Simulation Study of a Plastic Scintillator for an Electrical Personal Dosimeter

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***Abstract* – Plastic scintillators show several desired characteristics in dosimetry; especially tissue-equivalence is a definite advantage as an electrical personal dosimeter (EPD). The EPD based on an array-type Silicon Photomultiplier (SiPM) coupled to the polystyrene scintillator was proposed at the last time and has been improving. In this research, for the EPD application, the characteristics of plastic scintillator were studied through MCNP5 and LightTools simulation. For the reliable MCNP simulation, Gaussian energy broadening (GEB) was applied with the computed parameters from measured spectrum. The difference between simulation and measurement were 2.2% and 3.5% in terms of energy and FWHM each. To simulate the small-size effect in the plastic scintillator, the plastic scintillators of various sizes were simulated. The collapse of counting curve was shown in the MCNP simulation result. This was due to the escape of Bremsstrahlung photons and more clearly shown in the smaller scintillator, higher energy. In the LightTools simulation, the light collection efficiency of each size was simulated. Like the prediction, the efficiency decreased when the size of scintillator increased. The simulation results showed the plastic scintillator for the EPD must be small for the light collection, but also have minimum limit of size to avoid loss of count at the high energy.**

I. INTRODUCTION

After the massive nuclear reactor accident in Fukushima, Japan (2011), the world recognized the risk of nuclear power and radiation hazard again. The public interest in radiation safety has increased the demand for EPD.

The EPD is a radiation detector used to measure human exposure to the ionizing radiation. Ion chambers, thermo luminescent dosimeters (TLDs), and silicon-diode detectors with/without a scintillator have been commonly used as the EPD [1]. Each type of these dosimeters has advantages/disadvantages in terms of price, convenience, detection efficiency, and accuracy.

There are two types of scintillators used for radiation detection; inorganic materials (e.g. NaI(Tl), CsI(Tl)) and organic materials (e.g. plastics). The inorganic materials have advantages for gamma-ray detection because of their high Z-value and high density [1] [2]. The plastic scintillators have been far from gamma-ray detection except particular applications, even though they have some practical advantages; less expensive, short decay time, easily processed [3].

In dosimetry, the plastic scintillators show several desired characteristics including reproducibility, dose linearity, resistance to radiation damage, temperature insensitivity, and especially, tissue-equivalence (water equivalence) [2] [4]. The tissue-equivalence is the most desired characteristic of plastic scintillators as the EPD and it is based on similarity in the physical characteristics (Table 1) [5-8].

Material	Soft-Tissue (ICRU-44)	Polystyrene (Plastic)	Silicon	CsI	NaI
Z/A	0.54996	0.53768	0.49848	0.41548	0.42697
I (eV)	74.7	68.7	173.0	553.1	452
Density (g/cm^3)	1.06	1.06	2.33	4.51	3.667
Composition (Z: fraction by weight)	1: 0.102 6: 0.143 7. 0.034 8: 0.708 …	1: 0.077 6: 0.922	14: 1.0	53: 0.488 55: 0.511	11: 0.153 53: 0.846

Table 1. Comparison of physical characteristics between scintillation materials and tissue [9].

The absorbed dose rate can be defined in terms of the fluence rate (ϕ), photon energy (E), and mass energy-absorption coefficient (μ_{en}/ρ) [10]. Because the mass energy-absorption coefficient of plastic is almost equivalent to that of soft-tissue of human body (Fig. 1) [11], the computed absorbed dose in the scintillator is also almost same as the computed absorbed dose in the tissue (Fig. 2).

$$\dot{D} = \dot{\phi} \times (\frac{\mu_{en}}{\rho}) \times E_{\gamma} \quad (1)$$

At the last presentation, the EPD based on an array-type SiPM coupled to the plastic scintillator were proposed, has been improving, and tested [12]. Because, as previous mention, the physical characteristics of the plastic scintillator much differ from those of the general inorganic scintillator, the difference in radiation-interaction tendency should be considered to develop the small-size dosimeter system like EPD. In this research, for the EPD application, the characteristics of plastic scintillator were studied through radiation and light simulation with MCNP5 and LightTools.

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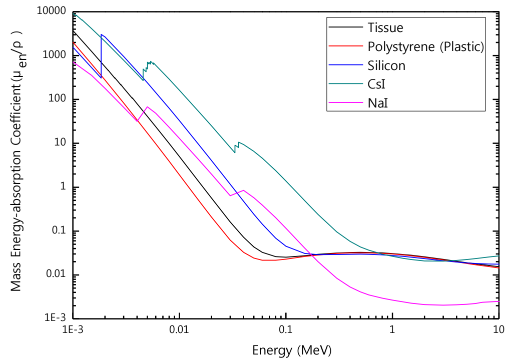

Fig 1. Comparison of mass energy-absorption coefficient between scintillation materials and tissue [11].

