Short Communication

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Study of a New Design of P-N Semiconductor Detector Array for Nuclear Medicine Imaging by Monte Carlo Simulation Codes

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Submission: 04-02-2014 Accepted: 13-05-2014

ABSTRACT

Gamma camera is an important apparatus in nuclear medicine imaging. Its detection part is consists of a scintillation detector with a heavy collimator. Substitution of semiconductor detectors instead of scintillator in these cameras has been effectively studied. In this study, it is aimed to introduce a new design of P-N semiconductor detector array for nuclear medicine imaging. A P-N semiconductor detector composed of N-SnO_2:F, and P-NiO:Li, has been introduced through simulating with MCNPX monte carlo codes. Its sensitivity with different factors such as thickness, dimension, and direction of emission photons were investigated. It is then used to configure a new design of an array in one-dimension and study its spatial resolution for nuclear medicine imaging. One-dimension array with 39 detectors was simulated to measure a predefined linear distribution of Tc^{99_m} activity and its spatial resolution. The activity distribution was calculated from detector responses through mathematical linear optimization using LINPROG code on MATLAB software. Three different configurations of one-dimension detector array, horizontal, vertical one sided, and vertical double-sided were simulated. In all of these configurations, the energy windows of the photopeak were ± 1%. The results show that the detector response increases with an increase of dimension and thickness of the detector with the highest sensitivity for emission photons 15-30° above the surface. Horizontal configuration array of detectors is not suitable for imaging of line activity sources. The measured activity distribution with vertical configuration array, double-side detectors, has no similarity with emission sources and hence is not suitable for imaging purposes. Measured activity distribution using vertical configuration array, single side detectors has a good similarity with sources. Therefore, it could be introduced as a suitable configuration for nuclear medicine imaging. It has been shown that using semiconductor P-N detectors such as P-NiO:Li, N-SnO_2:F for gamma detection could be possibly applicable for design of a one dimension array configuration with suitable spatial resolution of 2.7 mm for nuclear medicine imaging.

Key words: *Gamma camera, Monte Carlo N-particle simulation, P-N semiconductor detector*

INTRODUCTION

Anger scintillation camera is a selective choice for radionuclide distribution imaging. Since introducing gamma camera on 1964, it has improved greatly in all aspects such as spatial and energy resolution, uniformity, field of view, and type of detectors.[1] These improvements made it as a suitable choice for a variety range of clinical studies. Important parts of a gamma camera are collimator, sodium iodide crystal, optical channels, and photomultiplier tubes. Part of gamma camera disadvantage is due to limitation on scintillation crystal. These limitations include nonuniformity of the crystal or scintillator failures due to the sudden increase on temperature, which distorts the images. Emission history and humidity also decreases its sensitivity and causes high patient radiation dose. Big size of photomultiplier tubes and their heavy weights, low energy, and spatial resolution are other disadvantages of scintillation camera with respect to semiconductor detectors.[2] Due to these limitations, the semiconductor detectors are a good alternative to be used on gamma camera.[3] Some researcher used arrays of CdZnTe semiconductor gamma-ray detectors[4,5] and improved the energy resolution to 6% and spatial resolution to 6.2 mm in gamma camera.[1] Others have used different electrode configuration of planar[6] and coplanar electrode[7] as a charge sensing detectors.

In this study, it was planned to simulate a P-N semiconductor detector with Monte Carlo N-particle (MCNP) codes for detection of gamma radiation to be used in one-dimensional array for imaging in nuclear medicine.

MATERIALS AND METHODS

As powerful and multi-potential MCNP code could be used to simulate different radiation physics phenomena and get the selective parameters,[8] it is tried to simulate a P-N

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semiconductor detector made of a P-type NiO with Li impurities (P-NiO: Li) and N-type SnO_2 with F impurities N-SnO_2:F[9] to be used for nuclear radiation detection. Pulse height distribution of that has been determined with F8 tally in MCNP code as described by Ródenas *et al*. (2005).[10] This tally with Gaussian energy broadening code can resembles the output simulation pulse of the detector from photons with energy E through three various factors a, b, and c.[11] Relation between full width at half maximum (FWHM) and these factors are defined as $\mathrm{FWHM} = a + b\sqrt{(E + cE^2)}$;[12] therefore, these factors can be achieved measuring FWHM of a detector at least for three different sources.

