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Citation: Medical Physics 31, 3461 (2004); doi: 10.1118/1.1813873
View online: http://dx.doi.org/10.1118/1.1813873
View Table of Contents: http://scitation.aip.org/content/aapm/journal/medphys/31/12?ver=pdfcov
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Image reconstruction algorithm for a spinning strip CZT SPECT camera with a parallel slat collimator and small pixels

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(Received 17 March 2004; revised 13 September 2004; accepted for publication 18 September 2004; published 23 November 2004)

This paper discusses the use of small pixels in a spinning CdZnTe single photon emission computed tomography (SPECT) camera that is mounted with a parallel slat collimator. In a conventional slat collimation configuration, there is a detector pixel between two adjacent collimator slats. In our design, the pixel size is halved. That is, there are two smaller pixels to replace a regular pixel between two adjacent slats while the collimator remains unchanged. It has an advantage over our older design that uses tilted slats. In order to acquire a complete data set the tilted-slat collimator must spin 360° at each SPECT view while the proposed design requires only 180° at each SPECT view. Computer simulations and phantom experiments have been carried out to investigate the performance of the small-pixel configuration. It is observed that this design has the potential to increase the spatial resolution of the detector while keeping photon counts the same. © 2004 American Association of Physicists in Medicine. [DOI: 10.1118/1.1813873]

Key words: image reconstruction algorithm, single photon emission computed tomography, filtered backprojection reconstruction, imaging instrumentation

I. INTRODUCTION

A strip-shaped SPECT (single photon emission computed tomography) gamma camera has been developed using CdZnTe detectors.\(^1,2\) Since the cost of the detector is proportional to the detector area, the strip-shape (i.e., a narrow and long rectangular shape) detector was chosen to provide a large field-of-view imaging region with a relatively small detector surface area.

Instead of using a parallel-hole collimator, a parallel-slat collimator has been adopted. One motivation of using a slat collimator is that a slat-collimator can accept many more gamma ray photons than a hole collimator with the same spatial resolution.\(^3\) However, a slat collimator accepts more scattered photons than a hole collimator. Due to the excellent energy resolution of CdZnTe (about 3% at 140 keV\(^2\)), most of the scattered photons can be rejected. Since the strip detector is rather narrow, the projection data are most likely truncated if a parallel-hole collimator is used. The utilization of a parallel-slat collimator eliminates the data truncation problem. Similar designs have also been studied by other researchers.\(^4-8\)

For a parallel-hole collimator, a complete set of projections can be obtained by rotating the detector around the object by at least 180°. However, for a parallel-slat collimator, rotating the detector around the object cannot provide a complete data set. For planar integral measurements, a point in the object is said to be completely measured if for any plane cutting through this point, the planar integral of the slice of the object on this plane is measured. This condition can be met if the detector spins around its own axis 180° in addition to rotating around the object 180° as illustrated in Fig. 1. Thus an additional motion of the detector is required. For example, the detector is required to spin around its own axis in addition to rotating around the object as illustrated in Fig. 1. We refer to the angle ϕ as the SPECT-angle, and the angle θ as the spin-angle.

The projection data can be modeled as line integrals when a parallel-hole collimator is used. If the distance from the emission source to the detector is r, the detection efficiency is independent of r for a parallel-hole collimator. On the other hand, the projection data are weighted planar integrals for a parallel-slat collimator. The weighting function is a function of the distance r from the emission source to the detector. The detection efficiency is inversely proportional to the distance r.

To our knowledge, no exact analytical image reconstruction algorithm has been found for the parallel-slat rotating imaging geometry in Fig. 1. However, some approximate reconstruction algorithms are available. It has been suggested to use the three-dimensional (3D) Radon inversion formula to reconstruct the image by ignoring the distance dependent weighting factor in the measured projection data.\(^4,9\)

