Effect of geometric and motion tracking error for awake small animal SPECT

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***Abstract*–A series of simulation studies were performed to evaluate the effects of geometric and motion tracking errors on reconstruction image quality for a single pinhole collimator awake animal imaging SPECT system. List-mode SPECT data generated using a custom Monte Carlo program that incorporated experimental mouse motion data were reconstructed by MLEM with Siddon's ray tracing. To better understand the impact of motion tracking and system geometric parameter errors on reconstructed system data, an offset of up to 1 mm or degree was separately applied to each for evaluation. In the absence of motion tracking or system geometric error, the applied motion compensation algorithm successfully reconstructed volumes without any degradation or distortion. Presented results reveal that motion tracking errors propagate through the SPECT reconstruction process. However, it is confirmed that the impact of tracking errors in the currently employed motion tracking system, is minimal because of their accuracy. The results also reveal the direct and indirect impact of geometric errors to motion compensated reconstruction quality and that a wrong assumption of pinhole transaxial position produces the most amount of distortion of all the investigated errors. Finally, system geometric errors are shown to have a greater impact on reconstruction quality than equivalent tracking errors.**

I. Introduction

Imaging of awake unrestrained small animals can provide valuable biomedical information by eliminating the impact of anesthetics on animal function and by reducing the overall stress to the animal. Oak Ridge National Laboratory (ORNL) and Thomas Jefferson National Accelerator Facility (Jefferson Lab) are collaborating on the development of an awake small animal SPECT system to image un-anesthetized small animals. This system enables functional brain imaging studies for small animals without the use of anesthetic agents and is potentially translatable to clinical applications for human patients that cannot remain still (Parkinson's patients, Alzheimer's patients, small children, etc.). The system uses optical-based motion tracking of the target animal, which is unique from commercially available SPECT systems.

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In a typical pinhole SPECT system used for imaging stationary subjects, parameters to determine system resolution are well known and studied elsewhere [1], [2]. The ideal system resolution of pinhole SPECT can be computed by several geometric parameters (e.g. detector resolution, focal length, pinhole distance to axis of rotation). In addition to these, multiple scattering and attenuation are sources of image degradation and there are ways for minimizing or compensating for these errors [3]-[5]. Furthermore, experimental resolution is usually worse than the ideal resolution mainly because of inaccuracies in system geometry specification. Such errors are well characterized and various correction methods have been proposed [6]-[8]. However, our system, because of its unique motion compensation technology, has additional sources of error that are distinct from those of currently available SPECT systems.

Fundamental to generating motion corrected SPECT reconstructions is the quantification of the relationship between the SPECT gantry and motion tracking sub-systems. This relationship is defined by a translations and rotations determined through a system calibration process, which has its associated errors. In our system, both motion tracking errors and system geometry errors directly affect image reconstruction quality. The goal of this study is to investigate of the effect of these errors on the quality of motion-compensated pinhole image reconstruction quality. Therefore, we present several simulation studies that include verification of motion compensated reconstruction and evaluation of motion tracking and geometric error effects.

II. Methods

A. Experimental Setup

Fig. 1 depicts the current SPECT imaging system. The tracking system is located at the rear of the gantry looking forward and slightly down at the object or small animal. The system uses three cameras, each with a concentric infrared (IR) ring light module to illuminate three retro-reflective markers placed on the object —e.g. a quality control (QC) phantom or mouse head. The motion tracking system acquires 10-30 frames per second (fps) images of the object, computes and records six degrees of freedom (6DoF) pose data during the SPECT scan. A transformation matrix (x",y",z" to x, y, z) is computed to convert tracking system data into the gamma detection system coordinates since the tracking system and gamma detection system are operating in their own reference

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coordinate systems. This is accomplished using a QC phantom that consists of three markers and three embedded radioactive Co-57 point sources; depicted in Fig. 1.

Procedurally, an x-ray CT scan of the QC phantom is used to define the location of the radioactive QC sources and retroreflector markers in an intermediate QC reference coordinate system (x',y',z'). The transformation matrix between the gamma detection and intermediate coordinate systems is then computed using the positions of the radioactive QC phantom sources from a stationary SPECT scan and image reconstruction. Next, without moving the phantom the positions of the retroreflectors are determined in the tracking reference frame using the pose data. The transformation matrix between the intermediate and tracking coordinate systems is then computed. The final transformation matrix (x",y",z" to x, y, z) is obtained after combining the two transformation matrices. A more detailed description of this process is presented in [9]-[11].