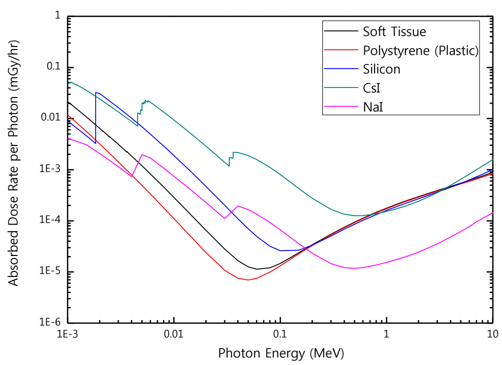

Fig 2. Comparison of computed absorbed dose per photon between scintillation materials and tissue.

II. VALIDATION OF MCNP SIMULATION

For radiation simulation of the plastic scintillator, the version 5 of a General Monte Carlo N-Particle Transport Code (MCNP5) was used [13]. To achieve reliable simulation, Gaussian energy broadening (GEB) effect was applied with computed parameters from the test measurement.

The composition in the simulation was described similar to the condition of gamma measurement (Fig. 3). In the test measurement, the $1 cm^3$ cubic polystyrene scintillator and photomultiplier tube (Hamamatsu, H6410) were used.

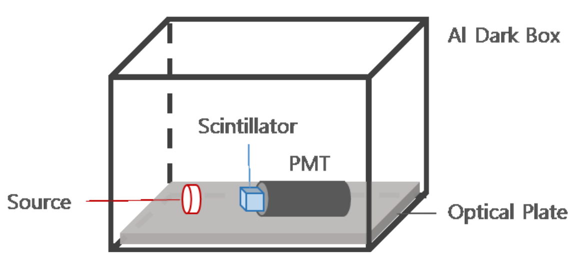

Fig 3. Diagram of gamma measurement and MCNP simulation condition.

With the measured spectra of 3 gamma sources (Na-22, Cs-137, Co-60), the GEB effect at the each Compton edge was assessed. From the assessed GEB effect at each energy, the input parameters required in the GEB option of MCNP5 were computed through the least-square approach. The GEB-applied MCNP5 simulation results showed closed spectra to the measured spectra (Fig. 4).

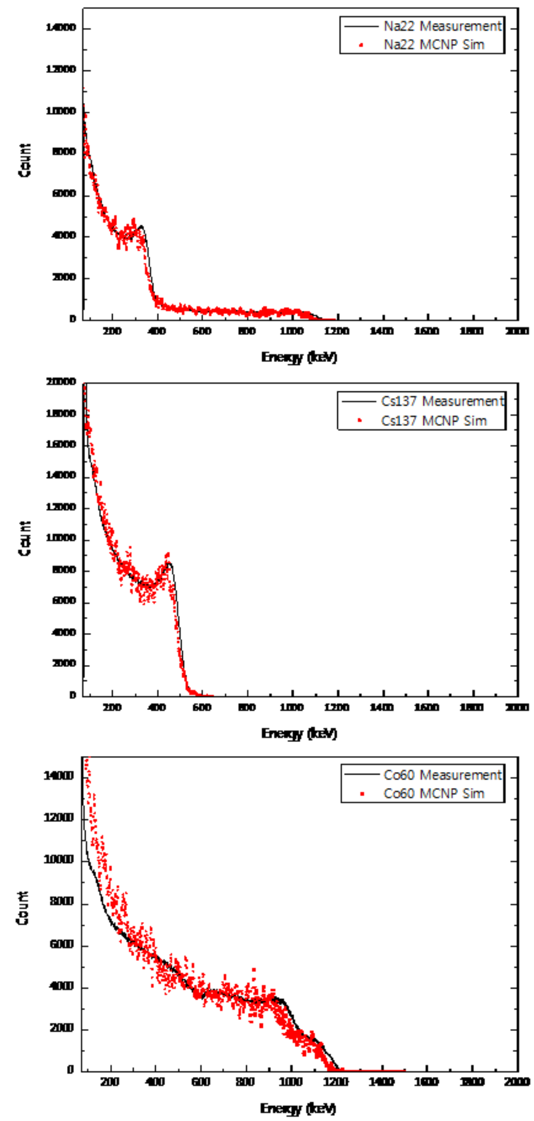

Fig 4. Comparison between gamma spectra from the measurement (line) and MCNP5 simulation (dot) with Na-22 (top), Cs-137 (Middle), Co-60 (bottom) sources.

