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# The effect of photomultiplier tube glass entrance window on plastic scintillator cast sheet photon dosimetry: A Monte Carlo study

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**Abstract.** Plastic scintillators are commonly used for medical dosimetry due to the density and effective atomic numbers that are closer to human soft tissue. When a photomultiplier tube (PMT) is used with a thin scintillator, reflected photon and electrons as a result of Compton scattering either inside the scintillator or PMT entrance window, might contribute to a significant source of additional absorbed dose. Monte Carlo simulation was used to study the effect of different PMT window materials on the absorbed dose of a 0.5 mm plastic scintillator cast sheet for parallel photon beam energy up to 1 MeV. The additional dose in the plastic scintillator from 400 keV to 1 MeV due to sapphire and lithium fluoride (LiF) glass are increases from 11 % to 47 % and 8 % to 31 %, respectively. Despite of the lower density of Quartz among other materials, Quartz and magnesium fluoride (MgF<sub>2</sub>) demonstrate almost similar trends of additional dose throughout the energies, which is closer to the sapphire. To reduce the unexpected additional dose, a plastic scintillator with a considerable thickness of a PMT window should be adopted for the ‘soft-tissue’ dose response.

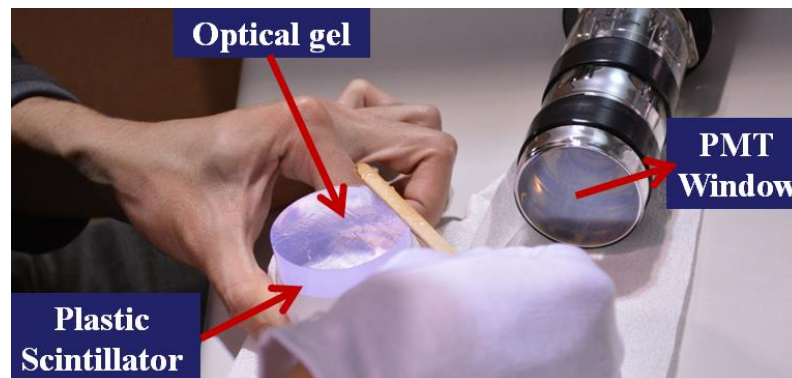
## 1. Introduction

There are significant advances in new detector materials for a range of applications due to the use of radiation in space exploration, nuclear environments, industrial and medical applications. Inadequate number of detectors due to their cost, size and complexity has been a strong driving force for the development of accurate, vigorous and reliable instruments [1]. Commercially available detectors are air ionization chamber, Geiger Muller counter, NaI(Tl), CsI(Tl) and semiconductor [2][3]. To be more reliable as a photon dosimeter, several studies have been conducted to understand their basic properties, which are include the calibration of detectors, energy dependence and detection efficiency. For medical applications such as interventional radiology (IVR) or depth dose measurements in phantom, plastic scintillator is a good candidate of photon dosimeter since its effective atomic number approximately equals to that of human soft tissue. The dose measurements for a small photon fields and area drives the needs of smaller size dosimeter with high accuracy. The use of detector system with a small size plastic scintillator had also been studied by researchers in radiotherapy field [4, 5]. The use of other dosimeter such as NaI(Tl) is available with high efficiency, however, it is known to exhibit a strong energy dependence [6].

The scintillation process is the most applied methods in the detection and spectroscopic measurement of a different type of radiations. A plastic scintillator requires a device that collects scintillation light and converts it to an electronic signal as shown in Figure 1. When a small plastic scintillator coupled with a photomultiplier tube (PMT) to be employed as a dosimeter, a PMT window



of considerable size and weight exists on the side of the plastic scintillator. There is a possibility that the PMT window glasses will influence the absorbed dose when thin plastic scintillators are used, which contribute to a source of unwanted scintillations. In this paper, the contribution of backscattered photon and electron from the window were evaluated by using Monte Carlo simulation. The insight would stimulates important questions concerning soft-tissue dosimetry by using a thin plastic scintillator.



