibration. To investigate whether useful results may be obtained with fewer counts, the projection data are randomly down-sampled to simulate weaker point sources. The rapid calibration method is applied, and the FWHM of the residues distributions are measured and plotted versus point source activity in Fig. 8. The accuracy is maintained for point sources as weak as 0.9 MBq (25 μ Ci), and the calibration still succeeds at even lower activity, thereby demonstrating the robustness of the technique over a wide range of count statistics.

The case of real time calibration presents the additional challenges of background scatter counts arising from the emission activity and of counts lost to gamma ray attenuation by the object being imaged. In order for real time calibration to be successful, the point source activity must be large enough that the dot images are distinctly visible over the background counts. Cross-talk interference from the emission activity is minimized by selecting a point source radionuclide with dissimilar gamma ray energy, for example ^{153}Gd point sources and $^{99\text{m}}\text{Tc}$ activity. A phantom study demonstrates the robustness of real-time calibration where a pair of 1.8 MBq (50 μ Ci) ^{153}Gd point sources is imaged along with a 30 mm $\times$ 30 mm cylindrical phantom filled with 260 MBq (7 mCi) of $^{99\text{m}}\text{Tc}$ solution, using the 32-minute scan protocol described above. As seen in Fig. 9, the dot images in the projection data are clearly seen over the scatter background counts, and the calibration is successful with residues having a 1.1 mm FWHM normal distribution. With typical peak counts of approximately 50 counts per pixel for the less-intense dot images, compared to an average background count of about 10 counts per pixel, the automated software succeeds in localizing the individual dots in the projection data. Although there is a small increase in the residues' statistical noise from 0.8 to 1.1 mm FWHM, the residues are small compared to the 3.9 mm FWHM intrinsic detector resolution and are still negligible. Although real-time calibration is robust this example, there may be other less successful situations where the point source gamma ray energy is similar to that of the emission activity (for example, if using ^{57}Co point sources with $^{99\text{m}}\text{Tc}$ activity or ^{153}Gd point sources with ^{153}Sm activity). In such cases, the calibration would best be done sequentially by first imaging the point sources alone and afterwards imaging the phantom or animal separately.

V. DISCUSSION

A. Geometric model

This device with multiple rotating pinholes and independently rotating gamma camera detectors presents a large number of degrees of freedom and requires a general description of the system geometry. The geometric model derived here does not assume *a priori* knowledge of parameters or accurate alignment of mechanical components. The projection and backprojection operations are expressed not as an explicit solution but instead as a set of vector equations. Although an explicit solution might be more computationally more efficient for projection and backprojection, this generalized approach provides the flexibility to handle the complex geometry of this device and potentially even more complex geometries in the future.

An interesting characteristic of this model is that it does not require the definition of a distance scale other than that of the gamma camera detectors. The absolute locations of the detector, the pinholes, and the point sources are not required in advance and instead are estimated during the calibration process. The gamma camera reports absolute X and Y coordinates of each

detected event, and its intrinsic distance scale is sufficient to calibrate the rest of the system geometry, provided the data sampling is sufficient.

Although the geometric model does not require knowledge of absolute dimensions, it does not preclude using them in the calibration. For example, the pinhole locations may be taken from mechanical drawings used in fabrication. By fixing the associated parameters during the least squares fit, this added knowledge strengthens the statistical accuracy of the other unknown parameters. However, if the assumed values are inconsistent with the measured dot coordinates, there may be systematic errors in calibration and a loss in spatial resolution. The decision to add absolute dimensions to the calibration should be based on whether the accuracy of the information exceeds the precision of the fit (Table I).

For this device, one absolute distance scale worth adding to the geometric model is the motorized stage for linear bed motion. The free parameter t defines the relative distance scale between the detected coordinates and the bed motion. For the apparatus used in this study, the calibrated value of the parameter t is found to be 0.981 (± 0.002 , according to the covariance matrix), which differs slightly from the ideal value of unity. An alternative is to assume that the absolute distance reported by the motorized linear stage is accurate and to scale the detected coordinates (X,Y) and all other distances by $1/t$ to avoid inconsistency between distance scales. Given the specified absolute accuracy of the linear stage (0.005 mm), this would be the preferred approach. However, the absolute distance scale of the detector may be used in all situations, including for devices without a precision linear stage for bed motion. Either way, the reconstructed spatial resolution and image quality would be the same, though the absolute scaling of the reconstructed images would be slightly different.

