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Design Studies of a CZT-based Detector Combined with a Pixel-Geometry-Matching Collimator for SPECT Imaging

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Abstract

Single Photon Emission Computed Tomography (SPECT) suffers limited efficiency due to the need for collimators. Collimator properties largely decide the data statistics and image quality. Various materials and configurations of collimators have been investigated in many years. The main thrust of our study is to evaluate the design of pixel-geometry-matching collimators to investigate their potential performances using Geant4 Monte Carlo simulations. Here, a pixel-geometry-matching collimator is defined as a collimator which is divided into the same number of pixels as the detector's and the center of each pixel in the collimator is a one-to-one correspondence to that in the detector. The detector is made of Cadmium Zinc Telluride (CZT), which is one of the most promising materials for applications to detect hard X-rays and γ -rays due to its ability to obtain good energy resolution and high light output at room temperature. For our current project, we have designed a large-area, CZT-based gamma camera (20.192 cm $\times$ 20.192 cm) with a small pixel pitch (1.60 mm). The detector is pixelated and hence the intrinsic resolution can be as small as the size of the pixel. Materials of collimator, collimator hole geometry, detection efficiency, and spatial resolution of the CZT detector combined with the pixel-matching collimator were calculated and analyzed under different conditions. From the simulation studies, we found that such a camera using rectangular holes has promising imaging characteristics in terms of spatial resolution, detection efficiency, and energy resolution.

Index Terms

CZT; pixel-geometry-matching collimator; spatial resolution; detection efficiency; deposited energy resolution; energy spectra

I. Introduction

The technology for gamma camera or SPECT has not changed much since it was first developed by Hal O. Anger. The basic components of scintillation crystal combined with photodetectors such as photomultiplier tubes are still largely used in clinical research. In fact, this implies that the technology is mature and robust. However, there have been longstanding developments of novel gamma camera technologies, most notably solid-state detectors employing direct-conversion materials such as cadmium zinc telluride (CZT) or cadmium telluride (CdTe). Although there have been limited efforts of commercializing CZT gamma cameras, none of the currently studied or available CZT-based gamma cameras offer sufficiently large detection areas to be used for multiple clinical applications. Simulated results indicated that using large collimator holes improved SPECT detection efficiency but the image resolution declined [1]. To solve this drawback, for our current project, we have designed a large-area (the largest, to our knowledge), CZT-based gamma camera (20.192 cm×20.192 cm) with a small pixel pitch (1.60 mm) and a thickness of 0.5 cm [thinner than typical NaI crystal (0.95 cm) for SPECT imaging]. The improvement of the spatial resolution in the pixelated detector due to the small size of the pixels was previously demonstrated [2]. In addition, we are developing a completely new application specific integrated circuit (ASIC) electronics for this camera. Furthermore, in order to expand the potential applications of this camera design, our goal is to design collimators that are minimally dependent on energies of gamma emissions from SPECT radiopharmaceuticals, taking advantage of superior energy resolution of CZT detectors and carefully designed collimators using high-density materials.

The main objective of designing the collimator is to test and verify the underlying improvement of the large detector performance by using the pixel-geometry-matching collimator technology. In this report, we show the results of Monte Carlo simulation studies for spatial resolution, detection efficiency, and energy resolution of the proposed collimator-detector system in various settings of design parameters.

II. Simulations of a pixel-geometry-matching collimator

In order to compare the variables of the collimator geometries (the shape of collimator holes, diameter and length, material), we employed Geant4, a Monte Carlo simulation toolkit to fully simulate the CZT detectors and collimators. Monte Carlo simulations provide means of conveniently analyzing the resolution and efficiency of the gamma cameras as well as optimizing the SPECT systems design by changing the various related parameters.

Geant4-based codes were developed to assess the potential use of pixel-geometry-matching collimators. The physics list we used was the Low Energy Electromagnetic Physics, and Livermore was chosen as the physics model whose validated energy range is 250 eV-100 GeV. The physics processes considered for gamma-ray photons include photoelectric effect, Compton scattering and Rayleigh scattering while pair production was not used because the energies of gamma ray photons for SPECT radiopharmaceuticals are too low to produce this interaction. In order to record information from the simulations, the detector was made to be sensitive to all of the particles which meant that we could register data as desired. To

balance the speed of the simulation and the accuracy of the results, different thresholds for secondary production have been set in various regions. The model of the gamma camera simulated for our studies is shown in Fig. 1.

