Phys. Med. Biol. **41** (1996) 297–307. Printed in the UK

X-ray induced luminescence and spatial resolution of La_2O_2S:Tb phosphor screens

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Received 12 June 1995, in final form 23 October 1995

Abstract. Absolute efficiency and modulation transfer function of laboratory prepared La_2O_2S:Tb phosphor screens of various coating thickness were studied. Detailed experimental data on the variation of absolute efficiency with x-ray tube voltage up to 200 kVp and screen coating thickness in transmission and reflection observation mode are given. Data were compared with similar results from other rare earth phosphor materials. Theoretical calculations were in good agreement with experimental data to permit estimation of intrinsic efficiency and coefficients related to light scattering and absorption within the phosphor material. The MTF of La_2O_2S:Tb screens was also experimentally and theoretically evaluated.

1. Introduction

The efficiency and spatial resolution of various phosphor screens employed in medical image detectors are important parameters that affect image quality and radiation dose to the patient. Efficiency relative to other phosphor screens (Stevels and Schrama-de Pauw 1976, Sklensky *et al* 1974) as well as conversion efficiency, cathodoluminescent efficiency, quantum efficiency, scintillation efficiency, detective quantum efficiency, and luminance efficiency have been studied in a large number of papers (Wang *et al* 1970, Wickersheim *et al* 1970, Alig and Bloom 1977, Swank 1973, 1974, Bunch *et al* 1987, Nishikawa and Yaffe 1990, Beutel *et al* 1993, Ginzburg and Dick 1993, Wowk *et al* 1994). However, the absolute efficiency of screens under fluoroscopy conditions, defined as the ratio of light flux ϕ emitted towards the observation side divided by the incident x-ray beam power $N (n = \phi/N)$, is of value to people dealing with x-ray intensifying screens and image intensifiers (Nomicos *et al* 1978, Giakoumakis and Nomicos 1985, Giakoumakis *et al* 1989, 1990, 1993).

In the present work a systematic study of the absolute efficiency of laboratory prepared La_2O_2S:Tb screens of various phosphor coating thicknesses was performed using x-ray tube voltages up to 200 kVp. Since radiographic screens are excited to luminescence in transmission and/or reflection modes of observation (i.e. the x-ray beam is incident on one side of the screen and light is detected at the opposite or the same side of the screen

0031-9155/96/020297+11$19.50

respectively), both modes of observation were employed for the purposes of the present study. Also the MTF of those La_2O_2S:Tb screens was studied in the transmission mode of observation, employing the square wave response function (SWRF) method (ICRU 1986) on digitized radiographic images. Experimental data were compared with corresponding theoretical models (Hamaker 1947, Ludwig 1971, Swank 1973, Beutel *et al* 1993).

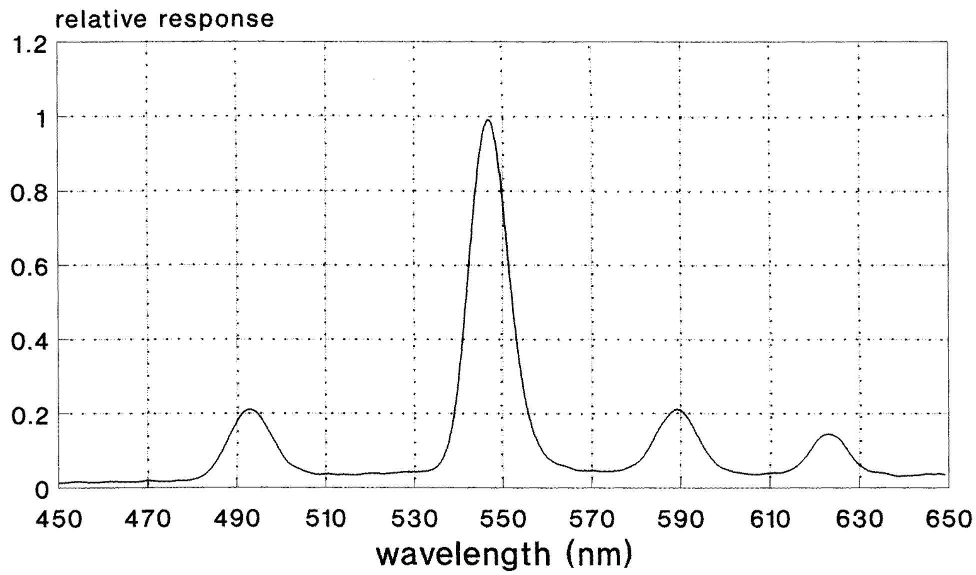

Figure 1. The spectral response of the La_2O_2S:Tb screen.

