Assessment of hybrid rotation-translation scan schemes for *in vivo* animal SPECT imaging

This article has been downloaded from IOPscience. Please scroll down to see the full text article.


(http://iopscience.iop.org/0031-9155/58/4/965)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 128.205.69.171
The article was downloaded on 25/01/2013 at 14:08

Please note that terms and conditions apply.
Assessment of hybrid rotation-translation scan schemes for in vivo animal SPECT imaging

Yan Xia¹,², Rutao Yao³, Xiao Deng³, Yaqiang Liu¹,², Shi Wang¹,² and Tianyu Ma¹,²

¹ Department of Engineering Physics, Tsinghua University, Beijing 100084, People’s Republic of China
² Key Laboratory of Particle & Radiation Imaging, Ministry of Education, People’s Republic of China
³ Department of Nuclear Medicine, State University of New York at Buffalo, Buffalo, New York 14214, USA

E-mail: maty@tsinghua.edu.cn

Received 19 March 2012, in final form 13 December 2012
Published 23 January 2013
Online at stacks.iop.org/PMB/58/965

Abstract
To perform in vivo animal single photon emission computed tomography imaging on a stationary detector gantry, we introduced a hybrid rotation-translation (HRT) tomographic scan, a combination of translational and limited angle rotational movements of the image object, to minimize gravity-induced animal motion. To quantitatively assess the performance of ten HRT scan schemes and the conventional rotation-only scan scheme, two simulated phantoms were first scanned with each scheme to derive the corresponding image resolution (IR) in the image field of view. The IR results of all the scan schemes were visually assessed and compared with corresponding outputs of four scan scheme evaluation indices, i.e. sampling completeness (SC), sensitivity (S), conventional system resolution (SR), and a newly devised directional spatial resolution (DR) that measures the resolution in any specified orientation. A representative HRT scheme was tested with an experimental phantom study. Eight of the ten HRT scan schemes evaluated achieved a superior performance compared to two other HRT schemes and the rotation-only scheme in terms of phantom image resolution. The same eight HRT scan schemes also achieved equivalent or better performance in terms of the four quantitative indices than the conventional rotation-only scheme. As compared to the conventional index SR, the new index DR appears to be a more relevant indicator of system resolution performance. The experimental phantom image obtained from the selected HRT scheme was satisfactory. We conclude that it is feasible to perform in vivo animal imaging with a HRT scan scheme and SC and DR are useful predictors for quantitatively assessing the performance of a scan scheme.
966 Y Xia et al

1. Introduction

Small animal single photon emission computed tomography (SPECT) is an essential tool for preclinical biomedical research (Meikle et al 2005). To expand the availability of SPECT, we developed an add-on SPECT technology (Shao et al 2007, Yao et al 2009, Ma et al 2009) that enables an animal positron emission tomography (PET) scanner to also perform SPECT imaging. The add-on SPECT uses the same PET detector gantry and electronics for detecting gamma events, and the only new hardware component used is a collimator insert placed inside the PET detector ring. This technology provides the benefits of lower overall cost for a PET/SPECT dual function systems and potential PET/SPECT dual tracer applications.

Figure 1 illustrates the setup of the add-on SPECT prototype system that we developed. The collimator insert is a slit-slat collimator which consists of a lead octagon tube and multiple tungsten annular slats stacks in the tube’s axial direction. The slit openings are along the vertical edges of the octagon tube. We selected a slit-slat collimator because it offers several attractive features (Rogers et al 1982, Metzler and Jaszcak 2006, Mahmood et al 2009, Chang et al 2009, Metzler et al 2006, Li et al 2009). First, the fan-beam projections through the slits offer a magnification factor which could be useful for improving the imaging resolution in the transverse plane. Second, the parallel collimation through the slats defines an axial field-of-view (FOV) that is equal to the extent of the slats. So with a stack of slats, a large axial FOV is readily achieved for whole body animal imaging. Third, the slats effectively segment the 3D imaging volume into multiple 2D imaging planes. The 2D tomographic image formation theory is well established and the scan scheme design is much simplified as compared to that for 3D imaging. For ease in mechanical implementation, the collimator insert was assembled in a single module and placed at a fixed position inside the PET detector ring. So both the collimator assembly and detector ring are stationary, only the imaging object is mobile.

To perform tomographic data acquisition on this system, the conventional scheme is to rotate the imaging object around the axial axis to acquire projection views over a 180° or 360° angular range. However, this option is problematic for imaging animals in vivo. Due to the effect of gravity, the body shape and organ positions of the animal would move during the
rotational scan process, as a live animal’s body cannot be rigidly constrained. The body and organ movements would compromise the quality of imaging data acquired. For good quality in vivo studies, a scan scheme with minimal rotation must be developed.