As there was no access to such a NiO-SnO_2 detector, FWHM data of a similar P-N semiconductor detector made of CdTe, model XR-100T[13] has been used. Plotting FWHM versus energy and matching above equation yield $a = -0.00037$ MeV, $b = 0.00648$ $MeV^{1/2}$, and $c = 0.6146$/MeV.

To evaluate functional performance and optimum dimension of a simulated detector, pulse height distribution from a Tc^{99m} radioactive source in the air and scattering medium of water and also its sensitivity versus detector thickness and source-detector distance and directions were measured.

In these evaluations, the detector cell was composed of two rectangular cubic made of SnO_2 and NiO, with dimension of 2×5 cm^2 and thickness of 0.2 mm (thickness of each layer was 0.1 mm). Pulse height distribution versus radiation energy of photons from a Tc^{99m} radioactive source in the air and scattering medium of water, when emitting from 7.5 cm and perpendicular to detector's surface are shown in Figure 1. Energy resolution in all of these measurements was 1.6%.

To evaluate detector performance, first the sensitivity versus source-detector distance was measured with energy windows of ± 1%. Counts from a Tc^{99m} source at 5, 10, 15, and 20 cm from the detector are shown in Figure 2. As expected it is shown that the sensitivity will reduce with the inverse square of distances due to reduction of field of view.

Sensitivity for detector thickness of 0.1, 0.2, 0.5, 1, 2, and 10 mm with source-detector distance of 5 cm was also measured and shown in Figure 3. As expected the sensitivity linearly increases with an increas e of detector thickness. As the electrical resistance of a semiconductor 1 mm thick made of SnO_2 and NiO will be very high (about few MΩ), and its electrical pulse is not measurable; therefore, detectors with less than a millimeter thick with low resistance, although with weaker sensitivity are preferred for signal measurements.

Detector sensitivity at a different direction was evaluated by measuring detector counts at different angles on *xy* and *yz* planes as shown in Figure 4. The sensitivity will increase on *yz* plane from 0° to 30° and will decrease a little up to 90° as shown in Figure 5.

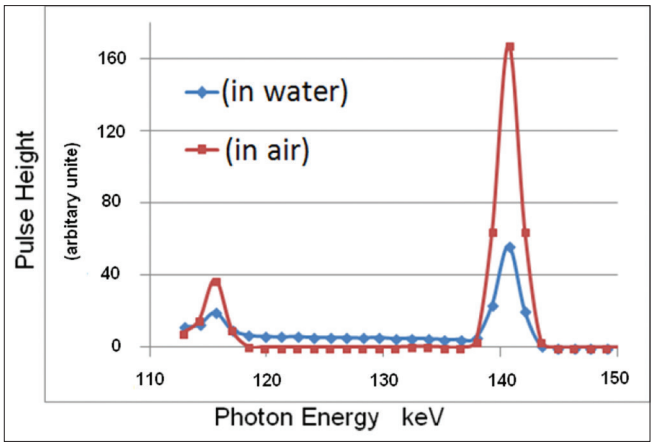

Figure 1: Pulse height distribution versus radiation photon energy in the air and water