2. Materials and methods

La_2O_2S:Tb screens were prepared by sedimentation on fused silica substrates as described in previous studies for other phosphor materials (Giakoumakis *et al* 1990, 1993). Screen coating thickness varied between 13.6 mg cm^{-2} and 162 mg cm^{-2}. Screens outside that range were not used because they had extremely low efficiency or poor spatial resolution for radiography. The phosphor material was supplied in powder form by Derby Luminescents Ltd (code No LT133) with a mean grain size of 7 μm.

The experimental set-up adopted for absolute efficiency measurements, comprising a Siemens Stabilipan x-ray unit and a photomultiplier tube with an extended sensitivity S-20 photocathode, has been analytically described in previous papers (Giakoumakis *et al* 1989, 1993). Screens were measured under fluoroscopy conditions in both transmission and reflection modes of observation. For each screen the variation of absolute efficiency with tube voltage was examined between 50 kVp and 200 kVp. The tube current was kept constant at 10 mA.

Absolute efficiency was calculated from the experimental data by taking into account (i) the ratio of light flux collected by the photocathode to the total light flux emitted by the screen towards the observation side and (ii) the matching factor between the spectral sensitivity of the S-20 photocathode and the La_2O_2S:Tb phosphor spectrum. The latter was measured with an Oriel 7240 grating monochromator (figure 1) and the matching factor was calculated as described in a previous report (Giakoumakis 1991).

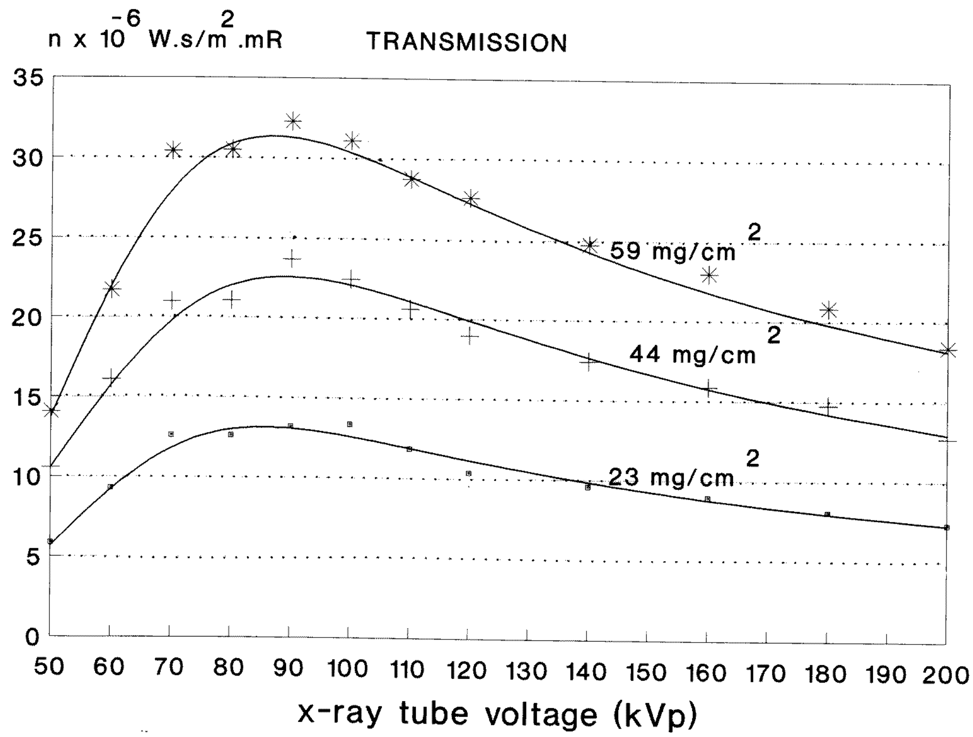

Figure 2. Absolute efficiency in transmission mode versus x-ray tube voltage for three La_2O_2S:Tb screens of 23, 44, and 59 mg cm^{-2} coating thickness. Solid lines, theoretical results; points, experimental data.

