Light emission efficiency of $GdAlO_3$:Ce (GAP:Ce) powder screens under X-ray radiography conditions

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Abstract. *The aim of this study was to evaluate the performance of $GdAlO_3$:Ce powder scintillator screens for use in medical imaging applications. This powder phosphor, also known as GAP:Ce scintillator, is a non-hygroscopic material, emitting blue light with short decay time and it has never been used in medical imaging. Various scintillator screens with coating thickness, ranging from 14.7 to 121.1 mg/cm^2, were prepared in our laboratory from $GdAlO_3$:Ce powder (Phosphor Technology, Ltd) by sedimentation on silica substrates. The Quantum Detection Efficiency (QDE) and Energy Absorption Efficiency (EAE) were evaluated. Absolute luminescence efficiency measurements were performed under exposure conditions employed in diagnostic radiology (50-140 kV, 63 mAs), using an experimental setup based on a photomultiplier tube. The emission spectrum of GAP:Ce, after calculating the matching factor, was found compatible with various existing optical detectors. QDE and EAE of GAP, comparing to YAP has exhibited higher values. Absolute Efficiency values were found to increase with increasing X-ray tube voltage. Although for values higher than 120 kVp a decrease was observed.*

Keywords: Inorganic Scintillators; QDE; EAE; Radiation detectors; $GdAlO_3$:Ce.

1 INTRODUCTION

Most medical imaging detectors are based on scintillator-optical detector (photodiodes, photocathodes, films etc) combination. Cerium (Ce^{3+}) doped scintillators or phosphors exhibit the property of very fast response. The latter is dominated by the very efficient 5d→ 4f electronic transitions in the Ce^{3+} ion [1-3]. Previous studies have shown that Yttrium Aluminium Pervoskite ($YAlO_3$:Ce) also known as YAP:Ce has attractive properties for use in medical imaging detectors e.g. in small animal PET detectors and in synchrotron radiation medical imaging. On the other hand Gadolinium based scintillators (e.g., Gd_2O_2S: Tb) are widely used in medical X-ray imaging applications. The aim of this work was to study $GdAlO_3$:Ce in which Yttrium has been replaced by Gadolinium (Gd) [4]. Using Gadolinium which is heavier than Yttrium, a higher absorption efficiency is expected. Cerium doped Gadolinium Aluminium Pervoskite ($GdAlO_3$:Ce also known as GAP) powder scintillator has never been tested under radiographic exposure conditions. Absolute luminescence efficiency measurements were performed for various X-ray tube voltages (50-140 kVp) used in radiographic applications. Parameters related to X-ray detection such as the energy absorption efficiency (EAE) and the quantum detective efficiency (QDE) were calculated. Emitted spectrum and spectral compatibility to optical sensors were determined by performing light emission spectra measurements and by taking into account the spectral sensitivity of the optical detectors.

2. Materials and Methods

2.1. Theory

Scintillators or phosphors are used in radiation detectors because of their ability to emit light when exposed to ionising radiation. The efficiency of a scintillator to detect photons is described by the quantum detection efficiency (QDE). QDE is the fraction of incident photons interacting with the scintillator [1]. For polyenergetic X-rays the QDE of a scintillator layer of coating thickness w is written as:

$$n_Q = \frac{\int_0^{E_0} \phi_0(E)\left(1-e^{-(\mu_{tot,t}(E)/\rho)w}\right)dE}{\int_0^{E_0} \phi_0(E)dE} \qquad (1)$$

E_0 is the maximum energy of X-ray spectrum and $\mu_{tot,t}(E)/\rho$ is the X-ray total mass attenuation coefficient of the scintillator. $\phi_0(E)$ is the X-ray photon fluence (photons per unit of area) incident on the scintillator. The spectrum $\phi(E)$ of a tungsten anode X-ray tube with no filtering may be given by the following relation: [5]:

$$\begin{aligned} &\phi(E) = \alpha_0[E] + \alpha_1[E]kVp + \alpha_2[E]kVp^2 + \alpha_3[E]kVp^3 && \text{for } E \le kVp \\ &\phi(E) = 0 && \text{for } E > kVp \end{aligned} \qquad (2)$$

The predetermined coefficients ($\alpha_i(E)$) are derived from measured data [20], which are necessary to reconstruct the X-ray spectra at any kVp.