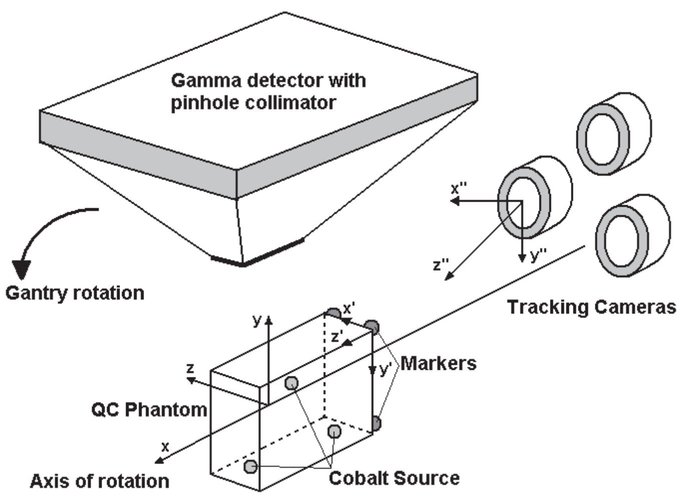

Fig. 1. Experimental setup for SPECT imaging system.

B. Monte Carlo simulation

For this study, Monte Carlo simulation was used to generate list-mode SPECT data. A digital mini-Derenzo phantom was created with hot rods of 2, 3, 4, 5 mm diameter and 50 mm legth surrounded by a hot rim (2 mm thickness) that were assigned the same activity. The resolution of the digital phantom was 0.5 mm and the detector resolution was 1 mm, which is the same as current system detector resolution.

A simplified flowchart of the custom program is depicted in Fig. 2. To generate list-mode data of photons detected by the gamma camera, pose data were imported from awake mouse scans and used to move the phantom. Gamma events were randomly generated from voxels within the mini-Derenzo phantom. Each gamma event was recorded with timing information to create list-mode data.

Image reconstruction was performed using a standard Maximum-Likelihood Expectation-Maximization (MLEM) algorithm. Since the SPECT data included motion information, the system response matrix was re-calculated every time a new pose data event was introduced. Each image reconstruction was terminated after 20 iterations. For simplicity, multiple scattering and attenuation were ignored and the pinhole was treated as an ideal circle; essentially, all detected rays were assumed to have passed strictly through the pinhole. Focal length of the pinhole detector was 100 mm and the radius of rotation (ROR) was 50 mm.

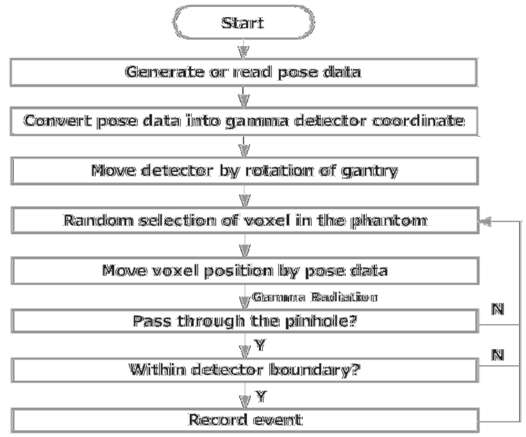

Fig. 2. A flowchart for Monte Carlo simulation to generate list-mode SPECT data.

C. Evaluation of motion-compensation methodology

To verify motion compensated reconstruction, experimental pose data from awake mouse scans were used to generate the motion of the digital mini-Derenzo phantom. Fig. 3 depicts the degree of motion produced by an awake mouse within the glass burrow during one such scan. To assess the maximum impact of motion, pose data from the most active mouse scans were selected for phantom motion implementation. Using the selected pose data with a measurement rate of the 10 fps, list-mode SPECT data were created for 120 gamma detector stops (positions) over 360 degrees and a dwell time of 5 secs/position.

To accomplish motion compensated reconstruction, the gamma detector was moved about a stationary image volume in accordance with the pose data and its rotation around the gantry. Both motion compensated and non-compensated volume reconstruction were performed and compared using center transaxial images.