Absolute efficiency was also calculated employing the theoretical model of Hamaker (1947) and Ludwig (1971). This model predicts the absolute efficiency of a phosphor screen excited by monochromatic x-rays by the following equations:

$$\begin{aligned} n_t = {} & [n_c \gamma t \mu (1+\rho)\,\mathrm{e}^{(-\mu w)}/2(\mu^2-\sigma^2)] \\ & \times[(\mu-\sigma)(1-\beta)\,\mathrm{e}^{(-\sigma w)} + 2(\sigma+\mu\beta)\,\mathrm{e}^{(\mu w)} - (\mu+\sigma)(1+\beta)\,\mathrm{e}^{(\sigma w)}] \\ & \times[(1+\beta)(\rho+\beta)\,\mathrm{e}^{(\sigma w)} - (1-\beta)(\rho-\beta)\,\mathrm{e}^{(-\sigma w)}]^{-1} \end{aligned} \tag{1}$$

$$\begin{aligned} n_r = {} & [n_c \gamma \mu\,\mathrm{e}^{-\mu w}/(\mu^2-\sigma^2)] \\ & \times[(\mu-\sigma)(\rho+\beta)\,\mathrm{e}^{(\sigma w)} + 2(\sigma\rho-\mu\beta)\,\mathrm{e}^{(-\mu w)} - (\mu+\sigma)(\rho-\beta)\,\mathrm{e}^{(-\sigma w)}] \\ & \times[(1+\beta)(\rho+\beta)\,\mathrm{e}^{(\sigma w)} - (1-\beta)(\rho-\beta)\,\mathrm{e}^{(-\sigma w)}]^{-1} \end{aligned} \tag{2}$$

where n_t and n_r are the absolute efficiencies in transmission and reflection modes respectively, n_c is the intrinsic efficiency of the phosphor, μ the mass attenuation coefficient for the incident x-ray photons, w the coating thickness (surface density) of the screen, t the transparency of the screen's substrate, $\rho = (1-r)/(1+r)$ where r is the reflectivity of the screen's substrate, γ is the conversion factor converting the energy fluence of the x-ray beam (W m^{-2}) to exposure rate (mR s^{-1}), and σ and β are coefficients directly related to the absorption (a) and scattering (s) coefficients of optical photons within the screen, by $\sigma = [a(a+2s)]^{1/2}$ and $\beta = [a/(a+2s)]^{1/2}$.

The spectral response of the x-ray tube and the absorption of the Al filter were also taken into account because the x-ray beam was polychromatic. Thus, the absolute efficiency

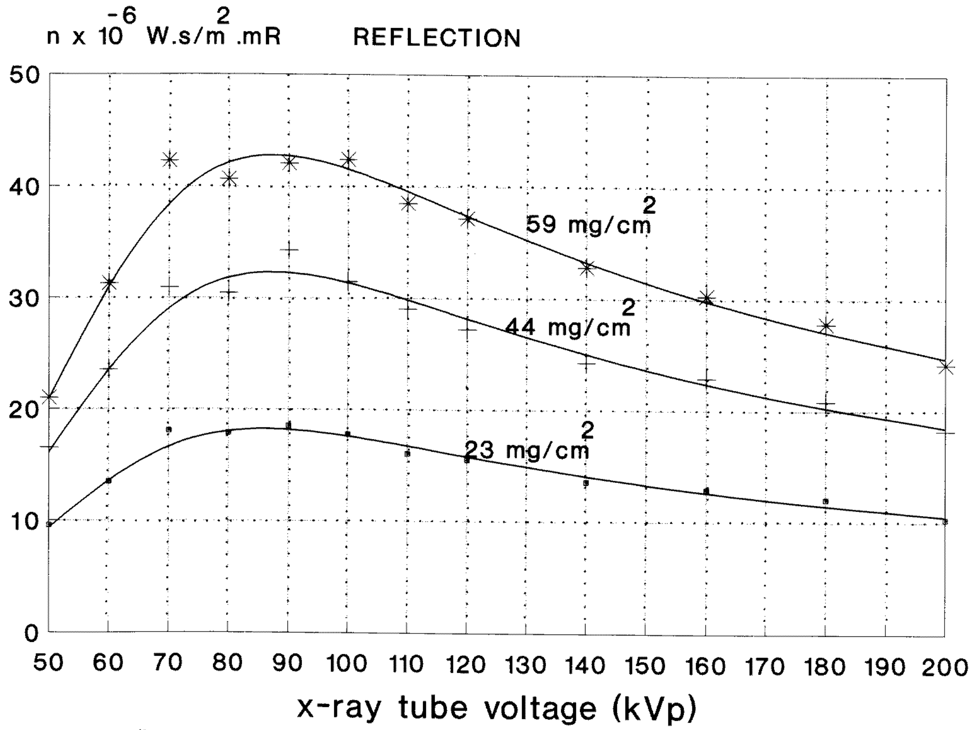

Figure 3. Absolute efficiency in reflection mode versus x-ray tube voltage for three La_2O_2S:Tb screens of 23, 44, and 59 mg cm^{-2} coating thickness. Solid lines, theoretical results; points, experimental data.