To compute the attenuated spectrum $\phi_0(E)$ of the X-ray beam caused by filters used in the experimental setup, the exponential law of absorption was used:

$$\phi_0(E) = \phi(E)e^{-(\mu_{tot,t}(E)/\rho)w} \qquad (3)$$

where $\phi(E)$ is the X-ray spectrum with no filtering computed by relation (2), $\mu_{tot,t}(E)/\rho$ is the mass attenuation coefficient of the filter, and w is the thickness of the filter in mg/cm^2.

X-ray imaging detectors are energy integrating systems, i.e., their output signal is proportional to the X-ray energy absorbed within the scintillator. Hence, when evaluating X-ray imaging systems, the calculation of the energy absorption efficiency (EAE) is also of importance [1]. EAE may be calculated by the relation:

$$n_\varepsilon = \frac{\int_0^{E_0} \psi_0(E)\left(\frac{\mu_{tot,en}(E)/\rho}{\mu_{tot,t}(E)/\rho}\right)\left(1-e^{-(\mu_{tot,t}(E)/\rho)w}\right)dE}{\int_0^{E_0} \psi_0(E)dE} \qquad (4)$$

Ψ_0 is the incident X-ray energy fluence and $\mu_{tot,en}$ is the total mass energy absorption coefficient of the scintillator. $\mu_{tot,en}$ includes all mechanisms of energy deposition locally at the point of X-ray interaction within the scintillator's mass. All secondary photons, e.g., K-characteristic fluorescence X-rays, created just after the primary interaction effect, are assumed to be lost [6–9]. Thus EAE, being a measure of the locally absorbed energy, represents more accurately the efficiency of a detector to capture the useful X-ray imaging signal (i.e., the spatial distribution of primary X-ray absorption events). Attenuation and absorption coefficients were calculated using tabulated data [8,9].

Light energy flux Ψ_λ emitted by a phosphor material when irradiated by an X-ray energy flux Ψ_X, may be given as follows:

$$\Psi_\lambda = \int_0^{E_0} \Psi_X(\mathrm{E})\bar{n}_\varepsilon(E)n_C \int_0^{W} \Psi_Q(E,w)\bar{g}_\lambda(\sigma,w)dwdE \qquad (5)$$

where η_c is the intrinsic X-ray to light conversion efficiency (ICE), expressing the fraction of absorbed X-rays converted into light within the phosphor. ψ_Q is the probability of an interacting X-ray photon to be absorbed at a depth $W<W_0$. g_λ is the fraction of light photons, created at depth W, that escape the phosphor and σ is an optical attenuation coefficient [10,11,12]. The second integral in (5) is defined as the light transmission efficiency (LTE) of the phosphor [11,13,14]. The first integral is used to integrate over the energies of X-ray spectrum. X-ray imaging scintillators are often evaluated by the absolute luminescence efficiency (η_A):

$$\eta_A = \overline{\Psi}_\lambda / X \qquad (6)$$

where X is the exposure rate incident on the phosphor, emitted by an X-ray tube with high voltage equal to E_0. To express the compatibility of emitted light with spectral sensitivity of the photodetector, the spectral matching factor α_S was calculated by the relation (7):

$$\alpha_S = \frac{\int S_P(\lambda) S_D(\lambda) d\lambda}{\int S_P(\lambda) d\lambda} \qquad (7)$$

where $S_p(\lambda)$ is the spectrum of the light emitted by the phosphor and $S_D(\lambda)$ is the spectral sensitivity of the optical detector coupled to the phosphor [15,16].