**Figure 1.** The exit face of the scintillator (non-wrapped part) is optically coupled to the PMT of the same diameter with optical silicon grease.

## 2. Monte Carlo simulation

Monte Carlo code for electron and photon transport (EGS5 code [7]) was used to calculate the absorbed energy and dose in scintillator for total effect with PMT window for 0.1 to 1 MeV photon energy. The plastic scintillator and PMT window material data and density for the calculations correspond to the manufacturer's data [8] and National Institute of Standard and Technology, NIST database [9], respectively as per our previous study [10]. The plastic scintillator material used in this study is EJ200 (Eljen Technology, Sweetwater, TX, USA) [8], while the readout device used is a photomultiplier tube Model R375 from Hamamatsu [11] with a diameter of 5.0 cm. To date, the thickness of standard plastic scintillator cast sheet available in the industry is within 0.5 mm to 150 mm, while for special large cast sheet, the thickness ranged from 1 to 5 cm with maximum diameter and length of 30 cm and 450 cm, respectively [12]. In this study, the calculations were performed for a 0.5 mm plastic scintillator for total effect with five different types of PMT window materials; quartz, sapphire, borosilicate, lithium fluoride (LiF) and magnesium fluoride ( $MgF_2$ ).

In the simulation process, photons interaction such as photoelectric absorption, Compton scattering and pair productions were considered. The parallel photons beam of the same radius with the scintillator was set to incident on the front face of the scintillator. In EGS5 calculation, the calculated absorbed doses in the scintillator were based on calculation of absorbed photon energy in some volume of material. When material is exposed to radiation, energy is absorbed in material. Absorbed dose is then calculated as the average energy transferred to small volume mass of plastic scintillator material by photon. Following conversion were used to convert the unit of MeV/g to Gy as outlined in equation 1 and 2.

$$1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J} \quad (1)$$

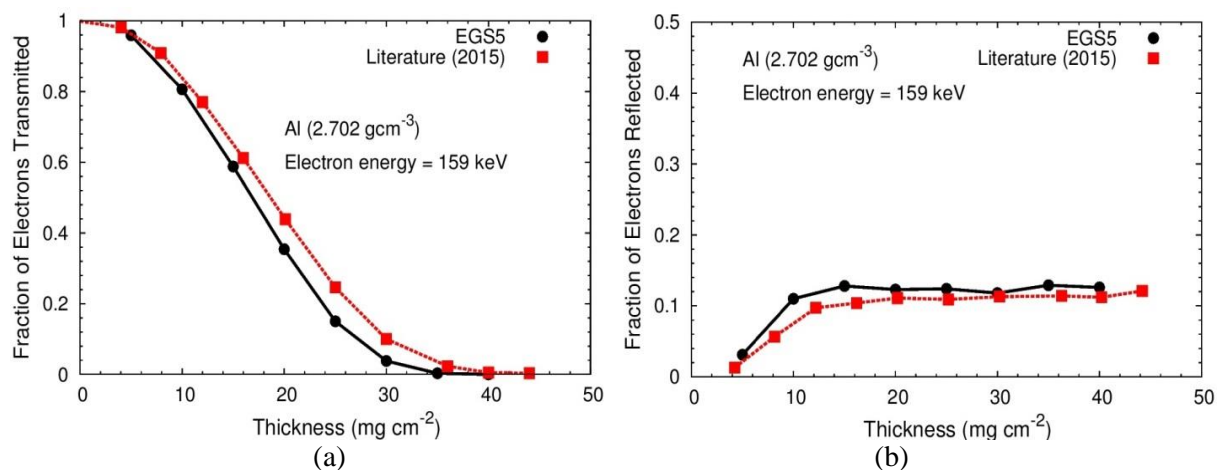
$$1 \text{ MeV/g} = 1.602 \times 10^{-13} \text{ (J/MeV)} \times 1000 \text{ (g/kg)} = 1.602 \times 10^{-10} \text{ Gy} \quad (2)$$

The electrons or photons generated in the PMT window that were backscattered to the scintillator were identified. The absorbed energy in the scintillator was scored separately by considering the contribution of reflected photons or electrons from the window. For comparison, the absorbed energy was also scored without the window. Consequently, the absorbed energy and dose in scintillator were scored with the total effect of PMT window as follows; (a) with PMT window, (b) with reflected photon only, (c) with reflected electron only and (d) without PMT window.

