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A theoretical study of CsI:Tl columnar scintillator image quality parameters by analytical modeling

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ABSTRACT

Medical X-ray digital imaging systems such as mammography, radiography and computed tomography (CT), are composed from efficient radiation detectors, which can transform the X-rays to electron signal. Scintillators are materials that emit light when excited by X-rays and incorporated in X-ray medical imaging detectors. Columnar scintillator, like CsI:T1 is very often used for X-ray detection due to its higher performance. The columnar form limits the lateral spread of the optical photons to the scintillator output, thus it demonstrates superior spatial resolution compared to granular scintillators. The aim of this work is to provide an analytical model for calculating the MTF, the DQE and the emission efficiency of a columnar scintillator. The model parameters were validated against published Monte Carlo data. The model was able to predict the overall performance of CsI:Tl scintillators and suggested an optimum thickness of 300 μm for radiography applications.

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1. Introduction

Medical X-ray digital imaging systems such as mammography, radiography and computed tomography (CT), are composed from efficient radiation detectors, which can transform the X-rays to electron signal for further processing. These detectors are, either converting directly the X-rays to electron with the use of suitable semiconductors like a-Se, PbI_2 or GaAs, also known as direct conversion detectors, or indirectly, known as indirect detectors, with the use of appropriate scintillators as a link between the X-rays and the electric signal generating semiconductors [1–7]. Scintillators are materials that emit light when excited by X-rays. They are usually employed in the form of single-crystals, granular scintillating screens, columnar scintillators or ceramic blocks, coupled to optical photon receptors, which are sensitive to the optical spectrum of the scintillator. In addition the capabilities of these systems are increased, when more efficient and faster scintillating materials are used. Furthermore image quality properties of the detectors like resolution, noise and signal-to-noise ratio are affected by the scintillator properties [5–8]. Former indirect detectors used granular Gd_2O_2S:Tb phosphor screens coupled to a radiographic film or a digital photoreceptor. These detectors, although efficient X-ray absorbers, typically exhibited poorer spatial resolution, than the direct conversion detection systems, for medium scintillator thickness. For thin phosphor thickness however, superior granular phosphor efficiency has been theoretically evaluated [9]. Indirect detectors are also efficient X-ray absorbers, leading to lower radiation doses. Thus, the compromise between X-ray energy absorption and spatial resolution affects the thickness and image quality properties (i.e. resolution) of a scintillator. A thicker scintillator would absorb X-rays more efficiently, but it will results in reduced spatial resolution. This effect has been reported for non-columnar phosphors [5,6,8,10].

This limitation has been partially overcome by developing structured (also known as columnar) scintillator, like CsI:T1 [11–16]. CsI:Tl is a high light yield scintillator, with X-ray absorption properties somewhat inferior to those of the granular Gd_2O_2S:Tb. Its main advantage is that its columnar form limits the lateral spread of the optical photons traveling towards the scintillator output. Therefore it may demonstrate superior imaging properties compared to granular scintillators, especially for scintillator thickness higher than 180 μm [9]. CsI:Tl has been widely used as a scintillator material either in single crystal form, or in columnar microstructures. The properties of complete X-ray detectors based on CsI:Tl have been previously studied thoroughly and investigated methodically in various publications [3,11–20].

Objective image quality expressions, defined in the spatial frequency domain, such as the Modulation Transfer Function (MTF), the Noise Power Spectrum (NPS) and the Detective Quantum Efficiency (DQE), have been previously estimated for granular phosphors either with analytical models [5,6,9,21–24], or with Monte Carlo simulations, including Mie scattering theory [25–29]. In the case of structured scintillators, the analytical modeling of their imaging performance usually considers materials with specific thickness but

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infinite lateral dimensions. However, the multiple reflections from the input and output scintillator-to-air interface, for single crystal scintillator, have been analytically modeled [30]. Recently new models, accounting for the lateral dimensions as well as for the multiple reflections at the input and output surfaces, have been published [31,32]. For CsI:Tl columnar phosphors a series of extended simulations have been performed with MANTIS and DETECT II [30–34] Monte Carlo codes. In these simulations the effect of thickness has been investigated for the following physical parameters: point response function (PRF), line spread function (LSF) and the optical photon percent transmission of the scintillator. The validity of these simulations has been established through comparison with experimental results. [33,36]. In addition, other approaches, studying the performance of CsI:Tl, by applying relations, that have been previously used for granular phosphors, have been utilized [9]. The aim of this work is to provide an analytical model for calculating the MTF, the DQE and the emission efficiency of CsI:Tl columnar scintillator. The parameters of the model regarding optical photon transmission and MTF degradation have been estimated by fitting physical parameters to published Monte Carlo efficiency and MTF data of only columnar CsI:Tl phosphors [33].

2. Materials and methods

2.1. Optical photon propagation and emission efficiency in columnar scintillators

The theoretical model describing the columnar geometry is based on an idea presented in the work of Zelakiewich and Shaw [37], where the transfer of signal in the scintillator can be modeled by accounting for the light transmission per layer.