was calculated by

$$n = \left(\int_0^{E_0} n(E) f(E)\, \mathrm{d}E \right) \Big/ \int_0^{E_0} f(E)\, \mathrm{d}E \tag{3}$$

where E_0 is the maximum energy of the x-ray photons determined by the tube voltage, $f(E)$ is the spectral distribution function of the x-ray beam, and $n(E)$ is the absolute efficiency of the screen for a monochromatic x-ray beam as given by relation (1) or (2). $f(E)$ is given by (Storm 1972)

$$f(E) = (1 - E/E_0) \exp(-\mu_{Al} d) \tag{4}$$

where d is the total Al filter thickness (22 mm, 2 mm tube filter + 20 mm Al employed to simulate x-ray attenuation by human tissue) and μ_{Al} is the aluminum x-ray attenuation coefficient.

The intrinsic efficiency n_c and coefficient σ of La_2O_2S:Tb phosphor were estimated by fitting relation (3) to the absolute efficiency experimental data . Values for μ in formulae (1) and (2) were calculated from data on lanthanum, oxygen, and sulphur (Storm and Israel 1967, Saloman *et al* 1988). Coefficient β was calculated from reflectivity measurements performed as described by Ludwig (1971).

The MTF of the La_2O_2S:Tb screens was measured using the SWRF method (ICRU 1986). The SWRFs were determined in transmission mode using a line-pair test pattern in contact with a screen–film combination; the latter consisted of laboratory prepared

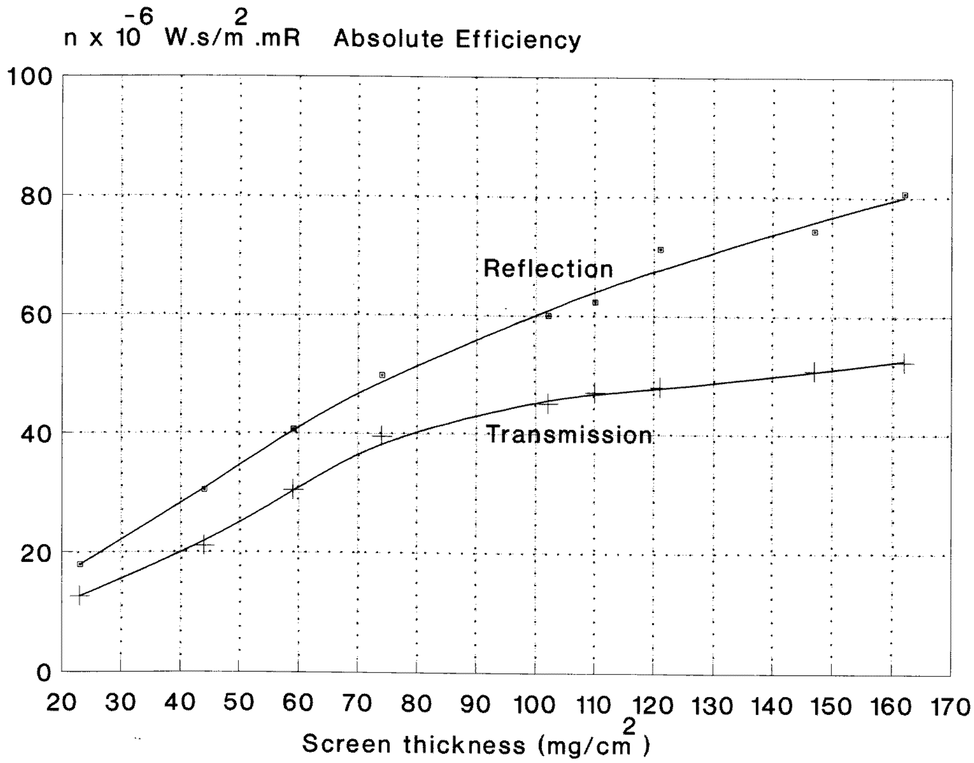

Figure 4. Absolute efficiency of La_2O_2S:Tb screens versus screen's coating thickness for both reflection and transmission mode, for 80 kVp x-ray tube voltage. Solid lines, theoretical results; points, experimental data.