A variety of scan schemes have been reported in the literature or implemented in commercial SPECT systems. While the general principle for all scan schemes is to satisfy the sufficiency condition for complete sampling (Orlov 1976), the choice of a particular scan scheme is system specific. For example, most of pinhole-based systems use a helical scanning orbit (Metzler et al 2003a, DiFilippo 2008) for artifact free volume imaging and more uniform imaging performance along the axial direction. But for U-SPECT-I system, only translational movement of the imaging object is used. This is because U-SPECT-I has a sufficient number of pinholes arranged at appropriate view angles (Beekman et al 2004); even without any rotation of object or detector involved, the projection sampling is still adequate for a small targeted volume. Translational movement was used on U-SPECT-I only to expand the FOV for whole-body animal imaging (Vastenhouw and Beekman 2007). Another example is the Linoview system (Walrand et al 2005). Due to its unique collimator design, the collimator and detector assembly were moved linearly instead of rotationally to achieve tomographic imaging.

The goal of this work was to assess the performance of hybrid rotation-translation (HRT) scan schemes for in vivo animal imaging, i.e. only small-angle rotation is allowed, on the add-on SPECT system. Due to the slit-slat collimator’s 2D fan-beam imaging geometry, we focused on studying the transverse in-plane movement schemes and imaging performance in this work; the patterns of the simulated and experimental phantoms were designed or selected accordingly. Axial movements and performance considerations were not included.

2. Materials and methods

2.1. Detector and collimator insert

The animal PET scanner used in this study was a microPET Focus-120 system (Siemens Preclinical Solutions, Knoxville, TN). It consisted of four detector rings with a 14.7 cm diameter and 7.6 cm axial extent (Laforest et al 2007). The bore opening of the scanner was 13.5 cm, which was the maximum diameter that the slit-slat collimator assembly could fit in. Each detector ring had 24 detector blocks. Each block consisted of a 12 × 12 array of lutetium oxyorthosilicate (LSO) crystals and each crystal had a pitch of 1.6 × 1.6 × 10 mm³.

The slit-slat collimator used is shown in figure 1. The slit tube was made of lead and the slats were made of tungsten. The center-to-center distance between the octagon tube’s opposite lead-plates was 64.5 mm. The thickness of the plates was 2.5 mm. The radius of the slit aperture was 33 mm. The slit-apertures’ opening angle α was 90° and the slit-opening width w was 0.6 mm. The slit-aperture positions and opening angle were selected so that the PET ring detectors were fully utilized without projection overlapping. There were a total of 70 slats covering an axial field-of-view of 75 mm (only three slats are shown in figure 1 for clarity). The inner and outer diameters of the slats were 84 and 132 mm, respectively. The thickness of the slats was 0.25 mm. Two concentric, narrow radial width (~1.5 mm), plastic rings were placed between neighboring slats as spacers. Figure 2 shows a slat with two spacer rings attached to it. The spacers’ thickness was 0.83 mm. The centers of the slats were stacked in parallel to the axial axis of the slit tube and the animal PET detector ring.

2.2. HRT scan scheme

A HRT scheme is a sequence of combined translational and rotational movements of the imaging object. The rational of the HRT scan is to use object translational movement to
obtain projections at different views; therefore, the object rotation can be reduced, or ideally, eliminated. This is illustrated in figure 3. The image object is moved from left to right horizontally—a translational movement. Two projection views, 1 and 2, can be acquired as the object is seen from different angles through the slit aperture.

We designed ten HRT schemes by permuting two translational paths and five rotational settings. The two translational paths are denoted as R and G to represent the round and grid path patterns, respectively. The paths are shown as dashed lines in figure 4. The rotational movements of the object, usually by a set of discrete angles, take place at each stop of a translational path. To facilitate the comparison of different scan schemes, each HRT scan scheme is denoted by a code. The code is a combination of the translation path indicator, i.e. R or G, and the number of the rotation steps. For example, R2 stands for a scan scheme that follows the R translation path and has two rotation steps at each translational stop. The specific settings of all ten HRT scan schemes are described in table 1.
Assessment of hybrid rotation-translation scan schemes for in vivo animal SPECT imaging

Figure 4. Illustration of the concept of the HRT scan. The translational movement paths R and G are shown in the left and right diagrams, respectively. The animal stays on bed in a prone position. At each translational movement stop, the bed is rotated to a few angular positions to provide additional projection views of the animal.

Table 1. Settings of the ten HRT scan schemes studied. The radius of the scanning path of R schemes is 6.5 mm.

<table>
<thead>
<tr>
<th>Scheme code</th>
<th>Number of rotational steps (rotational angles)</th>
<th>Number of translational steps (angular interval)</th>
<th>Scheme code</th>
<th>Number of rotational steps (rotational angles)</th>
<th>Number of translational steps (grid interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>1 (0°)</td>
<td>120 (3°)</td>
<td>G1</td>
<td>1 (0°)</td>
<td>11 × 11 (1.1 mm)</td>
</tr>
<tr>
<td>R2</td>
<td>2 (−10°, 10°)</td>
<td>60 (6°)</td>
<td>G2</td>
<td>2 (−10°, 10°)</td>
<td>8 × 8 (1.57 mm)</td>
</tr>
<tr>
<td>R3</td>
<td>3 (−10°, 0°, 10°)</td>
<td>40 (9°)</td>
<td>G3</td>
<td>3 (−10°, 0°, 10°)</td>
<td>6 × 6 (2.20 mm)</td>
</tr>
<tr>
<td>R4</td>
<td>4 (−10°, −3°, 3°, 10°)</td>
<td>30 (12°)</td>
<td>G4</td>
<td>4 (−10°, −3°, 3°, 10°)</td>
<td>5 × 5 (2.75 mm)</td>
</tr>
<tr>
<td>R5</td>
<td>5 (−10°, −5°, 0°, 5°, 10°)</td>
<td>24 (15°)</td>
<td>G5</td>
<td>5 (−10°, −5°, 0°, 5°, 10°)</td>
<td>5 × 5 (2.75 mm)</td>
</tr>
</tbody>
</table>