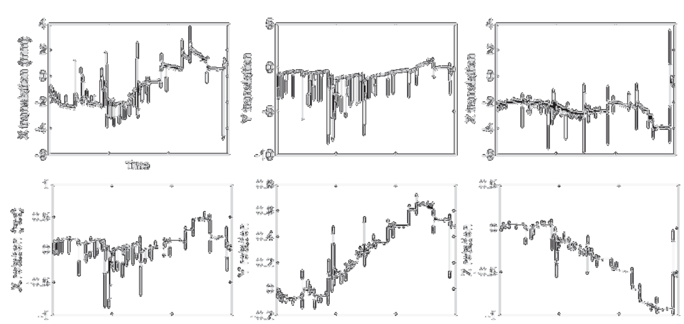

Fig. 3. Pose data acquired from an awake mouse motion tracking during a SPECT scan (typically 30~60 minutes). Presented pose data show mouse motion for a minute.

D. Evaluation of motion tracking error

With an ideal transformation matrix between the tracking system and the gantry system, the pose measurement should provide the exact location of the target object as a function of time. Inaccurate pose data, however, will cause erroneous motion compensation that leads to degraded image reconstruction. In a previous study, we characterized the tracking system noise and accuracy of measurement [12]. The noise levels for translations and rotations were less than 0.1 mm and deg, respectively. To verify the effect of motion tracking error, noise was added to the mouse pose data that were used to generate the SPECT data. This was implemented by incrementally increasing the random noise level for 6DoF from 0.1-1 mm or deg for translation or rotation, respectively. The same process described in section C was implemented and the motion compensated reconstructed images were compared in the same manner.

E. Evaluation of geometric error

There are several errors related to the gantry system pinhole geometry, e.g. transaxial shift, magnification, and detector tilting errors. Typically, they are classified as mechanical shift (aperture shift), electronic shift (detector shift), and magnification error (only for pinhole detectors). One can find a detailed description for those parameters in another report [8]. For a stationary SPECT scan, the effect of those errors are well-known and easily noticed because they have an almost linear relationship with system resolution and/or image degradation [8]. However, in our motion compensated SPECT system, geometric errors can produce other deleterious effects in the course of the compensation process. To verify the extent of these effects, the same mouse pose data was used to generate SPECT image reconstructions for small amounts of introduced detector-geometric-errors. With added errors to geometric parameters—i.e., detector shift, pinhole shift, and pinhole distance to axis of rotation (AOR) (magnification error)—the transformation matrix between the tracking system and the gantry system was re-computed and used for volume reconstruction. In short, list-mode data generation and transformation matrix calculation were performed based on wrong parameters while reconstruction was performed with correct parameters. The same process described in section C (evaluation of tracking system) was implemented and the motion compensated reconstructed images were compared in the same manner.

III. Results and Discussion

A. Evaluation of motion-compensation methodology

Center cross-sectional images (slices) of the reconstruction for the digital mini-Derenzo phantom are presented in Fig. 4. Qualitatively, the motion compensated reconstruction image (b) closely resembles that of the static case reconstruction image (a) while the non-motion compensated reconstruction image (c) reveals significant degradation with distortion and blurring. For a quantitative comparison, the full width half maximum (FWHM) of each corresponding circle (rod) was measured and this is presented in the intensity profile. The difference in FWHM was less than 0.1 mm for all rods. This is smaller than the theoretical SPECT system resolution (1 mm) and confirms that motion compensated SPECT reconstruction using data generated by the current motion tracking system is sufficient to reproduce target volumes without significant image degradation.