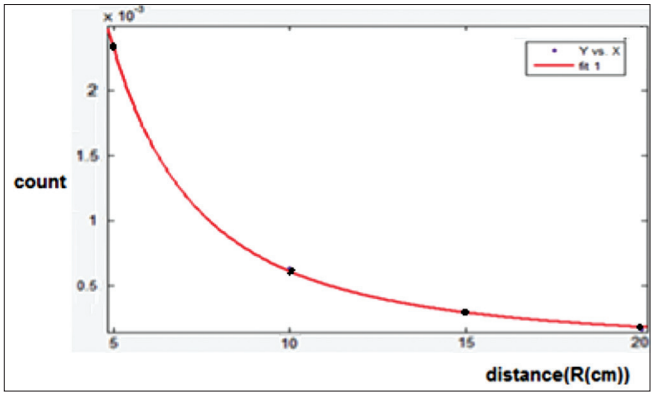

Figure 2: Detector counts versus source-detector distances

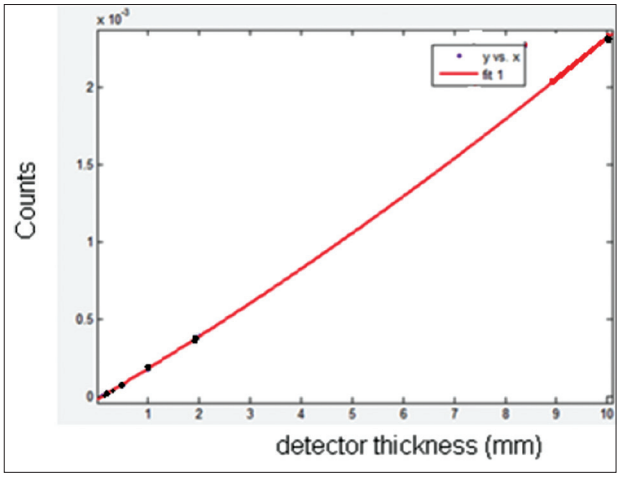

Figure 3: Detector sensitivity versus detector thickness

Sensitivity of the detector at different angles on *xy* plane, due to its small thickness is very low and for different radiation angles have no significant variations.

Results of these measurements confirm the physical principals of radiations, hence verifies performance of simulated detectors with Monte Carlo method. Therefore,

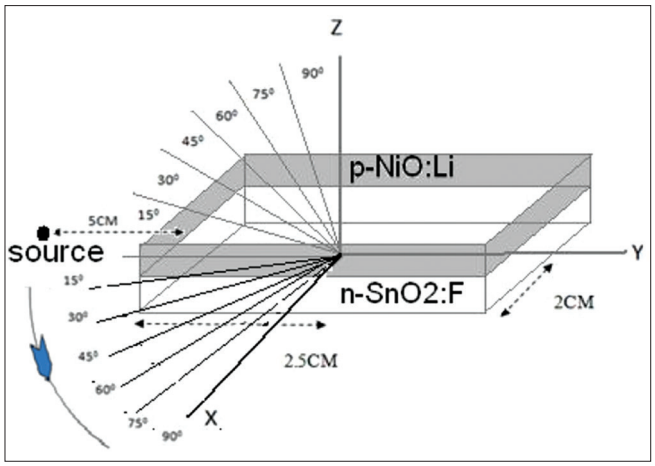

Figure 4: Situation of source and its direction to detector surface on xy and yz plane

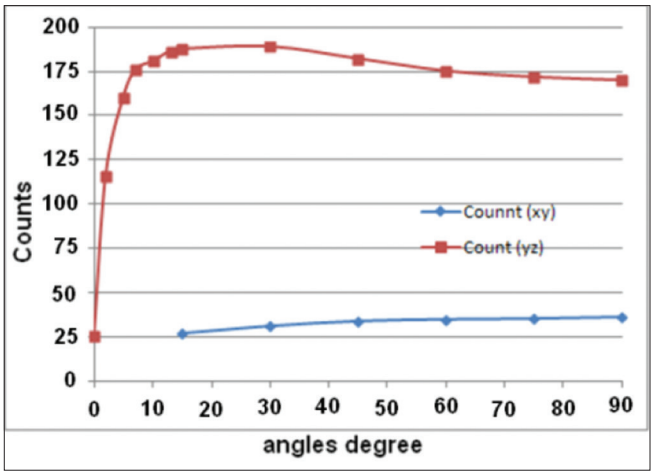

Figure 5: Sensitivity versus emission direction on xy and yz plane

several of these detectors have been used to design one dimension detector array. Detector arrays composed of 39 detectors with three different configurations of horizontal, vertical double-side, and vertical single side was then simulated, and the activity distribution of predefined linear sources and their spatial resolutions were measured.