In an earlier publication,\(^10\) we proposed a filtered backprojection algorithm that is able to compensate for the 1/r weighting function. In fact, the weighted planar integrals have a weighting function that is more complicated than 1/r.\(^11\) A closer approximation of the weighting function is (cos α)/r, where α is defined in Fig. 2. The sensitivity of (cos α)/r is derived by assuming a “small detector” or “point detector” model. If the slat collimator is ideal, each detector
cell can only measure the radioactivity from the slice between the two adjacent slats. If the point source is a distance \( r \) away from the "point detector," the detection solid angle is proportional to \( 1/r \). If the detector has a flat surface and \( \alpha \) is the angle between the normal direction of the detector’s flat surface and the ray from the point source to the detector center, the detection solid angle is proportional to \( \cos \alpha / r \) as illustrated in the Fig. 2. The sensitivity function \( \cos \alpha / r \) is not exact. In practice, the slat collimator is not ideal; activity from regions outside the slice that is between adjacent two slats may reach the collimated detector cell. This is the well-known, distance dependent collimator blurring effect. A recent investigation of the sensitivity and resolution of this slat collimator is reported in Ref. 3.

The basic idea to compensate for the weighting factor \( 1/r \) is by taking the angular derivative of the projection data. This idea was first suggested by Barrett\(^{12}\) and later was developed for cone-beam image reconstruction by Grangeat.\(^{13}\)

**Fig. 1.** Spinning strip CdZnTe SPECT camera imaging geometry.

**Fig. 2.** The measured planar integral is weighted by \( \cos \alpha \) and inversely by the distance \( r \).
In order to take the angular derivative, we previously proposed the use of a parallel-slat collimator, in which the slats have a small tilt angle $\delta$ of approximately $1^\circ$, as illustrated in Fig. 3. The angular derivative is calculated using projection data sets with spin angles $180^\circ$ apart. At each fixed SPECT-angle $\phi$, it is required that the detector spin over $360^\circ$. At the detector positions $\theta$ and $\theta+180^\circ$, the detector measures almost the same planar integrals except that the planes are tilted toward one direction by a small angle $\delta$ at $\theta$, while they are tilted toward the opposite angle by $\delta$ at $\theta + 180^\circ$. An approximate angular derivative can be obtained by subtracting the measurements at $\theta$ and at $\theta+180^\circ$. In the next section a simpler approach is presented to measure “tilted” data.

II. METHOD

A. Removal of $1/r$ factor

First we use a 2D example to explain how the angular derivative is able to compensate for the weighting factor $1/r$ in the projection data.

Let $g(x)$ be an unweighted measurement of a function $f(x,y)=f_p(r,\xi)$

$$g(x) = \int_0^\infty f(x,y)dy,$$

and let $h(\xi)$ be a $1/r$ weighted measurement

$$h(\xi) = \int_0^\infty \frac{1}{r} f_p(r,\xi)dr.$$

We will show that

$$\frac{dg(x)}{dt}\bigg|_{x=0} = \frac{dh(\xi)}{d\xi}\bigg|_{\xi=\pi/2},$$

with

$$t = -x.$$

In fact, the relationship:

$$x = r \cos \xi$$

$$y = r \sin \xi$$

between the Cartesian and polar coordinate system (see Fig. 4) gives

$$\frac{\partial x}{\partial \xi} = -r \sin \xi$$

FIG. 3. The collimator is slightly tilted. The difference of data at $\theta$ and $\theta + 180^\circ$ approximates the angular derivative.

FIG. 4. Cartesian and associated polar coordinate systems for Eq. (3).
\[ \frac{\partial y}{\partial \xi} = r \cos \xi. \] 

(8)

Thus,

\[
\frac{db(\xi)}{d\xi} \bigg|_{\xi=\pi/2} = \int_0^\infty \left. \frac{1}{r} \left[ \frac{\partial}{\partial \xi} \int_{\xi=\pi/2} S(r, \xi) \right] \right|_{\xi=\pi/2} dr \\
= \int_0^\infty \left. \frac{1}{r} \left[ (-r \sin \xi) \frac{\partial f}{\partial \xi} + (r \cos \xi) \frac{\partial f}{\partial \xi} \right] \right|_{\xi=\pi/2} dr \\
= \int_0^\infty \left. \frac{1}{r} \left[ (-r \sin \xi) \frac{\partial f}{\partial \xi} + (r \cos \xi) \frac{\partial f}{\partial \xi} \right] \right|_{\xi=\pi/2} dr \\
= -\int_0^\infty \left. \frac{\partial f}{\partial \xi} \right|_{\xi=\pi/2} dy \\
= \int_0^\infty \left. \frac{\partial f}{\partial t} \right|_{t=0} dy = \frac{dg(x)}{dt} \bigg|_{x=0}. \tag{9}
\]

Therefore, the angular derivative is able to “remove” the 1/r factor by converting the angular derivative to a linear derivative at \( \xi = \pi/2 \).