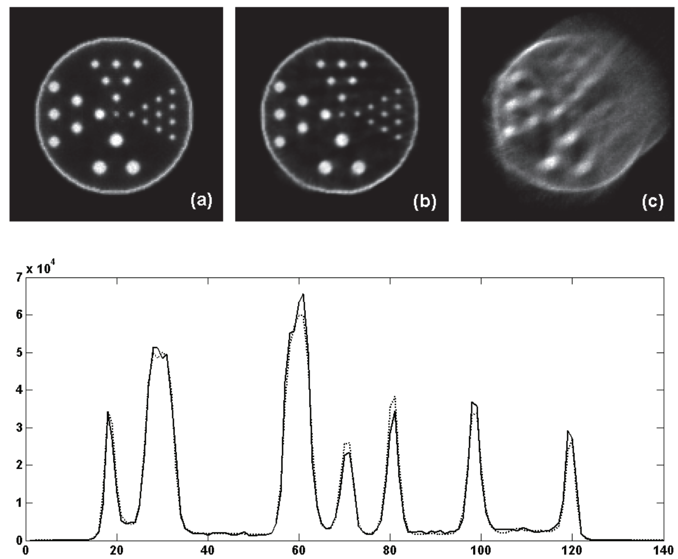

Fig. 4. Reconstruction images from a static scan (a), motion compensated reconstruction (b), and motion uncompensated reconstruction (c). The bottom intensity profiles from (a) and (b) shows successful motion compensated reconstruction.

B. Evaluation of motion tracking error

Fig. 5 shows the comparison of reconstruction with noise added pose data. The figure only presents the case of translation error along the z-axis and rotation error with yaw as examples. Random error of 0.1, 0.2, 0.5, 1 degree or mm, was added to each pose consecutively. Image blur is seen to increase along with error row-wise, as depicted from (a)-(d) for translation and (e)-(h) rotation. For a more detailed comparison, center line profiles for each of the reconstructed images (a)-(d) translation and (e)-(h) rotation are also presented Fig. 6 (top) and (bottom), respectively. The profiles in Fig. 6 reveal rod FWHM increasing slightly as added error increases from 0.1 to 1 degree or mm for rotation and translation, respectively. Note that rotation error has more impact on the outer regions of the phantom because voxel displacement due to rotation is proportional to the distance from the center of rotation. From these results, the current system's accuracy (0.1 mm or deg) is sufficient to achieve motion compensated SPECT reconstruction without introducing additional image degradation. The results for translation errors along the x- and y-axes, and rotational errors in pitch and roll were similar and are not presented here.

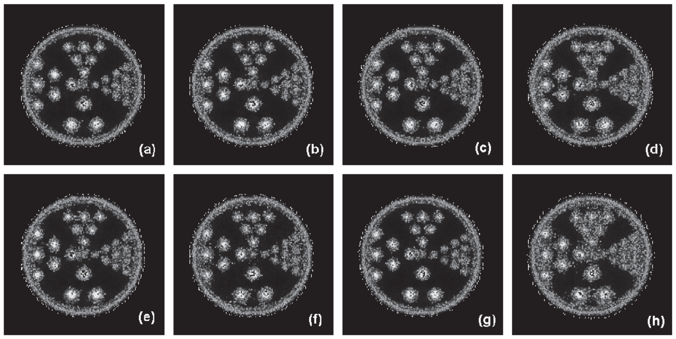

Fig. 5. Evaluation of motion tracking error. Image of reconstructed volume with various motion tracking errors. (0.1, 0.2, 0.5, 1 mm range random error to the translation (a)~(d), and 0.1, 0.2, 0.5, 1 degree random error to the rotation (e)~(h), respectively)

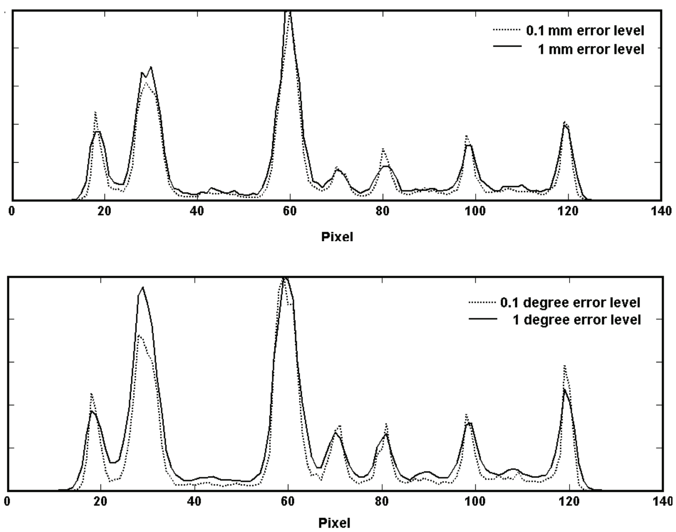

Fig. 6. Profiles for the reconstruction with translation error (upper) and rotation error (lower). The vertical axis is radioactivity [au].