B. Calibration

Both the full calibration and the rapid calibration succeed in estimating the 95 and 22 free geometric parameters needed to characterize this small animal scanning device. The automated pre-processing algorithms have no difficulty in isolating and locating the many dot images from eleven pinholes per detector and four point sources. Since the dot images are spaced apart well in the projection data (Fig. 3), it is likely that the algorithms would work well for a collimator design with more than 11 pinholes per detector. Even so, adding more pinholes may not necessarily lead to better image quality, as recent work from other groups suggests that there are diminishing returns from highly multiplexed projections in multi-pinhole SPECT.^{35,36}

In order for the calibration to be successful, there needs to be sufficient data sampling to allow for accurate estimation of all parameters. The degree of sampling depends on the number of point sources, rotation range, and bed motion range. For full calibration of all free parameters for this device, an arrangement of four point sources on the exterior of a 30 mm cylinder with 360° rotation and 20 mm linear bed motion is found to provide adequate sampling. There is the opportunity to optimize further the point source arrangement and bed motion for full calibration, which is a topic of future study. This is best done by analyzing the covariance matrix for simulated data of point sources at various locations in the field of view.³⁷ The optimal point source configuration will depend on the design of the scanner (pinhole configuration, detector size, magnification factor, etc.). Since full calibration only needs to be done once, a longer and better sampled data set may be acquired.

Unlike full calibration, rapid calibration has other constraints, namely to be more convenient for routine use, and for the case of real time calibration, not to occupy the same space as the animal or phantom being imaged. For this device, the use of two point sources and a 180° gantry rotation is found to be adequate for rapid calibration of 22 parameters. With 180°

rotation, two point sources are needed instead of one in order to provide the full angular sampling necessary for parameter estimation.

It may be practical to implement a simpler rapid calibration with fewer than 22 parameters. For example, several of the parameters describing the detectors' orientation with respect to the detectors' rotation axis may be constant from scan to scan, if the gantry mechanics are consistent and if the detector orbit radius is unchanged. This may be true if the SPECT scanner is dedicated for research use with the detached collimation device and if the detectors otherwise are not disturbed from day to day. If this cannot be guaranteed, a more conservative approach is to fully re-characterize the detectors' geometry each time during rapid calibration.

The relationship between multiple pinholes and system calibration is not studied here in depth, since only a single 22-pinhole configuration is tested. In the prior study by Bequé *et al* for the case of a single pinhole per detector, it was shown that precise knowledge of two of the distances between point sources is essential for calibration.¹⁰ A precision phantom adds complexity but more importantly introduces new uncertainties to the calibration. This group had shown that errors associated with the fabrication of the phantom contribute to a comparable loss of reconstructed spatial resolution.³⁷ For the 22-pinhole configuration used here in this study, the calibration algorithm succeeds in estimating the locations of the point sources and pinholes accurately without assuming precise knowledge of their geometry. The large number of pinholes adds many parameters (three per pinhole) to the full calibration and increases the complexity of data processing. However, the large number of pinholes improves the sampling significantly and increases the robustness of parameter estimation. Projecting multiple images of each point source appears to constrain the least squares fit by providing reliable information about the relative geometry of the point sources and pinholes. The added information and sampling from multiple pinholes provides an explanation why a precision point source phantom is not necessary for calibration of this prototype 22-pinhole SPECT device. Further study based on computer simulations of various numbers and configurations of pinholes would lead to a better understanding of the effect of multi-pinhole sampling on system calibration.