### B. Small pixel configuration

In the following we will show how a small-pixel configuration can provide “tilted” measurements that can be used to evaluate the angular derivative. Figure 5(a) shows a side view of the old configuration of the CdZnTe camera with a parallel slit collimator where the spacing between two adjacent slats is the detector pixel size, and Fig. 5(b) shows the small-pixel configuration where the size of the detection pixel is halved and an original pixel is replaced by two smaller pixels. Note that the collimator slats are not tilted.

Figure 5(c) is an exaggerated illustration of the asymmetric beam forms of the small-pixel configuration in a CZT camera. The detector pixel \( w_1 \) measures more data from the right than left, while the detector pixel \( w_2 \) measures more data from the left than right. Skew measurements are thus measured. The difference of these two skew measurements approximates the angular derivative of the measurements. A shorter slit length \( L \) gives a larger equivalent tilt angle. An optimal tilt angle is determined by the data noise. If the data are less noisy, a smaller tilt angle can be used.

The main advantage of this small-pixel configuration over our old tilted-slit configuration is that for the tilted-slit configuration the camera must spin 360° at each SPECT view in order to acquire all tilted measurements; on the other hand, the small-pixel configuration only requires the camera to spin 180° at each SPECT view. If we compare the small-pixel configuration with conventional regular-sized pixel configuration (with zero tilt angle of the slats), the small pixels have a potential to provide higher spatial resolution.

### C. Slat length

For a fixed gap between slats, the length of the slat affects the detection sensitivity and detector’s point response function. A shorter length gives higher detector sensitivity but worse spatial resolution. The relationship is exactly the same as the situation in a parallel-hole collimator: If we fixed the collimator hole size, the hole-length affects the detection sensitivity and detector’s point response function. It is the noise level (or the photon count) that determines the tradeoff of the sensitivity and resolution.

The length of the slat also affects the calculation of the angular derivative. In general, an angular derivative of function \( F(\xi) \) is defined by \( F'(\xi) = \lim_{\Delta \xi \to 0} [F(\xi + \Delta \xi) - F(\xi)] / \Delta \xi \). A longer slat length corresponds to a smaller \( \Delta \xi \), and a shorter length corresponds to a larger \( \Delta \xi \). A more accurate approximation of an angular derivative requires a longer slat length. However, when the data are very noisy, \( \Delta \xi \) cannot be too small. This tradeoff is similar to that of sensitivity and resolution.

### D. Image reconstruction

For the conventional parallel-slit collimation with regular-sized detector pixels and untilted parallel slats, the 3D image can be reconstructed by the Radon inversion formula \(^{14}\) by assuming that the measured projections are unweighted planar integrals. The reconstruction algorithm consists of two steps: (i) Take the second order derivative of the projection data (i.e., planar integrals), and (ii) backproject the processed projections. For the small-pixel imaging configuration, the image can still be reconstructed by the 3D Radon inversion formula with some modifications. Precisely, the image reconstruction algorithm consists of the following steps:

- **STEP 1:** At each fixed SPECT angle \( \phi \) and spin angle \( \theta \), take the angular derivative of the projection, see Eq. (3). Precisely, let

\[
p_{\theta \phi}(2k) = Data_{\theta \phi}(w_{2k}) - Data_{\theta \phi}(w_{2k-1})
\]

(10)

\[
p_{\theta \phi}(2k + 1) = Data_{\theta \phi}(w_{2k}) - Data_{\theta \phi}(w_{2k+1}),
\]

(11)

where \( Data \) is the measurement from the detector [see Fig. 5(d)], Equations (10) and (11) are not the same. Equation (10) can only be used for the two data points with no septal wall in between, and Eq. (11) can only be used for the two data points with a septal wall in between. Our projection data can be grouped into two sets. The first set contains the projections tilted toward left (with *even* indices \( 2k \)), while the second set contains the projections tilted toward right (with *odd* indices \( 2k - 1 \) or \( 2k + 1 \)). The angular derivative is achieved...
by a measurement in Set 1 subtracting an enmeshment in Set 2. This is illustrated in Fig. 5(d).