A. Detector Model

There are many properties that can weigh the quality of a detector among which the detection efficiency, spatial resolution and energy resolution are the most important. In general, the spatial resolution degrades when the detection efficiency improves. When compared to traditional scintillation-based indirect radiation detectors, CZT detectors, without the need for complex and expensive cooling device, provide superior radiation detection and energy resolution by directly converting photons absorbed to charges. The dimension of the CZT detector that is being currently built for our project is 20.192 cm×20.192 cm×0.5 cm (thickness) in 8×8 modules of 16×16 pixelated detectors yielding a total of 128×128 detector pixels.

B. Collimator Model

The pixel-geometry-matching collimator can be constructed similarly as long as the number of pixels is 128×128 and the center of each pixel is a one-to-one correspondence to the detector; that is, the collimator's hole size is matched to one detector pixel. The design of the collimator was characterized by the hole diameter, length, shape, material, and septal thickness. The variables and definitions of the detector and the collimator are listed in Table I.

III. Methods

The SPECT detector performance was evaluated here using spatial resolution, detection efficiency, deposited energy resolution and energy spectra.

A. Spatial resolution

The spatial resolution (denoted by R_{spa}) of the parallel-hole collimator is mainly dependent on the collimator features and the distance from the source to its surface as well as intrinsic resolution. To obtain the optimized collimator designs, the spatial resolution was calculated with a variety of collimator constructions.

1) Intrinsic resolution—The spatial resolution in gamma camera imaging is rather poor than other radiological facilities because of the limit of the intrinsic resolution (denoted by R_{int}) [3]. Due to the pixelated semiconductor detector we simulated with 128×128 pixels [(0.139 cm × 0.139 cm)/pixel], the particles are individually collected for each pixel, thus, the intrinsic resolution is almost equal to the size of the pixel pitch [2].

2) Collimator resolution—Collimator resolution (denoted by R_{col}), also an important index to determine the quality of the spatial resolution, describes the ability of the collimator to localize the gamma ray source. For a high resolution, the collimator holes need to be as long and narrow and the distance should be as short as possible. The collimator resolution can be calculated as follows [3]:

$$R_{col} = \frac{D}{L_{eff}} \times (S_0 + L_{eff})$$

Where L_{eff} is the effective length of the collimator, it equals to $L - 2/\mu$, μ represents the linear attenuation coefficient.

3) Spatial resolution—The scatter and septal penetration have contributions to the spatial resolution as well. To simplify the calculation, we only took the intrinsic and collimator resolution into consideration. Therefore, the theoretical spatial resolution can be calculated as [4]:

$$R_{spa} = \sqrt{R_{int}^2 + R_{col}^2}$$

B. Detection efficiency

Detection efficiency is defined as the probability that particles or photons emitted by a source will be detected, namely, the number of photons reaching the detector per emitted particle. Either a smaller hole diameter or a longer hole length of the collimator can lead to a worse detection efficiency. The efficiency [3] can be estimated by:

$$E_{eff} = \frac{\text{No. of radiations interacting with detector}}{\text{No. of radiations emitted by a source}}$$

C. Deposited energy resolution

With Geant4, the deposited energy in the CZT-based detector can be recorded and the interactions localized expediently. Deposited energy resolution is defined as the FWHM of a point- or line-spread function (PSF or LSF respectively) projected by the collimator onto the detector. The total deposited energy within a pixel can reflect the ability of a detector to respond to each interaction [5].

D. Energy spectrum

The distribution of the energy detected after each event is determined by smearing using a Gaussian probability distribution with a specified FWHM [6]. The FWHM, defined as the energy resolution and equal to the minimum difference of energy between particles or photons which is just sufficient to differentiate energy levels, is a useful measure of the detector. Usually, the energy resolution of NaI crystals is much worse than CZT semiconductor [7][8].

IV. Results and Discussion

A. Collimator resolution and Detection efficiency

Collimator hole diameter and length as well as the distance from the collimator surface strongly affect the collimator resolution and detection efficiency. For reference, the spatial

resolution and detection efficiency of the parallel-hole collimator with D of 1.29 mm and L of 25 mm, hole type of rectangle, circle, hexagon, are shown in Fig. 3 at intervals of 5 cm of S_0 from 0 cm to 30 cm. The number of photons emitted from a ^{99m}Tc point source is 10 million.

In Fig. 2, the detection efficiency and the spatial resolution decrease as the distance from the collimator surface increases. When L changes from 10 mm to 20 mm, the spatial resolution increases 120.097% but the detection efficiency decreases 239.17%. The amplification of the spatial resolution and the deflation of the detection efficiency are not obvious as L is larger than 20 mm. If the collimator has D of 1.0 mm and L 20 mm, the spatial resolution becomes 6.1834 mm FWHM at a distance of 10 cm from the surface of the collimator, while the FWHM of the typical Siemens high-resolution collimator with D of 1.11 mm and L of 24.05 mm is 7.4 mm [1] at the same distance.

