Effect of Focal Spot Size on Dose Calculation of a $ZnWO_4$ Thin-Film Scintillator for High-Resolution X-ray Imaging

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1. Introduction

Zinc tungstate ($ZnWO_4$) is an attractive material for inorganic scintillators due to its high density, effective atomic number, and high light yield (~10,000 photons/MeV) [1] It also exhibits excellent mechanical and chemical properties so that it has been widely used for high-resolution X-ray imaging as scintillators [2,3]. When thin-film scintillators are used, the sensitivity is less spread out, resulting in higher sensitivity.

In general, X-ray imaging systems using scintillators construct an image by collecting visible light generated by the scintillator hitting X-rays. Prior to scintillation evaluation, the X-ray imaging system is operated at a constant tube power, where tube voltage and tube current are inversely proportional. When tube current varies, the incident diameter of the electron source, as known as the focal spot, would be changed. It may result in the resolution of an image.

In this study, we investigated the absorbed dose distribution of $ZnWO_4$ thin-film scintillator by a tungsten phantom using the Monte Carlo N-Particle (MCNP) transport code. To achieve high-resolution X-ray imaging, the dose was preliminarily calculated depending on the focal spot size of an X-ray tube.

2. Method

2.1 Geometry Construction

Fig. 1 illustrates a typical high-resolution X-ray imaging system, containing an X-ray tube, a scintillator, a magnification lens, and a detector. To shorten the calculation time, a simple description was set up as shown in Fig. 2. A tungsten target and a beryllium window (Φ1.26 cm, 0.01 cm thickness) were placed inside the tube, and the interior of the tube was set to vacuum. The distance between the target and the window was separated by about 2.082 cm according to a microfocus X-ray tube model P030.24.12F100W (Petrick GmbH, Germany) specification. The thickness of the scintillation layer was calculated by Eq. 1, and 3 μm was obtained by using the known parameters.

$$t = \frac{sl}{M^2 D} \tag{1}$$

where, t is the thickness of scintillator for high-resolution X-ray images, s is the detector pixel size (6.5 μm), l is the distance between the magnification lens and the detector (21 cm), M is the magnification (8), and D is the diameter of the magnification lens (0.75 cm) in the imaging system. The scintillator was applied in the form of a 3 μm $ZnWO_4$ layer deposited on 1 mm thick quartz (Φ15 mm). It was separated by 0.918 cm from the Be window, *i.e.*, at a linear distance of 3 cm from the W target. A tungsten filter, with 15 mm in thickness, was designed to be positioned halfway between the window and the scintillator for absorbed dose calculation.

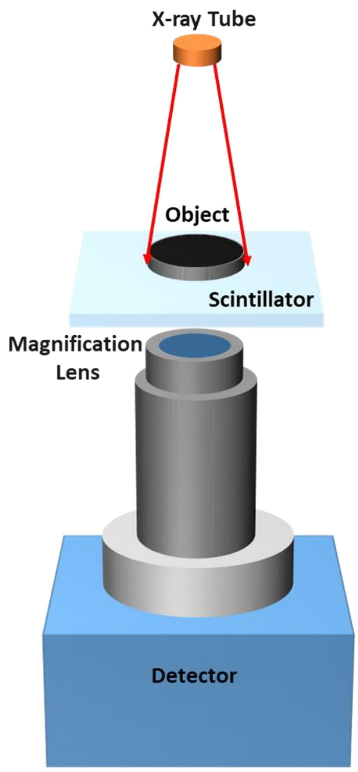

Fig. 1. Illustration of a general X-ray imaging system.

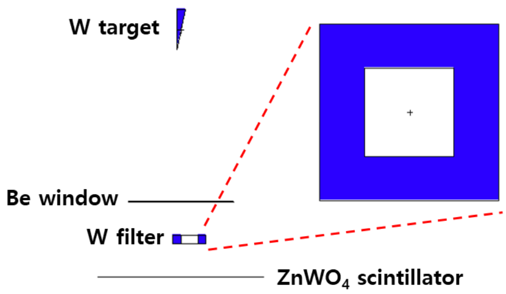

Fig. 2. Simple description of the X-ray scintillation part for MCNP dose simulation.

2.2 MCNP Simulation

The simulation was performed using the MCNP6 code developed from Los Alamos National Laboratory. The density of the vacuum was determined to be 10^{-20} g/cm^3. The W target was constructed in a truncated cylinder form and was placed in the centerline. The position of the electron source is at a point 1 cm away from the target and is incident with a mono-energy in the direction of the target (*i.e.*, uni-direction). The number and energy of electrons were applied differently depending on the variation in tube voltage. Additionally, the diameter of the incident electron beam was input in two extreme cases, (i) a point source and (ii) a disc source with the maximum radius. X-rays generated from the target were directed through the Be window in the vertical direction. The $ZnWO_4$ scintillator was designated as a tally, and it was simulated at 10^9 nps using the F4 mesh tally (mode p). The area of out-of-interest was defined as void. For importance, photons and electrons were set to "1", and in the void region, "0" was assigned.