**STEP 2:** Take the linear derivative with respect to $k$, obtaining $p_{\theta \phi}'(k)$, which is the second order derivative of the 3D Radon transform of the object.

**STEP 3:** Three-dimensionally backproject $p_{\theta \phi}'(k)$ into the image space. A 3D image is thus reconstructed.
III. COMPUTER SIMULATIONS AND PHANTOM EXPERIMENTS

A. Computer simulations

Computer simulations were performed to compare the images that were obtained from the conventional regular-sized detector pixel configuration and the small-pixel configuration. The reconstruction algorithm for the regular-sized pixel configuration was the Radon inversion algorithm and the reconstruction algorithm for the small-pixel configuration was the modified Radon inversion algorithm as outlined in Sec. II D. Note that none of these algorithms provide exact reconstructions due to the weighting in the projection data.

The phantom was a large uniform sphere containing four smaller hot and cold spheres as illustrated in Fig. 6. The radii of the spheres were 25, 3, 3, 0.85, and 0.6 units. The length unit is the regular pixel size (i.e., the gap width between adjacent two slats). The centers of the small spheres were 12.5 units away from the center of the large sphere. The intensity of the large sphere was 10, the hot spheres 20, and cold spheres 0. The center of the large sphere was on the axis of SPECT rotation. The distance between the detector and the axis of SPECT rotation was 47.5 units for one set of studies, and was 30 units for another set of studies. There were 64 regular detector pixels, or 128 small pixels on the detector. The size of the small pixel was 0.5 units. The projection data were numerically generated planar integrals with a weighting function \( \cos \alpha / r \). No attenuation was modeled in the projection data. The number of the SPECT angles was 120 over 360°. The number of the spin-angles was 64 over 180°. Projection data were generated using the small pixels configuration. The projection data for the regular-sized detector pixel were obtained by combining the projection data values between adjacent slats. The raw projection data generated numerically were noiseless. Poisson noise was then added to the data. For noisy data, the pixel count (i.e., the product of activity and view duration) varies from 0 to about 400. Both noiseless and noisy data were used in computer simulations.

The collimator geometric blurring effects were modeled in the data generation program. Without collimator blurring, a measurement is a weighted planar integral of the object on a plane parallel to the collimator slat. In Fig. 7, the slat length is \( L \), the small detector pixel size is \( d \), and a point source is at distance \( D \) away from the slat front edge and at distance \( t \) away from the line extended from the slat. If the point source is in region II, using relationship between two similar triangles, the length \( s \) of the illuminated region on pixel \( w_1 \) is given as

\[
\frac{d - s}{t} = \frac{L}{D}
\]

or

\[
s = d - \frac{tL}{D}.
\]

A similar expression can be obtained for a point source in region IV. When the point source is in region I or region V, \( s = 0 \). When the point source is in region III, \( s = d \). The \( s \) value as a function of the point source location as depicted as a trapezoidal curve on the top the figure.

When \( L \gg d \) (in our prototype \( L = 40 \) mm and \( d = 1.8 \) mm), in region II we have

---

**Fig. 6.** A spherical simulated phantom contains two hot spheres and two small spheres. The cold spheres have no activities. The activity density in the hot spheres are twice as much as in the background.

