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Imaging properties of cerium doped Yttrium Aluminum Oxide (YAP:Ce) powder scintillating screens under X-ray excitation

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Abstract

The aim of the present study was to evaluate the imaging performance of YAP:Ce powder scintillating screens under exposure conditions employed in diagnostic radiology (50–140 kV). Various screens were prepared in our laboratory from YAP: Ce powder (Phosphor Technology, Ltd.), with coating thickness ranging from 53 to 110 mg/cm^2. The imaging performance of the screens was assessed by experimental determination of the modulation transfer function (MTF) and the noise transfer function (NTF). MTF was determined by the edge spread function (ESF) method while NTF was estimated by noise power spectrum (NPS) measurements after uniform screen irradiation. In addition, parameters related to overall image quality, such as the signal-to-noise ratio transfer (MTF/NTF), were estimated. MTF curves were affected by the beam hardening effects caused by the patient simulating 20 mm thick aluminum phantom. Under these conditions MTF values were found to increase with the mean X-ray photon energy. A similar effect was observed for NTF curves. Results were compared with data obtained on CsI:Tl scintillator. Taking into consideration the very fast response of YAP:Ce, these data may be of interest in designing X-ray imaging detectors.

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Keywords: Scintillators; Image quality; Radiation detectors; YAP:Ce; CsI

1. Introduction

Scintillators, or phosphors, coupled to optical sensors (photodiodes, photocathodes, films, etc.) are employed in most radiation detectors used in medical imaging systems [1]. Cerium (Ce^{3+}) doped scintillators are of particular interest for medical imaging, because of their very fast response. The latter is due to an electric dipole transition in Ce ion [2,3]. $YAlO_3$:Ce (YAP:Ce) (cerium doped yttrium aluminum oxide) is a scintillator emitting blue light (300–450 nm) with a decay time of 30 ns [4,5]. These properties are very attractive for X-ray imaging since: (i) their light spectral distribution shows high compatibility to

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several existing optical sensors (i.e. charge coupled devices, photocathodes, radiographic films), (ii) fast decay time is a prerequisite for dynamic real-time imaging. YAP:Ce scintillator based image detectors have already been reported in literature [4,5]. These detectors however employ YAP:Ce in a crystal form and are evaluated under synchrotron or γ-ray irradiation conditions [4–7]. The imaging capability of these detectors is tested in terms of parameters such as Light yield/MeV and resolution. According to our knowledge YAP:Ce scintillator has not yet been studied in powder form under exposure conditions used in medical X-ray imaging, in conjunction with radiographic films. Additionally no frequency domain related parameters such as the modulation transfer function (MTF) and the noise transfer function (NTF) have been elaborated in order to evaluate YAP:Ce as a X-ray image detector. In this study YAP:Ce powder scintillator was examined under exposure conditions employed in medical diagnostic radiology. The scintillator was used in the form test screens prepared in laboratory with various thicknesses. The imaging parameters investigated were: the radiographic response (RR), MTF, NTF and the output signal to noise ratio transfer defined as (MTF/NTF).

2. Materials and methods

The scintillating screens were prepared in our laboratory by sedimentation of the phosphor powder (YAP:Ce) on fused silica substrates (spectrosil B). The phosphor was used in the form of screens prepared in our laboratory with various coating weights ranging from approximately 53–110 mg/cm^2, which are often used in various types of X-ray imaging applications. The density of this material was 4.15 g/ml and mean particle size 6.6 μm and quartile deviation of 0.28 (Phosphor Technology Ltd., datasheet). Na_2SiO_3 was used as binding material between the powder particles. Grain size affects both emission efficiency and spatial resolution; sizes in the range from 5 to 10 μm are generally accepted as a satisfactory compromise between emission efficiency and spatial resolution. The screens were brought in close contact with a piece of radiographic film (Kodak T-Mat) enclosed in a light tight cassette. The film-screen combination was irradiated by X-rays in a Philips Optimus radiographic unit. The exposure conditions employed in the experiments are shown in Table 1. Tube voltage was checked using an RMI model 240 multi-function meter. Incident exposure rate measurements were performed using a Radcal 2026C ionization chamber dosimeter (Radcal Corp. USA).

