Study of performance of small gamma camera consisting of crystal pixel array and position sensitive photomultiplier tube

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Abstract The performance of gamma camera with NaI(Tl) array coupled with position sensitive photomultiplier tube (PSPMT) R2486 has been studied. The pixel size of NaI(Tl) crystal is 2mm×2mm and the overall dimension of the array is 48.2mm×48.2mm×5mm. There are 484 pixels in a 22×22 matrix. Because each pixel can produce a much focused light spot and restrict the spread of photons, position resolution of the gamma camera is mainly determined by pixel size. It is shown that crystal array pixel can reduce shrinkage effect and improve intrinsic position resolution greatly via restricting the spread of photons. Experimental results demonstrate that its position resolution and linearity are much improved comparing with the gamma camera using planar crystals coupled with PSPMT.

Key words NaI(Tl), Pixel array, Position sensitive photomultiplier tube, Position linearity, Position resolution

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1 Introduction

In recent years a great effort has been made in developing compact gamma camera to improve nuclear medical imaging. Conventional Anger gamma camera[1] uses a NaI(Tl) scintillator block and an array of photomultiplier tube. It has large size and poor spatial resolution, thus it is not suitable for small object image. Though the gamma camera using planar crystal coupled with position sensitive photomultiplier tube (PSPMT[2]) could greatly improve spatial resolution,[3-5] planar crystals with adequate detection efficiency produce large light spread with respect to PSPMT size. The only way to fully take advantage of PSPMT intrinsic characteristics is the use of pixel array of appropriate size to optimize detection efficiency, light spread and light output. Each pixel can produce a much focused light spot which is mainly dependent on depth of photon interaction, light wavelength, surface characteristics, geometry and light transport effects. Based on the above consideration, a small gamma camera with scintillating pixel array and position sensitive photomultiplier tubes (PSPMT) has been recently developed to take a major step forward in improving nuclear medicine imaging.[6] Because of narrow light distributions in the pixels, it is possible to reach 1-2 millimeter and even less spatial resolutions. In this paper the performance of a small gamma camera using NaI(Tl) scintillating pixels (size 2mm×2mm) array coupled with Hamamastu R2486 PSPMT was investigated by using a radiation source of Am-241.

2 Image and readout methods

We have built up a small gamma camera of NaI(Tl) pixel array coupled with Hamamastu R2486 PSPMT. The square area of NaI(Tl) scintillating array is 48.2mm×48.2mm. The pixel size is 2mm×2mm with 0.2mm packing between pixels. The material between pixels is the powder reflector. There are total 484 pixels in a 22×22 matrix. The crystal thickness is 5mm, which allows a detection efficiency of more

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than 95% for 100 keV gamma rays. Pixel surface treatment and reflectors were chosen to optimize light output by using realistic technologies. The reflectivities of pixel on the side and the top are 100%, and 98% for back. There are a 1mm reflector and low-density sponge gap between aluminum window and pixel crystal array. The bottom of the pixel crystal couples to the glass window of PSPMT (Hamamatsu R2486-05) with silicon grease. The transmission for optical window is 85%. The PSPMT R2486 includes a bialkali photocathode, a 12-stage coarse mesh dynode structure, and multiple anode wires crossing each other in the X and Y directions. Spectral response is 300—600nm and wavelength of maximum response is 420nm. The window material is borosilicate glass with 3.0mm thickness and has an effective area ϕ 50mm. There are $16(x)+16(y)$ anodes in PSPMT R2486. The gain is 10^5 for high voltage 1250V. Fig.1 shows the principle of multiplication for PSPMT. Output signals from each dynode can be divided through external resistive chains and derived from X and Y electrodes as the position signals (see Fig.2). The positions of X and Y and total energy can be determined by the following formulas:

$$X = \frac{X_A - X_B}{X_A + X_B}$$

$$Y = \frac{Y_C - Y_D}{Y_C + Y_D}$$

$$E = X_A + X_B + Y_C + Y_D$$

The crossed-wire anode construction features high position resolution and linearity, and easy signal processing for scintillation imaging. The voltage circuit and resistive chains for signal processing simplify its connection to measuring instruments. The gamma ray (59.5keV) from radiation source Am-241 was collimated by a copper collimator with ϕ 1mm hole. In the experiment the PSPMT coupled with NaI(Tl) pixel array was light-tight, and the position of collimator related to radiation source could be changed by using step motor (HT—PWB) in x and y directions. Thus we could scan over full surface of NaI(Tl) pixel array. The whole system including beam scan, data acquiring and real time analysis was controlled by PC platform with LabVIEW software. Data acquiring procedure was in this way: first to run 3000 events to get