**Fig. 7.** The point response function of a slat collimator can be evaluated by varying a point source location and calculating the illuminated length in a particular detector pixel. The left figure uses the length \( t \) as the variable, and the right figure uses the angle \( \eta \) as the variable.
\[ s = d - \frac{\eta L}{D} = d - L \tan \eta = d - L \eta. \]  

where \( \eta \) which is measured from the vertical line (i.e., the extended line of the slat). The \( s \) value as a function of the point source location, parametrized by the angle \( \eta \), is depicted as a trapezoidal curve on the top of the figure. Using this result, we modeled the collimator blurring effect by using a weighted sum of nine weighted planar integrals as shown in Fig. 8. The effects of collimator blurring depend on the collimator slat height \( L \) and the gap \( 2d \) between the adjacent slats. In our computer simulation, \( d \) was 0.5 units and \( L \) was 22.2 units.

The reconstructed images were \( 64 \times 64 \times 64 \). Figure 9 shows the reconstruction results (three orthogonal central slices) from the noiseless projection data for the detector radius of rotation being 30 units. Line profiles are drawn for resolution/contrast comparisons. It is clear that the small-pixel configuration provides higher spatial resolution and better contrast than the regular pixel configuration does. Figure 10 shows the results for the study with the detector radius of rotation being 47.5 units.

The contrast of the reconstructions from the noisy data was evaluated for the large hot lesion, large cold lesion, and background, respectively. An averaged value was calculated from each set of the 10 voxel values. The contrast was evaluated according to the following definition:

\[ \text{Contrast} = \frac{\text{Lesion} - \text{Background}}{\text{Lesion} + \text{Background}}, \]

where Lesion was the maximum hot lesion value or the minimum cold lesion value, Background was the image value at the center of the large sphere.

In Case 1 of radius of rotation being 30 units, the regular-sized pixel configuration gave the contrast of the large hot lesion as 0.3401 and the contrast of the large cold lesion as 1.0603. For the small pixel configuration, the contrast of the large hot lesion was 0.3451, and the contrast of the large cold lesion was 1.1050. The true contrast of the hot lesion should be 0.33 and the true contrast of the cold lesion should be 1.

In Case 2 of radius of rotation being 47.5 units, the regular-sized pixel configuration gave the contrast of the large hot lesion as 0.3079 and the contrast of the large cold lesion as 0.8014. For the small pixel configuration, the contrast of the large hot lesion was 0.3246, and the contrast of the large cold lesion was 0.9119. The true contrast of the hot
lesion should be 0.33 and the true contrast of the cold lesion should be 1. It is shown that a smaller radius of rotation gave a better image contrast and spatial resolution. It is also observed that the small-pixel configuration gave better contrast and spatial resolution than the regular-pixel configuration.

Figures 11 and 12 show the reconstruction results (three orthogonal central slices) from the noisy projection data for radii of rotation being 30 and 47.5 units, respectively. The smallest hot and cold lesion are no longer visible. A uniform 20×20×20 region at the center of the phantom was selected to evaluate the noise variance in the reconstructions. Twenty noise realizations were used to evaluate the variance and the mean in this cubic region. In Case 1 of radius of rotation being 30 units, the regular-sized pixel configuration had the normalized standard deviation (i.e., the square root of the variance divided by the mean) of 0.2601, and the small-pixel configuration had the normalized standard deviation of 0.2771. In Case 2 of radius of rotation being 47.5 units, the regular-sized pixel configuration had the normalized standard deviation of 0.2602, and the small-pixel configuration had
the normalized standard deviation of 0.2755. It is observed that the small-pixel configuration generated images that were a little noisier than those generated by the regular pixel configuration.