C. Evaluation of geometric error

Typically, detector or pinhole shift creates circular blurring or a convolution of the displacement on the ideal reconstruction image (as depicted in Fig. 7(c) and (d)) and magnification error simply results in an enlarged or shrunken image (Fig. 7(b)). These errors are not normally an issue for stationary scans because they are correctable using measured system-geometry data. However, because our system performs motion compensation, any associated geometric errors can lead to inaccurate transformation matrix computation. This in turn can result in incorrect compensation of motion information during reconstruction despite the tracking system pose data being accurate.

Fig. 8 is a comparison of reconstructed images with various geometric errors. For detector and pinhole shift errors (1 mm respectively), reconstruction images of both cases (Fig. 8 (a), (b)) shows distortions that do not appear in the stationary case depicted in Fig 7(a), but that are similar to the artifacts seen in Fig. 7(c) and 7(d), respectively. Results of the motion compensated reconstructions reveal that pinhole shift error (Fig. 8(b)) has greater impact on image quality than detector shift error (Fig 8(a)) and that focal length error (Fig. 8 (c)) also degrades image resolution. This is in agreement with previous reports [9], revealing that for the same amount of offset, pinhole shift produces greater degradation of reconstructed images than detector shift because of its geometric role.

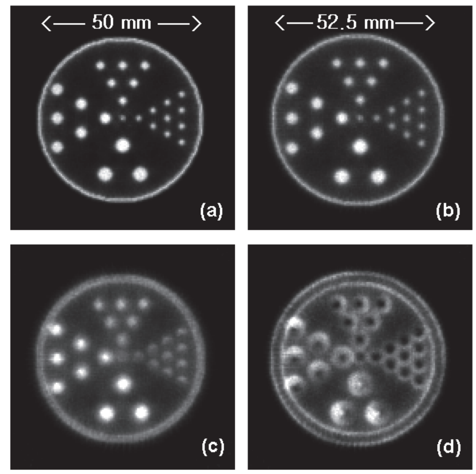

Fig. 7. Effect of geometric errors for stationary scan. Ideal reconstruction (a), enlarged reconstruction by pinhole-AOR distance error (b), detector transaxial shift error (c), and pinhole transaxial shift error (d).

With the current setup, a slight focal length error (1 mm) has a considerable impact on the image reconstruction because not only does it cause image size change but also distortion. Also, we have tested for pinhole and detector shift errors in the axial direction and get similar results with those of transaxial shifts. In summary, any geometric shift error, seems to have a non-uniform effect on image reconstruction and shape distortion similar to that for a stationary scan.

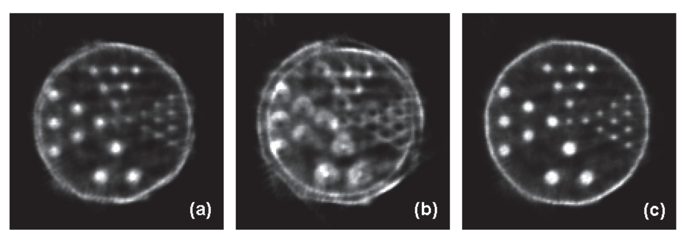

Fig. 8. Evaluation of geometric error affecting motion compensated reconstruction with detector transaxial shift error (a), and pinhole transaxial shift error (b), and pinhole-AOR distance error (c). All images show heavy distortion and degradation compared to the stationary case in Fig. 7 (a)

IV. Conclusion

We evaluated the affects of motion tracking and geometric errors on single pinhole motion compensated SPECT reconstruction. Small translation errors in pose data were seen to have minimal impact on image degradation even when we assumed that the level of error was greater than the current tracking system's error. Rotation errors in the pose data, however, proved to have a more significant impact than translational errors but not so much as to obviate the benefits of implementing a motion tracking system. Furthermore, for the same amount of error, it is clear that pinhole shift error has the greatest impact on motion compensated SPECT reconstruction amongst the geometric errors. Any error that affects accurate computation of the transformation matrix between the tracking and gantry systems and in the projection data projection/backprojection process results in image distortion and degradation. Hence, geometric errors, especially pinhole shift, should be corrected to get better motion compensated SPECT reconstruction. The impact of intrinsic motion tracking system errors also should be thoroughly measured and quantified.

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