An Investigation of the Imaging Characteristics of the Y$_2$O$_2$S:Eu$^{3+}$ Phosphor for Application in X-ray Detectors of Digital Mammography

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Y$_2$O$_2$S:Eu laboratory prepared screens were evaluated as mammographic image receptors and were compared to similarly prepared screens of Gd$_2$O$_2$S:Tb and Y$_2$O$_2$S:Tb phosphor materials, often used in X-ray imaging detectors. The evaluation was performed by determining the Modulation Transfer Function (MTF) and the spatial frequency dependent Detective Quantum Efficiency (DQE). Y$_2$O$_2$S:Eu exhibited higher DQE values at low frequencies and given its good spectral matching with digital optical detectors, it may be appropriate for use in X-ray digital mammography.

Introduction

Y$_2$O$_2$S:Eu is a phosphor material emitting red light due to the presence of Eu$^{3+}$ activator (Tanaka et al., 1976). Initial experimental data on absolute efficiency (emitted light flux over incident X-ray exposure rate) of Y$_2$O$_2$S:Eu phosphor screens have been obtained in a previous study (Giakoumakis et al., 1993). It has been found that the light producing efficiency of Y$_2$O$_2$S:Eu is comparable to that of Y$_2$O$_2$S:Tb, often employed in medical imaging (Arnold, 1979), and additionally that Y$_2$O$_2$S:Eu exhibits reduced intrinsic light attenuation properties. However, to our knowledge, Y$_2$O$_2$S:Eu has never been used in X-ray image detectors and its image quality characteristics have not been studied.

The low light attenuation properties of Y$_2$O$_2$S:Eu indicate that light produced within this phosphor material may be easier transmitted to the phosphor’s emissive surface and, thus, be efficiently captured by films, photodiodes or other means of optical detectors. Additionally, the emission spectrum of the Y$_2$O$_2$S:Eu red light is better matched, as compared to the green–blue light of Y$_2$O$_2$S:Tb, to the spectral sensitivity of photodiodes or CCD arrays employed in digital imaging systems. In the present work the imaging performance of the Y$_2$O$_2$S:Eu phosphor was studied under mammography conditions by determining the following parameters: (1) the modulation transfer function (MTF), which expresses the image contrast variation with spatial frequency and the spatial resolution of image detectors; and (2) the detective quantum efficiency (DQE), which describes the signal to noise ratio (SNR) transfer efficiency from the input to the output of an image detector. DQE is related to the patient radiation dose level required to obtain an adequate signal to noise ratio in the final diagnostic image.

Materials and Methods

The phosphor materials (Y$_2$O$_2$S:Eu, Y$_2$O$_2$S:Tb, Gd$_2$O$_2$S:Tb) were supplied in powder form by Derby Luminescents. Test screens of 32 mg/cm$^2$ and 50 mg/cm$^2$ were prepared in our laboratory by sedimentation of the phosphor powder on fused silica substrates. Details of the technique followed have been described in previous studies (Giakoumakis et al., 1993; Kandarakis et al., 1996; Cavouras et al., 1996).
The modulation transfer function

The modulation transfer function was experimentally determined employing the square wave response function (SWRF) method (Barnes, 1979). Each screen was used in combination with a film of appropriate spectral sensitivity (Agfa Scopix LT2B for $\text{Y}_2\text{O}_2\text{S}:\text{Eu}$ and Agfa Curix Ortho GS for $\text{Y}_2\text{O}_2\text{S}:\text{Tb}$ and $\text{Gd}_2\text{O}_2\text{S}:\text{Tb}$) and with a resolution test pattern (typ-53, Nuclear Associates), which comprises line pairs of spatial frequencies ranging from 2.5 to 100 cycles per cm. The pattern–screen–film combination was exposed to 30 kVp molybdenum target X-rays. The resulting pattern images were digitized using a MICROTEC Scannaker II SP (24-bit color, 1200 $\times$ 1200 dpi) CCD scanner. Low noise SWRFs were obtained by selecting 64 successive image traces transverse to the pattern bars. Trace amplitudes were normalized to the lower pattern frequency. The screen MTF was then calculated from the SWRF values employing Colman’s formula (Barnes, 1979). Results were corrected for screen–film non-linearities, via the absorption properties of the phosphor material. For incident X-ray energies exceeding the K-absorption edge of yttrium at 17 keV, $K_\alpha$ and $K_\beta$ characteristic radiation is produced due to the K-fluorescence effect. The sites within the phosphor material, where these K-characteristic photons are re-absorbed, become sources of additional optical photon generation. These photons degrade spatial