B. Phantom experiments

A Philip’s AXIS™ two-detector SPECT system was modified such that detector 1 was replaced by a prototype spinning CdZnTe camera while detector 2 remained as the NaI(Tl) camera. The detection area of the CdZnTe camera was $5.3 \times 34.5 = 182.85 \text{ cm}^2$, and the detection area of the NaI(Tl) camera was $39.4 \times 53.3 = 2100.02 \text{ cm}^2$. The detection area of the NaI(Tl) camera was 11.5 times the detection area of the CdZnTe camera. A low-energy-high-resolution parallel-hole collimator was mounted on the large NaI(Tl) detector, and the system spatial resolution (FWHM) at 10 cm was 7 mm. A parallel slat collimator was mounted on the small CdZnTe detector. There were two small detection pixels between adjacent slats. The slat height $L$ was 4 cm, and system spatial resolution (FWHM) was 14 mm at 10 cm away from the detector. A torso-shaped International Electrotechnical Commission (IEC) phantom (shown in Fig. 13) was used in the experiments. The phantom contained 4 hot and 2 cold spherical lesions. The inner diameters of the spheres were 1, 1.3, 1.7, 2.2, 2.8, and 3.7 cm, respectively. The length of the phantom was 18 cm. The phantom had a torso shape and was about 25 cm wide. Both the detector heads followed a same noncircular body-contour orbit. The distance from the axis-of-rotation to the imaging plane varied from 15.57 to 24.22 cm. The phantom was filled with 26 mCi of Tc-99m. No activity was in the cold lesions. The activity ratio of the hot lesions to the background was 8:1. Both detectors rotated around the phantom simultaneously for 40 minutes. There were 120 steps over 360° SPECT angles. The CdZnTe detector spun continuously, and the projection data were binned into 256 angles over 180° of spin.
angles. The CdZnTe camera had 192 small detection pixels, and the pixel size was 1.8 mm. The projection data from the NaI(Tl) detector were acquired in 256×256 arrays with a pixel size of 2.3 mm. The collimator slab has a rectangular shape with two round corners as shown in Fig. 2.

In the phantom experiments, we used a 15% energy window, centered at 140 keV, for both NaI(Tl) and CZT detectors. These two 15% energy windows have different effects for NaI and CZT cameras. Let us assume the NaI camera has 9% energy resolution and the CZT camera has 3% energy resolution at 140 keV. A 15% energy window of a NaI camera could accept photons with an actual energy window of 33%. On the other hand, a 15% energy window of a CZT camera could accept photons with an actual energy window of 21%. The CZT camera has a narrower actual energy window.

A standard 2D filtered backprojection algorithm was used to reconstruct the image from the NaI(Tl) detector, and this image served as the gold standard for other comparisons. The analytical algorithm presented in Sec. II C was used to reconstruct the image using the data with the small-pixel configuration of the CdZnTe detector. Next, the detector pixel values between adjacent slats were combined, forming regular-sized CdZnTe pixel configuration data. Figure 11.
shows a photograph of the IEC phantom, and a slice of the reconstruction by each of the three methods. No attenuation corrections or scatter corrections were performed. The same 3D post low-pass filter was applied to all reconstructed images.

The contrast was also evaluated for the reconstructions in these phantom experiments, for the largest hot and cold lesions. Fourteen voxels were selected in the largest hot lesion, largest cold lesion, and background, respectively. An averaged value was calculated from each set of the 14 voxel values. Then the contrast was evaluated according to Eq. (15). For the regular-sized pixel configuration, the contrast of the largest hot lesion was 0.38, and the contrast of the largest cold lesion was 0.49. For the small pixel configuration, the contrast of the largest hot lesion was 1.49, and the contrast of the largest cold lesion was 0.91. For the gold standard NaI(Tl) data reconstruction, the contrast of the largest hot lesion was 0.51, and the contrast of the largest cold lesion was 0.30. According to the injected activities, the true contrast of the hot lesion should be 0.78 and the true contrast of the cold lesion should be 1.

IV. DISCUSSION

This paper investigated the use of a small CdZnTe camera to image an object with the same size of field-of-view as a large NaI(Tl) camera. This is achieved by making the detector in a narrow-and-long strip shape and by using a parallel slat collimator. In a conventional design of a gamma camera with a parallel slat collimator, usually there is a single detection pixel between two adjacent slats. The image reconstruction is obtained via the 3D Radon inversion algorithm, which assumes that the projection data are unweighted planar integrals. This paper investigates that if a regular-sized detection pixel is replaced by two smaller pixels, the image spatial resolution and contrast may be improved with the same photon counts. A reconstruction algorithm is suggested by observing that the two adjacent small pixels measures gamma photons with different, asymmetric beam forms. The finite difference of the data can be approximately treated as an "angular derivative" [see Eq. (3)] which helps to compensate for the distance-dependent $1/r$ factor in the data.

