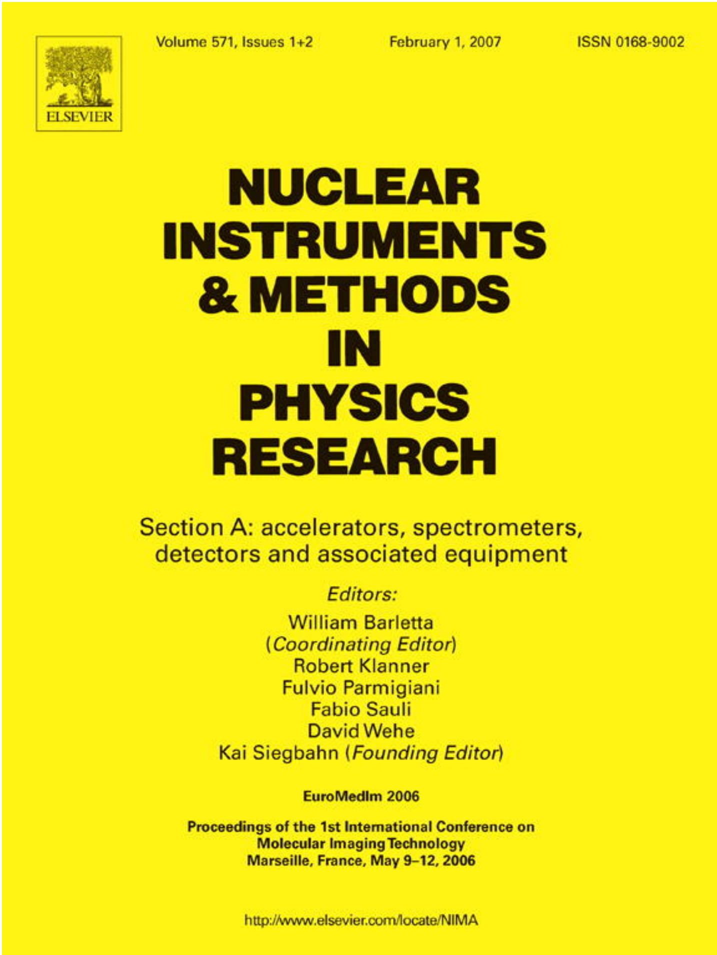
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Investigation of the effect of the scintillator material on the overall X-ray detection system performance by application of analytical models

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Abstract

The purpose of the present work was to model a modern X-ray detection system and to investigate the effect of the scintillator material on the detector's output signal. The scintillators were used in the form of screens. The parameters investigated were the Modulation Transfer Function (MTF), the Detective Quantum Efficiency (DQE) and the Energy Absorption Efficiency (EAE). The results for some well-known scintillators ($Y_3Al_5O_{12}$:Ce, Y_2O_3:Eu, ZnSCdS:Ag, $Lu_3Al_5O_7$, $CdWO_4$) are presented. Typical radiographic conditions were considered as input parameters. For simulation purposes, the intrinsic conversion efficiency (η_c), the total number of optical photons produced per incident X-ray (m_0), the attenuation coefficients and other optical parameters of the scintillator materials, were taken as input data. The complete simulation procedure was performed in a specially designed Graphical User Interface (GUI). The results showed that the Y_2O_3:Eu scintillator presented similar behavior to that of ZnSCdS:Ag, exhibiting higher DQE at zero spatial frequencies. For higher frequencies, however, the DQE values of $Lu_3Al_5O_7$ and $CdWO_4$ prevailed.