The conventional 360° rotation-only scan scheme, denoted by code O, was used as the reference scheme. With the O scan scheme, a set of projection data is acquired after each rotational stop. With a HRT scheme, either it is R or G, the object is first moved through its translational path. At each translational stop, the object is rotated through its rotational stops. A set of projection data is acquired at each rotational stop. R1 and G1 are two special HRT schemes that consist of only translational movements.

2.3. Scan scheme performance evaluation indices

Four indices were defined to quantitatively assess the performance of the scan schemes: sampling completeness (SC), sensitivity (S), conventional system resolution (SR) and directional resolution (DR).

The concept of index SC is similar to that of SC(%) defined for pinhole SPECT (Metzler et al 2003b). In this study SC was defined as the percentage of the projection views that a scan scheme acquires over the ideal complete projection views for 2D tomographic imaging. It is
an explicit translation of the requirement for 2D Radon transform theorem (Radon 1986). \( SC \) was calculated by the following formula:

\[
SC = \left(\frac{m}{n}\right) \times 100\%,
\]

(1)

where \( m \) is the total number of projection views acquired with a scan scheme, and \( n \) is the number of projection views required for adequately sampling 360°. In this work, we chose \( n = 120 \), for most orbits contain only 120 shoot step which provides 120 different view angles at most. For a scan scheme, the 360° view angle range is uniformly divided into \( n \) bins with a bin size of \( 360° / n \) or 3°, and \( m \) is the number of the bins that have at least one projection view collected in it.

Sensitivity \( S \) is derived directly from the standard system detection efficiency. The \( S \) at point \( P \) of image object is calculated as the sum of contributions of sensitivity from each slit and at each scan step (Accorsi et al. 2008), which is

\[
S = \sum_i \sum_j S_{i,j},
\]

(2)

\[
S_{i,j} = \frac{w_{\text{eff,sens}} d^2}{4\pi (d + t)ah_{i,j}} \sin^3 \theta_{i,j},
\]

(3)

where \( S_{i,j} \) stands for the sensitivity acquired through \( i \)th slit at \( j \)th scan step, \( I \) is the total number of slits, i.e. eight, in this study, and \( J \) is the total number of movement steps for a scan scheme. As is illustrated in figure 5, \( h \) is the distance from \( P \) to the slit plane, \( \theta \) is the projection incidence angle, \( w \) and \( \alpha \) are slits’ opening width and angle, respectively, \( d \) is the gap between the slats, \( a \) is the slat’s radial height, \( t \) is the slat thickness. \( w_{\text{eff,sens}} \) is the sensitivity equivalent effective slit width (Novak et al. 2008),

\[
w_{\text{eff,sens}} = w + \frac{1}{\mu} \left( 1 - \cot^2 \frac{\alpha}{2} \cot^2 \theta \right) \cdot \sin \theta \cdot \tan \frac{\alpha}{2}.
\]

(4)

System resolution (\( SR \)) is a widely used index in collimator design (Beekman and Vastenhouw 2004, Novak et al. 2008). The \( SR \) at \( P \) calculated from the \( i \)th slit at \( j \)th scan step is

\[
SR_{i,j} = \sqrt{R_{\text{det}}^2 \left( \frac{h_{i,j}}{f} \right)^2 + w_{\text{eff,reso}}^2 \left( 1 + \frac{h_{i,j}}{f} \right)^2}
\]

(5)
Assessment of hybrid rotation-translation scan schemes for in vivo animal SPECT imaging

Figure 6. Illustration of the definition of directional resolution. Line $EF$ passes the interested image pixel $P$. Its direction angle is $\beta$ relative to the object reference vector. In a simplified projection model, image distributions from both lines $EF$ and $AB$ may form the same projection line $GH$ on the detector. The length of $AB$ is the conventional $SR_{i,j}$, the length of $EF$ is defined as $DR_{i,j}(\beta)$.

where $w_{\text{eff,reso}} = w - \frac{\ln(0.5)}{P} \cdot \sin \theta \cdot \cot \frac{\alpha}{2} \cdot (\tan^2 \frac{\alpha}{2} - \cot^2 \theta)$ (Novak et al 2008), $R_{\text{det}}$ is detector’s intrinsic resolution, $f$ is the radial distance from the slit aperture center to the detector ring, and $w_{\text{eff,reso}}$ is the resolution equivalent effective slit width. As the pitch of the pixelated detector scintillators is 1.59 mm, $R_{\text{det}} = 1.59$ mm.

