Coded-aperture Gamma Imager for the Measurement of Ambient Dose Equivalent Rate

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1. Introduction

Many sorts of gamma-ray imaging systems combined with a visible light camera have been developed in homeland security and radioactive waste management operations for monitoring sparse radioactive sources in a large area [1]. When monitoring over the large area, providing the ambient dose equivalent is recommended by the ICRP as the operational quantity for assessing effective dose. Nonetheless, there have been few studies that have attempted to estimate the ambient dose equivalent rates using gamma-ray imaging systems.

In the case of Compton camera, it is difficult to determine the location and energy of the low-energy gamma-ray as Compton camera utilizes a scattering phenomenon that occurs primarily at gamma ray in the energy range over 300 keV. On the contrary, one of the advantages of a coded-aperture based gamma camera is that it has a high dynamic range, in that it can image both low-energy gamma rays (5 MeV) for which roughly half interact via pair-production.

There are several published studies on methods for dose assessment from various gamma-ray spectra measured using scintillation-based survey meters or detectors. Among them, the inverse matrix method [3], the energy-band method [4] and the G(E) function [5] have been widely used. The G(E) function method is suitable for accurate dose measurement using scintillation detectors whose responses strongly depend on photon energy. This model is described herein, from the coded aperture based gamma camera equipped with a cerium doped gadolinium aluminum gallium garnet ($Gd_3Al_2Ga_3O_{12}$(Ce) or GAGG(Ce)) scintillator array, and the representative results of the dose estimation are presented.

2. Methods and Results

This section describes the components and performance of the developed gamma camera, the G(E) function method for the gamma camera, and measurement results of the ambient dose equivalent rates to be presented.

2.1 EPSILON-G

The developed gamma camera, termed EPSILON (**E**nergetic **P**article **S**ensor for the **I**dentification and **L**ocalization of **O**riginating **N**uclei)-G(gamma), is presented in Fig.1. The EPSILON-G can read-out 12 × 12 silicon photomultipliers (SiPMs), resulting in an instrument with 144 pixels which is coupled with 4 × 4 × 20 mm_t GAGG(Ce) scintillator array that has an intercept area of 50.2 × 50.2 mm^2. GAGG(Ce) has a high-density, high absorption coefficient material and can provide scintillation performance characteristics that are competitive with both traditional scintillation solids (NaI(Tl), CsI(Tl)) as well as advanced cerium doped silicates such as LYSO(Ce) and $LaCl_3$(Ce). The use of this scintillator with these excellent properties allowed them to have excellent sensitivity and ability to analyze nuclides. In addition, unlike the Compton camera, the application of the coded-aperture mask allowed excellent angular resolution and linearity to dose to be competitive [5].

Fig. 1. Design of EPSILON-G (left) and illustration of use examples of equipment (right)

2.2 Factors for converting response spectrum to H(10)*

The response matrix of GAGG(Ce) scintillator array in the EPSILON-G was calculated by the response functions obtained by a Monte Carlo simulation of the Monte Carlo N-Particle eXtended (MCNPX). The response functions were calculated for a broad parallel beam incident normally to the face of the coded aperture. The upper limit of the photon energy was set to 3 MeV, and the response functions were calculated for a broad parallel beam incident on the coded aperture face, as shown in Fig. 2. The correction for the angular dependence of the detector response in a terrestrial radiation field could be ignored because the lateral side of the GAGG(Ce) scintillator array is shielded by tungsten bars with a thickness of 1 cm.

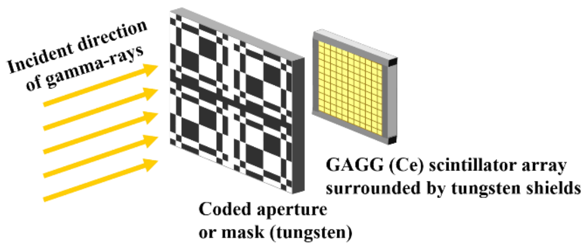

Fig. 2. Simulation geometry used in the Monte Carlo calculation for the gamma-ray response of EPSILON-G.

The relationship between the measured spectrum and the response matrix is given by

$$\mathrm{S_i} = \mathrm{M_{ij}}\ \phi_\mathrm{j}\ f$$

where S_i is the measured spectrum (or counts in the i-th channel in the spectrum), M_{ij} is the response matrix, ϕ_j is the gamma-ray fluence at an energy corresponding to the j-th channel, and f is the open fraction that has 50% in the centered mosaic modified-uniform redundant array (MURA) pattern. Factors for converting the measured spectrum of GAGG(Ce) scintillator array to the ambient dose equivalent rate, H*(10), can be calculated as follows:

$$H^*(10) = \left(\frac{H^*(10)}{\phi}\right)_j f^{-1} M_{ij}^{-1} \mathrm{S_j} = F_j S_j,$$
$$F_j = \left(\frac{H^*(10)}{\phi}\right)_j f^{-1} M_{ij}^{-1}$$

where $(H^*(10)/\phi)_j$ is the conversion coefficients of the gamma-ray fluence to ambient dose equivalent for gamma-rays with an energy corresponding to the j-th channel. The conversion factor, F_j, was calculated with 50 × 50 response matrices as a function of the incident photon energy, as shown in Fig. 3.