Equation (3) is valid only for the special case of $\alpha=0$. The general case where $\alpha$ does not need to be 0 is considered in Ref. 10, and the result is as follows: Let $l(\xi) = \int_0^\infty f_p(r, \xi) (\cos \alpha) rdr$, then we have $dg(x)/dl|_{x=0} = \cos^2 \alpha dh(\xi)/dl|_{\xi=m2}$ because $d\xi = \cos \alpha d\xi$. The purpose of presenting Eq. (3) in this manuscript is to illustrate the idea that taking the angular derivative is able to remove the effect of the weighting factor $1/r$. We still do not have an exact method to compensate for the $\cos \alpha$ effect. After taking the angular derivative, the factor $\cos \alpha$ becomes $\cos^2 \alpha$ and this makes the approximate algorithm less accurate. We believe...
that the \( \cos \alpha \) factor in the data must be properly compensated for in order to derive an exact reconstruction algorithm.

This algorithm is inspired by our previous publication,\(^{10}\) where the collimator consists of a set of slightly tilted parallel slats. Our current small-pixel configuration has an advantage over our previous tilted slat configuration: The tilted slat configuration requires a 360° spinning at each SPECT view, while the small-pixel configuration does not need this tilt angle and the detector only needs to spin 180° at each SPECT view. This is important because for a given imaging time at each SPECT angle, a larger angular spinning range requires higher angular spinning speed of the detector and causes larger angular blurring.

In our phantom experiments, the detection area of the NaI\(^{\text{Tl}}\) camera is 11.5 times larger than the detection area of the CdZnTe camera. In agreement with this, the phantom experiments show that the images from the CdZnTe camera are noisier than the images from the NaI(Tl) camera. This implies that our prototype CdZnTe detector may be too small in order to compete with large conventional NaI(Tl) cameras. However, the CdZnTe system provides better image contrast than the NaI(Tl) system, especially for the cold lesions. This could be credited to the better energy resolution of the CdZnTe detector than the NaI(Tl) detector. Comparing the two configurations of the CdZnTe camera, they both use the same parallel slat collimator, and thus they acquire the same number of gamma-ray photons. However, the beam forms of the incoming photons are different; the beam forms are asymmetric for the small pixel configuration. Different algorithms are used to reconstruct the images from these two configurations. These two algorithms are approximate methods. None of them are able to correct for attenuation effects. None of them can exactly compensate for the weighting function, which is approximated as \( \cos \alpha / r \), in the measurements. However, the algorithm derived for the small-pixel configuration is able to compensate for the \( 1/r \) factor. We must point out that the weighting factor \( \cos \alpha / r \) has a mixed effect on the reconstructed images. The \( 1/r \) factor tends to make the center of the object darker, while the \( \cos \alpha \) tends to make the edges darker. We also ran some computer simulations with the weighting factor \( 1/r \) with reconstruction profiles shown in Fig. 14, similar to the profiles in Fig. 10. We observe that, with or without the \( \cos \alpha \) factor imbedded in the projection data, the small-pixel configuration gives better spatial resolution than the regular pixel configuration.

The computer simulation and phantom experiment results show that the CdZnTe camera images have a better contrast than the NaI(Tl) camera images, especially for the cold lesions. The CdZnTe small-pixel configuration images have better contrast and spatial resolution than the CdZnTe regular-sized pixel configuration images.

Our main goal of using a smaller detector pixel size is not to obtain a higher spatial resolution, but to make the data acquisition and hardware design much easier. However, it is observed via computer simulations and phantom experiments that the small-pixel configuration provides better spatial resolution than the regular pixel configuration. The image resolution is mainly determined by the gap and length ratio of the slat collimator, similar to the hole-size and hole-length ratio in the case of a parallel-hole collimator. One may ask: “Should collimators be designed with one or two pixels between slats?” Our answer is Two. This design gives many options for imaging reconstruction. By having two pixels between the slats, some extra tomographic information can be obtained and used for image reconstruction. If one prefers using the conventional design of one pixel between the slats, one can simply sum the projection data obtained from these two pixels.

ACKNOWLEDGMENT

This work was supported in part by NIH Grant Nos. R33 EB001489 and R21 EB003298, and by Philips Medical Systems, Inc.