Table 1
Experimental exposure conditiond for YAP:Ce irradiation

	Setup 1	Setup 2	Setup 3	Setup 4
kVp	60	60	70	70
mAs	80	125	80	10
mR	2.7	4.3	6.1	11.7
mmAl	20	20	20	—

In order to determine the radiographic response, the irradiated films were developed in an Agfa Scopix LR 5200 film processor, operated at 36 °C. The films were then digitized on an Agfa Duoscan digitizer, with scanning parameters 100 dpi, 8 bit. A 100×100 pixels area of each image was extracted. The radiographic response under X-ray excitation was determined as the mean gray level value of the 100×100 pixels. It should be noticed that the pixel gray levels, corresponding to 8 bit digitization, ranged from 0 to 255; low level pixel values (e.g. close to 0) correspond to high values of film optical density (high signal) while high level pixel values (close to 255) correspond to low values of film optical density (low signal) [8].

The modulation transfer function was experimentally determined by the edge spread function (ESF) method. A Nuclear Associates resolution test pattern containing Pb lines of various widths corresponding to various spatial frequencies (from 0.5 lp mm^{-1} to 5 lp mm^{-1}) was imaged by bringing each of the screens in close contact with a piece of radiographic film (Kodak T-MAT). The test pattern-screen-film combination was enclosed in a light tight cassette. The combination was exposed to X-rays and films were developed under condition similar to those used for the radiographic response measurements. Seven pattern images were obtained on the films, which were then digitized with scanning parameters 1000 dpi, 8 bit. A 128×64 portion of each image, containing the image of the edge corresponding to the 0.5 lp mm^{-1} line of the test pattern, was extracted. Then the pixel rows vertically directed with respect to the edge were averaged to obtain ESF profiles. The latter were differentiated to compute the line spread function (LSF) profiles. LSF was then Fourier transformed and normalized to unity to obtain the MTF. The resulted MTF was divided with an appropriate sinc function to correct for the digitizer MTF [8].

The noise transfer function was obtained through the noise power spectrum. The latter was determined after uniform irradiation of each phosphor screen brought in close contact with the film. Exposure geometry, X-ray tube voltages and radiographic film selected were as in the case of MTF determination. After irradiation and film development, the film images were digitized employing the same technique previously described for MTF measurements. A region of interest of 128×128 pixels was selected and image density profiles along pixel rows were obtained. A Hanning window was applied to each profile data, which were then subjected to Fast Fourier Transform (FFT) and squared. This process was repeated for each row and data obtained were averaged. The noise power spectrum obtained in this way; besides the phosphor screen-film noise, comprises the noise due to the digitizing scanner. However no correction was applied to eliminate the scanner noise source, since the correction methods suggested in the literature will eliminate film noise as well [9,10], thus the evaluation of YAP:Ce phosphor-film combination could not be performed. NTF was then calculated as the square root of the NPS normalized to zero spatial frequency [9].

Finally the output SNR of the screen-film combination was determined as the ratio of the MTF over the NTF of the screen-film combination. In order to compare the response of YAP:Ce phosphor-film combination with other novel scintillators, a set of CsI single crystal scintillator, with various thicknesses, provided by "Cryos-Beta Ltd" Ukraine, were irradiated with exposure conditions (called hereafter setup5) of 70 kVp 10 mAs and 20 mmAl additional filtration, leading to en exposure of 0.8 mR. CsI radiographic response and MTF were calculated similarly to YAP:Ce-film combinations.

3. Results and discussion

In Fig. 1, the variation of the response of YAP:Ce-Kodak TMAT screen-film combination, with various phosphor coating thickness under various exposure conditions is demonstrated. As it can be observed from Fig. 1 and Table 1 the output signal of the screen-film combinations increases with air-kerma. This behavior was expected since, when exposure level increases, a larger number of X-ray photons of a given energy are absorbed within a screen of a given thickness. This increases the output signal [11]. A point worth noticing is that under the same exposure conditions, the output signal of the phosphor screen-film combinations is not practically affected by screen thickness. This comes to a contradiction to what someone might expect from the exponential law of radiation absorption ($1-e^{-\mu x}$), μ being the X-ray attenuation coefficient and x the phosphor coating thickness.

