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CdZnTe strip detector SPECT imaging with a slit collimator

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Abstract
In this paper, we propose a CdZnTe rotating and spinning gamma camera attached with a slit collimator. This imaging system acquires convergent planar integrals of a radioactive distribution. Two analytical image reconstruction algorithms are proposed. Preliminary phantom studies show that our small CdZnTe camera with a slit collimator outperforms a larger NaI(Tl) camera with a pinhole collimator in terms of spatial resolution in the reconstructed images. The main application of this system is small animal SPECT imaging.

1. Introduction

The Anger camera has been the most widely used camera in SPECT (single photon emission computed tomography) since its invention in 1958 (Anger 1984). The Anger camera includes a NaI(Tl) scintillation crystal that is viewed by an array of photomultiplier tubes. A collimator, which includes a grid- or honeycomb-like array of radiation absorbent material, is located between the scintillation crystal and the patient. The collimator limits the angle of acceptance of radiation to be received by the scintillation crystal. The outputs of the photomultiplier tubes are processed and corrected to generate an output signal indicative of the position and energy of the detected radiation. The collected radiation data are then used to reconstruct an image that represents a region of interest. Parallel-hole collimators are routinely used in SPECT scans. Pinhole collimators are best used for very small objects (e.g., thyroid) placed close to the pinhole. Recently pinhole collimator SPECT imaging has received a lot of attention in small animal imaging.

One drawback of using a NaI(Tl) scintillator is its poor energy resolution. The advantage of using a solid-state detector is the excellent energy resolution and direct gamma-ray conversion without using photomultiplier tubes. The superior energy resolution of semiconductors comes from the fact that it takes only 3–6 eV to produce an electron–hole
pair in a semiconductor detector, compared to approximately 30 eV to produce a photon in a NaI(Tl) scintillator, and only around 30% of the scintillating photons reach the photomultiplier tube. A cadmium telluride (CdTe) detector gamma camera was developed as early as 1979 (Mauderli et al 1979, Entine et al 1979). This device included a linear array of CdTe detectors separated by tungsten plates, and it had a square (approximately 4 cm × 4 cm) active area.

Solid-state cameras were also reported using germanium crystals (Urie et al 1981, Mauderli et al 1981, Malm et al 1982, Mauderli and Fitzgerald 1987). A typical design used an 11.5 mm thick, 45 mm × 45 mm segmented germanium detector placed behind parallel tungsten plates oriented perpendicular to the face of the detector. The crystal was segmented to form a plurality of channels, with the plates aligned with the segmentations. A 4.5 cm diameter viewing aperture was located between the detector and the activity source. Projection data acquired at multiple angular orientations while the detector–collimator assembly was rotated about its centre were mathematically processed to reconstruct a two-dimensional image of the activity distribution.

For most medical applications, it would be desirable to have a detector with good energy resolution so that events which have undergone Compton scattering in the patient can be rejected. The semiconductor detector with the best energy resolution is germanium (0.54% full-width at half-maximum (FWHM) at 140 keV), but the germanium detector operates at cryogenic temperatures. Other semiconductor detectors such as HgI₂, CdTe and CdZnTe operate at room temperature. The targeted energy resolution for CdZnTe is less than 4% at 140 keV while it is between 9% and 10% for a NaI(Tl) scintillator. Thus CdZnTe is a medium-quality, room-temperature semiconductor detector. CdZnTe semiconductor chips have been used to build a gamma-ray detector (Matherson et al 1998, Butler et al 1998). Considerable effort is now being devoted to improving the yield of this material so that it can be grown in large quantities and thus allow for production of inexpensive detectors.

In addition to excellent energy resolution, another advantage of a solid-state detector is its compact size. A solid-state gamma camera can be made small, lightweight and portable, as opposed to the bulky Anger camera. In fact, Digirad Corporation, San Diego, California, has commercialized this small camera. A version of Digirad 2020tc Imager™, with an active imaging area of 20 cm × 20 cm and with a traditional parallel-hole collimator attached, weighs approximately 50 pounds. The imaging head is made up of 64 closely packed ‘imaging modules’, each with an area dimensional of 2.5 cm × 2.5 cm and a thickness of 1.2 cm. Each module contains an 8 × 8 element CdZnTe detector array and microelectronics (Butler et al 1998).