La_2O_2S:Tb screens and Agfa Curix EA0449 radiographic films. The test pattern used (type 1-83) was made of lead with a nominal thickness of 0.05 mm and comprised line pairs of 17 spatial frequencies ranging between 0.5 lp cm^{-1} and 50 lp cm^{-1}. Images of that test-pattern–screen system obtained on the radiographic films using a Phillips diagnostic x-ray unit at 80 kVp were transferred to a computer by means of a 470 000 pixel CCD camera and a frame grabber (Screen Machine II $512 \times 512 \times 8$). For each screen the SWRF density pattern (pixel values) was computed from the screen's digital image as the mean of a large number of density patterns along parallel lines drawn vertically to the test-pattern line pairs, in order to eliminate noise. The SWRF patterns were normalized to the image contrast of the lowest spatial frequency, 0.5 lp cm^{-1}, as described in a previous report by Hillen *et al* (1987). The MTF was then calculated employing the following relation:

$$\mathrm{MTF}(f) = (\pi/4)[\mathrm{SWRF}(f)/1 + \mathrm{SWRF}(3f)/3 - \mathrm{SWRF}(5f)/5 + \mathrm{SWRF}(7f)/7 - \cdots]. \qquad (5)$$

However, the MTF calculated in (5) is the combined effect of the video acquisition system MTF and screen MTF (film MTF ≈ 1 for frequencies $\leqslant 10$ mm^{-1} (Beutel *et al* 1993)). Thus La_2O_2S:Tb screen MTF was determined as follows:

$$\mathrm{MTF}_{\mathrm{La_2O_2S:Tb}} = \mathrm{MTF}_{\mathrm{com}}/\mathrm{MTF}_{\mathrm{VAS}} \qquad (6)$$

where $\mathrm{MTF}_{\mathrm{com}}$ is the combined system MTF including screen, calculated in (5), and $\mathrm{MTF}_{\mathrm{VAS}}$

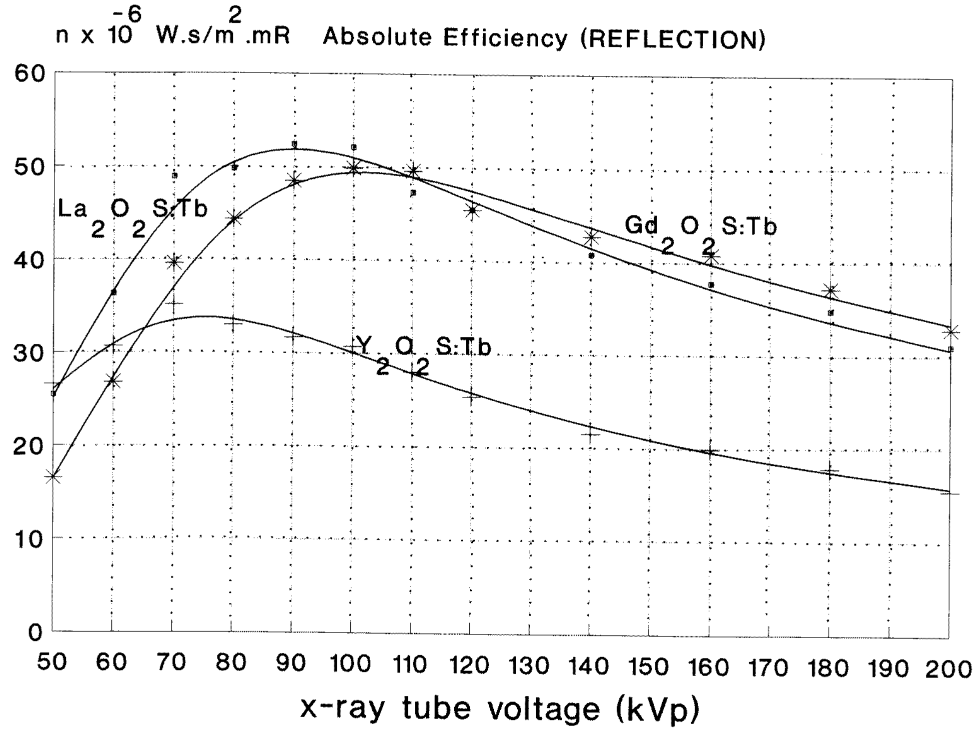

Figure 5. The variation of absolute efficiency measured in reflection mode for Y_2O_2S:Tb, La_2O_2S:Tb and Gd_2O_2S:Tb screens of approximately the same coating thickness (70 mg cm^{-2}). Solid lines, theoretical results; points, experimental data.