It has been assumed, that a column of total thickness T can be divided in N layers of thickness $\Delta t = T/N$. If an X-ray spectrum $f(E)$ is incident perpendicular to the phosphor input surface, then the amount of the X-ray photons absorbed in a layer at depth $n\Delta t$ can be calculated as [38]

$$f_n(E) = f(E)e^{-\mu n\Delta t}\mu\Delta t \tag{1}$$

where μ is the linear attenuation coefficient of the scintillator and $n = 1,2,3,\ldots,T$. The number of the optical photons generated at this layer, denoted as $S_n(E)$, equals to $S_n(E) = f_n(E)n_C(E/E_\lambda)$ [38,39], where n_C is the intrinsic conversion efficiency, showing the optical photon power produced per absorbed X-ray power. For CsI:Tl n_C is 0.135 [9]. $n_C E/E_\lambda$ is the number of optical photons per absorbed X-ray and equals to 55 optical photons per keV for CsI:Tl [33]. These photons propagate either in the forward (271–89°) or in the backward (91–269°) direction. The optical photons energy losses can be attributed, either to the internal optical photon absorption in the phosphor mass, or to the optical photons escape from the scintillator boundary surfaces [32]. It is assumed that half of the produced optical photons are propagating forward and half backward. The forward propagating optical photons are subjected to absorption within the material. In addition the lateral propagated photons at angles near 271° and 89° may escape the crystal [32]. Accordingly, only a fraction hereafter called k, of the produced optical photons in the nth layer, arrives at the $(n+1)$th layer that is: $S_{n+1}(E)_n = S_n(E)k$. If the $N-n$ layers to the crystal output are considered, then $S^f_{N-n}(E,u)_n = S_n(E)k^{N-n}$, where the index f denotes the forward direction and the index n denotes the origin from the nth layer. If R_1 is the reflectivity at the output boundary surface, then a fraction,$(1-R_1)S^f_{N-n}(E)_n =\ (1-R_1)S_n(E)k^{N-n}$, escapes to the output and the rest $R_1S_n(E)k^{N-n}$ is reflected and propagates backwards. The backward reflected optical photons, arriving at the input surface of the crystal are equal to the k^N fraction of $R_1S_n(E)k^{N-n}$. Therefore the total number of the optical photons arriving at the input are $S_n(E)k^{N-n}R_1k^N$. At the input surface, a fraction of the photons is again reflected back to the output. This fraction is equal to $S_n(E)k^{N-n}R_1k^NR_2$, where R_2 is the reflectivity of the input interface. By (i) assuming multiple reflection paths to the output-input boundaries and (ii) considering the sum of the optical photons that were initially propagating forwards and backwards and finally reach the output by multiple reflections, the optical quanta generated at the nth layer and escaping to the output are given by [32,39]

$$S_{t,n}(E) = (1-R_1)S_n(E)k^{N-n}\frac{1}{1-k^{2N}R_1R_2} + (1-R_1)S_n(E)R_2k^nk^N\frac{k^{2N}R_1R_2}{1-k^{2N}R_1R_2} \tag{2a}$$

Finally the total number of optical photons escaping the scintillating column can be obtained by summing Eq. (2a) over phosphor thickness and energy spectrum as

$$S_{1,T} = \sum_E\sum_n S_{t,n}(E) \tag{2b}$$

A more detailed description of the optical photon propagation between the input and output surfaces of the column can be found in Nikolopoulos et al. [32].

A parameter expressing the sensitivity of the scintillator is the Detector Optical Gain, DOG, defined as the number of the emitted optical photons per incident X-ray photon. DOG can be calculated as [39]

$$DOG = \sum_E \frac{\sum_n S_{t,n}(E)}{\sum_E f(E)} \tag{2c}$$

2.2. Signal in the spatial frequency domain

By following the work of Zelakiewich and Shaw [37], we have further assumed that in each layer an image quality degradation occur, characterized by a layer signal transfer function $MTF_L(u)$, where u is the spatial frequency. Thus the corresponding signal degradation per layer, denoted hereafter as $S_{n+1}(E,u)_n$, equals to $S_{n+1}(E,u)_n = S_n(E)kMTF_L(u)$. By adopting a similar reasoning to that of the previous section, the spatial frequency depended signal, from the optical photons generated at the nth layer and escaping to the output, can be expressed as

$$S_{t,n}(E,u) = (1-R_1)S_n(E)k^{N-n}{MTF_L}^{N-n}(u)\frac{1}{1-k^{2N}{MTF_L}^{2N}(u)R_1R_2} + (1-R_1)S_n(E)R_2k^n{MTF_L}^n(u)k^N{MTF_L}^N(u)\frac{k^{2N}{MTF_L}^{2N}(u)R_1R_2}{1-k^{2N}{MTF_L}^{2N}(u)R_1R_2} \tag{3}$$

By considering all the column layers, as well as, the X-ray energy spectrum, the total number of the emitted optical photons expressed, in the spatial frequency domain can be calculated as

$$S_T(u) = \sum_E\sum_n S_{t,n}(E,u) \tag{4}$$

The MTF is expressed as the frequency depended signal normalized to zero frequency; it, can be calculated by normalizing Eq. (4) to zero spatial frequency as follows:

$$MTF_T(u) = \frac{S_T(u)}{S_T(0)} \tag{5}$$

2.3. Noise in spatial frequency

The noise power spectrum NPS(u), expresses noise distribution in the spatial frequency domain. Its calculation should consider a series of probabilistic processes such as: (i) the statistics of the X-ray photon interactions in the phosphor, (ii) the statistical nature of the optical

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