C. Accuracy

Full calibration and rapid calibration produce accurate descriptions of the system geometry, as assessed in three ways. The uncertainties derived from the covariance matrix are below 0.1 mm for distances and 0.5 milliradian for angles, suggesting a high degree of precision in the calibration and indicating the significance of all parameters in the geometric model. The residues of the calibration, computed as the differences between the measured and predicted coordinates of the dot images, have a normal distribution with 0.8 mm FWHM. The backprojection error in image reconstruction is estimated to be 0.12 mm RMS using parameters derived from independent rapid calibration scans.

The main aim of this study, in addition to deriving and implementing the calibration method for this new and complex geometry, is to demonstrate that the calibration is practical and sufficiently accurate for small animal imaging. The 0.8 mm FWHM residues in the projected dot coordinates are small in comparison to the 3.9 mm FWHM intrinsic resolution of the detector. By Eq. (19), the 0.12 mm RMS error in backprojection is much smaller than the contributions from the 0.9 mm pinhole diameter and from the intrinsic detector resolution. Thus the accuracy of the calibration is sufficient for small animal imaging with this device. The lack of artifact in reconstructed images of a point source (Fig. 6) supports this conclusion. With this level of calibration accuracy, reconstructed spatial resolution and image quality depend primarily on the overall design of the scanner (pinhole diameter, pinhole configuration, detector resolution, magnification factor, image reconstruction algorithm, etc) and not significantly on the geometric model. A full evaluation of the device design and its imaging performance with phantom and animal studies is in progress.

An important note is that the residues of the calibration include non-statistical errors from unexpected mechanical shifts, commonly called “jitter”, associated with the rotation of the pinhole collimator and the detectors. Very little jitter is expected in the pinhole rotation due to the precision rotary stage of the detached collimation device used in this study. However, it is well known that gamma cameras, which weigh upwards of 400 kg, experience noticeable mechanical jitter as they are rotated.³⁸⁻⁴⁰ As illustrated in Fig. 10, for the case of a conventional mounted pinhole collimator, the jitter affects both the pinhole and the detector equally and causes an error of similar magnitude in the backprojected ray. However, a detached collimation device has the advantage over conventional mounted pinhole collimators in that jitter affects only the detector and not the pinhole collimator. Because of pinhole magnification, the effect of the jitter on reconstructed spatial resolution is minimized. Thus the need for jitter correction is most likely eliminated with detached collimation, but if found to be needed for less stable scanners, it is straightforward to include angular dependencies in the appropriate parameters to model shift and sag of the detectors during rotation. By reducing the impact of mechanical jitter, detached pinhole collimation devices have the potential to achieve better reconstructed spatial resolution than conventional pinhole collimators mounted directly to gamma camera detectors.

VI. CONCLUSIONS

A geometric model and calibration process are developed for multi-pinhole SPECT with independently rotating detectors and pinholes and with linear bed motion. The method is applied successfully to a prototype detached small animal SPECT device having a total of 22 pinholes and using a clinical dual-detector SPECT scanner. A full calibration scan of four point sources with 360° rotation estimates all 95 free parameters of the geometric model. A rapid calibration scan of two point sources and 180° rotation estimates the subset of 22 parameters associated with repositioning the device with respect to the clinical SPECT detectors. The calibration is found to be highly accurate, having residues of 0.8 mm FWHM in the projected data and contributing 0.12 mm RMS to the reconstructed data. The inaccuracies due to calibration are small in comparison to those from the pinhole diameter and the detector, and thus the calibration has accuracy suitable for high resolution small animal SPECT imaging.

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FIG. 1.

Photograph of the prototype detached collimation device used in the calibration experiments. A lead cylindrical collimator with a total of 22 tungsten pinhole inserts (11 per side, facing each detector) is mounted horizontally onto a rotary stage. A linear stage forms the base of the device and allows an animal bed to be positioned and moved linearly within the cylinder. The entire device is placed on the patient table of a dual-detector clinical SPECT scanner. A motion control device (not shown) allows the rotary stage and linear stage to be moved nearly synchronously with the step-wise rotation of the gamma camera.

FIG. 2.