According to this law X-ray absorption increases with screen coating thickness, thus the amount of light generated within the scintillator is also increased. Hence more optical photons are expected to fall (impinge) on the film [9]. To investigate the output signal emission of YAP:Ce, as a function of the increasing screen coating thickness, the optical properties of this scintillator should be taken into consideration. These properties determine the interactions of optical photons, generated in the screen, and affect light transmission and escape to the screen output. Screen optical properties and light interactions have been previously expressed by the inverse light diffusion length [9]. The latter is an optical parameter, usually denoted as σ, characterizing optical photon absorption and scatter within the scintillator material. The value of σ for YAP:Ce was determined by taking into account the variation of this coefficient with light wavelength [9–13]. For the mean wavelength (368 nm) of the light spectrum emitted by YAP:Ce scintillator, as calculated by spectra obtained from literature [6,7], a value of $\sigma = 82.7\,\mathrm{cm}^2/\mathrm{g}$ was found [13]. This value is among the larger values reported in the literature [11–16]. This high σ value may explain the behavior observed in Fig. 1, since the increased optical absorption especially in thick phosphor screens may compensate the higher X-ray photon absorption.

Fig. 2 demonstrates measured MTF values of YAP:Ce phosphor screen irradiated by a 70 kVp–10 mAs (Table 1) X-ray spectrum. The mean energy of this X-ray spectrum equals to 40.8 keV [10]. By inspecting Fig. 3 it may be observed that thin phosphor screens exhibit higher MTF curves than thick ones. This suggests that MTF is principally affected by the fraction of optical photons generated and directed laterally with respect to the incident X-ray beam [9,17]. If these photons arrive at the screen emissive surface, they are distributed onto a broad area causing light spread and image quality degradation. The fraction of these lateral photons is determined by the angular distribution of the light generation process and the light attenuation effects (scattering and absorption) during light propagation. Light spread is principally more significant in thick screens [17]. However as it may be observed from Fig. 3, the 88 mg/cm^2 phosphor screen seems to exhibit higher MTF values than the thinner screen of 70.7 mg/cm^2. This can be explained by considering the effect of the shape of output light distribution (e.g. light burst) in MTF degradation. In thick screens, generally, light shows a broader distribution at the screen-emitting surface. For YAP:Ce phosphor however, a high value of the optical attenuation parameter σ suggesting high light scatter and absorption within the phosphor material, was found. This implies that laterally directed light photons, both primary and scattered, have a large probability to be absorbed. This property becomes more important in thick screens, where long lateral paths have to be traveled by

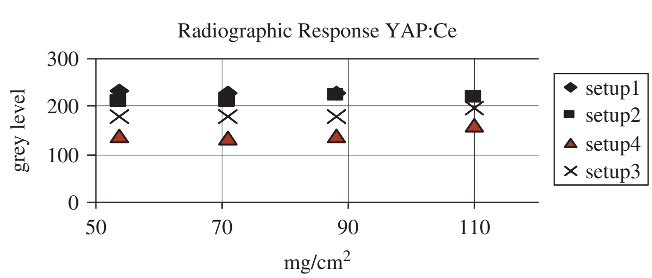

Fig. 1. Radiographic response of YAP:Ce phosphor.

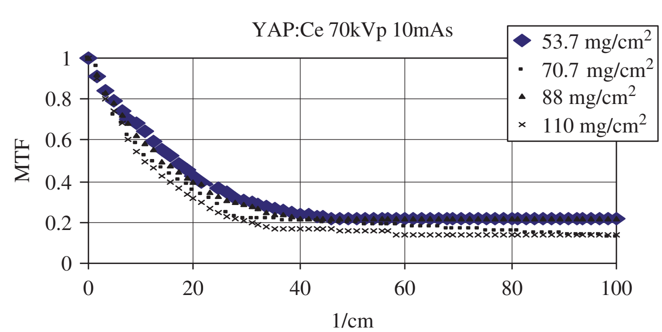

Fig. 2. MTF of YAP:Ce for experimental setup 4.