### 3. Result and discussion

#### 3.1. Calculated transmitted-reflected electrons of the aluminium for 159 keV electron

EGS5 code had been used widely to transport or simulate radiation like photons [13] in materials. For electrons, as a benchmark of our study, we have calculated the fraction of electrons that reflected and transmitted after interaction with aluminium for comparison with literature data. Such comparison is very important to ensure that the electrons interactions within the material are properly handled by the code. Figure 2(a) and (b) shows the calculation of transmitted and reflected electron as a function of aluminium thickness for electron energy of 159 keV. The calculated values have a considerably good agreement with the literature [14], to validate the subsequent calculations result.

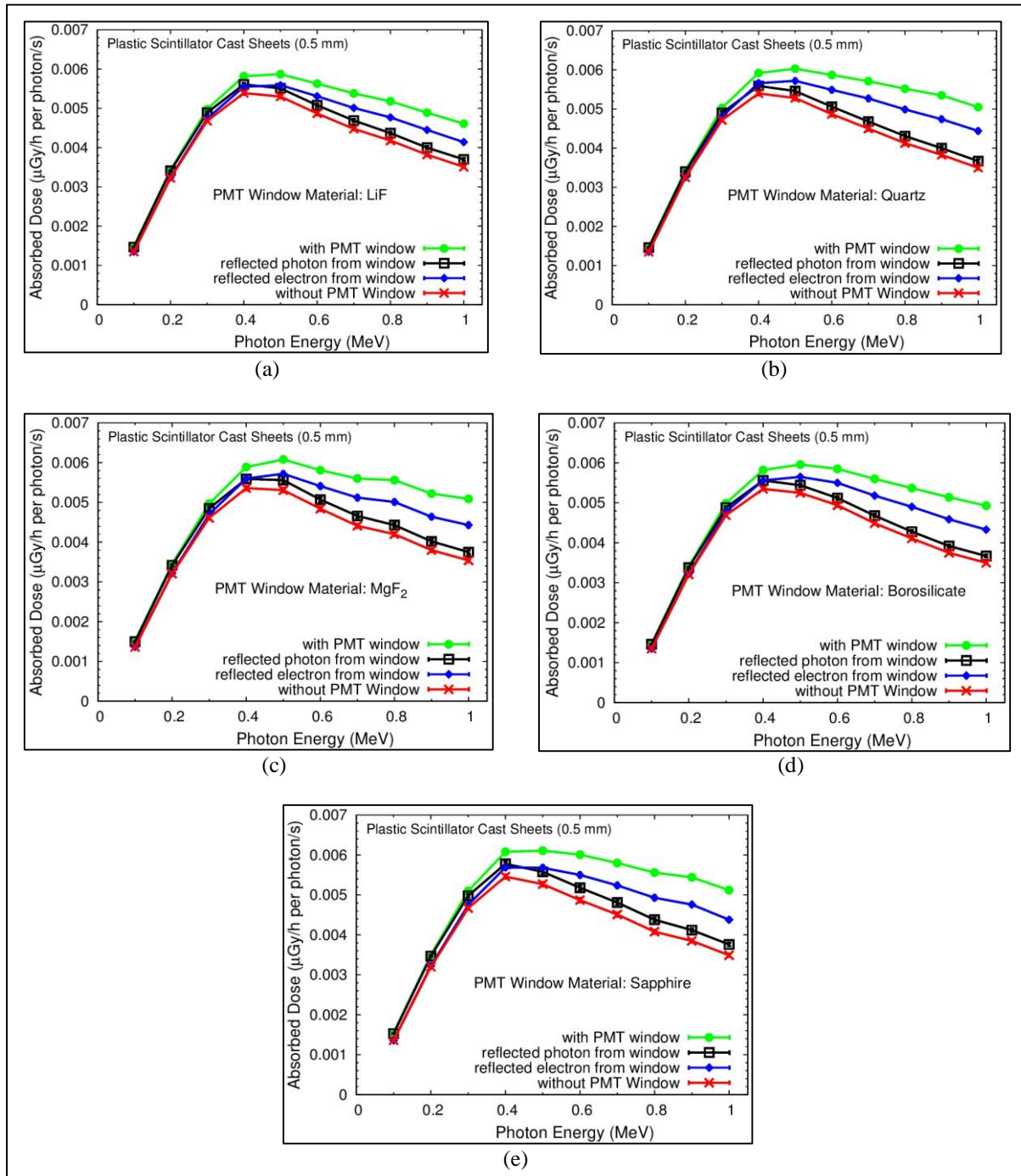


**Figure 2.** Comparison for the fractions of electrons that (a) transmitted and (b) reflected as a function of aluminum thickness.

#### 3.2. Absorbed dose of plastic scintillator without and with PMT window materials; reflected electron and photons

Figure 3 (a), (b), (c), (d) and (e) demonstrate the absorbed dose of plastic scintillator without and with (reflected photon and electron) PMT for lithium fluoride (LiF), quartz, magnesium fluoride (MgF<sub>2</sub>), borosilicate and sapphire, respectively. It can be observed that the absorbed dose linearly increases from 0.1 MeV up to 0.4 MeV for both reflected photon and electron. However, absorbed dose started to