In double-side detector array both side of the detectors could detect the radiation photons, while in single side detector array one side of the detectors are covered with a lead layer and emitted photons from one side will be detected.

In all of these configurations each detector will receive emitted photons from source voxels distributed on a linear narrow $^{99}Tc^{m}$ tube at 5 cm in front of that.

Compton scattering formula predicts a decrease of 1% in energy of 140 KeV photons, undertaking scatter of 15°. Therefore, detector outputs, setting a narrow ± 1% energy window, will counts only nonscattered emitted photons of sources or scattered <15° in source-detector directions. Denoting g_i for i^{Th} detector output, f_j for activity of j^{Th} voxel of the source and $A_{i,j}$ for probability of emitted photons from j^{Th} voxel of the source to be received with i^{Th} detector, there would be the following formula:[14]

$$g_i = [A_{i,j}]\, f_j \text{ for } i = 1, 2, \ldots, n \text{ and } j = 1, 2, \ldots, m$$

Finally, activities of m image pixels were calculated from counts of n detectors using mathematical linear optimization algorithm through LINPROG code in MATLAB software (R2009a).

RESULTS

In a simulation, an array with 36 horizontal detectors, 2 mm long, 1 mm width, 0.2 mm thick, and 4 mm apart from each other, was placed at 50 mm in front of 71 narrow linear source voxels, 2 and 0.2 mm long with 1.9 mm separation, and different activities as shown in Figure 6a. Disintegration probability of source voxels No. 13, 29, 43 and 57 was, respectively 0.05, 0.15, 0.25, 0.45, and 0.002 for the other sources. The measured activity spectrum using ± 5% energy window is shown in Figure 6b.

Peak activities of the sources could not be seen on the measured spectrum with this configuration of detectors.

A vertical array with 36 double-side detectors, 5 cm long, 2 cm wide, 0.2 mm thick and at 5 mm distance from each other was simulated to measure the activity of 70 linear source voxels 0.2 mm long and 2.4 mm separation with different activities as shown in Figure 7a. Disintegration probability of source voxels No. 13, 29, 43, and 57 was, respectively 0.05, 0.15, 0.25, 0.45, and 0.0015 for the other sources. The measured activity spectrum using ± 1% energy window is shown in Figure 7b.

Measured spectrum in this configuration, also does not resemble to the position of the peak activities of sources and hence cannot be used for imaging.

Another similar vertical array with 36 single side detectors was simulated to measure the activity of 71 source voxels of no equally activities, as described for double side detectors. Position of sources and detector array is shown in Figure 8a. In this configuration, peak activity of the sources has been detected in measured spectrum with spatial resolution of 2.7 mm.

DISCUSSION

One-dimension detector array composed of several thin P-N semiconductor detectors with different configurations used for detection of a linear distributed $^{99}Tc^{m}$ sources.