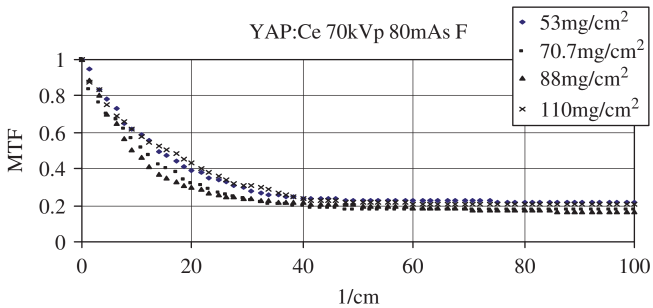

Fig. 3. MTF of YAP:Ce for experimental setup 3.

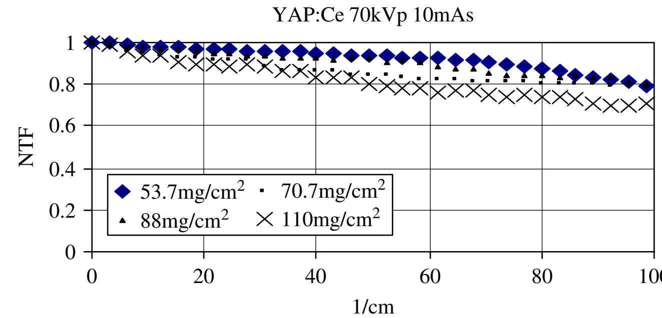

Fig. 4. NTF of YAP:Ce for experimental setup 4.

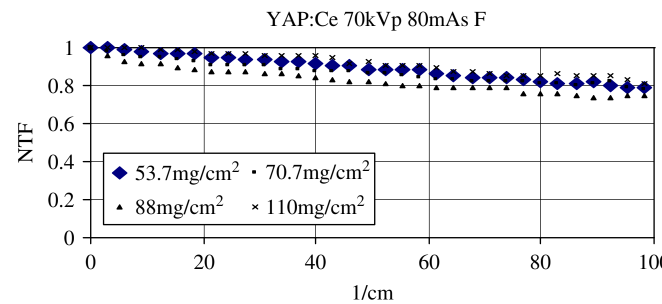

Fig. 5. NTF of YAP:Ce for experimental setup 3.

light photons to escape the phosphor. This effect contributes to a more narrow output light distribution (narrow light bursts) resulting in MTF and image quality improvement.

Fig. 3 demonstrates measured MTF values of YAP:Ce phosphor irradiated by setup 3 (Table 1) X-ray spectrum. The mean energy of this spectrum was 51 keV [10]. It is observed that the MTF curves corresponding to these exposure conditions (mean energy 51 keV) are higher than the MTF curves previously shown in Fig. 2 (mean energy 40.8 keV). This is due to the deeper average penetration of the 51 keV mean energy X-ray beam with respect to the 40.8 keV beam. Thus X-rays are absorbed closer to the phosphor's rear surface giving more narrow light bursts. Hence the contribution of light spread to MTF degradation is of lower significance. This effect was found to be more pronounced in the case of the 110 mg/cm^2 phosphor screen (see Figs. 2 and 3). The higher MTF values shown in Fig. 3, as compared to those shown in Fig. 2, may be attributed to the combined effects of the higher X-ray penetration and the importance of the lateral light photonattenuation (high value of σ).

Figs. 4 and 5 demonstrate the measured NTF values for YAP:Ce, for 70 kVp–10 mAs and 70 kVp–80 mAs-F (Table 1) X-ray spectra, respectively. It can be observed that the shape of the NTF curves follow the MTF curves in both cases. This may be explained by the fact that NTF can be expressed as the weighted sum of the squares of the thin layers MTFs [9,11,18]. These MTFs are affected by the shape of the output light bursts, as it has already been noted. The degradation of NTF with frequency however is slower that the corresponding MTF degradation. This effect has been previously explained by considering that the overall MTF is expressed as a weighted sum of the MTFs of each thin layer [9,12,17–19].

In Figs. 6 and 7 the (MTF/NTF) ratio of YAP:Ce, for two exposure conditions (setup 4 and setup 3) is demonstrated. The shape and the value of the (MTF/NTF) ratio, is affected by the corresponding variations of both MTF and NTF.