For a scan that acquires and uses many projections for tomographic imaging, the conventional weighted average of $SR_{i,j}$ from all slit apertures and for all movement steps, is used to measure the average system resolution (Beekman and Vastenhouw 2004), i.e.

$$SR_{\text{conv}} = \frac{\sum_{j=1}^{J} \sum_{i=1}^{I} S_{i,j} \times SR_{i,j}}{\sum_{j=1}^{J} \sum_{i=1}^{I} S_{i,j}}.$$  \hspace{1cm} (6)

The conventional system resolution $SR$ is insufficient for describing the complete relationship between an emission source and the resulting projection. As illustrated in figure 6, $SR$ is represented by the line segment $AB$ in the emission space; it is the back-projection of line segment $GH$, the corresponding projection resolution on the detector side. The conventional $SR$ derivation is based on the assumption that $AB$ and $GH$ are parallel. However, the emission distribution passing through $P$ is not limited to be along $AB$ only. Other emission distributions such as the one represented by line segment $EF$ may form the same projection $GH$. To evaluate the image spatial resolution in different directions, such as $EF$, we introduce a new resolution measure, the directional resolution $DR_{i,j}(\beta)$, to account for the effect of the angle $\beta$, the emission source’s distribution orientation.

To calculate the directional resolution $EF$ in figure 6, we first define a reference vector to represent the image object’s orientation. $EF$ has an angle $\beta$ relative to the object reference vector. The reference vector represents a fixed reference frame that is attached to the object.
For example, it may start at the center of a mouse’s left eye, and point toward the center of the right eye. When the object or animal is rotated, the reference vector’s orientation changes relative to the imaging system’s coordinate frame. As shown in figure 6, the object reference vector’s orientation angle at \( j \)th scan step is \( \gamma_j \) relative to the imaging system reference vector.

For the SPECT system described in this work, all the slits are stationary relative to the detector gantry. Each slit opening is parallel to the detector surface behind it. The orientation angle of the \( i \)th slit opening is denoted by \( \delta_i \), as shown in figure 6.

By applying the sine theorem in \( \Delta PEA \) and \( \Delta PFB \), the directional resolution \( DR_{i,j}(\beta) \) for a projection passing through \( i \)th slit and at the \( j \)th object movement step is

\[
DR_{i,j}(\beta) = EF - EP + PF = \left[ \frac{AP \cdot \sin \theta''_{i,j}}{\sin (\theta''_{i,j} - \beta - \gamma_j + \delta_i)} + \frac{PB \cdot \sin \theta'_{i,j}}{\sin (\theta'_{i,j} + \beta + \gamma_j - \delta_i)} \right] \cdot \frac{SR_{i,j}}{2} \times \left[ \frac{\sin \theta''_{i,j}}{\sin (\theta''_{i,j} - \beta - \gamma_j + \delta_i)} + \frac{\sin \theta'_{i,j}}{\sin (\theta'_{i,j} + \beta + \gamma_j - \delta_i)} \right].
\]

(7)

By applying the cosine theorem in \( \Delta OPA \) and \( \Delta OPB \), one has

\[
\theta'_{i,j} = \arccos \left( \frac{OB^2 + \frac{SR_{i,j}^2}{4} - OP^2}{SR_{i,j} \times OB} \right),
\]

(8)

\[
\theta''_{i,j} = \arccos \left( \frac{OA^2 + \frac{SR_{i,j}^2}{4} - OP^2}{SR_{i,j} \times OA} \right),
\]

(9)

and

\[
OP = \frac{h_{i,j}}{\sin \theta_{i,j}},
\]

(10)

\[
OB = \sqrt{OP^2 + \frac{SR_{i,j}^2}{4} + OP \cdot SR_{i,j} \cdot \cos \theta_{i,j}},
\]

(11)

\[
OA = \sqrt{OP^2 + \frac{SR_{i,j}^2}{4} - OP \cdot SR_{i,j} \cdot \cos \theta_{i,j}}.
\]

(12)

Due to the possibility of infinite values of \( DR_{i,j}(\beta) \), i.e. when the direction of line \( FE \) overlaps with that of line \( OP \), it is not feasible to use (6) to calculate the weighted average of all \( DR_{i,j}(\beta) \). So we propose to calculate the overall \( DR \) by the following:

\[
DR(\beta) = \left[ \sum_{j=1}^{J} \sum_{i=1}^{I} S_{i,j}^0 DR_{i,j}(\beta)^p \right]^q, \quad (13)
\]

where \( p \) and \( q \) are the numerical values that weigh in the effect of the resolution factor \( DR_{i,j}(\beta) \) and the sensitivity factor \( S_{i,j} \) respectively; they were determined to be \(-1\) and \(3\), respectively, through a numerical searching procedure described in the appendix.