is the MTF of the video acquisition system. The latter was determined from images captured with the test pattern mounted on the light box. The linearity of the video acquisition system was verified by digitizing a step wedge radiographic image of known optical densities (Doler *et al* 1994). Additionally, the MTF was theoretically calculated using Swank's model equations (Swank 1973):

$$\begin{aligned}\mathrm{MTF}(E,f) = {}& \mu\tau\rho_1\,\mathrm{e}^{-\mu w}\\ &\times[2q(\tau\rho_0+\mu)\,\mathrm{e}^{-\mu w}-(\mu+q)(q+\tau\rho_0)\,\mathrm{e}^{qw}-(\mu-q)(q-\tau\rho_0)\,\mathrm{e}^{-qw}]\\ &\times\{(1-\mathrm{e}^{-\mu w})(\mu^2-q^2)[(q+\tau\rho_0)(q+\tau\rho_1)\,\mathrm{e}^{qw}\\ &-(q-\tau\rho_0)(q-\tau\rho_1)\,\mathrm{e}^{-qw}]\}^{-1} \qquad (7)\end{aligned}$$

where $q=(4\pi^2f^2+\sigma^2)^{1/2}$, $\tau=\sigma/\beta$, $\rho_0=(1-r_0)/(1+r_0)$, $\rho_1=(1-r_1)/(1+r_1)$, where r_0 is the reflectivity of the screen–film interface and r_1 the reflectivity of the screen–substrate interface. μ, σ, β and w are defined in equations (1) and (2).

Since equation (7) holds for monoenergetic x-rays an integration over the x-ray spectrum was performed as follows:

$$\mathrm{MTF}(f)=\left(\int_0^{E_0}\mathrm{MTF}(E,f)f(E)\,\mathrm{d}E\right)\Big/\int_0^{E_0}\mathrm{MTF}(E,0)f(E)\,\mathrm{d}E. \qquad (8)$$

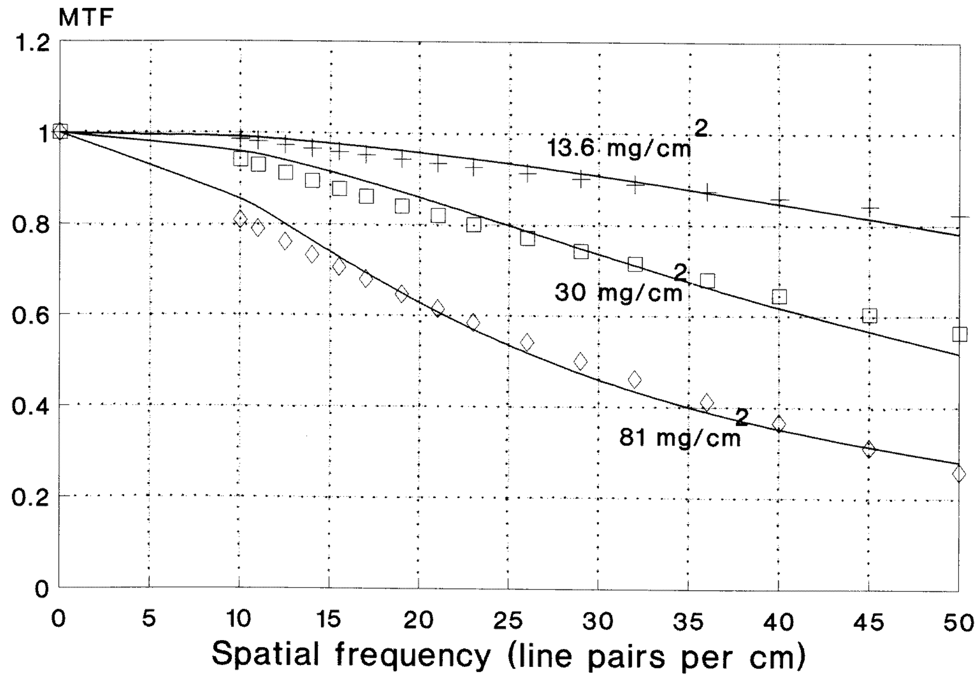

Figure 6. MTF curves for three La_2O_2S:Tb screens of 13.6, 30, and 81 mg cm^{-2} coating thickness. Solid lines, calculated MTF values; points, experimental data.