The spectra from the simulation described even the scattered photon from aluminum dark box at the lower energy. The errors in the MCNP5 simulation were less than 1%. In terms of the energy of Compton edge and FWHM at that edge, the difference between simulation and measurement were 2.2% and 3.5% each. This difference also can be reduced through more precise energy-channel calibration of measured spectra and re-computation of GEB effect at each energy.

III. SIZE EFFECT TO GAMMA-RAY ABSORPTION

Angular response is one of the important characteristics of EPD. To keep angular response of the EPD uniform to all directions, geometric structure of the scintillator has limited options; Sphere is the most ideal, but practically cube or cylinder is preferred if optical coupling to the detector surface is considered.

Because the structure is limited, the size of scintillator is only variable in view of geometry. In a radiation measurement with inorganic scintillators, the size of scintillator is not such an important issue. It is only related to the detection efficiency of a system. Even in the radiation measurement with plastic scintillator, the size is also not such an important issue because large plastic scintillator is generally used.

However, in the proposed dosimeter, the small-size of plastic scintillator can be an issue. When the size of scintillator increases, the detector has disadvantage in terms of the light collection efficiency and the base noise from dark counts of the SiPM. In contrast, when the size decreases, the detection efficiency decreases and the loss of count can occur at high energy gamma-ray.

To estimate the effect of the scintillator size, MCNP5 simulation was performed under the various size condition in the target energy of gamma-ray. Considering the area of unit SiPM, the size of plastic scintillator increased on a 3cm basis (Table 2). Other parameters were identical with the previous MCNP5 simulation correlated to the measurement.

Size of scintillator	$(3mm)^3$	$(6mm)^3$	$(9mm)^3$	$(12mm)^3$	$(15mm)^3$
Energy of gamma source (keV)	300	600	900	1200	1500

Table 2. List of simulated size of the scintillator and gamma-ray energy.

The result spectra of simulation were in Fig. 5 and Fig. 6. Because of their low Z-value, in the measured and simulated spectra of plastic scintillator, there were no photoelectric peaks; only Compton edges were shown. Gamma sources used in the simulation had multiple energies, so there were multiple Compton peaks. The result spectra showed the collapse of counting curve when energy of incoming gamma-ray was high.

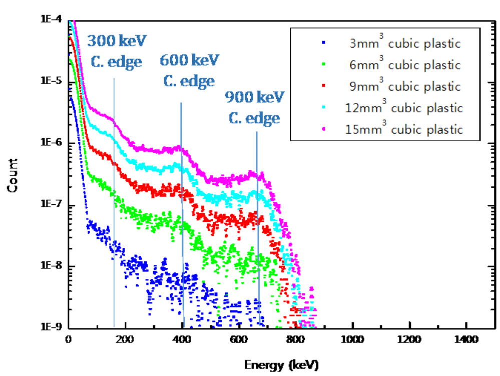

Fig 5. Result spectra of MCNP5 simulation (300keV, 600keV, 900keV).

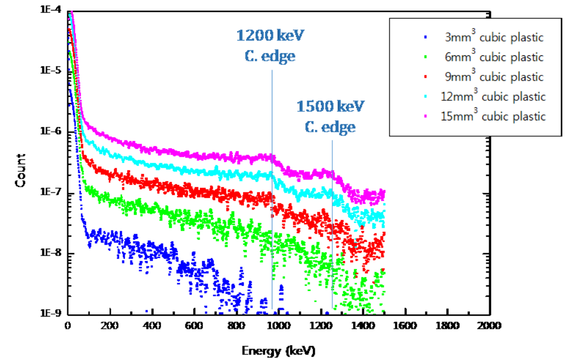

Fig 6. Result spectra of MCNP5 simulation (1200keV, 1500keV).

In Fig. 5, the collapse of counting curve was shown at the curve of $3mm^3$ cube only. However, in Fig. 6, the collapse of counting curve was shown at the curve of $6mm^3$ as well. If EPD has maximum target energy over 1.5MeV, the plastic scintillator should be larger than $6mm^3$ to avoid the loss of count. In the simulation which GEB option was not applied, this collapse of counting curve was shown more obviously.