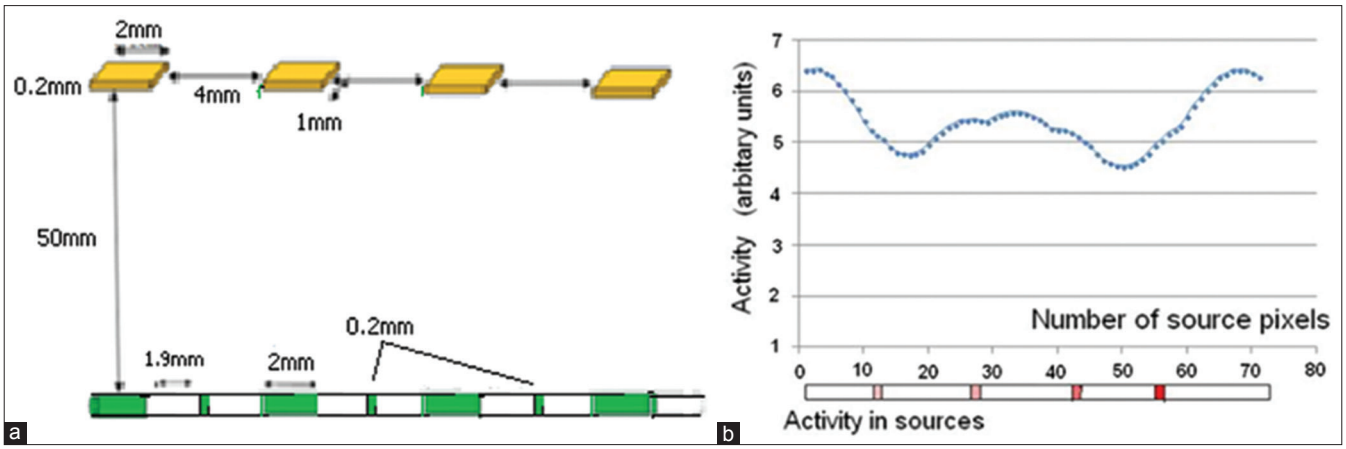

Figure 6: (a) Detector array with 36 horizontal detector and (b) 71 source voxels with different activity

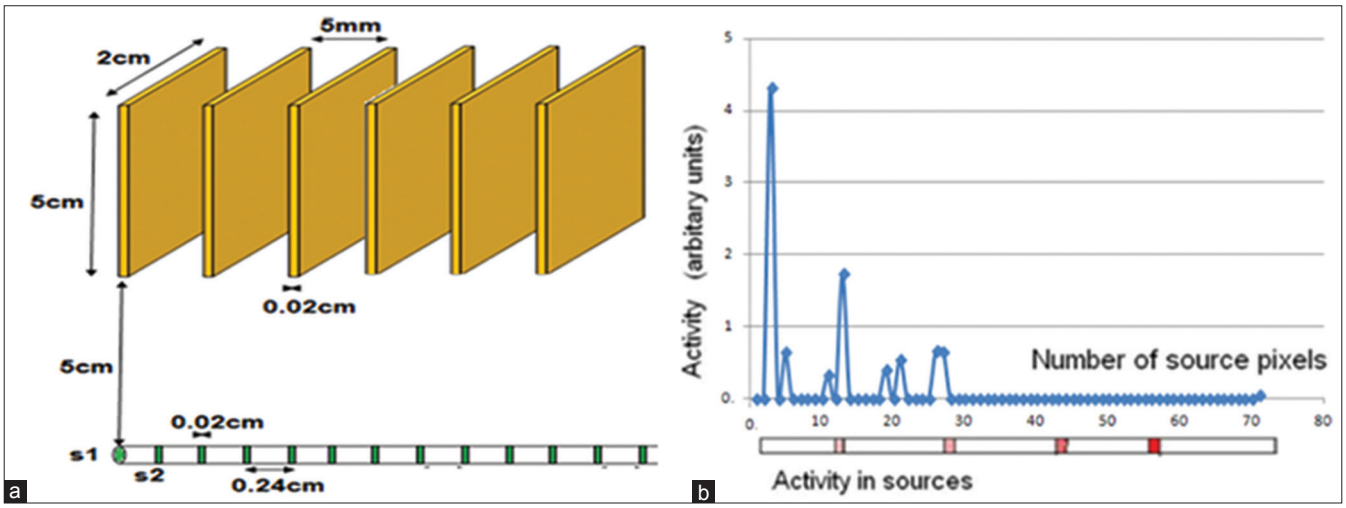

Figure 7: (a) Detector array with 36 vertical double side detector and (b) 71 source voxels with no equally activity