Without losing generality, \( \beta = 0 \), which is the direction parallel to the object reference vector, was evaluated as a test case in the remainder of this paper.
2.4. Monte Carlo simulation studies

Two phantoms were studied through Monte Carlo simulation with the GATE package (Jan et al. 2004). The first phantom used the same specification of the ultra-micro hot-rod phantom (Data Spectrum Inc., Hillsborough, NC). The diameters of the rods in the six sections were 2.4, 2.0, 1.7, 1.35, 1.0 and 0.75 mm, respectively. The center-to-center distance in each section was twice that of the rod diameter. The height of the hot rods was 30 mm. The total activity of ⁹⁹mTc source in the hot rods was 4.6 mCi. The phantom was scanned by each of the scan schemes listed in table 1, with the acquisition time of 6000 s for each scan. The second phantom consisted of 80 hot rods which were arranged in a grid pattern. Each rod was 0.25 mm in diameter and 30 mm in height. The distance between adjacent rods was 2.5 mm. A total of 1 mCi ⁹⁹mTc solution was uniformly distributed in the rods. A set of SPECT data was acquired with each of the scan schemes studied. The total acquisition time for each scheme was 1 min.

For both phantom studies, the energy window used was 120–160 keV. An ML-EM algorithm was used to reconstruct the simulated data. The system matrix used was derived from a Monte Carlo simulation (Yao et al. 2009). The voxel size of the reconstructed image was 0.25 mm × 0.25 mm × 1 mm³.

The reconstructed images of the grid-patterned hot-rod phantom were filtered with a 2D Gaussian function (FWHM = 0.075 mm). Each rod in the images was fitted with a 2D Gaussian function to extract the rod’s horizontal image resolution (IR) in terms of FWHM. The congregation of the rod resolutions form an image, represented by IR(β)|β = 0, for comparison with the corresponding SR and DR(β)|β = 0 images. Only rods in the central FOV were used for the extraction of resolution to avoid issues in the edge area due to reconstruction.

2.5. Analytical evaluation

A 25 mm diameter disc was scanned hypothetically with the scan schemes described in table 1. For each scheme, the values of SC, S, SR and DR(β)|β = 0 at each pixel center of the disc were calculated with equations (1), (2), (6) and (13), respectively. The pixel size of the disc was set to 2.5 mm × 2.5 mm to match that of the IR(β)|β = 0 image of the grid-patterned hot-rod phantom.

To quantify the closeness between the resolution indices, such as between IR and SR, we introduced the normalized mean square error (NMSE):

\[
NMSE = \frac{\sum_{i=0}^{N-1} \sum_{j=0}^{N-1} (f_A(x, y) - f_B(x, y))^2}{\sum_{i=0}^{N-1} \sum_{j=0}^{N-1} f_B(x, y)^2},
\]

where \(f_A(x, y)\) is the image of one resolution index, e.g., SR, normalized to its average value, \(x\) and \(y\) are image pixel indices, \(f_B(x, y)\) is the image of another resolution index, e.g., IR, normalized to its average value, and \(N\) is the size of images.

The NMSE in (14) is for one scan scheme. We define a joint NMSE that accounts for all the 11 schemes:

\[
\text{joint-NMSE} = \frac{\sum_{\text{orbit}=O,R_1,\ldots,R_5,G_1,\ldots,G_5} \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} (f_A(x, y) - f_B(x, y))^2}{\sum_{\text{orbit}=O,R_1,\ldots,R_5,G_1,\ldots,G_5} \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} f_B(x, y)^2}.
\]

2.6. Experimental hot-rod phantom

An ultra-micro hot-rod phantom (Data Spectrum Inc., Hillsborough, NC) was scanned with the conventional O scheme and the HRT G5 scheme. The diameters and the center-to-center
3. Results

3.1. Monte Carlo simulated phantom studies

Figure 7 shows the reconstructed images of the ultra-micro hot-rod phantom scanned with each scheme. Each image is labeled with the scan scheme code used to obtain the simulation data. The 0.75 mm hot-rod sections (at 3 o’clock position) from the R1 and G1 schemes are more blurred than that with other schemes. For example, the images from the R2–R5 scan schemes have better hot-rod identification in the outer column of the 0.75 mm section than R1 scheme does. Another observation is that, in any column with two images, e.g. the 1 o’clock section, the top image is slightly clearer than the bottom image. In other words, the R group of scan schemes outperforms the G group of scan scheme group, given the same number of rotation steps are used.

The reconstructed images of the grid-patterned hot-rod phantom study are shown in figure 8. To reduce statistical noise, the images shown are from a summation of 30 transaxial slices which corresponds to 30 mm in thickness.
Assessment of hybrid rotation-translation scan schemes for in vivo animal SPECT imaging

In the image acquired with the O scan scheme, the four rods at the center of FOV are severely blurred, i.e. this region is significantly inferior to that at the edge of FOV in terms of resolution. For the images acquired with the R1 and G1 schemes, the cylinders in the central area are sharp while those near the borders are blurred. The middle two rows of rods show clearly that the horizontal resolutions improve from the edges to the center of FOV. The image of the R1 scheme shows better resolution in the edge areas than that of the G1 scheme. As compared to the images from the O, R1 and G1 schemes, the images acquired with the other HRT schemes show overall superior image quality, and there is much less variation in terms of horizontal or vertical resolution.