For 40 years, all SPECT imaging has been done using Anger scintillation cameras, and incremental improvements have been made over the years. It seems that scintillation cameras have reached their limits. It is important to advance to the next generation of gamma camera and make semiconductor gamma cameras practical. In a typical SPECT study, the energy resolution is approximately 10% at 140 keV. Our strip solid-state camera is able to obtain an energy resolution of 3.6% at 140 keV (Griesmer et al 2001). The CdZnTe detector has an excellent energy resolution, which is the main reason that we choose to use CdZnTe detector over the traditional NaI(Tl) detector in our gamma camera. With significantly reduced scattering by using the CdZnTe detector, some small lesions can be detected with the proposed solid-state camera while they may not be detected with an Anger camera.

Recently Digirad decided to stop using the CdZnTe partially because of the cost consideration. Instead, they use a combination of a Cs(Tl) scintillator and a photodiode to receive and convert gamma rays into electric signal. Nonetheless, research on the CdZnTe camera is still very active because it has great potential (Matherson et al 1988). Extensive research on the CdZnTe detector in Arizona University has resulted in an excellent spatial

This research is directed towards building a small animal SPECT imager using a CdZnTe detector and a slit collimator to achieve both high spatial resolution and excellent energy resolution (Gagnon et al 2001). The idea of using a slit collimator was inspired by the recent applications of pinhole collimators in small animal SPECT imaging (Weber et al 1994, Jaszczak et al 1994, Habraken et al 2001, McElroy et al 2002, Meikle et al 2002, Wilson et al 2002, Tsui et al 2002, Smith et al 2002, Wu et al 2002, Beque et al 2003, Schramm et al 2003, Song et al 2003). With a pinhole collimator, the image spatial resolution depends on both the pinhole size and the image magnification factor due to the imaging geometry. A larger detector size can provide a larger image magnification factor by placing the object closer to the pinhole. A strip detector, instead of a conventional square or circular detector, is able to obtain a relatively better spatial resolution than the square or circular detector with the same detection area. Instead of using a pinhole collimator, a slit collimator is mounted in front of the detector (see figure 1). A slit collimator can accept much more photons than a pinhole collimator can. This set-up results in a cost-effective, high-resolution CdZnTe gamma camera for small animal imaging. During data acquisition, the detector spins around its own axis while rotating about the object. The measurements are weighted planar integrals of the object.

Some preliminary investigations of slit collimators have been performed in the early 1980s (Kujoory et al 1980, Gindi et al 1982). Similar ideas have also been used in astronomy telescope and x-ray CT (Touma 1993, Rudin 1980). In some papers the term ‘slit-collimator’ is mentioned, but they actually mean a collimator made of a set of parallel blades (Keyes 1975, Webb et al 1992, 1993).

2. Methods

In this section, we discuss a strategy to achieve a high spatial resolution, the trade-off of system sensitivity (i.e., detection efficiency) and the spatial resolution, and analytic image reconstruction algorithms.
The idea of using a pinhole collimator to achieve a high spatial resolution is extended to using a slit collimator in this paper. A main feature of our camera is its long-and-narrow strip-shaped, instead of the conventional square shape. The advantage of using a strip-shaped camera will become clear at the end of this section.

2.1. Spatial resolution of a slit collimator

Figure 2 illustrates cross-cut side views of a slit collimator. At view (a), the slit collimator looks similar to a pinhole collimator. The image spatial resolution, characterized by FWHM, is illustrated in figure 2(c) and given by

\[
r = d \left(1 + \frac{D}{F}\right)
\]  

(1)
where $F$ is the focal length of the slit collimator, $d$ the width of the slit, and $D$ the distance from the object to the slit. Relationship (1) is obtained by considering two similar triangles shown in figure 2(c). Here the resolution, $r$, is the best possible reconstructed image resolution, assuming that the detector has a perfect spatial resolution and the data are noise free.

