Development of a three-layer phoswich alpha-beta-gamma imaging detector

Seiichi Yamamoto¹⁾ and Hiroyuki Ishibashi²⁾

¹⁾Radiological and Medical Laboratory Sciences, Nagoya University Graduate School of Medicine, Nagoya, Japan and

²⁾Hitachi Chemical, Ibaraki, Japan

Corresponding author: Professor Seiichi Yamamoto

1-1-20 Daiko-Minami, Higashi-ku, Nagoya, 461-8673

Tel:+81-52-719-1559, Fax:+81-52-719-1559

e-mail: s-yama@met.nagoya-u.ac.jp

Abstract

For radiation monitoring at the sites of such nuclear power plant accidents as Fukushima Daiichi, radiation detectors are needed not only for gamma photons but also for alpha and beta particles because some nuclear fission products emit beta particles and gamma photons and some nuclear fuels contain plutonium that emits alpha particles. In some applications, imaging detectors are required to detect the distribution of plutonium particles that emit alpha particles and radiocesium in foods that emits beta particles and gamma photons. To solve these requirements, we developed an imaging detector that can measure the distribution of alpha and beta particles as well as gamma photons. The imaging detector consists of three-layer scintillators optically coupled to each other and to a position sensitive photomultiplier tube (PSPMT). The first layer, which is made of a thin plastic scintillator (decay time: ~5 ns), detects alpha particles. The second layer, which is made of a thin Gd_2SiO_5 (GSO) scintillator with 1.5 mol% Ce (decay time: 35 ns), detects beta particles. The third layer made of a thin GSO scintillator with 0.4 mol% Ce (decay time: 70 ns) detects gamma photons. Using pulse shape discrimination, the images of these layers can be separated. The position information is calculated by the Anger principle from 8 x 8 anode signals from the PSPMT. The images for the alpha and beta particles and the gamma photons are individually formed by the pulse shape discriminations for each layer. We detected alpha particle images in the first layer and beta particle images in the second layer. Gamma photon images were detected in the second and third layers. The spatial resolution for the alpha and beta particles was ~1.25 mm FWHM and less than 2 mm FWHM for the gamma photons. We conclude that our developed alpha-beta-gamma imaging detector is promising for imaging applications not only for the environmental monitoring of radionuclides but also for medical and molecular imaging.

I. INTRODUCTION

The reactors at the Fukushima Daiichi nuclear power plant were severely damaged by a tsunami caused by an earthquake. Huge amounts of radionuclides were released into the environment from the damaged reactors in Japan [1-2]. For radiation monitoring at the sites of nuclear power plant accidents such as Fukushima Daiichi, radiation detectors are needed not only for gamma photons but also for alpha and beta particles because some nuclear fission products emit beta particles and gamma photons and some nuclear fuels contain plutonium that emits alpha particles. Recently we successfully developed a radiation detector that can simultaneously monitor alpha and beta particles as well as gamma photons for radiation monitoring [3]. Our developed alpha-beta-gamma detector, which consists of three-layer scintillators optically coupled to each other and to a photomultiplier tube, provides good separation of these different types of radiation. Similar multilayered detectors for different types of radiation were also developed by other groups [4-12]. However, most of these layered detectors did not have the imaging capability. In some applications, an imaging detector is needed to identify the plutonium particle distribution that emits alpha particles [13], the Sr-90 distribution that emits beta particles, and the radiocesium in food that emits beta particles and gamma photons. For this purpose, we expanded the layered concept to an imaging detector that can measure the distribution of alpha and beta particles as well as gamma photons to realize an alpha-beta-gamma imaging detector.

II. MATERIALS AND METHODS

2.1 Principle of operation of alpha-beta-gamma imaging detector

Figure 1(A) shows a schematic drawing of the developed alpha-beta-gamma imaging detector, which consists of three-layer scintillators optically coupled to each other and to a position sensitive photomultiplier tube (PSPMT).

The first layer, which is made of a thin plastic scintillator (decay time: ~5 ns), detects alpha particles. We selected a thin plastic scintillator for the alpha particle detector because it is transparent and its energy spectrum can be obtained [14-15]. The second layer, which is made of a thin Gd_2SiO_5 (GSO) scintillator with 1.5 mol% Ce (decay time: 35 ns) [16], detects beta particles. The third layer made of a thin GSO scintillator with 0.4 mol% Ce (decay time: 70 ns) [17] detects gamma photons. Using pulse shape discrimination [18-21], the counts of these layers can be separated. The position information is calculated by the Anger principle from 8 x 8 anode signals from the PSPMT. The images for the alpha and beta particles and the gamma photons can be separated by the pulse shape discrimination of each layer.

Fig.1 Schematic drawing of developed alpha-beta-gamma imaging detector

2.2 Developed alpha-beta-gamma imaging detector

We show a photo of the developed alpha-beta-gamma imaging detector in Fig. 2. The plastic scintillator's size for the first layer was 50 x 50 x 0.05 mm. Its thickness was determined to be 0.05 mm because the range of alpha particles such as Am-241 (energy: ~5.5 MeV) in plastic is around 0.05 mm, and all of their energy is absorbed in the first layer and second and third layers do not detect alpha particles.