2.2 Experiments

$GdAlO_3$:Ce was purchased in powder form (Phosphor Technology Ltd, England, code: UM58#9438) with mean grain size of approximately 8.9 μm and quartile deviation of 0.32 (Phosphor Technology Ltd., datasheet). The phosphor was used in the form of thin layers to simulate the intensifying screens employed in X-ray radiography. Five screens from 14.7 to 121.1 mg/cm^2 thick were prepared by sedimentation of $GdAlO_3$:Ce powder on fused silica substrates (spectrosil B). Sodium orthosilicate (Na_2SiO_3) was used as binding material between the powder grains[14]. The phosphor screens were exposed to X-rays on a Philips Optimus radiographic unit, employing X-ray tube voltages ranging from 50 to 140 kVp. Tube filtration was 2.5 mm Al. An additional 20mm filtration was introduced in the beam to simulate beam quality alternation by a human body [11]. The absolute luminescence efficiency was determined, according to (6), by performing X-ray exposure and light flux measurements [17]. The experimental setup was previously described by Valais et al (2005) [18]. The spectral matching factor, was determined by measuring the emitted light of the GAP:Ce powder phosphor while the spectral sensitivities of the optical detectors were obtained from manufacturers' data.

2.3 Calculations

Using relations (5) and (6) the absolute luminescence efficiency may be calculated as a function of the intrinsic physical parameters of the phosphor material. Calculation of the physical quantities employed in relation (5) were performed as described in detail in previous studies for other materials [15,19]. These quantities were used in order to fit relation (5) to the experimental absolute luminescence efficiency data. The energy absorption efficiency (EAE), η_ε, expressing the fraction of X-ray energy locally absorbed as well as the quantum detection efficiency (QDE), expressing the fraction of X-ray quanta interacting with the phosphor, were calculated by considering exponential X-ray absorption [1,7].

3 Results and Discussion

Figure 1 and 2 illustrate the variation of calculated QDE and EAE with X-ray tube voltage for the screens, with coating thicknesses of 14.7, 31.0, 53.7, 67.2 and 121.1 mg/cm^2 according the relations (1), (2), (3) and (4). As it can be seen the quantum detection efficiency values are higher than the energy absorption efficiency values. This can be explained by the fact that EAE does not include the effect of scattered, *K* or *L*-fluorescence, and bremsstrahlung radiations while QDE expresses all the mechanisms of X-ray quanta interaction with the phosphor. Energy absorption efficiency value at 80 kVp for $GdAlO_3$:Ce for 121.1 mg/cm^2 screen was found at 0.275. For comparison purposes similar calculations were performed for the YAP 121.1 mg/cm^2 coating thickness screen and at 80 kVp was found 0.227. Also for QDE, $GdAlO_3$:Ce exhibits higher values than YAP. This can be explained by the presence of Gadolinium which is heavier than Yttrium.

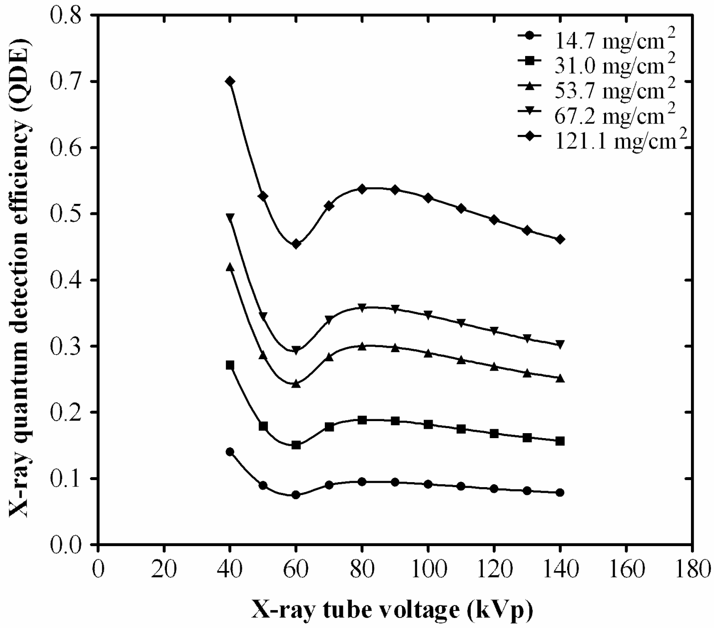

Figure. 1 Variation of calculated QDE for $GdAlO_3$:Ce powder screens with X-ray tube voltage

