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A theoretical model describing the light emission efficiency of single-crystal scintillators in the diagnostic energy range

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ABSTRACT: The aim of this study was to develop a theoretical model to examine emission features of single-crystal scintillators, used in medical imaging detectors, under X-ray excitation. For this purpose, the number of optical photons that were produced inside the crystal and escaped to the output was modeled for variant X-ray tube voltages in the energy range of Computed Tomography and for different thicknesses of the crystalline material. The theoretical model that was used to estimate the optimum dimensions and the radiation conditions of the crystal, was validated against experimental data obtained by a single-crystal scintillator irradiated by X-rays. For implementation a Gd_2SiO_5:Ce crystal was used. Theoretical and experimental results will be useful in designing Hybrid Tomographic imaging systems based on a common gamma-ray and X-ray detector (PET/CT or SPECT/CT).

KEYWORDS: X-ray detectors; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA)

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1 Introduction

Medical imaging systems such as X-ray radiography and fluoroscopy, X-ray Computed Tomography (CT), Single Photon Emission Tomography (SPECT), Positron Emission Tomography (PET) are based on scintillator radiation detectors. Scintillators are materials that emit light when excited by ionizing radiation and are usually used in the form of single-crystals, granular scintillating screens or ceramic blocks, coupled to optical photon detectors. The sensitivity of these systems is increased when more efficient and faster scintillating crystals are used [1, 2].

A growing interest in the development of dual modality PET/CT or SPECT/CT scanners prompts the comparative study of numerous scintillators to select the best one. For this purpose, a theoretical model to simulate light emission characteristics of single-crystal scintillators might be useful [3, 6].

Various theoretical models investigating the light emission by granular and non-granular scintillators have been previously published [5, 11]. In all these models, however, only the thickness was considered while the other dimensions (e.g. area or lateral thickness) were assumed infinite.

In the present study, the light emission efficiency was modeled as a function of crystal's dimensions (height and thickness), optical photons emission angle and X-ray photons energy. For this purpose a crystal of finite dimensions was considered. The present theoretical model was validated against experimental results obtained by irradiating a single-crystal scintillator by X-rays.

2 Materials and methods

2.1 Theoretical model

The theoretical model was based on crystal's geometry and the basic principles of Optics (Law of refraction, total internal reflection). A single-crystal scintillator of finite dimensions was considered to be irradiated at normal incidence by X-rays. A fraction of X-ray energy was absorbed in a random site inside the crystal [10]. Optical photons, generated at this site, were assumed to propagate isotropically within the crystal bulk. The path length of the optical photons in the crystal, varied according to their emission angle and generation site.

2.1.1 Output without reflection

For emission angles optical photons escape the crystal without reflection at the inner crystal's surfaces. The path length, $L(y,\phi,t)$, traveled by optical photons to reach crystal's output is given by the following equation [Figure 1]:

$$L(y,\phi,t) = \frac{T-t}{\cos\phi} \tag{2.1}$$

where y is the height and t is the thickness of the crystal at the point of X-ray energy absorption, ϕ is the emission angle of optical photons and T is the total thickness of the crystal.

2.1.2 Output with reflection

Optical photons are subject to totally internal reflection for emission angles $\tan^{-1}[y/(T-t) < \phi < 90^0 - \theta_{\text{crit}}$. Their path is given by the following equation [Figure 2]:

$$L(y,\phi,t) = \frac{y}{\sin\phi} + \frac{\left[T - \left(t + \frac{y}{\tan\phi}\right)\right]}{\cos\phi} \tag{2.2}$$

where, θ_{crit} is the critical angle of incidence at the inner surface of the crystal [12].

The function $G(t,k)$ gives the fraction of optical photons, created within an elementary thin layer that escape from crystal's surface and is given by the equation [3, 9–11]:

$$G(t,k) = \sum_{y=0}^{H} \sum_{\phi=0}^{\pi/2} A(\phi) \cdot e^{-k \cdot L(y,\phi,t)} \tag{2.3}$$

where $A(\phi)$ is a function of optical photons' emission angle, H is the total height of single-crystal and k is the light absorption coefficient [5]. This factor is affected only by absorption phenomena because scattering phenomena are negligible in single-crystals.