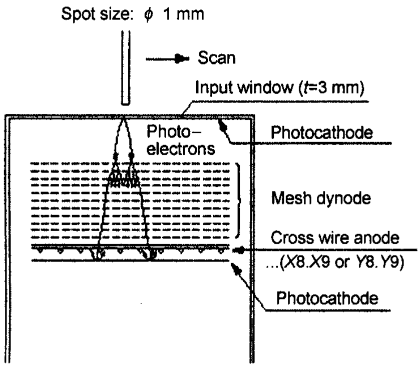

Fig.1 The principle of multiplication for PSPMT.

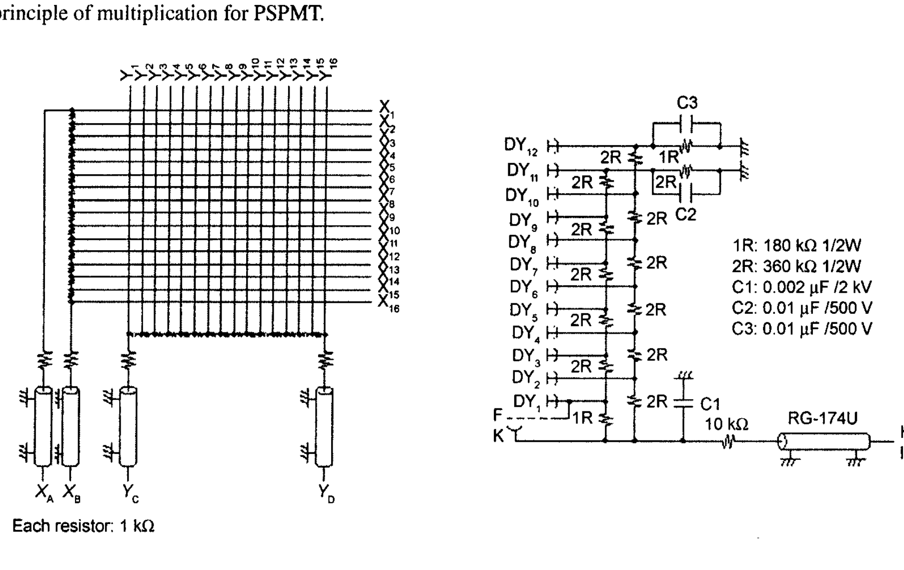

Fig. 2 The resistor chain distribution of PSPMT. The multiple anode wires are crossing one another in the X and Y directions.

an energy spectrum for given position, and then take the full width at half maximum (FWHM) of the full energy peak as a proper window width. In the following real data acquiring only the events, energy of which was located in above window, would be recorded. By using energy and X and Y position information, the center of gravity of scintillating light could be calculated. All the data analysis proceeded with Physics Analysis Workstation (PAW [7]) software. In the experiment all information including energy window width, image position and count number for each irradiation spot and so on was stored as independent file.

3 Results and discussion

3.1 Energy resolution and energy response

The measured energy resolution on the centre is 15% at FWHM for Am-241. The energy window width is about 12keV. The energy response of gamma camera can be described by two parameters: integral uniformity and differential uniformity. Integral uniformity is defined as the maximum variation in count density over the entire field-of-view. Differential uniformity is defined as the maximum rate of change of count density over a specified distance. From the maximum (Max) and minimum (Min) counts in the pixels lying within the useful field-of-view and central field-of-view we could get the integral uniformity as follows:

$$\text{Integral uniformity} = \pm\frac{\text{Max} - \text{Min}}{\text{Max} + \text{Min}}\times 100\% \quad (1)$$

For each row or column of pixels in the X and Y directions within the useful field-of-view and central field-of-view, we could get the maximum count difference in any 6 contiguous pixels. From the highest (High) and lowest (Low) value of this maximum count difference in the sets of rows and columns then the differential uniformity was given by:

$$\text{Differential uniformity} = \pm\frac{\text{High} - \text{Low}}{\text{High} + \text{Low}}\times 100\% \quad (2)$$

The test results show that the integral uniformity and differential uniformity of energy is 35% and 27%, respectively. Energy response for all measured points is shown in Fig.3.