Illustration of the system geometry for an independently rotating collimator and detector. A point source at location r_S in image voxel space (x,y,z) projects through a pinhole at location r_P and interacts with the gamma camera detector at location r_I , which corresponds to the pixel (X,Y) in the detector's coordinate system. The location r_D and direction n_D represent the electronic center and normal vector of the detector. The detector and pinhole collimator rotate independently with rotation angles θ_D and ϕ_P about the two axes as shown. The tilt angles Φ and ψ describe the orientation of the detector with respect to its rotation axis. The point dr represents the origin of the coordinate system associated with the gantry reference frame, whose coordinate axes $(x^{(D)}, y^{(D)}, z^{(D)})$ are not shown here and are specified by three rotation angles α , β , and γ relative to the image coordinate axes. The axial coordinate $z^{(D)}$ in this reference frame is along the detector axis of rotation.

FIG. 3.

Typical projection image from a full calibration using four point sources and eleven pinholes per detector. The smaller dot images arise from point sources that are further from the pinholes. The larger dot images are less numerous and arise from point sources that are closer to the pinholes. Each dot tracks an ellipse-like orbit as a function of the rotation angle.

FIG. 4. Histogram of residues from a typical full calibration using four point sources and 360° gantry rotation. The distribution is approximately Gaussian with 0.8 mm FWHM.

FIG. 5. Histogram of residues from a typical rapid calibration using two point sources and 180° gantry rotation. The distribution is approximately Gaussian with 0.8 mm FWHM.

FIG. 6.

Reconstructed transaxial (Left) and axial (Right) images of a ^{57}Co point source in the center of the field of view, using real time calibration by simultaneous acquisition of two ^{153}Gd point sources. Images are reconstructed using the iterative OS-EM algorithm with a Gaussian model of the point spread function and with a voxel size of 0.2 mm. The measured transaxial and axial FWHM are 1.1 mm and 0.8 mm, respectively. The asymmetry is attributed to the physical dimensions of the active element of the point source, which is a cylinder with 1.0 mm diameter and with 0.5 mm axial height. The remainder of the image volume shows no visible artifacts or streaks that might possibly arise from angular step motion of the detectors and pinholes during data acquisition or from miscalibration of the system geometry.

FIG. 7.

Histogram of reconstruction error due to rapid calibration with two point sources and 180° gantry rotation. Reconstruction error is defined as the distance between a source voxel and the backprojected ray, based on the geometric parameters derived from two independent rapid calibrations. The root mean square (RMS) error is 0.12 mm over the entire image field of view for a mouse (32 mm × 32 mm × 96 mm).

FIG. 8.

Stability of the rapid calibration method over a range of point source activity. The FWHM of the residues distribution from rapid calibration is plotted with respect to point source activity for simulated data sets derived from random down-sampling of actual projection data from 7.4 MBq (200 μCi) ^{57}Co point sources. The calibration succeeds over a wide activity range. At very low activity (0.1 MBq), there are insufficient counts for the automated algorithm to localize the individual dots, and the algorithm fails.

FIG. 9. Real-time calibration using two ^{153}Gd point sources and a phantom filled with $^{99\text{m}}\text{Tc}$ solution. Simultaneous imaging of the point sources and emission activity complicates dot localization because of scattered background counts and because of lost counts due to gamma ray attenuation by the phantom. Although there is noticeable scatter in the projection data (upper image) from the 260 MBq $^{99\text{m}}\text{Tc}$ in the phantom, the 1.8 MBq ^{153}Gd point sources are clearly seen and easily localized by the automated software. The residues (lower image) have a 1.1 mm FWHM distribution and exhibit a small increase in noise compared to the case where 7.4 MBq ^{57}Co point sources are scanned alone (Fig. 5). Even so, the residues are small compared to the 3.9 mm FWHM intrinsic spatial resolution of the detector.

FIG. 10.