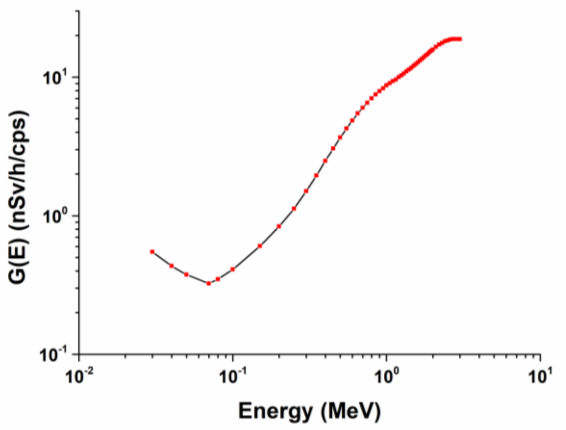

Fig. 3. The factor for converting the measured pulse height spectrum to ambient dose equivalent calculated using 50 × 50 response matrix.

2.4 H(10) measurement results*

When a standard disk type Cs-137 source with an activity of 20.09 μCi located at the distance of 50 cm from the system, Fig. 4 plots the fluctuation of the ambient dose equivalent rate obtained from the EPSILON-G and the measurements from a GM monitor (FHZ 612, Thermo Scientific). The GM monitor was calibrated to measure the ambient dose equivalent rate in the range from 0.1 μSv/h to 300 μSv/h. Unlike the trend toward ambient dose equivalent rates over time given in the GM monitor, the trend given in the EPSILON-G is less fluctuating because the detection efficiency of the GAGG(Ce) scintillator array is superior than the GM monitor.

The evaluated mean value of the ambient dose rates for the aforementioned Cs-137 source is provided in Table I. The EPSILON-G and the GM monitor featured a mean dose rates of 0.356 ± 0.012 μSv/h and 0.366 ± 0.044 μSv/h, respectively. The dose rates obtained from the Cs-137 source was in close agreement with the dose rates measured from the GM monitor. In order to verify the validity of the derived conversion factor, the ambient dose equivalent rates measured for Ba-133 and Na-22 are also measured, as given in the table. The Ba-133 and Na-22 has an activity of 5.68 μCi and 0.94 μCi, respectively, and these source was located at the distance of 30 cm from the system. The dose rates measured by EPSILON-G are within an error of 20.9% from that rates measured by the GM monitor. Hence, it can be concluded that EPSILON-G would provide the ambient dose equivalent as the operational quantity for assessing effective dose in area monitoring.

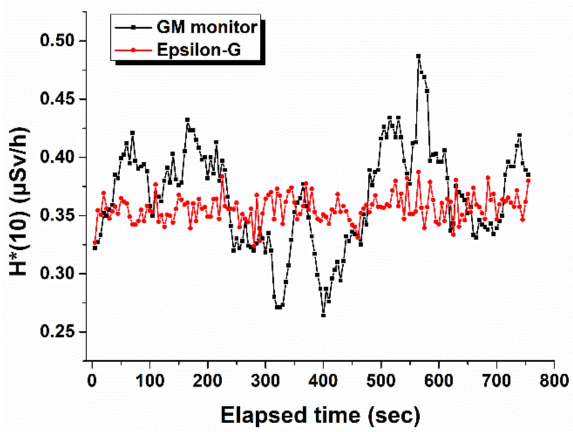

Fig. 4. Comparison of the ambient dose equivalent rate, $H^*(10)$, over time obtained with EPSILON-G (red) and a GM monitor (black).

Table I: Comparison of the ambient dose equivalent rate measured by the GM monitor and EPSILON-G

Isotope	Ambient dose equivalent rate (μSv/h) $H^*(10)$		$\dot{D}_{GM}/\dot{D}_{Epsilon-G}$
	$\dot{D}_{GM}$	$\dot{D}_{Epsilon-G}$	
Ba-133	0.251 ± 0.036	0.214 ± 0.011	1.173 ± 0.179
Cs-137	0.366 ± 0.044	0.356 ± 0.012	1.028 ± 0.126
Na-22	0.255 ± 0.041	0.211 ± 0.011	1.209 ±0.204

3. Conclusions

EPSILON-G can be a useful tool for not only providing a radionuclide distribution map but also an operational quantity in area monitoring. Thus far G(E) function method was used to estimate the dose rates and the dose rates measured by EPSILON-G were in close agreement with the dose rates measured from the GM monitor.

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