Monte Carlo studies of metal/phosphor screen in therapeutic X-ray imaging

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Abstract

In order to provide the optimal design parameters, we have investigated the characteristics of a combination of metal plate and phosphor screen, a typical X-ray sensor in electronic portal imaging system, by using Monte Carlo simulation. Detection efficiency and spatial resolution of the X-ray sensor were estimated based on the bremsstrahlung spectrum of the incident X-ray and for various thicknesses of metal plate and phosphor screen. The detection efficiency was calculated from the total absorbed energy and the spatial resolution was defined from the spatial distribution of the absorbed energy. Simulation results showed a trade-off relationship between the detection efficiency and the spatial resolution. It was also found that the detection efficiency and the spatial resolution were mainly determined by thickness of metal plate and phosphor screen, respectively. The simulation will be useful when determining the optimal thickness of phosphor screen as well as of metal plate for the sensor design of therapeutic X-ray imaging. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The combination of metal plate and phosphor screen, which converts incident X-ray into visible light, with a TV camera is still the most popular detector system among various electronic portal imaging devices (EPIDs) [1–4]. The metal plate is used to increase the conversion efficiency of phosphor screen by producing high-energy electrons when irradiated by X-ray. In commercial products, brass, steel and copper with the range of 1–2.25 mm in thickness are used [4,5]. In the case of phosphor screen, a terbium doped gadolinium oxysulfide (Gd\(_2\)O\(_2\)S: Tb), which is commonly applied to diagnostic radiology, with the range of 150–500 mg/cm\(^2\) in coverage is used [4,5]. Because the metal plate/phosphor screen is the first stage of
transferring anatomical information in the imaging chains of TV camera-based EPID, it is largely responsible for the total performance of the system. Therefore, the optimal design of the metal plate/phosphor screen as an X-ray sensor must be done.

In this study, accounting for the maximized detection efficiency and spatial resolution, we have investigated the characteristics of various combinations in thickness of metal plate and phosphor screen by using Monte Carlo simulation. Based on results of simulation, we give a full detail of the optimal combination between metal plate and phosphor in this manuscript.

2. Methods

2.1. Definitions

As briefly described in the above section, we considered two quantities, such as detection efficiency and spatial resolution as a touchstone of good performance. The detection efficiency was calculated from the total absorbed energy with phosphor screen for incident photon energy. Whereas the spatial resolution was defined by the full-width at half-maximum (FWHM) of a point spread function, which is the distribution of the optical photon-flux over the surface of the phosphor screen opposite to metal side. We have assumed that the optical photon is generated in the center of a small cubic box of which total intensity is proportional to the total absorbed energy in the box and then propagates isotropically without attenuation. The reflection from the metal-phosphor interface is neglected. The optical photon-flux collected over the solid angle of a rectangular pixel of size $2X \times 2Y$, can be expressed by [6–8]

$$P(z) = \int_{-Y}^{Y} \int_{-X}^{X} \frac{N_{\text{opt}}}{4\pi} \times \frac{z}{(x^2 + y^2 + z^2)^{3/2}} \, dx \, dy,$$

where $x$, $y$ and $z$ are two-dimensional coordinates of the end-sided phosphor screen and distance to the light source, respectively. $N_{\text{opt}}$ is the number of photons generated at which the X-ray energy is absorbed within phosphor screen and can be calculated by

$$N_{\text{opt}} = e \times \frac{E_{\text{abs}}}{E_{\text{opt}}}.$$

In Eq. (2), $e$ is the intrinsic conversion efficiency in the range of 15–20% [9,10], $E_{\text{opt}}$ and $E_{\text{abs}}$ are the optical photon energy (2.28 eV for 545 nm wavelength from Gd$_2$O$_2$S : Tb) and the locally absorbed energy within phosphor screen from the secondary fast electrons, respectively.

2.2. Monte Carlo simulation

In order to determine the energy absorption within the phosphor screen, we used Monte Carlo N-Particle, version 4B (MCNP4B) code [11], which simulates X-ray interactions in metal plate and phosphor screen. The use of MCNP4B code had been successfully implemented into our previous work obtaining the NaI(Tl) detector response function for incident $\gamma$-ray [12]. In this study, the X-ray detector was simply modeled as shown schematically in Fig. 1, which consisted of copper plate (0–50 mm) in contact with Gd$_2$O$_2$S layer (0.1–5 mm). Despite of complexity of phosphor screen, we modeled into Gd$_2$O$_2$S monolayer with reduced density of 3.67 g/cm$^3$ accounting for other compositions like polyurethane polymer binder [5,13]. For the incident X-ray beam, a pencil beam with bremsstrahlung spectrum, incident perpendicularly on

![Fig. 1. Monte Carlo geometry used in determining the total and local energy absorption within phosphor layer for various thickness combinations of metal plate/phosphor layer. Pencil beam of bremsstrahlung X-ray from the target of 6 MV LINAC is incident perpendicularly on the planar X-ray detector with 20 cm radius.]
the X-ray detector was considered. Bremsstrahlung spectrum from the target of the 6 MV linear accelerator (LINAC) was also simulated by MCNP4B using the data in the Refs. [14,15].