As it can be seen in Figs. 6 and 7 the best ratio value is observed for the 53.7 and 110 mg/cm^2 phosphor-film combinations respectively. In Fig. 8 the radiographic response of the CsI scintillator-Agfa-GS film combination is demonstrated. It may be observed that the radiographic response of the CsI–Agfa GS combination is better than the YAP:Ce-Kodak T-MAT combination, since the latter has been irradiated with higher exposure conditions.

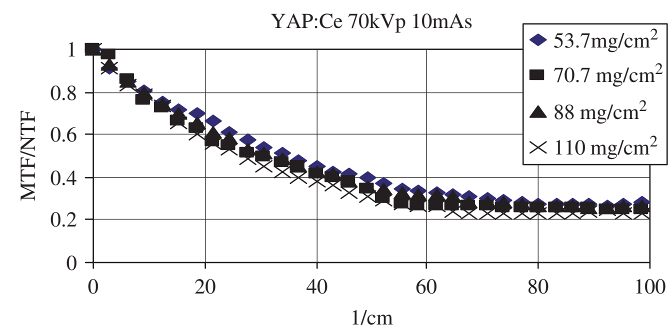

Fig. 6. The ratio MTF/NTF of YAP:Ce for experimental setup 4.

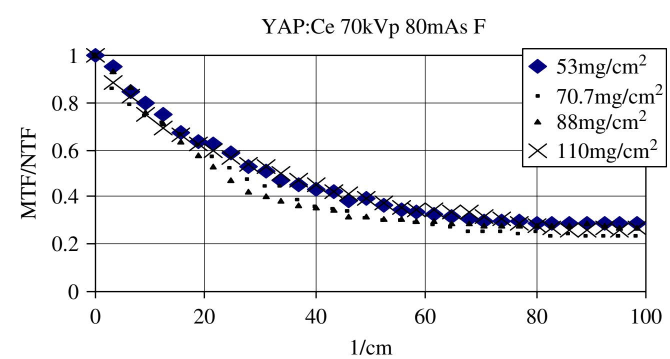

Fig. 7. The ratio MTF/NTF of YAP:Ce for experimental setup 3.

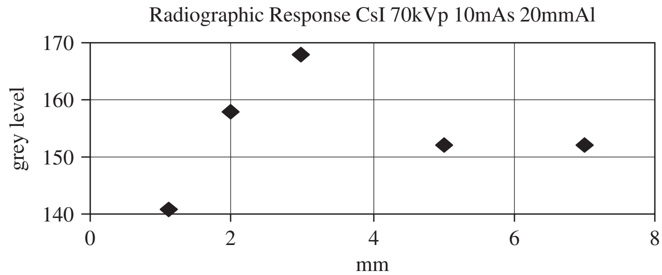

Fig. 8. Radiographic response of CsI phosphor.

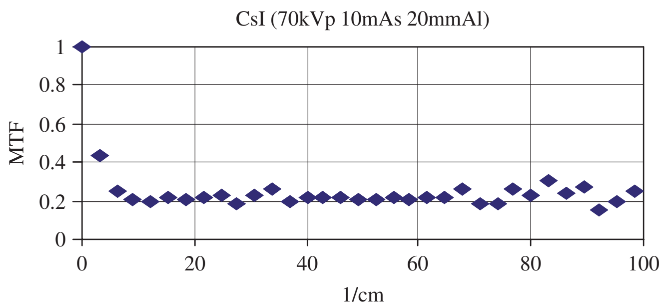

Fig. 9. MTF of CsI phosphor for experimental setup 5.

However the MTF values of CsI based screen-film combination is poorer for the exposure conditions under consideration as it can be observed from Fig. 9.

4. Conclusions

In this study the cerium doped yttrium aluminum oxide YAP:Ce powder scintillator was evaluated in conjunction with an appropriate film as detector for X-ray radiography. A set of test screens with various coating thickness were prepared. It was found that all the screen-film combinations had equivalent radiographic response for the same exposure conditions. By comparing the MTF curves of screen combinations it was found that the energy of the X-ray photons plays an important role in the signal transfer characteristics of YAP:Ce Moreover the inverse diffusion length σ was found equal to $82.7\,cm^2/g$, which is one of the largest values reported in literature. This high value might explain the shape of the MTF and NTF curves of YAP:Ce phosphor for different coating thickness and X-ray energies.

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