The resolution in terms of FWHM value projected on the detector is scaled up by the slit geometry magnification factor $F/D$, that is

$$R = r \frac{F}{D}.$$  

(2)

If the detector pixel size is set to, say, 1.8 mm, then the detector resolution is fixed at $R = 3.6$ mm, which is twice the pixel size according to the Nyquist sampling principle. In other words, the detector itself cannot resolve objects smaller than 3.6 mm. According to (2), we have a lower bound of the resolution in terms of FWHM value of the reconstructed image as

$$r \geq R \frac{D}{F} = 3.6 \frac{D}{F} \text{ (mm)}.$$  

(3)

If we ignore the effect of the measurement noise and reconstruction algorithm, the image spatial resolution is affected by the slit-width $d$ (see (1)) and by the detector resolution $R$ (see (3)).

If an imaging system consists of two sub-systems in series, the resolution in terms of FWHM of the overall system is related by the following square-sum law:

$$\text{FWHM}_{\text{Overall}}^2 = \text{FWHM}_{\text{System1}}^2 + \text{FWHM}_{\text{System2}}^2.$$  

(4)

Thus the overall image spatial resolution in terms of FWHM of our slit-collimator camera can be estimated as

$$r = \sqrt{\left[d \left(1 + \frac{D}{F}\right)\right]^2 + \left[\frac{R D}{F}\right]^2} = \frac{\sqrt{d^2(F + D)^2 + R^2 D^2}}{F}.$$  

(5)

A good resolution (i.e., small $r$) requires a large $F$ and a small $d$, a small $D$, and a small $R$. For example, if $F = 200$ mm, $D = 40$ mm, $d = 0.6$ mm, $R = 3.6$ mm, then the best possible image resolution calculated from (5) is $r = 0.82$ mm.

We also observe from (1) or (5) that a good spatial resolution can be achieved by using a long focal length $F$ and a short distance $D$. However, the focal length $F$ cannot be too large; a large $F$ results in a poor system detection sensitivity as will be shown in section 2.2.

### 2.2. System sensitivity

The system sensitivity (that is, detection efficiency) of a gamma camera is determined by the geometric efficiency, intrinsic efficiency and some other factors. The intrinsic efficiency refers to the efficiency with which the detector absorbs incident radiation events and converts them into potentially usable detector output signals. The intrinsic efficiency depends on the detector material and photon energy. For detectors of similar thickness, the CdZnTe detectors have somewhat greater intrinsic efficiency than the NaI(Tl) detectors (Cherry et al. 2003). The thickness of our CdZnTe detector is 5 mm, and it is only used for low-energy imaging.

The geometric efficiency is determined by the detection solid angle. In the strip detector geometry, the solid angle is composed of two angles $\alpha_1$ and $\alpha_2$ as shown in figure 3, where $\alpha_1$ is in the slit-normal direction and $\alpha_2$ is in the slit-linear direction. It is seen that $\alpha_1$ is inversely proportional to $D$ and $\alpha_2$ is inversely proportional to $D + F$. Thus the overall geometric efficiency is given as

$$\text{Efficiency} \propto \frac{1}{D(D + F)}.$$  

(6)
The detector’s geometric efficiency is determined by the detection solid angle, which is composed of angles $\alpha_1$ and $\alpha_2$.

and the system sensitivity is

$$\text{Sensitivity} \propto d \frac{1}{D(D+F)}.$$  (7)

From (7) one concludes that a good system detection sensitivity requires a small $D$, a small $F$ and a large $d$. On the other hand, (5) implies that a good system spatial resolution requires a small $d$, a small $D$, but a large $F$. Thus the selection of the slit width $d$ and the focal-length $F$ must consider the trade-off of the system sensitivity and spatial resolution. A small $D$ is always desired for both sensitivity and spatial resolution considerations. However, $D$ cannot be too small. The lower bound of distance $D$ is determined by the object size and the detector length $L$. A longer detector length $L$ allows a shorter distance $D$, still keeping the object within the detector’s field-of-view. This justifies that a strip-shaped detector can offer a better spatial resolution than a square-shaped detector, if these two detector areas are the same.