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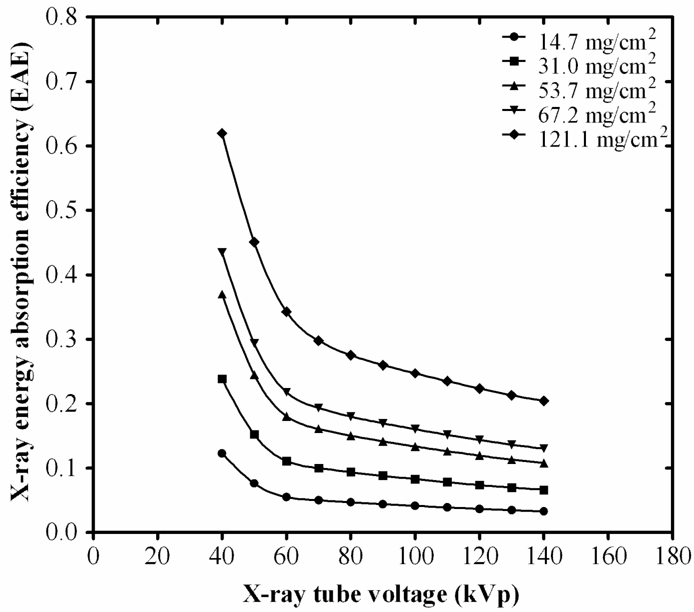

Figure. 2 Variation of the calculated EAE for $GdAlO_3$:Ce powder screens with X-ray tube voltage.

Figure 3 shows the variation of absolute luminescence efficiency of the $GdAlO_3$:Ce screen with X-ray tube voltage. Points represent experimental data. An important observation is that absolute efficiency maintains high values within a range of X-ray tube voltages from 100 to 120 kVp. The highest absolute efficiency values were observed for the 67.2mg/cm^2 screen.

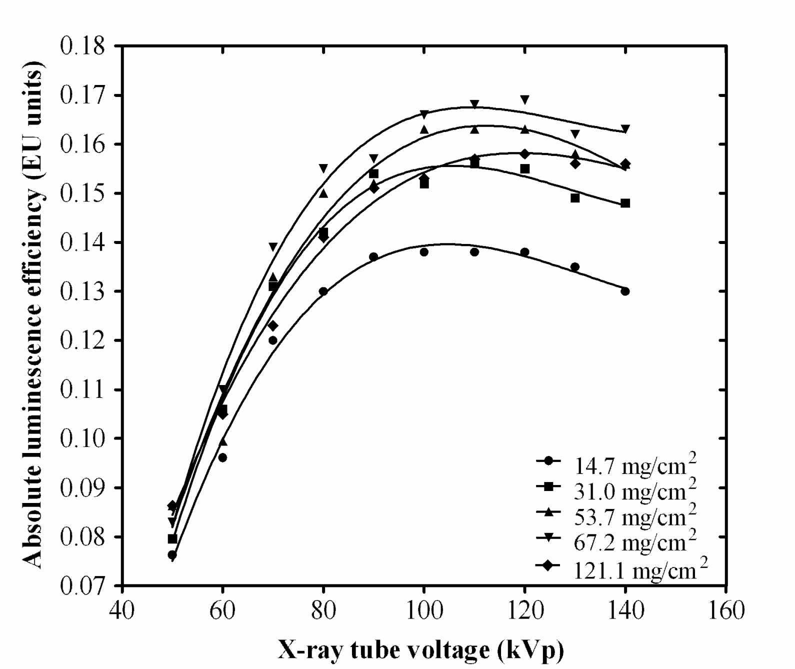

Figure. 3 Absolute luminescence efficiency of the GAP: Ce powder phosphor with X-ray tube voltage for various coating thicknesses. Points correspond to experimental values. Efficiency units: $\mu W \times m^{-2} /(mR \times s^{-1})$.