Fig.4 shows the count-rate performance of all measured points. The test results show that the integral uniformity and differential uniformity of count-rate is 34% and 27%, respectively.

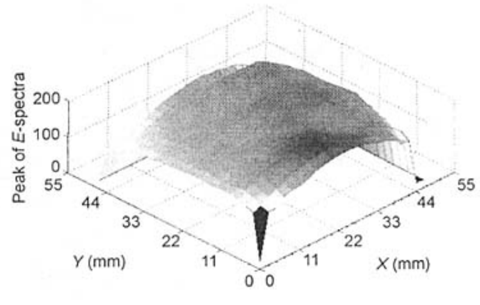

Fig.3 All measured points' energy response obtained by irradiating scintillating array with a collimated Am-241 source.

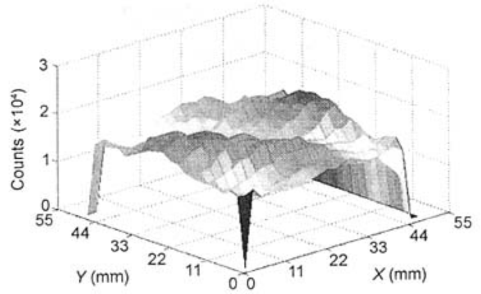

Fig.4 All measured points' count-rate performance obtained by irradiating scintillating array with a collimated Am-241 source.

3.2 Position linearity

All pixels on the surface of NaI(Tl) array coupled with PSPMT has been scanned by a step motor. The scan range is from –24 mm to +24 mm with the step of 2.2mm in X and Y direction, respectively. Total 484 points have been scanned, among which 26 points on circumference are below the signal threshold. Thus we only get 458 data to be analyzed. Fig.5 shows the real position of all measured points, while Fig.6 shows the position response of all measured points. From Fig.6, it is clear that the image is significantly shrunk from circumference to the center. This is due to the fact that the PSPMT's useful field-of-view is ϕ50mm, and the distance from the points of circumference to center is $24\times\sqrt{2}$ =34mm. It means that the points of circumference show a lack of credibility. In order to reduce statistical error, about 60000 events (100 second) have been taken for each point.

The image position $R_j(i)$ (i, j = –10, ..., –1, 0, +1, ..., +11) can be determined by Eq.(3), j and i are

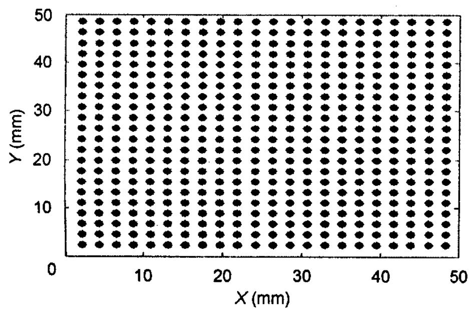

Fig.5 The real position of all measured points.

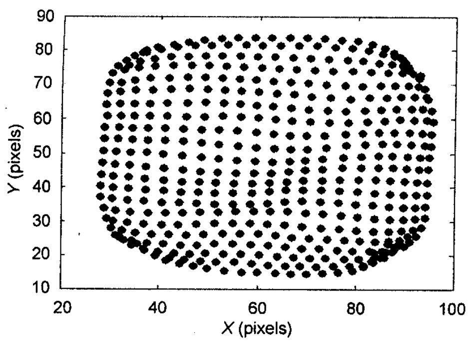

Fig.6 The position response of all measured points.

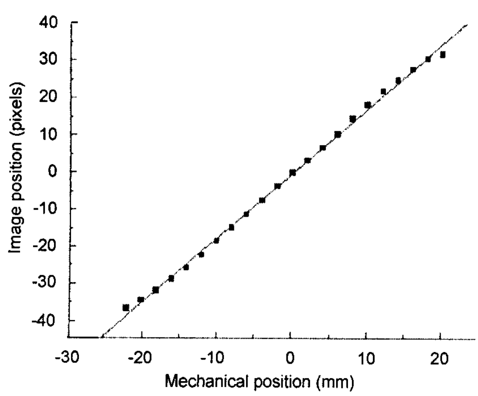

Fig.7 A typical position response curve of the system with j=1 (0.57mm/pixel).