Fig. 2 Developed alpha-beta-gamma imaging detector

The size of the GSOs with 1.5 mol% Ce for the second layer and 0.4 mol% for the third layer was 50 x 50 x 0.5 mm. The energy loss of 2MeV electrons of 0.05mm plastic scintillator is ~10keV [22], the detection of the in the first layer is almost zero because the energy loss was much lower than energy threshold level of the detector (~300keV). The beta particle absorption for Y-90 (maximum energy: ~2 MeV) in 0.5-mm thick GSO was ~80% from the rough calculation

100 [22]. The third layer detects rest of the beta particles, so ~20% of the beta particles from Y-90 are detected in the third layer.

The detection efficiency of the 0.05mm plastic scintillator for Cs-137 gamma photons (662keV) is calculated to be ~0.05% and the detection efficiency of 0.5mm thick GSO for Cs-137 gamma photons is calculated to be ~3.5%. Thus the detection efficiencies of second and third layers for Cs-137 gamma photons are almost the same, ~3.5% and ~3.4%,
105 respectively. Thus the relative detection efficiencies for first, second and third layers are expected to be 0.7%, 50.3% and 49.0%, respectively.

These three types of scintillators were optically coupled to each other and to a PSPMT (Hamamatsu Photonics, H8500) with a 2-mm thick acrylic resin light guide to form a phoswich imaging detector. An aluminized Mylar sheet covered the scintillators for the light shield and the reflector.

110 The analog signals from the PSPMT were fed to the weight summing boards behind the PSPMT. The weighed sum signals were fed to the 100-MHz analog to digital (A-D) converters of the data acquisition system and integrated for 320 ns. The positions were calculated using the Anger principle by FPGA. Pulse shape analysis was done digitally by the dual integration method by FPGA. We used 150-ns integration time for partial integration and 320-ns integration time for full integration [23].

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2.3 Performance evaluation

Am-241 alpha particles (5.5 MeV), Sr-Y-90 beta particles (maximum energy: 0.54 and 2.8 MeV), and Cs-137 gamma photons (662 keV) were used for the imaging performance measurements of the developed imaging detector for the alpha and beta particles and the gamma photons, respectively. The Am-241 alpha source has 15mm diameter with the
120 radioactivity of 2kBq. The Sr-Y-90 beta source is made of ~2mm diameter several sources and the total radioactivity of 100Bq. The Cs-137 gamma source has ~1mm diameter point source with the activity of 370kBq.

First we measured the pulse shape spectra for the alpha and beta particles and the gamma photons using these three radiation sources to evaluate the pulse shape spectra's separation and to set the pulse shape threshold levels for each type of radiation. One of these sources was set on the imaging detector surface, and data were acquired by repeating the same
125 procedures for the other two types of sources. We could obtain the pulse shape spectra for the three-layer scintillators that corresponded to the alpha and beta particles and the gamma photons.

For the performance evaluation of the alpha particles, the Am-241 alpha source was positioned on the imaging detector with a slit chart for the resolution evaluation.

Because the resolution chart was directly positioned on the aluminized Mylar, the energy loss by the air was negligible. The thickness of aluminized Mylar was ~2um, so the energy loss by the aluminized Mylar was also negligible. After acquiring the data, pulse shape analysis distinguished each image.

For the performance evaluation of the beta particles, the Sr-Y-90 beta source was positioned on the imaging detector with a slit chart for the resolution evaluation. It was positioned ~1cm from the detector surface to uniformly irradiate the beta particles to the detector. After acquiring the data, pulse shape analysis distinguished each image.

For the performance evaluation of the gamma photons, the Cs-137 gamma source was positioned on the imaging detector with a tungsten resolution phantom. The Cs-137 gamma source was positioned ~4cm from the detector surface when irradiating to the detector.

After acquiring the data, pulse shape analysis distinguished each image.

Figure 3 shows a photo of the slit chart used for the spatial resolution evaluation for the alpha and beta particles (left) and the tungsten slit phantom used to evaluate the spatial resolution for the gamma photons (right). The tungsten phantom was 5 mm thick.

Fig. 3 Slit chart used for spatial resolution evaluation: alpha and beta particles (left) and tungsten slit phantom used for gamma photons (right). Sizes shown in mm in figures are the widths of the slits.

III. RESULTS

Figure 4 shows the pulse shape spectra for irradiating the alpha and beta particles and the gamma photons. The right peak was from the first layer (mainly from the Am-241 alpha particles), the middle peak was from the second layer (mainly from the beta particles of Sr-Y-90 and the Cs-137 gamma photons), and the left peak was from the third layer (mainly from the Cs-137 gamma photons). We set the pulse shape discrimination thresholds at the bottom of each distribution.