Figure 4 shows the measured light emission spectrum of the $GdAlO_3$:Ce phosphor. As it can be seen, the light emission spectrum of this phosphor consists roughly of two Gaussian bands with maxima at 330 and 354nm.

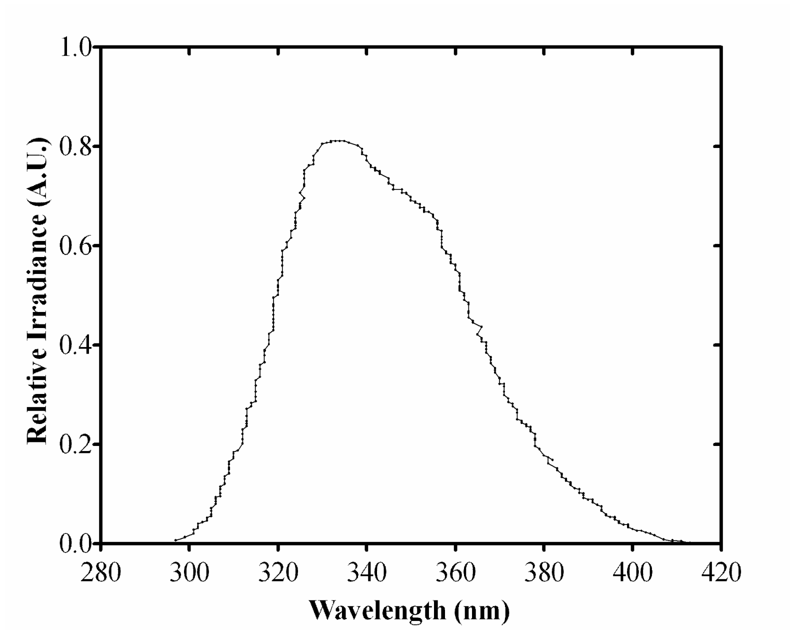

Figure. 4 Optical emission spectrum of $GdAlO_3$:Ce phosphor.

Table 1 shows the values of the spectral matching factors of the $GdAlO_3$:Ce calculated according to relation (7). $GdAlO_3$:Ce exhibits excellent compatibility with the GaAs and E/S 20 photocathodes. It exhibits low compatibility with amorphous Si detectors and MAMMORAY film. In addition it was found incompatible with the Silicon (Si) photodiode detectors.

Optical Detectors	$GdAlO_3$:Ce
GaAs	0.900682
Si	0.086278
AmorSi	0.345324
MAMORAY	0.655185
E/S 20	0.824169

Table 1 : Spectral matching factors

4 Conclusions

In the present study, the quantum detection efficiency (QDE), the energy absorption efficiency (EAE), the absolute luminescence efficiency and the spectral compatibility of five $GdAlO_3$:Ce powder scintillator screens, were investigated under X-ray radiographic conditions. The X-ray quantum detection efficiency (QDE) and the X-ray energy absorption efficiency (EAE) were found lower than currently employed materials (e.g. Gd_2O_2S:Tb, CsI:Na) for detection of X-rays used in radiographic applications [14]. Although comparing to YAP scintillator, GAP maintains higher EAE and QDE values. Peak absolute efficiency was obtained for the 67.2 mg/cm^2 layer at X-ray tube voltages from 100 to 120kVp However, absolute luminescence efficiency maintains low values, within the radiographic energy range. The emission spectrum of $GdAlO_3$:Ce screen showed good spectral compatibility with currently used detectors. Taking also into account its very fast response, it could be considered for applications in X-ray radiographic imaging systems.

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