3. Results and Discussion

The focal spot is also a factor that affects image resolution, and the focal spot formed in two extreme cases of very low tube current and very high tube current was examined. When the tube current is very low, that is, when the tube voltage is very high, the electrons incident on the target are a point source, and vice versa, the electrons are incident on a circular plane. Fig. 3 depicts the focal spot of the generated X-rays relying on the incident cross-sectional area of the electron beam. At the lowest current, the focal spot converges to zero, but at the highest current, it coincides with the highest part of the truncated cylindrical target (~4 mm).

X-rays generated by electrons hitting the target pass through a W filter and reach the scintillator. Fig. 4 shows the dose distribution absorbed by the scintillator under the two tube current conditions. In the parts with the W phantom, it was confirmed that the doses were almost zero in both cases. Furthermore, the slope at the boundary was slightly steeper when the focal spot was 0. Therefore, the resolution would be better when the focal

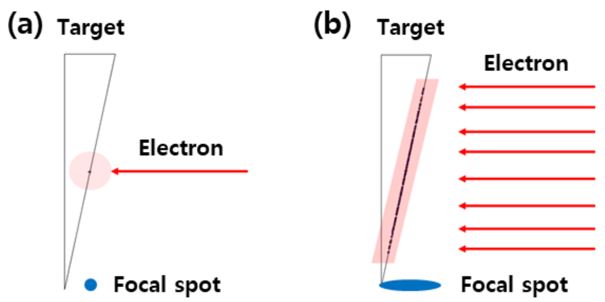

Fig. 3. Focal spot of X-rays at the (a) lowest tube current and (b) highest tube current.

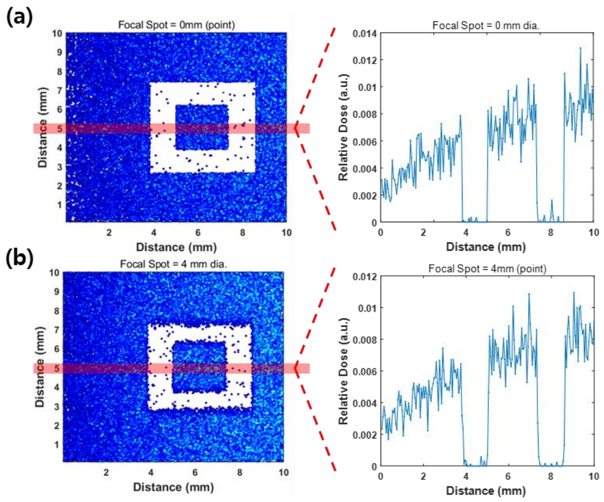

Fig. 4. Absorbed dose distribution of $ZnWO_4$ scintillator and relative dose corresponding to the red line by X-rays with a focal spot of (a) zero and (b) 4 mm.

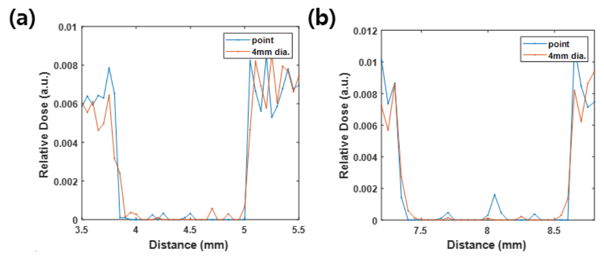

Fig. 5. Comparison of relative dose depending on the focal spot for each location: (a) 3.5~5.5 and (b) 7~9 mm.

spot is small, where the tube current is small. However, since the difference in the slope in the two cases is not so large as shown in Fig. 5, further calculation using other software such as OPTICS or DETECT, which can simulate the behavior of visible light, is needed.

4. Conclusions

The X-ray focal spot may vary depending on the tube current and affect the resolution of the X-ray image. The absorbed dose by the scintillator was calculated in two extreme situations, where the focal spot was the minimum and the maximum, and the degree of changes in the dose was evaluated using a W filter. In the region where the edge of the filter exists, a sharper change in dose can be observed when the focal spot is small. It suggests that the use of lower tube currents can enhance the resolution of X-ray images. Nevertheless, for a more accurate analysis, research using simulations covering the visible light region should also be conducted.

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REFERENCES

[1] C. Grupen and I. Buvat (eds.), Handbook of Particle Detection and Imaging, Springer, New York, 2012.
[2] V. B. Mikhailik and H. Kraus, Luminescence of $CaWO_4$, $CaMoO_4$, and $ZnWO_4$ scintillating crystals under different excitations, Journal of Applied Physics, Vol.97, p.083523, 2005.
[3] P. Belli, R. Bernabei, F. Cappella, R. Cerulli, F. A. Danevich, A. M. Dubovik, S. d'Angelo, E.N. Galashov, B. V. Grinyov, A. Incicchitti, V. V. Kobychev, M. Laubenstein, L. L. Nagornaya, F. Nozzoli, D. V. Poda, R. B. Podviyanuk, O. G. Polischuk, D. Prosperi, V. N. Shlegel, V. I. Tretyak, I. A. Tupitsyna, Ya. V. Vasiliev, and Yu. Ya. Vostretsov, Radioactive contamination of $ZnWO_4$ crystal scintillators, Nuclear Instruments and Methods in Physics Research A, Vol.626-627, pp.31-38, 2011.