Transactions of the Korean Nuclear Society Spring Meeting
Changwon, Korea, October 24-25, 2024

Monte Carlo modeling of x-ray phosphor screens

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***Keywords : Phosphor screen, collection efficiency, modulation transfer function, light photon simulation**

1. Introduction

The X-ray film continues to be utilized as a detector in various applications, however, Digital Detector Arrays (DDAs) increasingly replacing traditional film [1]. In indirect conversion DDAs, x-ray quantum energy is first converted into light using a scintillator or phosphor screen. This light is subsequently transformed into electrical signals by a photodiode or switching transistor array, which are then used to generate images.

Among the various x-ray converters, the terbium-doped gadolinium oxysulfide (Gd_2O_2S:Tb) granular phosphor screen is widely adopted due to its well-established technology. To optimize the performance of phosphor screens, it is essential to accurately evaluate their performance and develop reliable models. The Monte Carlo method is a powerful tool for simulating the performance of phosphor screens. In many detectors, an optical coupler is typically employed between the x-ray converter and the detection plane. We conducted simulations under two conditions: the first is an ideal phosphor model without an air gap, functioning as an optical coupler; the second is a more realistic model incorporating an air gap [3, 4].

This study aims to simulate various phosphor screen models using DETECT 2000, a Monte Carlo simulation tool. The performance of these models will be assessed by analyzing Modulation Transfer Function (MTF), and Collection Efficiency η, with particular focus on the reflective coefficient (RC) at screen backing and depth of the x-ray interaction position in model.

2. Methods

2.1 Simulation

DETECT2000 is a Monte Carlo code designed to simulate the transport of optical photons. In DETECT2000, the input file allows for the configuration of various parameters related to the phosphor screen, including its geometry, the refractive index n of the material, the reflection coefficient of surfaces, and the physical and optical parameters that influence optical photon interactions, absorption mean free path (μ_{abs}) and scattering mean free path (μ_{scatt}). Additionally, the position of x-ray interaction, where x-rays are converted into light photons, can also be specified.

2.2 Phosphor screen model

The phosphor screen model used in this study is a Gd_2O_2S:Tb granular screen, which has air gap between phosphor screen and photon detecting surface. Physical and optical parameters employed, were referenced from [2].

It is assumed that photons interacting with the lateral surfaces are neither reflected nor scattered, but rather transmitted. Consequently, the RC at the lateral surfaces of both the Gd_2O_2S:Tb screen and the air gap are set to 0.

Assuming an ideal scenario where the detecting surface is directly attached to the phosphor screen, the detecting surface would be located at the plane z = 0 mm. Conversely, if we assume a more realistic scenario where an air gap exists, the detecting surface in this simulation is located at the plane z = -0.001 mm.

2.3 Evaluation

2.3.1 Collection efficiency

Collection efficiency η is an intuitive metric for evaluating the performance of a phosphor screen, as only the photons that reach the detecting surface can be converted into electrical signals used for imaging. In this study, we evaluated the collection efficiency based on variations in two parameters; the depth z within the phosphor screen where photons are generated, and the RC at the screen backing.

2.3.2 MTF

The MTF is a quantitative metric that can measure the spatial resolution of imaging systems. In general, MTF can be obtained by Fourier transforming the line spread function (LSF) based on the Fourier slice theory.

$$\mathrm{MTF}(u) = \left|\mathrm{FT}\left\{\frac{\mathrm{LSF}(x)}{\int \mathrm{LSF}(x)dx}\right\}\right| \tag{1}$$

When the PSF is symmetric at all angles, it can be sampled in the radial direction and then Hankel transformed to obtain the MTF.

$$\mathrm{MTF}(u) = 2\pi \int \mathrm{psf}(r) J_0(2\pi q r) r dr \tag{2}$$

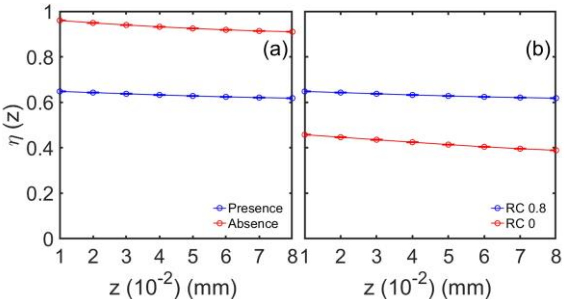

Fig.1. Collection efficiency for depth z for (a) both the presence and absence of an air gap with an RC value of 0.8, and (b) for different RC values in the presence of air gap.

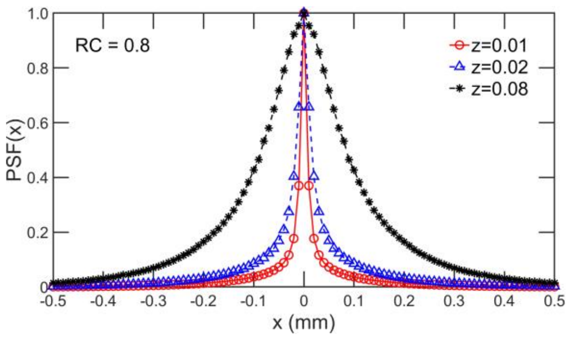

Fig.2. Point Spread function (PSF) at different depths z with the RC value fixed at 0.8.

$$J_0(r) = \frac{1}{\pi}\int_0^{\pi} \cos(r \sin\theta)\, d\theta \quad (3)$$

Where $J_0(r)$ is the zero-order Bessel function.

3. Preliminary Results

Fig. 1 (a) shows that the presence of an air gap result in lower collection efficiency and a different slope compared to the case without an air gap. Fig.1 (b) shows that the collection efficiency increases as the RC value increases

Fig.2 shows the PSF for different values of depth z. As z increases, the PSF broadens.

Fig. 3 presents MTFs calculated using two methods for different RC values with fixed depth z. Comparing Figs.3 (a) and (b), the graphs exhibit similar values and shapes, indicating that Hankel transform MTF can be a valid alternative to Fourier transform MTF for analysis. Unlike collection efficiency, the MTF demonstrates better distribution with smaller RC values.

4. Conclusion

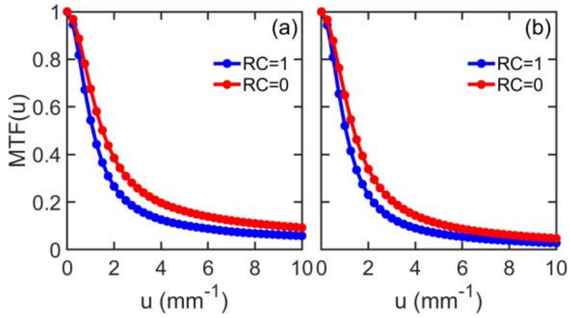

Fig.3. MTF calculated using a) Fourier transform and b) Hankel transform for different RC values with the depth z fixed at 0.01mm

In this study, we evaluated the MTF performance of a phosphor screen under various parameter conditions using DETECT2000. The collection efficiency can be influenced by the presence of an air gap and the RC value. We confirmed that a higher RC value can increase collection efficiency. However, a higher RC value does not necessarily ensure better imaging performance, as it can degrade the spatial resolution of the detector by causing a wider spread of light photons.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT). (No. RS-2024-00340520).

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