The film’s MTF was considered equal to unity for frequencies up to 100 cycles/cm (Beutel et al., 1993).

The screen MTF was also theoretically evaluated (Kandarakis et al., 1997) by modeling the screen to consist of a large number of elementary fluorescent layers of thickness $dt$. The screen was considered to be excited by an incident X-ray fluence, which mathematically may be expressed by a spectral distribution function $S_\lambda$ in relation (2). A fraction $\eta_0$ of this fluence is detected by the screen material and the rest is transmitted without interaction.

Each absorbed X-ray quantum interacts with the phosphor material at a particular thin layer at depth $t$ from the screen surface and a number ($m_0$) of optical photons are produced. A fraction $G_L$ of these light photons are transmitted through the screen material and are emitted from the screen output. In fact, $G_L$ is the Fourier transform of the output light photons distribution per absorbed X-ray divided by $m_0$ and, thus, it depends on spatial frequency $\omega$ (Swank, 1973). The total number of optical photons emitted per unit of screen area was obtained by summing up the light flux contributions from each particular screen layer and integrating over all incident X-ray energies, considering polyenergetic X-ray beams. Thus, the screen MTF was evaluated as:

$$\text{MTF}(\omega) = \frac{N_L(\omega)}{N_L(0)} \quad \text{(1)}$$

where $N_L(\omega)$ is the spatial frequency dependent mean number of totally emitted optical photons given by:

$$N_L(\omega) = \int_0^{E_0} S_X(\omega) \eta_0(\omega, t_0) \, dE \, \text{MTF}(\omega) = \int_0^{E_0} S_X(\omega) \eta_0(\omega, t_0) \, dE \, \text{MTF}(\omega)$$

where, $E_0$ is the energy of X-ray photons ranging up to $E_0$ which is the maximum photon energy of the incident X-ray fluence. The latter is given by a molybdenum target X-ray spectrum expressed by the function $S_X(E)$ (Tucker et al., 1991), $t_0$ is the coating thickness of the screen, $\eta_0(E,t_0)$ is the X-ray quantum detection efficiency (QDE) approximated by (Morz and Danos, 1978):

$$\eta_0(E, t_0) = 1 - \exp[-\mu(E)t_0] \quad \text{(3)}$$

where, $\mu(E)$ is the X-ray attenuation coefficient calculated from data published by Storm and Israel (1967), $m_0(E)$ in (2) is the mean number of optical photons created within the phosphor material per X-ray quantum detected by the phosphor screen and it is given by:

$$m_0(E) = \int_0^{E_0} S_P(E) E \, dE \int \frac{dE}{S_P(E)} \quad \text{(4)}$$

where $S_\lambda$ is the spectrum of the emitted light, which was measured in our laboratory by an Oril 7240 grating monochromator, $E_\lambda$ is the energy of the optical photons. $\lambda_1$ and $\lambda_2$ are the lower and upper wavelengths of the spectrum, respectively. The denominator in (4) is equal to the mean energy of the emitted optical quanta.