B. Deposited energy resolution

The interaction depth is parallel to the z coordinate in our simulation. The energy deposited in the CZT detector within a pixel is projected to the x coordinate and x - y plane at 13 cm distance from the source to the collimator with $L = 20$ cm and $D = 1.09$ mm. Different shapes of the collimator holes and materials of the detector are compared using 20 million events each.

Fig. 3 shows the projection images on the x - y plane with different materials and hole types of the collimators. Rectangular holes provided 21.53% higher detection efficiency but a 10.07% lower spatial resolution than circular holes did at the same radius averagely. The lead-based collimators are more blurred and have more noise compared with the tungsten-based ones. Fig. 4 shows the tails outside the PSF peak at 122 keV of ^{57}Co simulated with lead material are more serious due to the multiple Compton scattering between the particles and the holes with respect to tungsten material [9]. The FWHM of the deposited energy for tungsten-based and lead-based collimators with the two types of holes are showed in Table II respectively. From Table II, we came to the conclusion that tungsten material is a better choice than lead as far as the FWHM of the deposited energy is concerned because of its higher linear attenuation coefficient.

C. Energy spectra

The energy spectra were simulated with ^{57}Co and ^{111}In point sources located at 15 cm on the center axis of the FOV from the collimated detector face. D is 1.09 mm and L is 20mm for the tungsten-based collimator. The material changes from CZT semiconductor to NaI scintillator. The total number of events which are emitted isotropically from a ^{57}Co and an ^{111}In radioactive source, are 100 million and 10 million respectively. The FWHM of the Gaussian probability distribution is assumed as 4% for CZT and 10% for NaI at 122 keV [8] here to sample the energy to get the energy spectra.

The comparison of energy spectra for ^{57}Co and ^{111}In from CZT-based and NaI-based detectors are shown in Figs. 5 and 6 correspondingly. As shown in Fig. 5, the CZT detector can clearly resolve the 122 keV photopeak from the 136 keV of ^{57}Co while NaI crystal can

not. The counts are normalized for a better comparability. Fig. 6 indicates that when the energy is low, CZT and NaI almost have the same performance, however, as energy goes up, the CZT has a much higher energy output than NaI due to its better stopping power.

V. Conclusion

The simulations to evaluate the design of a CZT-based detector combined with a tungsten-based pixel-geometry-matching collimator is carried out preliminarily. The results showed that such a camera with a pixel-geometry-matching collimator had a higher intrinsic resolution due to the small pixels and thus a better spatial resolution. The comparison of the detection efficiency between this detector and conventional ones with Monte Carlo simulations is underway. The tungsten-based collimator can reduce the rate of penetration compared with the lead-based. At the same time, the energy resolution improves by using CZT material instead of NaI crystal. Furthermore, these results have indicated that the large CZT detector combined with a tungsten-based pixel-geometry-matching collimator is a promising gamma camera technology for a novel SPECT system.

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Fig. 1.
Picture of the collimator and the detector modeled by Geant4.

Fig. 2.
Theoretical spatial resolution and detection efficiency with different hole lengths and source-to-collimator distances.

Fig. 3.
Projection images versus different materials and hole shapes of the collimators.

Fig. 4. Projection distribution of the deposited energy within a pixel versus different materials and hole shapes of the collimators.

Fig. 5.
Comparison of energy spectra of ^{57}Co obtained by CZT-based detector and NaI-based detector.

Fig. 6. Comparison of energy spectra of ^{111}In obtained by CZT-based detector and NaI-based detector.

TABLE I

Variables and definitions of the detector and the collimator.

Variables	Definitions	Units
D	Hole diameter.	mm
L	Hole length.	mm
S_0	Distance from source to the collimator face.	cm
S_1	Distance from source to the detector face.	cm
N_0	Total number of emitted gamma from point source.	/
N_1	Total number of gamma interacting with the detector.	/
R_{int}	Intrinsic resolution.	mm
R_{col}	Collimator resolution.	mm
R_{spa}	Spatial resolution.	mm
E_{eff}	Detection efficiency.	%

TABLE II

The FWHM of the deposited energy with different types of holes.

Hole Type	Hole Material	FWHM/mm
circular	Tungsten	6.708
rectangular	Tungsten	6.972
circular	Lead	7.759
rectangular	Lead	8.173