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Keywords: X-ray spectra; Simulation; Image quality

1. Introduction

Computer simulation modeling has been proved as a reliable and promising technique for the evaluation of the performance of medical imaging detectors. The latter are evaluated by parameters related to image quality and patients' dose. Image quality parameters include the Modulation Transfer Function (MTF), accounting for detector spatial resolution and signal transfer properties and the Detective Quantum Efficiency (DQE), which accounts for the signal to noise ratio transfer efficiency. Patient dose parameters are related to the X-ray spectrum, the X-ray tube half value layer (HVL) and the entrance surface air-kerma on the patient. Current work on medical imaging system evaluation is usually focused on characterizing imaging detectors theoretically and experimentally in terms of their entrance surface air-kerma, within commonly used conditions [1–3]. None of these works, however, have presented an easy to use computer interface, where the evaluation of the imaging performance of an X-ray detector, under a variety of exposure conditions (kVp spectrum, filtration, etc.) can be achieved prior to its construction. The scope of this work is to present such user friendly software, which models an X-ray detection system and to investigate the effect of the scintillator material on the detector's output signal. A computer algorithm was developed to simulate the irradiation process. Typical radiographic conditions including beam quality, in terms of the X-ray spectrum and exposure, were considered as input

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parameters (X-ray photons spectrum from 30 to 140 keV). For simulation purposes, the intrinsic conversion efficiency (η_c), the total number of optical photons produced per incident X-ray, the attenuation coefficients (μ_{en}/ρ) and other optical parameters of the scintillator materials under study, were taken as input data. The complete simulation procedure was performed in a specially designed user-friendly graphical user interface (GUI). The software was utilized to investigate the performance of several scintillators such as $CdWO_4$, Y_2O_3:Eu, $Lu_3Al_5O_3$, $Y_3Al_5O_{12}$:Ce (or YAG:Ce) and ZnSCdS:Ag.

2. Materials and methods

In order to simulate the performance of an imaging system with different X-ray outputs (kVp, exposure), a software environment was developed on a third level programming language, Mathworks Matlab ver. 7. This language was chosen due to its programming simplicity. X-ray spectra with different anode materials (Molybdenum and Tungsten) may be simulated and their peak energy varied from 40, for mammography, to 140 keV for X-ray radiography. All spectra were simulated by an interpolating polynomials algorithm. This method uses polynomials to calculate the X photon number per tube load, $\Phi(E)$/mAs at each energy bean exactly at the X-ray tube exit. The analytical expression of $\Phi(E)$ per X-ray energy beam is given by the following formula [4]:

$$\Phi(E) = \alpha_o(E)\,\mathrm{keV} + \alpha_1(E)\,\mathrm{keV}^2 + \alpha_2(E)\,\mathrm{keV}^3 + \alpha_3(E)\,\mathrm{keV}^4. \tag{1}$$

Moreover, the beam hardening due to inherent tube Al filtration, as well as, the voltage ripple was also simulated.

The radiation detector was assumed to be in the form of a granular scintillator screen. Granular scintillation materials are widely employed in conventional and digital imaging systems [1–3]. Important parameters that characterize the performance of an imaging system are: (i) the EAE denoting the amount of X-ray energy absorbed by the detector and used for light emission. It is a function of X-ray energy and the detector material and it can be calculated by the following formula [1–3]:

$$\mathrm{EAE}(E) = \frac{\mu_{en}/\rho}{\mu_{tot}/\rho^{(1-e^{-\mu_{en}/\rho T})}} \tag{2}$$

where μ_{en}/ρ is the mass energy absorption coefficient, μ_{tot}/ρ is the total attenuation coefficient and T is the screen surface density. (ii) The MTF, which denotes the optimum of detail that an imaging setup can resolve. It is a function of the X-ray spectrum and the optical properties of the scintillator material. If $M(u)$ is the frequency depended signal then MTF can be calculated as $\mathrm{MTF} = M(u)/M(0)$ where [5]

$$M(u) = \sum_E \sum_T \Phi(E) \mathrm{e}^{-\mu_{en}/\rho^t} (\mu_{en}/\rho) n_C (E/E_\lambda) G(\sigma(u), t), \tag{3}$$

where η_C is the intrinsic conversion efficiency of the phosphor and E_λ is the energy of the emitted optical photons. Parameter $G(\sigma, t)$ expresses the fraction of the light quanta generated at depth t, that escape to the output. The expression used for calculating $G(\sigma(u), t)$ as well as the values of the parameters incorporated in Eq. (3) are found, or derived from Refs. [5–9]. (iii) The DQE is an overall metric of image quality and is a function of X-ray energy and the physical and optical properties of the radiation detector. DQE in the spatial frequency domain can be evaluated as [5–9]

$$\mathrm{DQE}(u) = \Phi_o \left(\frac{M(0)}{\Phi}\right)^2 \frac{\mathrm{MTF}(u)^2}{\mathrm{NPS}(u)} \tag{4}$$

where Φ_o is the total X-ray fluence and NPS(u) is the noise power spectrum and can be calculated according to literature [5].