indices of row and column for the pixel array.

$$R_j(i) = \sqrt{(X_i - X_0)^2 + (Y_i - Y_0)^2} \quad (3)$$

Fig.7 shows a typical position response curve of the system with j=1. The straight line can be expressed as:

$$R_1(i) = -0.38032 + 1.74025 \times i \quad (4)$$

The data are fit with a straight line with the minimum bend. The position linearity covers the whole crystal dimension (48mm) perfectly coinciding with the intrinsic response. The slope of position linearity is constant within 10% in a range of 40mm. A slope change of about 40% occurred at the PSPMT boundary (4mm). We could get values of $R_j(i)$ (j = −10, ..., −1, 0, +2, ..., +11, $j \neq 1$) by using the same procedure.

$$R_j(i) = a + b \times i \quad (5)$$

The results are shown on Fig.8.

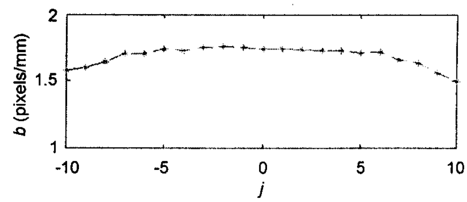

Fig.8 Linear measuring coefficient for all measured rows.

The position response of gamma camera can be described by differential non-linearity and absolute non-linearity. In case of uniform distribution of mechanical position of impact point the differential non-linearity is defined as standard error of distance between borders upon two image points:

$$\Delta R_j(i) = \sqrt{(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2}$$

$$(i = -10, \ldots, 0, \ldots, +11, j = -10, \ldots, 0, \ldots, +11) \quad (6)$$

and

$$\Delta_j = \frac{\sum_{i=0}^{21} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}}{21} \quad (7)$$

Thus the differential non-linearity for j^{th} row is

$$\eta_j = \sqrt{\frac{\sum_{i=0}^{21} (\Delta R_j(i) - \Delta_j)^2}{21}} \quad (8)$$

Absolute non-linearity is defined as maximum deviation between image position and straight line fit. Fig.9 and Fig.10 show the differential non-linearity and the absolute non-linearity for all measured rows respectively. The average value of differential non-linearity and absolute non-linearity is 0.375 mm and 1.426 mm, respectively.

3.3 Position resolution

The position resolution can be obtained by plotting the deviation distribution from image position to strait fit for all measured points.

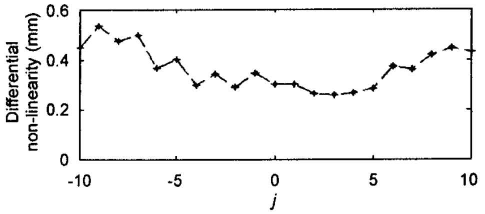

Fig.9 Differential non-linearity for all measured rows.

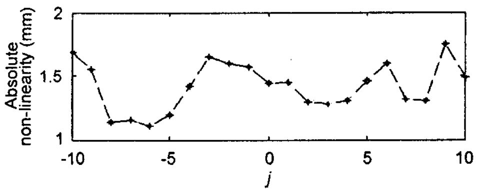

Fig.10 Absolute non-linearity for all measured rows.

Fig.11 shows all measured points' position response curve. In reference frame, x coordinate data are real distance from all measured points to center, y coordinate data are test distance from all image points to center. The line equation is $f(x)=1.517x+0.787$.

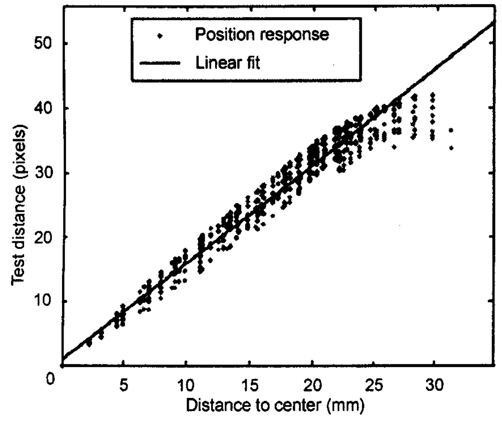

Fig.11 All measured points' position response curve (step length 2.2mm)(0.66mm/pixel).