In order to examine emission features of the scintillator, light emission efficiency was determined as the fraction of the total light output to the incident X-rays spectrum (crystal's input). Taking into account the various thicknesses t inside the crystalline material, where optical photons are created within an elementary thin layer and the spectrum of the incident X-rays, the light emission efficiency (LE) can be calculated by the following formula [3, 6–10]:

$$LE = \frac{\sum_{E=0}^{E_{\max}} \sum_{t=0}^{T} f(E) \cdot e^{-\mu(E) \cdot t} \cdot \mu(E) \cdot \Delta t \cdot n_c \cdot G(t,k) \cdot \gamma}{\sum_{E=0}^{E_{\max}} f(E)} \tag{2.4}$$

where $f(E)$ is the number of incident X-ray photons with energy E, $\mu(E)$ is the X-ray photons mass attenuation coefficient, Δt is the thickness of a thin layer, n_c is the X-ray to light conversion efficiency of the scintillator, and γ is the factor converting the exposure rate (mR/sec) to energy fluence (Wm-2) of the X-ray beam.

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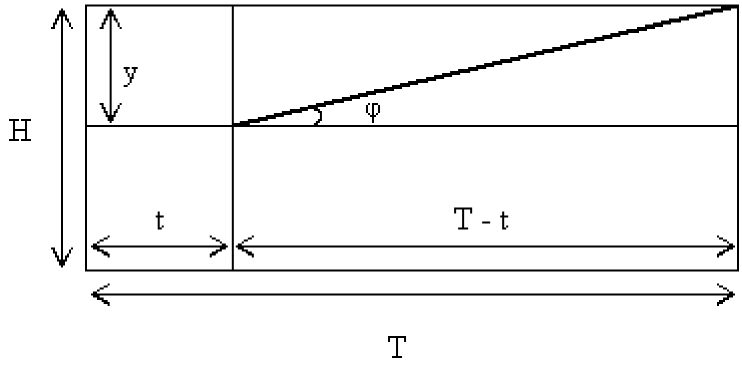

Figure 1. The path length of transmitted optical photons without reflection at the inner surface of the crystal.

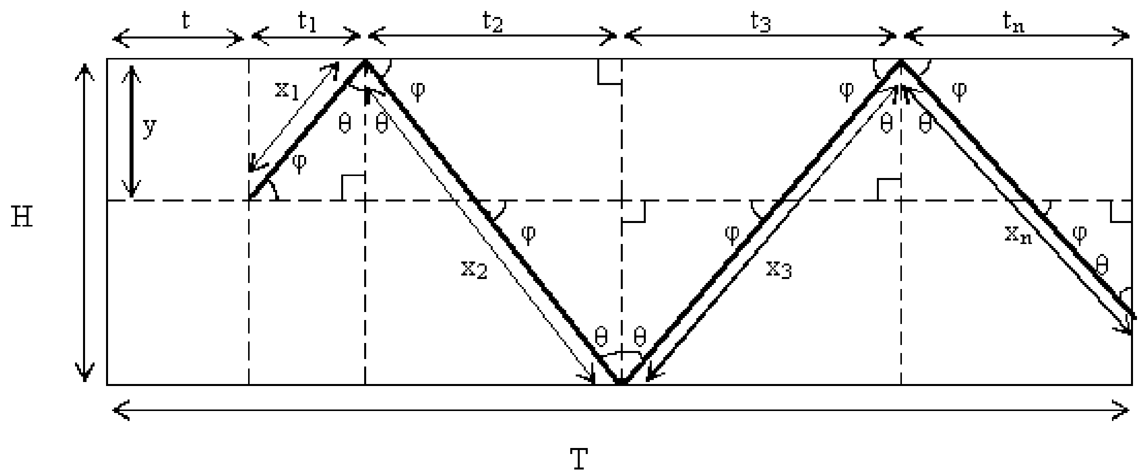

Figure 2. Total internal reflection of optical photons up to the output.

The model was used to simulate the light emission efficiency of a GSO:Ce crystal of finite dimensions (10x10x10mm) doped with 0.5 % mol of Cerium. Gd_2SiO_5:Ce (or GSO:Ce) is a non-hygroscopic scintillator, with very short decay time, which is used in Positron Emission Tomography (PET) systems and is suitable for simultaneous PET/CT detectors due to its low afterglow [1–3].