The software tool was used to test the performance of the following scintillator materials: $CdWO_4$, Y_2O_3:Eu, $Lu_3Al_5O_3$, $Y_3Al_5O_{12}$:Ce, ZnSCdS:Ag of coating thickness 80 mg/cm^2. The optical parameters used for the evaluation of Eqs. (3) and (4) are demonstrated in Table 1.

3. Results and discussion

In Fig. 1, the user interface of the software tool is demonstrated. In order to simulate the spectrum, the user should input the kVp value, the voltage ripple, the mAs or the desired exposure (X) and the type of X-ray tube filtration. The phosphor detector may be selected from a list of phosphor materials already stored. The phosphor material coating thickness is selected by the user. The program output comprises the X-ray spectrum, the energy absorption efficiency, the MTF and the DQE of the detector. Additionally, parameters such as the HVL, the X-ray spectrum mean energy and the exposure (or air kerma) related with the produced X-ray spectrum are given. The X-ray spectrum plotted in the upper window of Fig. 1 corresponds to 80 kVp.

In Fig. 2, the MTF curves of the $CdWO_4$, Y_2O_3:Eu, $Lu_3Al_5O_3$, $Y_3Al_5O_{12}$:Ce, ZnSCdS:Ag, phosphor materials, with a coating thickness of 80 mg/cm^2 irradiated with 80 kVp is demonstrated. It may be observed that for the given X-ray conditions, the $CdWO_4$ and $Lu_3Al_5O_3$ phosphor materials exhibit the highest MTF values. These MTF values are not seriously affected by the X-ray absorption properties of the scintillator. They are principally

Table 1
Optical and intrinsic parameters of scintillators under study

	$Y_3Al_5O_{12}$:Ce	Y_2O_3:Eu	ZnSCdS:Ag	$CdWO_4$	$Lu_3Al_5O_3$
η_C	0.05	0.095	0.207	0.097	0.03
σ (cm^2/gr)	26.5	25.0	33.8	43.8	34.6
λ (nm)	540	613	545	490	435

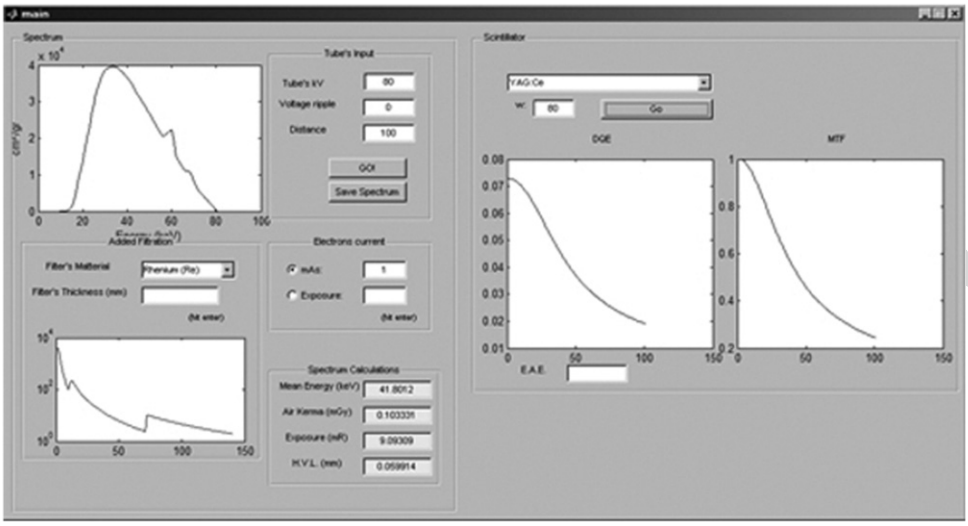

Fig. 1. User interface of the software tool.