slightly reduced after 0.4 MeV up to 1 MeV. A prerequisite to understand the response of a specific type of detector is the knowledge of the dominant mechanism by which radiation interacts and hence loses energy in matter [6]. This can be due to the dominant interaction mechanism for photon energies below 0.4 MeV is the photoelectric effect, whereas the Compton scattering begins to be relevant above 0.4 MeV. Moreover, the different energies of the photon beam resulted in different penetrating depths and absorption mechanisms of the beam inside the plastic scintillator. The penetration depth is governed by the energy of the individual photons, the atomic number, density and thickness of the object, which result from the different absorption mechanisms that occur in the plastic scintillator [15]. Increasing the photon energy (0.4 MeV up to 1 MeV) causes increment in the penetrating ability and decrement in the probability of interaction, and hence resulted in less absorbed

photon energies in the plastic scintillator. Whilst, the low energy photon beam (<0.4 MeV) resulted in most radiation attributed from the photoelectric effect, which is the dominant mechanism that contribute to the higher absorption and hence excitation.



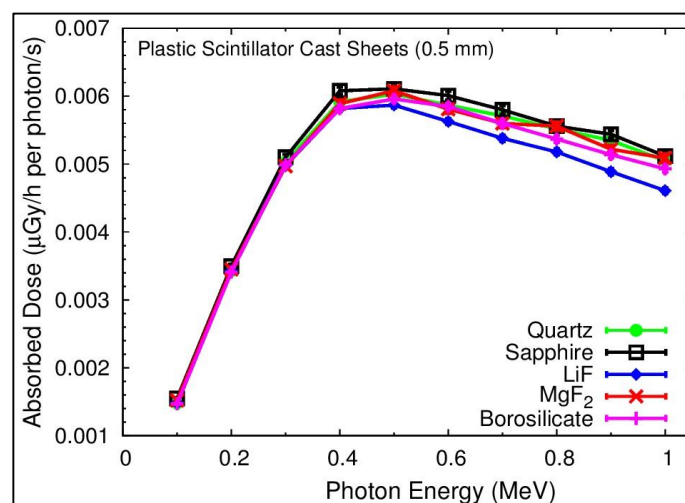
**Figure 3.** Absorbed dose of plastic scintillator without and with (reflected photons and electrons) for PMT window materials; (a) lithium fluoride (LiF), (b) quartz, (c) magnesium fluoride (MgF<sub>2</sub>), (d) borosilicate, and (e) sapphire.