Additional simulation to prove the reason was also performed (Fig. 7). In the simulation without Bremsstrahlung effect, Compton edge was clearly shown even the extreme minimum size ($1mm^3$). This could be supposed that Bremsstrahlung photons occurred from Compton scattering escapes in the small plastic scintillator.

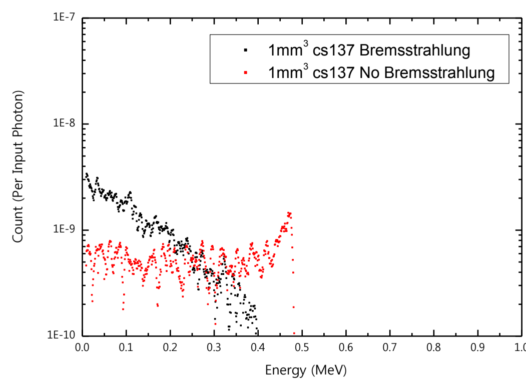

Fig 7. Comparison between simulation results with Bremsstrahlung effect (Black) and no Bremsstrahlung effect option (Red).

IV. LIGHT COLLECTION SIMULATION

Using the version 5.1 of LightTools [14], the collection of light produced from the plastic scintillator was simulated. In the simulation, light produced from the whole volume of plastic scintillator. The produced light from the scintillator passed layers of optical grease (Saint-Gobain, BC630), epoxy of SiPM, and finally was absorbed in the silicon layer. The layout and diagram of LightTools simulation is described in Fig. 8.

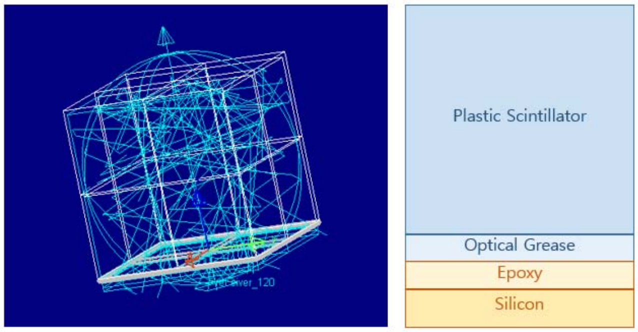

Fig 8. Layout (left) and diagram (right) of LightTools simulation.

Both cases of bare and Teflon-coated plastic scintillator were simulated. Optical parameters required for a plastic scintillator and coating surface were from references [15, 16]. To the surface coated with Teflon, Lambertian reflection model was applied [16]. All parameters of the light simulation is summarized in Table 3.

Parameter	Polystyrene (Scintillator)	BC 630 (Optical grease)	Epoxy	Silicon	PTFE
Refractive Index (at 450nm)	1.61	1.465	1.5318	4.67	1.35
Transmittance (at 450nm)	0.9964 /10mm	0.95 /2mm	0.99 /5mm	0	0.06 /1mm
Note	-	-	-	LightTools library	Lambertian reflection (Reflectance: 98%)

Table 3. Optical parameters for light collection simulation in a scintillator.

The result of light collection simulation is in Table 4. As the prediction, light collection efficiency decreased when the size of scintillator increased and the decrease was more rapidly in the bare scintillator.

Size	$(3mm)^3$	$(6mm)^3$	$(9mm)^3$	$(12mm)^3$	$(15mm)^3$
Bare plastic (%)	11.239	12.073	8.4175	4.785	3.0843
PTFE coated plastic (%)	42.026	41.119	40.662	36.866	23.393

Table 4. Light collection efficiency in the scintillator of each size.

The light collection efficiency of the bare plastic scintillator was less than 15%. It indicates the importance of reflective coating and optical coupling of plastic scintillator. In the coated plastic scintillator, the light collection efficiency was around 40% and this is similar value with other references. The decrease of light collection efficiency was slowly until the size of 12mm, but rapid decrease was shown when the size exceeded 12mm. Considering the decrease of light collection efficiency, maximum size limits of plastic scintillator are 6mm (bare plastic) and 12mm (coated plastic) practically.

V. Summary

For the development of an EPD using a plastic scintillator, the radiation and light simulation study about the plastic scintillator were performed with MCNP5 and LightTools. For the more reliable simulation, GEB was applied in MCNP5 simulation with computed parameters from the measured gamma spectrum. In the MCNP5 simulation result, the loss of count was indicated when the plastic scintillator was small and the energy of gamma-ray was high. In the light collection simulation, the light collection efficiency decreased when the size of plastic scintillator increased. From both simulation, the plastic scintillators for an EPD have maximum/minimum size limits to avoid the loss of count and loss of light collection efficiency.

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