3. Results and discussion

In figures 2 and 3 the variation of absolute efficiency with tube voltage is presented in transmission and reflection mode respectively for three screens of different thickness. Peak efficiency was in the range between 70–90 kVp, depending on screen thickness. In figure 4 efficiency at 80 kVp is plotted against coating thickness, both in transmission and in reflection mode. Screens in reflection mode were more efficient than in transmission mode, because in the latter light photons travel longer distances to reach the emitting screen surface. Solid lines in figures 2–4 represent the best fitted curves through the experimental data achieved employing relations (1)–(3), giving $\sigma = 30$ cm^2 g^{-1} and $n_c = 0.18$; the latter is higher than values reported previously for cathodoluminescence efficiency (Wickersheim *et al* 1970, Alig and Bloom 1977). Coefficient β, found by reflectivity measurements, was equal to 0.03. The variation of absolute efficiency with tube voltage for three phosphor materials (Y_2O_2S:Tb, La_2O_2S:Tb, and Gd_2O_2S:Tb) with approximately the same coating thickness (70 mg cm^{-2}) is presented in figure 5. Data for Gd_2O_2S:Tb and Y_2O_2S:Tb phosphors were obtained using the same experimental set-up and theoretical calculations as for La_2O_2S:Tb (Giakoumakis and Nomicos 1985, Giakoumakis *et al* 1989, 1990). Gd_2O_2S:Tb screens are more efficient at higher and La_2O_2S:Tb screens are better at lower and intermediate tube voltages. It is interesting to note that Y_2O_2S:Tb is more efficient than Gd_2O_2S:Tb at relatively low kVp (lower than 65 kVp for data shown in figure 5) and it also seems to be more efficient than La_2O_2S:Tb at even lower voltages (lower than 50 kVp in figure 5). The peak efficiency value of La_2O_2S:Tb obtained at 90 kVp is higher than that of Gd_2O_2S:Tb obtained at 100–110 kVp. Differences in absolute efficiency may be attributed

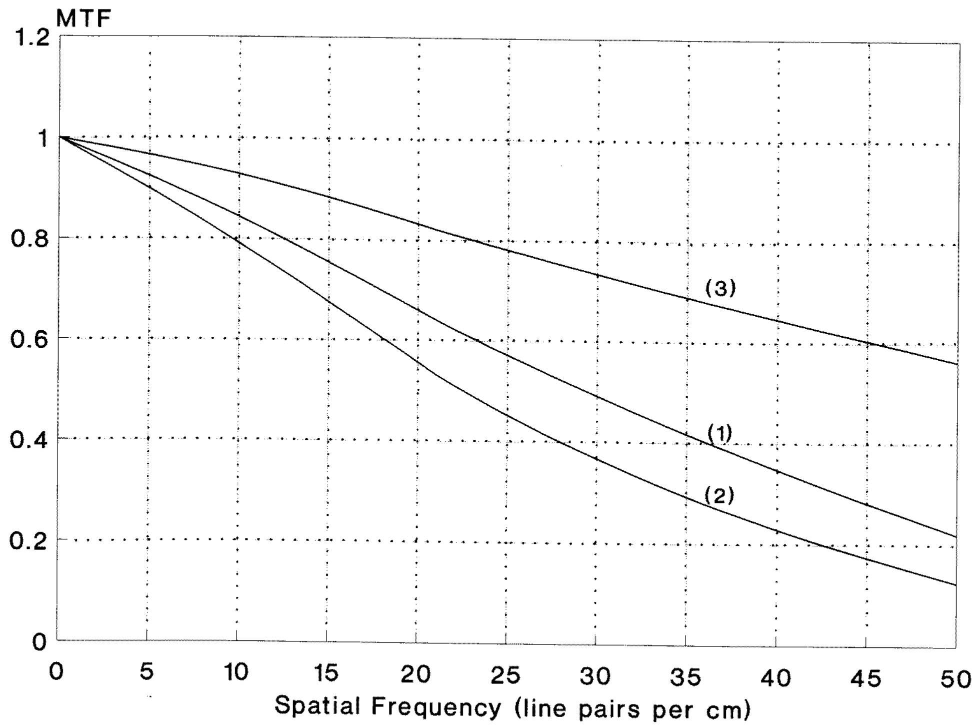

Figure 7. The MTF curve of the video acquisition system (1) and the measured (2) and corrected (3) MTF curves of a 30 mg cm^{-2} La_2O_2S:Tb phosphor screen.

mainly to differences in x-ray attenuation coefficients (K-edge absorption energies) among phosphor materials, since deviations in σ, β, and n_c (table 1) were insignificant.