Figures 10(a) and (b) show the performance comparison of the R and G scan schemes, respectively, using the hypothetical scan results of the 25 mm diameter disc. For each HRT scan scheme, the $SC$, $S$, $SR$ and $DR(\beta)|_{\beta = 0}$ and $IR(\beta)|_{\beta = 0}$ values in the FOV are displayed as images in incremental rows in one column. The results of the O scheme, the conventional scan scheme, are shown in the first column of both figures 10(a) and (b) to serve as a reference. The horizontal section profiles passing the center of the $SC$, $S$, $SR$ and $DR(\beta)|_{\beta = 0}$ images in figure 10 are extracted and compared in figure 11. The results in figures 10 and 11 are arranged in parallel—the profiles in figures 11(a) and (b) are from the images in figures 10(a) and (b), respectively.

It can be seen from the first rows of figures 10(a) and (b), and accordingly in figures 11(a) and (b), that except for R1 and G1, the rest of eight HRT schemes have similar $SC$ values as compared to the O scheme. The sensitivity performances of all schemes are also very close, as shown in figures 10 and 11. For the scan schemes studied, the average sensitivity values over the FOV vary within a very small range, from $3.55 \times 10^{-4}$ to $3.64 \times 10^{-4}$. The maximum sensitivity loss of the R and G schemes studied, as compared to the O scheme, is less than 3%.
Figure 9. Top: the $IR(\beta)|_{\beta=0}$ images derived from the hot-rod phantom images in figure 8. Bottom: the central horizontal section profiles extracted from the $IR(\beta)|_{\beta=0}$ images on top.

The row of $SR$ images in figure 10(a) shows that the O and R scan schemes have similar pattern and little visible differences. In figure 11(a), the $SR$ profiles of R1 to R5 schemes overlap with each other and appear as a single curve, and the profile of the O scheme is slightly higher than that of the R schemes. So there is little difference among R schemes and they are all slightly better than the O scheme in terms of $SR$. By observing the row of $SR$ images in figure 10(b) and accordingly in figure 11(b), similar conclusions can be drawn for the G1 to G5 schemes, i.e. there is a little difference among them and they are all slightly better than the O scheme.

All the $DR(\beta)|_{\beta=0}$ images in figure 10 show little variations in the horizontal direction or unique feature that is visually prominent. The corresponding section profiles in figure 11, however, reveal that variations and differences do exist. As compared to the section profiles of $SR$ images, $DR(\beta)|_{\beta=0}$ shows larger difference between scan schemes. The O scheme has a bell shape that is different from all other schemes, and its values in the central peak area are higher than all other schemes. This means that all the HRT schemes have improved resolution in the central area as compared to the O scheme, as shown in figure 8. The other schemes share a shape of a bowl with an elevated central area; the relative heights of the central area and the borders of the bowl vary depending on the scan scheme. Among the R and G group HRT scan schemes, respectively, R1 and G1 have the highest and R2 and G2 have the lowest $DR(\beta)|_{\beta=0}$ profiles; the differences between other schemes are clearly smaller. According to their $DR(\beta)|_{\beta=0}$ profiles, R1 and G1 schemes show sharp resolution degradation trend toward the FOV edge. For R and G schemes with matching number of rotations per each translation
Assessment of hybrid rotation-translation scan schemes for *in vivo* animal SPECT imaging

Figure 10. Pixelwise performance indices of the ten HRT and the O scan schemes displayed in two panels. In each panel, each column corresponds to one scan scheme, each row corresponds to a performance index. (a) R and O schemes. (b) G and O schemes.

Step, an R scheme in figure 11(a) has lower $DR(\beta)|_{\beta=0}$ values than its G scheme counterpart in figure 11(b).

By comparing the representative curve patterns of the $IR(\beta)|_{\beta=0}$ and $DR(\beta)|_{\beta=0}$ profiles, i.e. those of O, R1 and G1, the $DR$ and $IR$ show clear resemblance while $SR$ and $IR$ do not. The joint-NMSE values between $IR$ and $SR$, and $IR$ and $DR$, are 0.0767 and 0.0665, respectively. This indicates quantitatively that the corresponding $DR(\beta)|_{\beta=0}$ images match $IR(\beta)|_{\beta=0}$ better than the $SR$ images do. Since $IR(\beta)|_{\beta=0}$ results represent what is measured by the imaging system, in other words the gold standard of predictive indices, its closeness...
Figure 11. Central horizontal section profiles extracted from the SC, S, SR, DR(β)|β = 0 and IR(β)|β = 0 images in figure 11. (a) R and O schemes. (b) G and O schemes.
to $DR(\beta)|_{\beta=0}$ therefore indicate that $DR(\beta)$ is a more relevant resolution performance index than the traditional $SR$ definition.