The function $G_L(\omega, \sigma, \beta, t)$ in (2) expresses the fraction of optical quanta, created by one X-ray quantum absorbed by a thin layer at depth $t$, being transmitted through the phosphor material and emerging at the screen’s emissive surface. $G_L(\omega, \sigma, \beta, t)$ is a spatial frequency ($\omega$) dependent function that can be calculated (see Appendix) if the values of optical parameters $\sigma$ and $\beta$, related to optical scattering and absorption, are known. $S_R(E, t)$ is a function representing a weighing factor and accounting for the relative X-ray absorption by a thin layer at depth $t$, given by:

$$S_R(E, t) = \mu(E) \exp[-\mu(E)t] \, dE \int \frac{dE}{\mu(E)} \exp[-\mu(E)t] \, dE \quad \text{(5)}$$

For incident X-ray energies exceeding the K-absorption edge of yttrium at 17 keV, $K_\alpha$ and $K_\beta$ characteristic radiation is produced due to the K-fluorescence effect. The sites within the phosphor material, where these K-characteristic photons are re-absorbed, become sources of additional optical photon generation. These photons degrade spatial
The emitted optical quanta are associated with the incident X-ray quanta $N_L$ as follows:

$$N_L = N_{\text{e}} \eta Q(E_0, t_0) \hat{m}(E_0) G_L(0, \sigma, \beta, t_0)$$

From relations (7)–(10) and assuming Poisson distribution ($\epsilon = 0$) for $m_0(E)$ (Shaw and Van Metter, 1984; Nishikawa and Yaffe, 1990), and polyenergetic X-rays:

$$\text{DQE}(\omega) = \eta_Q(E_0, t_0) \frac{\hat{m}(E_0)}{1 + \frac{\text{MTF}(\omega)}{\text{SNR}_r^{\text{out}}(\omega)}}$$

(11)

where $\hat{m}(E_0)$ is the mean number of light quanta emitted per X-ray quantum absorbed in the screen, averaged over the X-ray spectrum $\hat{m}(E_0)$ as calculated as follows:

$$\hat{m}(E_0) = \int_0^{E_0} G_L(0, \sigma, \beta, t_0) dE$$

(12)

$$\hat{m}(E) = \int_0^{E_0} G_L(0, \sigma, \beta, t_0) dE$$

(13)

is the mean number of light quanta emitted per X-ray absorbed for monenergetic X-ray beams.

Finally, $\eta_Q(E_0, t_0)$ in (11) is the quantum detection efficiency averaged over the X-ray spectrum as follows:

$$\eta_Q(E_0, t_0) = \frac{1}{\int_0^{E_0} G_L(0, \sigma, \beta, t_0) dE}$$

(14)

**Results and Discussion**

In Fig. 1 and 2 the MTFs of Y$_2$O$_2$S:Eu screens are compared to the MTFs of Y$_2$O$_2$S:Tb and Gd$_2$O$_2$S:Tb screens of approximately equal coating weight. Figure 1 shows the experimental MTF data obtained for the 32 mg/cm$^2$ screens and Fig. 2 for the 50 mg/cm$^2$ screens. All screens were prepared and measured under the same conditions. In both figures the MTF of the Gd$_2$O$_2$S:Tb screen was better than the corresponding MTFs of the yttrium based phosphors, thus expressing the high detail visibility obtained using Gd$_2$O$_2$S:Tb screens. This may be explained because the volume density of Y$_2$O$_2$S is about half that of Gd$_2$O$_2$S (Zweig and Zweig, 1983). Thus, for the same coating weight Y$_2$O$_2$S screens are thicker causing wider spread to light photons traveling towards the screen output, resulting in wider point spread function (PSF), and worse spatial resolution. Additionally, since light attenuation in Gd$_2$O$_2$S:Tb is higher ($\sigma = 30$ cm$^2$/g) than in Y$_2$O$_2$S:Eu ($\sigma = 17.4$ cm$^2$/g), the wide angled traveling photons in Gd$_2$O$_2$S:Tb are greatly attenuated, thus, further limiting the spread of output light photons. The lower light attenuation in Y$_2$O$_2$S:Eu is in accordance with the fact that optical scattering is less significant for the longer wavelengths of the red light emitted by this phosphor.
Figures 3 and 4 show the results obtained for the spatial frequency dependent detective quantum efficiency using experimental MTF values. For the range of spatial frequencies up to 22 cycles/cm for the 32 mg/cm² screens and up to 17 cycles/cm for the 50 mg/cm² screens, Y₂O₂S:Eu exhibited higher DQE and Gd₂O₂S:Tb, while the DQE of Y₂O₂S:Eu was better than that of Y₂O₂S:Tb in the whole frequency range. The rather high DQE values of the europium phosphor at low frequencies must be attributed to the lower light attenuation (σ) within the screen material, which reduces optical photon losses and quantum noise. This contributes to the improvement of SNR_{out} and DQE. In the high frequency range the DQE of Gd₂O₂S:Tb attains higher values than the DQEs of the yttrium phosphors due to the increased differences amongst the corresponding MTFs [see relation (11) and Figs 1 and 2].
The variation of the calculated zero spatial frequency DQE with screen coating weight is presented in Fig. 5. As expected from Figs 3 and 4, the DQE(0) of the Y$_2$O$_2$S:Eu screens is notably higher than the two other materials. The difference in DQE(0) between Y$_2$O$_2$S:Eu and the terbium activated phosphors increases with coating weight due to the lower light attenuation properties of the europium activated phosphor.