Locally distributed energy absorption was estimated in cubic cells of phosphor layer in Monte Carlo simulation. Then, the center point of the cell was assumed to be the representative position as the energy absorption or optical photon-source point. This is more accurate approach compared to the approximation given in the Ref. [8], a continuum of point sources distributed over the end-sided surface of phosphor layer.

3. Results and discussion

3.1. Bremsstrahlung spectrum

Simulated bremsstrahlung spectra, number and intensity, for 6 MV LINAC are shown in Fig. 2. To confirm the simulation result, Schiff intensity spectrum [15,16], widely used in the analysis of experimental results, was also calculated and represented in the same figure. The maximum energy, 7.58 MeV, is due to LINAC energy of electron beams used to produce the bremsstrahlung X-ray [14]. The normalized number spectrum is, then, implemented to the source-input of Monte Carlo simulation as described in the above section.

3.2. Detection efficiency

For the incident bremsstrahlung X-ray with the mean energy of 2.55 MeV, the detection efficiencies in unit of energy and percentage are presented as a function of metal thickness for three cases of phosphor thickness, such as 0.1, 1 and 3 mm, in Fig. 3. The results show that, the detection efficiency rapidly approaches to the maximum value and then decreases very slowly, as the metal thickness increases. We can analyze this characteristic by using the electron flux shape from the metal plate, shown in Fig. 4, and the electron range in phosphor layer. Number of electrons penetrating metal plate is dependent upon their energies and corresponding ranges, so that the distribution as a function of metal thickness shows a maximum value. When the thickness of phosphor layer is comparable to the range of electrons, the energy absorption is uniform, but if the thickness of phosphor layer is greater than the range of electrons, the energy absorption is governed by the electron flux as shown in Fig. 4.

From the simulation result, we also find that, the improvement of detection efficiency due to the metal plate is more effective, as the phosphor thickness is thinner. In other words, the metal plate

Fig. 2. Normalized spectra as a function of energy. Solid and dotted histograms represent the intensity and number spectrum resulted from Monte Carlo simulations, respectively. Confirming the result of Monte Carlo simulation, the intensity spectrum calculated by Schiff formula is also plotted as a line graph.

Fig. 3. Detection efficiencies (in unit of MeV and %) as a function of metal thickness for 0.5, 1 and 3 mm-thick phosphor, which are calculated by total energy absorption using Monte Carlo simulation for the bremsstrahlung X-ray spectrum with mean energy of 2.55 MeV.
improves the energy absorption to about 4 times higher for 0.1 mm of phosphor thickness, but only about 1.2 times at maximum for 5 mm of phosphor thickness.

3.3. Spatial resolution

Based on the Monte Carlo simulated spatial distribution of energy absorption, we calculated the distribution of optical photon flux collected by 10 × 10 μm² pixel area as a function of pixel position on the free surface of the phosphor screen. While Fig. 5 shows the results for various phosphor thicknesses without metal plate, Fig. 6 represents the results for 1 mm-thick phosphor layer with various metal plate thicknesses. As shown in figures, it is observed that the spatial broadening is largely affected by the phosphor thickness but the metal plate could be negligible. From the results, it can be inferred that electrons emitted from metal plate is not significantly spread, but is well confined along the direction-line of the incident X-ray. Supplementary Monte Carlo simulation showed that 90% of electron flux emitted from the metal plates of thickness from 1 to 5 mm is confined within the area of 1 mm-diameter.

In order to suggest a criterion for determining the design parameter of X-ray detector, we put the detection efficiency and spatial resolution together in Fig. 7 as a function of phosphor thickness. In
this figure, we can say that the metal does not degrade the spatial resolution. In addition, it can be also observed that the relative enhancing effect of metal on the detection efficiency for thick phosphor layer becomes smaller.

4. Conclusions

Using Monte Carlo simulation, we estimated the spatial resolution as well as detection efficiency for various combinations of metal plate/phosphor screen as a X-ray detector in TV camera-based EPID. The results show that, the improvement of detection efficiency by metal plate is very small over 1 mm-thick metal plate, although the metal plate enhances the energy absorption within phosphor screen. Moreover, it was found that the detection efficiency strongly depends upon the emitting electron flux from metal plate. On the other hand, from the strong directionality of electrons, the degradation of spatial resolution due to the metal thickness could be disregarded. Experimental verification of these simulation results is under design currently in KAIST and Catholic Medical Center. Once proved experimentally, this study will be a very useful guide to design the X-ray detector of electronic portal imaging system as well as another imaging system using the similar detector structure.

References