The row of $DR(\beta)|_{\beta=0}$ images shown in figure 10 do not show a circular symmetry. This is different from the images of $SC$, $S$ and $SR$ but is expected. For example, the $DR(\beta)|_{\beta=0}$ values for the rods on the central horizontal line are radial direction resolution, the $DR(\beta)|_{\beta=0}$ values for the rods on the central vertical line are tangential direction resolutions. They should not be the same. But the $DR(\beta)|_{\beta=0}$ values along the central horizontal line and the $DR(\beta)|_{\beta=\pi/2}$ values along the central vertical line are the same, because they are both radial direction resolutions.

3.3. Experimental phantom study

Figure 12 shows the images of the ultra-micro hot-rod phantom scanned with the O (left) and the G5 (right) schemes. The 1 mm diameter hot-rod is the smallest that is distinguishable in both images. No imaging resolution loss is observed with the HRT-G5 orbit compared to the O orbit. The zigzag artifacts along the top-right ring area of the phantom might be caused by inadequate projection sampling introduced when the phantom was placed off-center of FOV in the imperfect home-made octagon collimator tube.

4. Discussion

The goal of this work was to determine a scan scheme for an animal SPECT system with a stationary detector gantry. Intuitively, the rotational movement of animal should be completely avoided, or at least be minimized to facilitate in vivo animal scan. But on this SPECT system, the collimator cannot provide adequate projection views with a stationary-object scanning protocol. So a scan protocol that would provide tomographic data acquisition and minimize the animal rotation is required. The HRT scan schemes were proposed to satisfy these requirements. For these new scan schemes, it is important to evaluate their efficacy and find the better one. To facilitate the assessment, we have defined sampling completeness ($SC$), sensitivity ($S$), conventional system resolution ($SR$), directional resolution ($DR(\beta)$) as the figures-of-merit. We used the image resolution measures from a phantom study, $IR(\beta)$, for assessing and comparing the validity of the $DR(\beta)$ and $SR$. 

![Figure 12. Experimental hot-rod phantom results acquired with (a) the conventional rotation O and (b) the HRT G5 scheme.](image-url)
4.1. What is new in DR

The conventional SR was originated from imaging systems with a parallel-hole collimator and the filtered back-projection reconstruction algorithm. It assumes that when a projection is back-projected into image space, the spread is only along the direction parallel to the original projection upon the detector. This is not true as clearly shown in figure 6 with the pinhole-based illustration—the spread is a function of orientation angle $\beta$. To address this issue, the directional resolution concept was devised for better quantifying the resolution performance in this study. Two factors contribute to the current form of $\text{DR}(\beta)$ in (13): (a) an orientation-related resolution model $\text{DR}_{i,j}(\beta)$ for each scan stop, which replaces the conventional orientation-isotropic resolution model $\text{SR}_{i,j}$; and (b) a new approach to combine $\text{DR}_{i,j}(\beta)$ into one $\text{DR}(\beta)$, the contribution from individual projection is inversely related to the projection’ spread (or resolution $\text{DR}_{i,j}(\beta)$) and proportionally related to the projection’s magnitude (sensitivity, $S_{i,j}$). As mentioned, the choice of using the reciprocal of $\text{DR}_{i,j}(\beta)$ is due to its possible infinite values in certain projection directions.

It is apparent that equations (13) and (6) calculate the average resolution indices differently. To exclude the effect of this difference in the comparison of $\text{DR}$ and $\text{SR}$, we also calculated the average $\text{SR}$ with an analogous form of average $\text{DR}$

$$\text{SR} = \left[ \frac{\sum_{j=1}^{J} \sum_{i=1}^{I} S_{i,j}^q \text{SR}_{i,j}^q}{\sum_{j=1}^{J} \sum_{i=1}^{I} S_{i,j}^q} \right]^{\frac{1}{2}}$$

The joint NMSE between this new $\text{SR}$ and $\text{IR}(\beta)|_{\beta = 0}$ was 0.0790, it is higher than the joint NMSE between $\text{DR}(\beta)|_{\beta = 0}$ and $\text{IR}(\beta)|_{\beta = 0}$. This confirms that $\text{DR}$ is a more relevant measure of resolution than $\text{SR}$.

Although it is highly desired, the $\text{DR}(\beta)$ as presented in this work is not an absolute quantitative resolution index. To design a resolution index with features of $\text{DR}(\beta)$ and also the absolute resolution performance, is a direction for future research.

4.2. Axial consideration

For a slit-slat collimator-based SPECT system, its axial resolution may be considered to be independent of the transverse in-plane resolution (Metzler et al 2006). For this reason, axial movements and resolution evaluations were not included in this study. Compared to that in the transverse plane, the sampling design and performance evaluation in the axial direction are 1D tasks. A standard way to implement axial direction sampling is through using a helical scan scheme. In the case of the add-on SPECT in this study, this could be accomplished by adding object movements along the axial axis. The net effect of a helical scan in terms of axial sampling is that the scan would expose an image object to multiple detectors—or to the same detector but placed at multiple positions. The overall effect of this multiple detector or position sampling is that the axial variation of the detector responses, either for individual image voxels or the image object as a whole, is averaged out so that the system could achieve a more uniform axial imaging performance.