Fig. 4 Pulse shape spectra for irradiating alpha and beta particles and gamma photons

Figure 5 shows images of the first layer (A), the second layer (B), and the third layer (C) when irradiating the alpha particles from Am-241 (5.5 MeV). The slit chart image was mainly observed in the first layer. The percentage of relative detected counts in each layer for the alpha particles is listed in Table 1.

From the smallest resolved width of the chart (0.625 mm: vertical middle sector of the chart), the spatial resolution for the alpha particles was estimated to be less than ~ 1.25 mm FWHM. The energy resolution for the Am-241 alpha particles (5.5 MeV) was 16.6% FWHM (Fig. 5(D)).

(A)

(B)

(C)

(D)

Fig. 5 Images of first (A), second (B), and third layers (C), and energy spectrum (D) when irradiating alpha particles from Am-241

Table 1 Percentage of **relative** detected counts for alpha particles

	Percentage
First layer	93.5%
Second layer	6.1%
Third layer	0.4%

Figure 6 shows images of the first layer (A), the second layer (B), and the third layer (C) when irradiating the beta particles from Sr-Y-90 (0.54 and 2.8 MeV). The percentage of **relative** detected counts in each layer for the beta particles is listed in Table 2.

The slit chart image was mainly observed in the second layer and slightly observed in the third layer. From the smallest resolved width of the chart for the beta particles (0.625-mm slit: upper third slits), their spatial resolution was estimated to be ~1.25 mm FWHM. The energy spectrum showed a typical broad distribution from them (Fig. 6(D)).

Fig. 6 Images of first (A), second (B), and third layers (C) and energy spectrum (D) when irradiating beta particles from Sr-Y-90

Table 2 Percentage of relative detected counts for beta particles

	Percentage
First layer	0.4%
Second layer	87.7%
Third layer	11.9%

Figure 7 shows images of the first layer (A), the second layer (B), and the third layer (C) when the gamma photons are irradiated from the Cs-137. The slit chart image was observed in the second and third layers. The percentage of relative detected counts in each layer for the gamma photons is listed in Table 3.

From the smallest resolved width of the slits (1 mm: left side sector of the slits of the phantom), the spatial resolution for the gamma photons was estimated to be less than 2 mm FWHM. The energy resolution for the Cs-137 gamma photons (662 keV) discriminated for second layer was 16% FWHM (Fig. 7(D)) and that discriminated for third layer was 19% FWHM (Fig. 7(E)). Right peak in Fig. 7 (D) or (E) is the photo-peak form 662keV gamma photons and the left peak is the higher part of the Compton scatter component.

(A)

(B)

(C)

(D)

(E)

Fig. 7 Images of first (A), second (B), and third layers (C), energy spectrum for second layer (D) and energy spectrum for third layer (E) when irradiating gamma photons from Cs-137

Table 3 Percentage of relative detected counts for gamma photons

	Percentage
First layer	0.6%
Second layer	60.0%
Third layer	39.4%

IV. Discussion

We successfully developed a three-layer phoswich alpha-beta-gamma imaging detector. The first layer only detects alpha particles; the second detects beta particles. Although the third layer detects only gamma photons, the second layer also detects gamma photons because both the second and third layers are made of GSO with identical thickness. Thus the discrimination of beta particles and gamma photons is needed for the second layer image. We can use the subtraction method for this purpose. Because gamma photons are detected in the second layer and third layers, and the GSO thickness for these two layers is the same, their detection efficiency is almost the same with a slightly higher detection fraction for the second layer. This is because of the higher photo-peak channel and higher fraction of the lower energy component in the distribution in the second layer (Fig. 7 (D)) than that in the third layer (Fig. 7 (E)). By subtracting the third layer image from the second layer image by multiplying a constant value for the third layer image, corrected beta particle images can be derived.

The advantage of the developed imaging detector is that one detector can be used for separately imaging the distributions of the alpha and beta particles and gamma photons. This is an advantage when the types of detected radionuclides are not obvious. The ability to detect energy information and position distributions is another advantage of the developed imaging detector.

Its disadvantage is the slight contaminations of different types of radiation to other layers. Although the contaminations of the alpha particles to the second (6.1%) and third layers (0.4%), the beta particles to the first layer (0.4%), and the gamma photons to the first layer (0.6%) were small, the beta particles to the third layer were relatively high (11.9%), probably because the GSO's 0.5-mm thickness for the second layer failed to sufficiently absorb higher energy beta particles from Y-90 (2.8 MeV). A slightly thicker GSO might decrease the contamination of the beta particles in the third layer.

IV. CONCLUSIONS

We successfully developed a three-layer phoswich alpha-beta-gamma imaging detector that will be useful for such imaging as plutonium particles that emit alpha particles, radiostrontium that emits beta particles, and radiocesium in foods that emits beta particles and gamma photons. The developed alpha-beta-gamma imaging detector will also be useful for autoradiography to develop the radionuclides of alpha and beta emitting radionuclide therapy.

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VI. REFERENCES

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