Generally, the reflected photon and reflected electron exhibited almost similar trend of absorbed dose for photon energies below 0.4 MeV for all PMT window materials. Whilst, reflected electrons contribute significantly higher to the additional absorbed dose in comparison to the reflected photon for photon energies 0.4 MeV up to 1 MeV. Within that range also, the absorbed dose without PMT window can be observed to be significantly lowered than absorbed dose with the PMT window materials. This can be ascertained from the significant additional dose of a PMT quartz window for 0.4 to 1 MeV photons (20 % to 43 %) in comparison to one without quartz as shown in Figure 3(b). These circumstances can be explained from the dominant interactions occur inside the plastic scintillator below 0.4 MeV is the photoelectric effect, whereas the Compton scattering begins to be relevant above 0.4 MeV, as discussed previously. Compton interaction is the scattering of incoming photons, which is deflected through an angle,  $\theta$  with respect to its original direction [6]. During interaction, the incident photons will transfer part of its energy to the scattered electron, which results in a decrease in energy of the incident photon and contribute to an unwanted scintillation being produced in the plastic scintillator. The probability of Compton scattering per atom of the absorber depends on the number of available electrons as scattering targets and therefore increases linearly with  $Z$ . Therefore, the effect of the reflected electron and reflected photon on the absorbed dose can be significantly differentiate at 1 MeV in the high- $Z$  material; sapphire ( $Z_{\text{eff}} = 10.454$ ) [16] in Figure 3(e), which increase up to 19% in comparison to low- $Z$  material; LiF ( $Z_{\text{eff}} = 8.14$ ) [17] in Figure 3(a), which increases up to 13.5%.

### 3.3. Total absorbed dose of plastic scintillator with PMT window materials; quartz, sapphire, borosilicate, lithium fluoride (LiF) and magnesium fluoride ( $\text{MgF}_2$ )

The data in Figure 4 indicates that sapphire glass contributes the highest additional dose to the plastic scintillator, while the lowest dose given by LiF material. The additional dose in the plastic scintillator for energy ranged from 0.4 MeV to 1 MeV due to sapphire and LiF glass are increases from 11 % to 47 % and 8 % to 31 %, respectively. The second lowest material that contributes to the additional dose is borosilicate. This can be explained from the probability of the different interactions occurring within the material, which depends on the density of the material and photon energy. Different materials will have different threshold energy and regions of high cross-sections, which results in different mechanism (either Photoelectric or Compton) dominating the characteristics as explained in Section 3.2. Both processes lead to the partial or complete transfer of the photon energy to the electron, which results in the incident photon undergoing scatter over a range of angles or being completely absorbed.



**Figure 4.** Total absorbed dose of plastic scintillator for five PMT window materials

The rate of the photon attenuation by the material depends on the atomic number, atomic mass and density of the material [15]. Due to the change in the photon direction after the interaction with the electron, Compton scattering results in a portion of the incident radiation ‘bouncing off’ or being fully scattered by the material [6]. Therefore, material within the primary photon beam, which includes the detector itself becomes the actual source of unwanted scintillation. The low- $Z$  number ( $Z_{\text{eff}} = 8.14$ ) [17] and density ( $\rho = 2.63 \text{ g/cm}^3$ ) of LiF result in a lower photon absorption coefficient, where the dominant mechanism is through photoelectric absorption. Otherwise, sapphire glass consists a relatively high percent of aluminum (Al) element in its mixture, which contribute to the high  $Z_{\text{eff}}$  ( $Z_{\text{eff}} = 10.454$ ) [16] and density ( $\rho = 3.987 \text{ g/cm}^3$ ), and hence increasing the unwanted scintillations in the plastic scintillator.

#### 4. Conclusion

The use of plastic scintillator along with the PMT has contributed to the significant additional absorbed dose. Contribution of the additional absorbed dose in plastic scintillator mainly depends on the thickness and types of PMT window material, which consist of different density and  $Z$  number, and therefore different absorption and scattering mechanism. In conclusion, a plastic scintillator with considerable thickness along with a good choice of PMT window thickness and material should be adopted for the ‘soft-tissue’ dose response, in order to reduce the unwanted additional dose.

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