Fig.12 shows the deviation distribution from image position to strait fit for all measured points. Thus we can get position resolutions of 2.5 mm for step length 2.2 mm, which is much improved comparing with the gamma camera using planar crystals coupled with PSPMT.[8-13] The results demonstrate that array of crystal pixels can reduce shrinkage effect and improve intrinsic spatial resolution greatly via restricting the spread of photons. The results also indicate that spatial resolution of gamma camera using scintillating crystal array coupled with PSPMT is limited by pixel size.

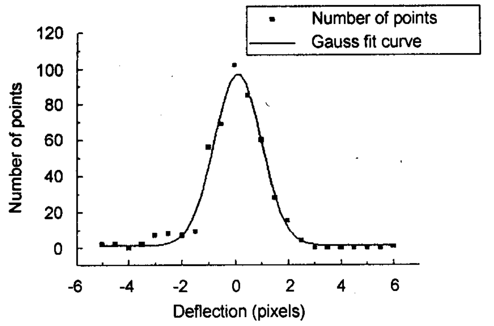

Fig.12 The deviation distribution from image position to strait fit for all measured points.

4 Conclusions

Experimental results indicate that gamma camera with scintillating array of crystal pixels have a good position resolution and good linearity and energy response. The slope of position linearity is constant within 10% in a range of 40mm. A slope change of about 40% occurred at the PSPMT boundary (4 mm). Table 1 is the comparison of gamma camera using scintillating array of crystal pixels or planar crystal coupled with PSPMT.[14]

Table 1 Comparison of gamma cameras using scintillating array of crystal pixels or planar crystal coupled with PSPMT

Parameters	Pixel array coupled with PSPMT (59.5 keV gamma ray)	Planar crystal coupled with PSPMT (59.5 keV gamma ray)
Energy resolution on centre	15%	21%
Integral uniformity (energy)	35%	50%
Differential uniformity (energy)	27%	36%
Position resolution	2.5 mm	4 mm
Differential non-linearity (position)	0.38 mm	0.69 mm
Absolute non-linearity (position)	1.43 mm	3.3 mm

Because each pixel can produce a much focused light spot and restrict the spread of photons, spatial solution of the gamma camera is mainly determined by pixel size. On the other hand, the shrinkage effect mainly comes from the PSPMT. By right of these factors, position resolution of the gamma camera with scintillating pixel array and PSPMT has improved greatly. Experimental results demonstrated that array of crystal pixels can reduce shrinkage effect and improve intrinsic spatial resolution greatly via restricting the spread of photons. Compared with a small gamma camera using a planar NaI(Tl) crystal and a PSPMT, the camera's performance has been greatly improved.

References

1 Bird A J, Ramsden D. Nucl Instr Meth, 1990, **A299**: 480-483

2 Hamamatsu Photomultiplier Tube Hamamatsu Photonics K.K. Electron Tube Center, Position sensitive photomultiplier tube with crossed wire anodes R2486 series, Specifications manual (in Japanese), 1993

3 Clancy R L, Thompson C J, Robar J L, *et al.* IEEE Trans Nucl Sci, 1997, **44**(3): 494-498

4 Smith L E, He Z, Wehe D K, *et al.* IEEE Trans Nucl Sci, 1998, **45**(3): 963-969

5 Guru S V, He Z, Ferreria J C, *et al.* Nucl Instr Meth, 1994, **A353**: 328-333

6 Pani R, Scafe R, Pellegrini R, *et al.* Nucl Instr Meth Phys Res A, 2002, **477**: 72-76

7 CN/ASD Group. PAW users guide, Program Library Q121. CERN, October 1993

8 Pani R, Scopibaro F, Pellegrini R, *et al.* Phys Med, 1993, **9**(2-3): 233-236

9 Pani R, Soluri A, Pellegrini R, *et al.* Nucl Instr Meth, 1994, **A348**: 551-556

10 Scopinaro F, Pani R, Soluri A, *et al.* Nucl Med Commun, 1994, **15**: 905

11 Blazek K, de Notaristerfani F, Maly P, *et al.* IEEE Trans Nucl Sci, 1995, **NS-42**(5): 1474

12 Baccaro S, Blazek K. Nucl Instr Meth, 1995, **A361**: 209

13 Barone L M, Blazek K, Bollini D, *et al.* Nucl Instr Meth, 1995, **A 360**: 302

14 ZENG Hai-Ning. Study of a small gamma camera based on PSPMT, University of Science and Technology of China, Doctoral Dissertation, 1999