2.2 Experiments

The GSO:Ce crystal was irradiated by X-rays in a Philips Optimus X-ray unit with a tungsten anode target and 2 mm Al filter. Various X-ray tube voltages from 40 to 140 kV were employed. The beam was filtered by 20 mm of aluminum in order to simulate beam hardening by patient's body.

The X-ray exposure rate was measured at the crystal's position using a Radcal 2026C dosimeter. Light energy flux measurements were performed as follows. The light emitted by the irradiated crystal was measured by a calibrated photomultiplier (EMI 9798B) equipped with an extended sensitivity S-20 photocathode. The crystal was positioned at the input port of an integration sphere

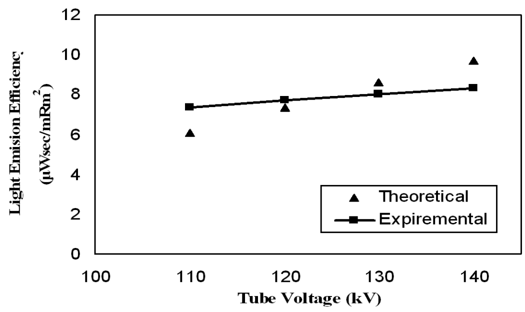

Figure 3. Comparison of theoretical and experimental light emission efficiency curves for tube voltages between 110-140kV.

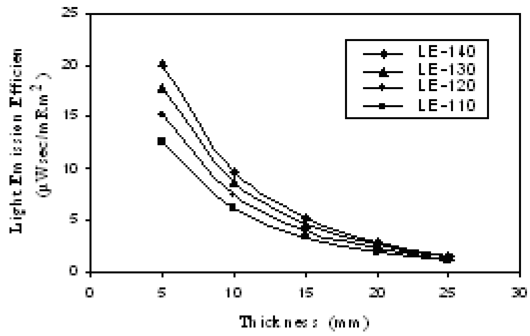

Figure 4. The light emission efficiency curve for various thicknesses of the crystal at 110, 120, 130, 140 kV.

(Oriel 70451) whereas the calibrated photomultiplier was adapted on the integration sphere's output port. Integration sphere reduces experimental errors due to illumination non-uniformities [1, 2]. The photocathode of the photomultiplier was directly connected to a Cary 401 vibrating reed electrometer. This was performed in order to avoid electronic noise amplification due photomultiplier's dynode high voltage. The exact light flux of the crystal was determined by performing the following corrections on the experimental data according to relation [1, 2]:

$$\dot{\Psi}_{\lambda} = \frac{i_{\text{elec}}}{S n_p a_s \tau} \tag{2.5}$$

where i_{elec} is the electrometer's output current in picoamperes (pA), S is the area of the irradiated scintillator, n_p is the photocathode's peak photosensitivity expressed in pA/W, which was used as a factor converting the output photocathode current into light energy flux. a_s is the spectral matching factor of the scintillator's emission spectrum to the spectral sensitivity of the photocathode (extended S-20) and is the integration sphere throughput, expressing the ratio of the total light flux exiting the sphere's output port to the total flux at the input port

3 Results and discussion

The model was compared to GSO:Ce experimental data in the energy range between 110-140 kV, employed in X-ray Computed Tomography (CT) applications. Satisfactory agreement between model and experimental data was obtained if the light absorption coefficient k was equal to 0.09746 mm-1 [3, 4]. The deviation between model and experimental data was about 1.25%.

Figure 3 shows an experimental light emission efficiency curve of the GSO:Ce crystal for various X-ray tube voltages compared to the theoretical model predictions. It is observed that light emission efficiency of GSO:Ce crystal increases with increasing X-ray tube voltage.

Furthermore, the light emission efficiency of GSO:Ce crystal was theoretically evaluated for various thicknesses of 5, 10, 15, 20, 25 mm. Figure 4 shows that light emission efficiency is reduced with increasing crystal's thickness.

The light emission efficiency of GSO:Ce crystal was found optimum at 140 kV and for 5 mm thickness.

In conclusion, a theoretical model to predict the light emission efficiency of single crystal scintillators was developed. The model may be used to determine optimum crystal dimensions for use in PET/CT or SPECT/CT imaging systems.

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