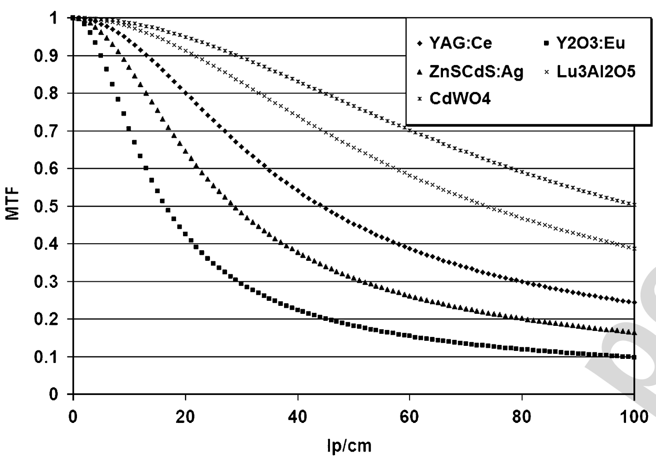

Fig. 2. Calculated MTF values of 80 mg/cm^2 scintillator detectors irradiated with an 80 kVp X-ray spectrum.

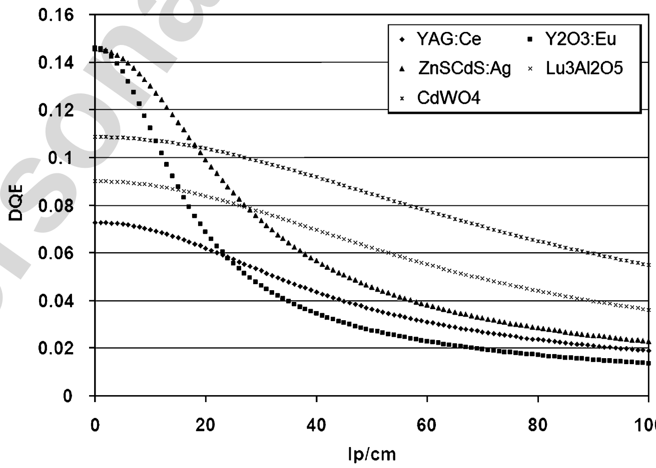

Fig. 3. Calculated DQE values of 80 mg/cm^2 phosphor detectors irradiated with a 80 kVp X-ray spectrum.

affected by the directivity of light generation and the light attenuation effects (scattering and absorption); e.g. the fraction of the laterally directed optical photons that arrive at the screen emissive surface. These photons spread out on the screen surface and cause image quality degradation.

The amount of the photon spread is directly related to the value of σ. Phosphors that exhibit high σ tend to absorb more efficiently the lateral emitted optical photons. Therefore, the emitted light photon spatial distribution of the detectors with high σ are shaped narrower. This results into higher MTF values [5,6,9].

In Fig. 3, the DQE values of the above phosphor are ploted. It may be observed that for lower frequencies, up to 20 lp/cm, the DQE values of Y_2O_3:Eu and ZnSCdS:Ag, are higher, due to their higher light output. This high light output is due to the higher EAE and light output capabilities (higher η_C) and lower light absorption (lower σ) of these scintillators. For higher frequencies however, the higher signal transfer characteristics of $CdWO_4$ and $Lu_3Al_5O_3$ prevails.

4. Conclusions

A computer algorithm, based on commercially available software, was developed to simulate the irradiation process. The X-ray spectrum was simulated with the interpolating polynomials method.

The simulated spectrum was used to irradiate several X-ray scintillators, $CdWO_4$, Y_2O_3:Eu, $Lu_3Al_5O_3$, $Y_3Al_5O_{12}$:Ce and ZnSCdS:Ag. It was found that the performance of Y_2O_3:Eu and ZnSCdS:Ag was higher for spatial frequencies up to 20 lp/cm. For higher spatial frequencies however, the performance of $CdWO_4$ and $Lu_3Al_5O_3$ prevails. The computer simulation will be further developed to incorporate data for more X-ray scintillator materials as well as contrast and SNR studies through software phantom simulations.

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