Conclusively, the Y$_2$O$_2$S:Eu screens exhibit better signal to noise ratio than Gd$_2$O$_2$S:Tb and Y$_2$O$_2$S:Tb in the low frequency range but lower spatial resolution. These results may be of value in the design of detectors employed in digital imaging systems, since in the latter the main purpose is to optimize the signal to noise ratio or DQE (Hillen et al., 1987). Additionally, since the red light produced by europium activated phosphors is very well...
matched to the sensitivity of digital optical detectors such as Si photodiodes and CCD arrays (Cavouras et al., 1996). \(\text{Y}_2\text{O}_2\text{S}:\text{Eu} \) could be an appropriate phosphor for use in X-ray digital mammography.

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References


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**Appendix**

The problem of light propagation through the phosphor material has been modeled as a diffusion process described by a diffusion differential equation (Swank, 1973). According to the solution of this equation, the fraction of spatial frequency dependent light quanta generated in the phosphor material at depth $t$ and transmitted to the screen output is given as a function of the optical parameters $\sigma$, $\beta$ (Ludwig, 1971; Swank, 1973; Beutel *et al.*, 1993).

$$G_t(\omega, \sigma, \beta, t) = \frac{\sigma \rho_{11} [(\alpha + \sigma_{\rho_0})e^{\omega t} + \sigma_{\rho_1}e^{-\omega t}] - (\sigma_{\rho_0} - \sigma_{\rho_1})e^{\omega t} - (\sigma_{\rho_0} - \sigma_{\rho_1})(e^{\omega t} - e^{-\omega t})}{(\sigma_{\rho_0} - \sigma_{\rho_1})(e^{\omega t} - e^{-\omega t}) - (\sigma_{\rho_0} + \sigma_{\rho_1})e^{-\omega t}}$$  \hspace{1cm} (A1)

$q$ in relation (A1) is an optical parameter defined as

$$q = \left(\sigma^2 + 4\sigma^4 \frac{\sigma_{\rho_0}^2}{\sigma_{\rho_1}^2}\right)^{1/2}$$  \hspace{1cm} (A2)

where $\sigma$ is an optical parameter called reciprocal diffusion length given by:

$$\sigma = \sqrt{[\pi(a + 2\omega)]}$$  \hspace{1cm} (A3)

$a$ and $s$ being the light absorption and scattering coefficients of the phosphor, $\omega$ is the spatial frequency, $d$ is the density of the phosphor coating, $\rho_0$, $\rho_1$ are given by:

$$\rho_n = \frac{(1 - r_n)}{(1 + r_n)} \hspace{1cm} n = 0, 1$$  \hspace{1cm} (A5)

where, $r_0$ and $r_1$ are the reflectivities at the film–screen interface and at the screen–substrate interface, respectively. Values for $\rho_1$ and $\rho_2$ were taken from previous studies (Giakoumakis *et al.*, 1993; Cavouras *et al.*, 1996).

Finally, $\beta$ is an optical parameter given by:

$$\beta = \sqrt{[\pi(a + 2\omega)]}$$  \hspace{1cm} (A6)