On the other hand, if a pinhole collimator with a square detector (i.e., $L = W$) is used, instead of using a slit collimator with a strip detector (i.e., $L \gg W$), the spatial resolution (FWHM) and sensitivity (geometric efficiency) can be estimated (Cherry et al. 2003) as

$$r_{\text{pinhole}} = d \left(1 + \frac{D}{F}\right) \quad \text{(assuming a perfect detector and perfect pinhole)}$$  (8)

$$\text{Sensitivity}_{\text{pinhole}} \propto d \frac{1}{D^2}.$$  (9)

Comparing the pinhole collimator with the slit collimator, we note that the spatial resolution relations (8) and (1) are the same, while (9) and (7) differ in estimating the sensitivity. A small $D$ is always desired for all cases. If the object size is $S$, to avoid measurement truncation, we must have

$$\frac{SF}{D} < L$$  (10)
where $F/D$ is the magnification factor for pinhole and slit-hole imaging geometries. If the focal-length $F$ is chosen to be the same for these two imaging geometries and the detection areas are kept the same, the $D$ value for the slit-hole/strip-detector configuration can be smaller than the $D$ value for the pinhole/square-detector configuration, because the $L$ value of the slit-hole/strip-detector configuration is larger than the $L$ value of the pinhole/square-detector configuration. As a result, the slit-hole/strip-detector configuration is able to provide better spatial resolution.

For example, in our prototype CdZnTe detector, $L_{\text{slit}} = 345$ mm and $W_{\text{slit}} = 53$ mm, and the detection area is $18,285$ mm$^2$. If a square detector were built with the same detection area, the side-length would be $L_{\text{square}} = \sqrt{18,285} = 135.22$ mm. The shortest $D$ value from (10) for the slit detector is $D_{\text{slit}} = SF/L_{\text{slit}}$, and for the square detector is $D_{\text{square}} = SF/L_{\text{square}}$. Using (1) and (8), for an object of a size $S = 70$ mm, the resolution ratio is

$$\frac{r_{\text{square}}}{r_{\text{slit}}} = \frac{1 + \frac{S}{L_{\text{square}}}}{1 + \frac{S}{L_{\text{slit}}}} = \frac{1 + \frac{70}{135.22}}{1 + \frac{70}{345}} = 1.26.$$  \hspace{1cm} (11)

In this example, there is a 26% improvement in spatial resolution by using a strip detector over a square detector.

2.3. Image reconstruction algorithms

Due to the nature of convergent beam measurements, the 3D image reconstruction cannot be decomposed into a series of 2D slice-by-slice image reconstruction. Two analytical reconstruction algorithms are proposed in this section.

2.3.1. Analytical algorithm I. The measurements of this imaging system are weighted planar integrals, instead of line integrals, because a 1D array of pixels is used on the CdZnTe detector. Assuming that the detector width is small, the weighting factor in the planar measurement can be approximated by

$$\text{factor} = \frac{\cos \alpha}{\rho} \sin \beta$$  \hspace{1cm} (12)

where $\rho$, $\alpha$ and $\beta$ are defined in figure 4. An empirical pre-scaling factor $|\sin \beta|^{3/2}$ has been chosen by trial-and-error with computer simulations, to make the reconstruction of a uniform sphere to be almost constant in the central image slice. The pre-scaling factor $|\sin \beta|^{3/2}$ is first applied to the projection measurements.
After this pre-scaling step, the data are assumed to be unweighted planar integrals (i.e., 3D Radon transform) of the object and we use the Radon inversion formula to reconstruct the image. Since in the 3D Radon inversion formula, the measurements are required to be parallel planar integrals and our data are convergent planar integrals, the next step is to resort the data into parallel planar integral format. An example of rebinning is illustrated in figure 5. We refer to this step as the rebinning step. The rebinning is performed for all possible directions in the 3D space. If the detector rotates around the object in a circular orbit, for some directions it is impossible to form a set of parallel planar measurements, simply because some measurements are not available. Unmeasured values are assumed to be zero in the rebinning step.

The well-known Radon inversion formula is now ready to be applied to the rebinned data for image reconstruction (Deans 1983):

\[
f(\bar{x}) = -\frac{1}{8\pi^2} \int \int_{S^2} P''(t_{1,\bar{x},\bar{\theta}}) \, d\bar{\theta}
\]

where the image \( f(\bar{x}) \) is the backprojection of the second derivatives of parallel Radon data \( P(t) \) over the unit sphere \( S^2 \).