Comparison of the effect of a mechanical shift on a mounted versus detached pinhole collimator. For a conventional mounted pinhole collimator, an unexpected mechanical shift affects both the pinhole and detector, causing an error in the backprojected ray (solid line) that is similar in magnitude to the mechanical shift. For a detached collimation device, the shift affects only the detector and not the pinhole. The corresponding error in the backprojected ray is reduced by the pinhole magnification factor and is much smaller than that of the mounted pinhole collimator.

TABLE I

Typical statistical uncertainties derived from the covariance matrix for full calibration using four point sources and a 360° rotation angle. The small values indicate that each parameter in the geometric model is relevant and that the data sampling is adequate

Parameter [units]	Uncertainty
R [mm]	0.07
U, V [mm]	0.09
Θ_0, Φ, Ψ [mrad]	0.3
dx, dy, dz [mm]	0.04
α, β [mrad]	0.1
γ [mrad]	0.4
r_p [mm]	0.06
$r_p \phi_0$ [mm]	0.02
z_p [mm]	0.06
b_x, b_y	0.0003
t	0.002
x_S, y_S, z_S [mm]	0.03

TABLE II

Results for rapid calibration with one vs two point sources and 180° vs 360° gantry rotation. The numbers in parentheses represent statistical uncertainties in the last decimal place for each parameter, as derived from the covariance matrix. The calibration parameters for both 180° and 360° rotation with two point sources have relatively small uncertainties, on the order of 0.1 mm and 0.5 milliradian, whose effects are further reduced by pinhole magnification. However, the calibration using one point source and 180° rotation has substantially larger uncertainties, indicating insufficient sampling. Note that these values do not reflect the total variance in the parameters between calibrations. Measurement of actual residues (Fig. 5) or reconstruction errors (Fig. 7) provides more reliable assessment of calibration accuracy

Parameter [units]	2 point sources, 360°	2 point sources, 180°	1 point source, 180°
$R^{(1)}$ [mm]	245.52 (4)	245.73 (5)	245.77 (25)
$U^{(1)}$ [mm]	-0.34 (9)	-0.09 (11)	-1.74 (53)
$V^{(1)}$ [mm]	0 (fixed)	0 (fixed)	0 (fixed)
$\Theta_0^{(1)}$ [mrad]	0 (fixed)	0 (fixed)	0 (fixed)
$\Phi^{(1)}$ [mrad]	0.5 (2)	1.2 (2)	0.3 (1)
$\Psi^{(1)}$ [mrad]	-5.9 (3)	-8.2 (4)	-8.0 (2)
$R^{(2)}$ [mm]	244.63 (4)	244.81 (5)	247.27 (42)
$U^{(2)}$ [mm]	1.46 (8)	1.05 (10)	-0.96 (67)
$V^{(2)}$ [mm]	0.75 (4)	0.71 (5)	0.48 (22)
$\Theta_0^{(2)}$ [mrad]	1.3 (4)	2.0 (4)	1.3 (25)
$\Phi^{(2)}$ [mrad]	-0.4 (1)	-0.5 (2)	-4.3 (11)
$\Psi^{(2)}$ [mrad]	-3.3 (3)	-4.0 (4)	-6.8 (22)
dx [mm]	-1.07 (6)	-1.32 (8)	-6.52 (62)
dy [mm]	5.37 (8)	5.24 (10)	-5.47 (48)
dz [mm]	4.77 (6)	4.76 (7)	3.95 (58)
α [mrad]	-5.3 (1)	-5.6 (1)	-3.1 (13)
β [mrad]	3.1 (1)	2.6 (2)	4.4 (7)
γ [mrad]	-32.7 (3)	-32.1 (3)	-19.6 (14)
$x1$ [mm]	-4.57 (1)	-4.49 (2)	-3.15 (5)
$y1$ [mm]	-18.21 (1)	-18.18 (2)	-16.47 (6)
$z1$ [mm]	-17.56 (1)	-17.55 (2)	-17.37 (5)
$x2$ [mm]	5.03 (1)	5.05 (1)	N/A
$y2$ [mm]	11.68 (1)	11.72 (1)	N/A
$z2$ [mm]	10.14 (1)	10.13 (1)	N/A