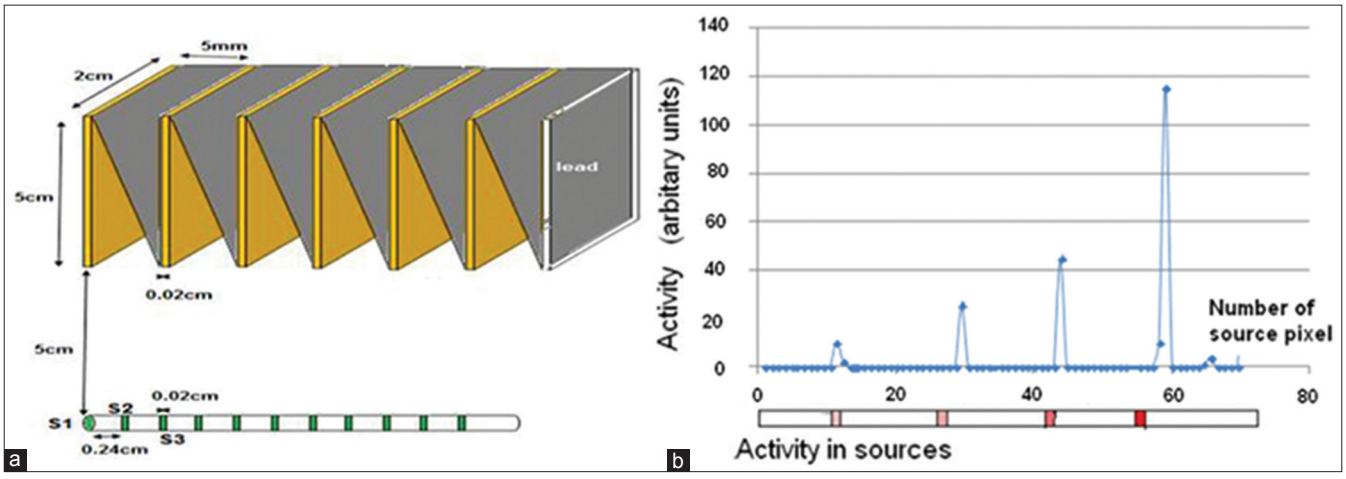

Figure 8: (a) Detector array with 36 vertical single side detector and (b) 71 source voxels with no equally activity

System matrix elements $a_{i,j}$, for horizontal configuration array is maximum at $j = i$ and will gradually decrease for sources farther than that on both side. In this configuration field of view of every detectors is vide and position of single sources as shown in Figure 6a is not detectable. Therefore, it is not applicable for imaging purposes.

On double-side vertical configuration the system matrix elements of $a_{i,j}$ is minimum at $j = i$ and will gradually

changes for sources farther than that on both side. It will first increase and then due to increase of source-detector distance will decrease. Field of view of detectors in this configuration is similar to horizontal array and cannot detect the position of the sources as shown in Figure 7a; therefore, is not applicable for imaging purposes. To limit the detector field of view, single side vertical array was used. In this configuration as shown in Figure 8a, position of sources could be detected with spatial resolution of 2.7 mm.

CONCLUSION

It has been shown that a configuration of single side detector array composed of semiconductor P-N detectors such as P-NiO: Li, N-SnO_2:F is applicable for gamma detection with suitable spatial resolution of 2.7 mm. Fine energy resolution of the P-N detectors are promising this technique to be used for two-dimensional detector array as a gamma camera with scattered photon rejection during image data acquisition.

ACKNOWLEDGMENTS

The authors would like to thanks research Vice Chancellor of Mashad University of Medical Sciences for financial support of this research as a medical physics M.Sc. thesis and also Mr. Sh. Bayani from Medical Physics Research Center for his sincere cooperation's.

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How to cite this article: Hajizadeh-Safar M, Ghorbani M, Khoshkharam S, Ashrafi Z. Study of a New Design of P-N Semiconductor Detector Array for Nuclear Medicine Imaging by Monte Carlo Simulation Codes. J Med Sign Sence 2014;4:231-5.

Source of Support: Medical Physics Research Center; Mashad University of Medical Sciences Mashad, Iran, **Conflict of Interest:** Nill

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