This algorithm is not exact when applied to the measurements acquired from a slit collimator imaging geometry, because after the pre-scaling using a factor \( |\sin \beta|^{3/2} \) the scaled planar integrals are still not unweighted planar integrals, while the Radon inversion formula is exact only for unweighted planar integral measurements.
2.3.2. Analytical algorithm II. Analytical algorithm I mentioned above is essentially the 3D Radon inversion algorithm with a pre-scaling step and a convergent-to-parallel geometrical rebinning step. Another possible reconstruction method is to modify a cone-beam image reconstruction algorithm, for example, Grangeat’s algorithm (Grangeat 1991). The resultant convergent slit algorithm is as follows.

First, the projection data are first scaled by pre-scaling factor $|\sin \beta|^{-5/4}$, which have been selected by trial-and-error using computer simulations, to make the reconstruction of a uniform sphere to be almost constant in the central image slice. This step is similar to that in analytical algorithm I except that a different pre-scaling factor is used.

Second, a derivative is taken along the 1D detection array for each angular position. Analytical algorithm I does not have this step.

Third, the data are rebinned from the convergent format into parallel format. The rebinning procedure is the same as in analytical algorithm I.

**Figure 6.** Computer simulation set-up and computer generated phantom used for simulations: a large sphere containing four smaller cold spherical lesions. The centres of the lesions are on the $x$ and $y$ axes, and $12.6$ mm away from the centre of the large sphere (i.e., the origin). The intensity ratio is 2.1; the large sphere has a higher intensity.
3. Computer simulation and phantom experiment

3.1. Computer simulations

In computer simulations, a spherical phantom as shown in figure 6 was used. The diameter of the large sphere was 50.4 mm. The diameters of the four smaller cold spheres were 12.6, 9, 5.4 and 1.8 mm, respectively. The centres of the four cold spheres were on the detector orbit plane. The activity in the large sphere was 10. The smaller spheres had an activity density of 5. The detector pixel size was 1.8 mm, and there were 192 pixels on the detector. The distance from the slit to the detector (i.e., the focal length \( F \)) was 200 mm. The distance between the slit and the axis of rotation (\( \phi \)) was 40 mm.

During data acquisition, there were 128 views for spinning angle \( \theta \) over 360°, and there were 120 SPECT-views for rotation angle \( \phi \) over 360°. The \( \cos \alpha \sin \beta / \rho \) weighting factor was included in projection data generation; however, no attenuation or scatter was included.

Forth, at each angular direction a derivative is taken for the rebinned data. On the other hand, a second-order derivative is taken in algorithm I.

The final step is backprojection, similar to that in (13). Neither algorithm I nor algorithm II is exact reconstruction algorithm. As will be demonstrated in computer simulations, algorithm II gives a more accurate reconstruction than algorithm I.
in projection data generation. A perfect slit was assumed, that is, \( d \) was arbitrarily small.

Two data sets were generated. One projection data set was noiseless, while Poisson noise was added in the second projection data set. The image was reconstructed in a 192 \( \times \) 192 \( \times \) 192 array.

The reconstruction results with noiseless data are shown in figure 7. The reconstruction results with noisy data are shown in figure 8. The computer reconstruction code was written in IDL, which is an interactive data language developed by Research Systems, Inc., Boulder, Colorado, USA. The backprojection step was implemented using Marr’s fast backprojection method (Marr et al 1980).

The profiles in figure 7 are drawn along the \( y \)-axis in each reconstructed image volume, and they illustrate that the analytical algorithm II gives a more accurate reconstruction than algorithm I. The \( z \)-direction blurring and distortion are mainly caused by the incomplete data acquired by a circular (SPECT rotation) orbit. This circular orbit can only provide sufficient data for the region close to the orbit plane.