5. Conclusion

In this work, we assessed the performance of ten HRT scan schemes for in vivo animal imaging on a stationary detector SPECT system. Four analytic evaluation indices, $\text{SC}$, $\text{S}$, $\text{SR}$ and $\text{DR}(\beta)$ were used to quantify the performance of each scan scheme in each point.
of the FOV. The directional resolution index $DR(\beta)$ is a new index that we introduced to account for the effect of the relative orientation between the measured projection and its back-projected image distribution. For all the scan schemes, a grid-patterned hot-rod phantom was simulated to extract the spatial resolution performance, which served as a reference for comparing the predictive value of the conventional index $SR$ and the new resolution index $DR(\beta)$. A selected HRT scan scheme was tested with an experimental phantom study.

Eight of ten HRT schemes evaluated showed close to 100% sampling completeness, and achieved better resolution than the conventional full-angle rotation-only scheme with negligible sensitivity loss. The $DR(\beta)$ values calculated show closer resemblance to the resolution measures from the simulated phantom. The experimental phantom image obtained was satisfactory. Since the rotation steps in the selected HRT schemes are limited to a small angle range, e.g. $-10^\circ$ to $10^\circ$, the gravity impact can be significantly reduced for in vivo animal imaging. We conclude that it is feasible to perform in vivo animal imaging with a HRT scan scheme, and $SC$ and $DR$ are useful predictors for quantitatively assessing the performance of a scan scheme.

Acknowledgments

This work was partially supported by the Specialized Research Fund for the Doctoral Program of Higher Education (SRFDP200800031071), the National Natural Science Foundation of China (no 10675069), and the Roswell Park Alliance Foundation under grant 62-2426-01.

Appendix

The $p$ and $q$ values in (13) were determined through the following numerical searching procedure.

First, a value from the list $\{-3, -2, -1.5, -1, -0.5, -0.25\}$ and a value from the list $\{-5, -3, -2, -1, -0.5, 0.5, 1, 2, 3, 5\}$ were selected and assigned to $p$ and $q$, respectively. Since $DR(\beta)\vert_{\beta = 0}$ may be infinite when $p > 0$, only the negative cases of $p$ were calculated. Consequently, there were a total of 60 ($p, q$) pairs. The values of each ($p, q$) pair was used to calculate a $DR(\beta)\vert_{\beta = 0}$ image for all the scan schemes described in table 1, as well as the conventional rotation-only scheme. The $DR(\beta)\vert_{\beta = 0}$ images were then compared to the $IR(\beta)\vert_{\beta = 0}$ resolution image by calculating the joint NMSE as defined in (15). The ($p, q$) pair that yielded the minimal joint NMSE was first identified.

Figure A.1 shows the plot of the joint-NMSE values between $IR(\beta)\vert_{\beta = 0}$ and $DR(\beta)\vert_{\beta = 0}$ with the 60 ($p, q$) pair values. It can be seen that for all the $q$ values except $q = 2$ and $q = 5$, the minimal joint-NMSE values occur when $p = -1$. Therefore $p$ was assigned the value $-1$.

The graph in figure A.2 shows the joint-NMSE values between $IR(\beta)\vert_{\beta = 0}$ and $DR(\beta)\vert_{\beta = 0}$ as $p$ was fixed at $-1$ and $q$ value changed from $-10$ to $10$ with a fine sampling interval of 0.2. The $q$ value that gives the minimal joint NMSE is 3. Therefore $q$ was assigned the value of 3 in (13). The joint NMSE between $IR(\beta)\vert_{\beta = 0}$ and $SR$ as a function of $q$ is also shown for comparison. Here $SR$ was calculated from the analogous form of $DR$, as shown near the end of section 4.1. With the $p = -1$ and $q = 3$, it is clear that the $DR(\beta)\vert_{\beta = 0}$ image is closer to $IR(\beta)\vert_{\beta = 0}$ image than $SR$. 
Figure A.1. To search the $p$ and $q$ values that yield the minimal joint NMSE, $p = -1$ was selected as it paired well with most $q$ values shown according to this criterion.

Figure A.2. The joint-NMSE values between the $DR(β)|β=0$ and $IR(β)|β=0$ images are plotted as functions of $q$ when $p$ was set to $-1$. The joint-NMSE values between the $SR$ and $IR(β)|β=0$ images are also plotted for comparison.

References


Assessment of hybrid rotation-translation scan schemes for in vivo animal SPECT imaging

Radon J 1986 On the determination of functions from their integral values along certain manifolds IEEE Trans. Med. Imaging 5 170–6
Vastenhouw B and Beekman F 2007 Submillimeter total-body murine imaging with U-SPECT-I J. Nucl. Med. 48 487–93
Yao R, Ma T and Shao Y 2009 Derivation of system matrix from simulation data for an animal SPECT with slit-slat collimator IEEE Trans. Nucl. Sci. 56 2651–58