### 3.2. Phantom experiments

A prototype CdZnTe gamma camera with a slit collimator was built by Philips Medical Systems in Cleveland. An AXIS\textsuperscript{TM} two-detector system was modified, and head no. 1 was replaced with a spinning CdZnTe camera. The other head (i.e., head no. 2) was unchanged and remained to be a NaI(Tl) detector (see figure 9(a)). The NaI(Tl) head was mounted with a pinhole collimator, with a pinhole diameter of 1 mm. The distance from the pinhole to the detector was 16 cm. The CdZnTe head was mounted with a slit collimator, with a slit width of 0.6 mm and a slit length of 130 mm. The distance from the slit to the detector was 17.5 cm. The gantry rotated around 360° with 120 stops. Imaging time at each stop was 60 s and the
total imaging time was 2 h. The CdZnTe detector/collimator unit continuously span and the projection data were binned into 512 spin angles at each stop. The CdZnTe detector had 192 pixels and the pixel width was 1.8 mm. A 512 × 512 matrix was used to store projection data for the NaI(Tl)/pinhole imaging configuration, and the detector pixel width was 1.17 mm.

The projection data sets for both imaging detectors were acquired simultaneously with the identical scanning time. The detection area of the CdZnTe detector was 34.5 cm × 5.3 cm = 182.85 cm². The detection area for the NaI(Tl) detector was 54 cm × 40 cm = 2160 cm². The NaI(Tl) was about 12 times larger than the CdZnTe detector. During the 2 h scan, the CdZnTe detector collected 6.99 × 10⁸ photon counts and the NaI(Tl) collected 1.25 × 10⁷ photon counts. The slit (slit width = 0.6 mm) configuration had 56 more counts than the pinhole (pinhole diameter = 1 mm) configuration. The slit configuration could collect even more photons if the slit width were 1 mm wide.

A micro Deluxe Phantom™ (Data Spectrum Corporation, Hillsborough, NC, USA) was used in the phantom experiment. The phantom had an outside diameter of 5 cm, and contained six sections of small cold rods with diameters: 1.2, 1.6, 2.4, 3.2, 4.0 and 4.8 mm, respectively (see figure 10(a)). The height of the rods was 3.4 cm. The phantom was filled with 29 mCi (1.073 GBq) of Tc-99m. The phantom was positioned such that the distance between the phantom and the collimators was made as small as possible before data truncation occurred.
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Figure 10. (a) Micro Deluxe Phantom\textsuperscript{TM} with cold rods. The rod diameters: 1.2, 1.6, 2.4, 3.2, 4.0 and 4.8 mm. (b) Reconstructed image from the CdZnTe detector with a slit collimator. (c) Reconstructed image from the NaI(Tl) detector with a pinhole collimator.

For both collimator geometries if the distance is too small, the projection data are truncated because of the finite detector size.

For the CdZnTe/slit data, image was reconstructed by analytical algorithm II as presented in section 2.3.2. The code was identical with that for computer simulations, and the reconstruction time was 2.5 min on a laptop Compaq PC (2.4 GHz, 1 GB RAM). For the NaI(Tl)/pinhole data, image was reconstructed by well-known Feldkemp’s cone-beam algorithm \cite{Feldkamp1984}. The images reconstructed from the CdZnTe/slit data and NaI(Tl)/pinhole data are shown in figures 10(b) and (c), respectively. Due to the noise, none of these imaging systems were able to reach their best possible theoretical spatial resolution as predicted in (1) and (8). From figure 10, it is clear that the CdZnTe/slit system outperformed the NaI(Tl)/pinhole system, even though the NaI(Tl) was about 12 times larger than the CdZnTe detector.

4. Discussion

The CdZnTe detector has an excellent energy resolution, and this is the main reason that we chose to use CdZnTe detector over the traditional NaI(Tl) detector in our gamma camera. The proposed imaging system with a slit collimator has many advantages over the system of a square detector mounted with a pinhole collimator. First, a slit collimator accepts more photon counts than a pinhole collimator. Second, for the same detector area and pixel size, a longer detector allows a larger number of pixels in one dimension, thus resulting in a higher spatial resolution for the final reconstructed image.
Similar to the situation with the pinhole collimator, a rotating slit collimator does not measure a complete data set when the detector rotates in a circular (planar) orbit. Imaging geometries that can provide a complete data set as well as multi-slit imaging geometries are under investigation and will be reported in future publications.

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