Table 1. Optical data for the three phosphors.

	n_c^a	σ^b (cm^2 g^{-1})	β^b
Y_2O_2S:Tb	0.18	30	0.03
La_2O_2S:Tb	0.18	30	0.03
Gd_2O_2S:Tb	0.20	30	0.03

[a] Intrinsic efficiency of the phosphor.
[b] Coefficients directly related to the absorption and scattering coefficients of optical photons within the screen.

The variation of MTF with spatial frequency for La_2O_2S:Tb screens of different thicknesses is shown in figure 6. Solid lines represent theoretical results obtained by relations (7) and (8) and dots experimentally determined MTF data. In figure 7, curve 2 shows the combined effect of the MTF of a 30 mg cm^{-2} screen and the MTF of the video acquisition system; curve 2 was obtained using Coltman's formula (relation (5)) and performing SWRF measurements. As observed, the combined MTF of the screen decreases to 0.13 at the limiting frequency of 50 lp cm^{-1}. Curve 1 is the MTF of the video acquisition system, also obtained employing relation (5) on the digitized image of the test pattern alone. After experimental determination of curves 1 and 2, it was possible to derive

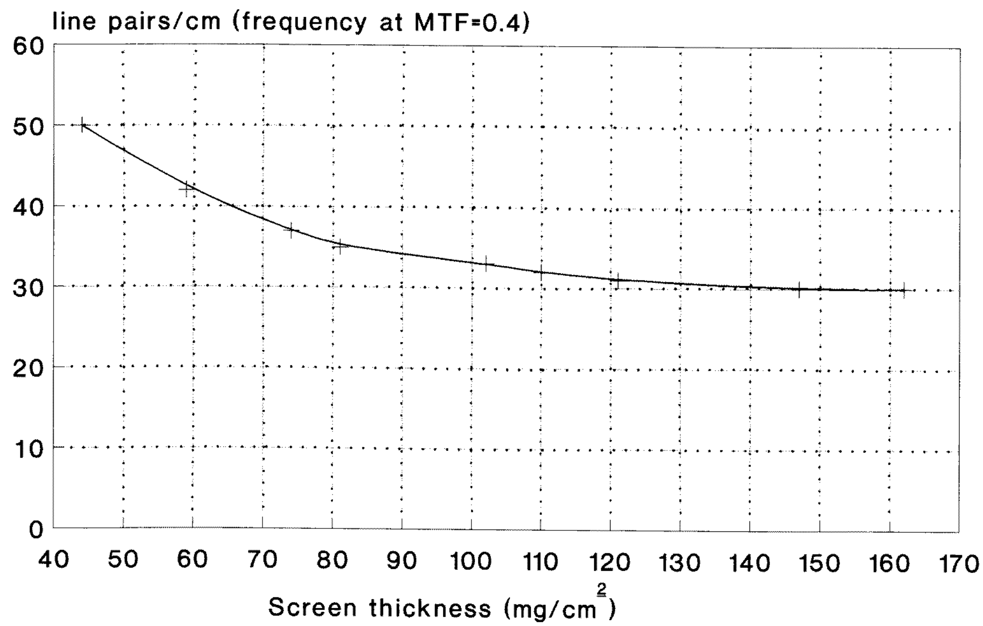

Figure 8. Calculated values of resolution (frequency at MTF = 0.4) against screen coating thickness for La_2O_2S:Tb screens.

the MTF of the 30 mg cm^{-2} La_2O_2S:Tb screen using relation (6). As it can be deduced from figures 6 and 7, the resulting correction provides curves in good approximation to the curves which were theoretically obtained by Swank's model (relations (7) and (8)). The agreement between theoretically and experimentally determined MTF curves is indicative of the validity of the method employed in the present study. The video acquisition system can provide reliable results for frequencies up to 50 lp cm^{-1} and for thicknesses from about 10 to 110 mg cm^{-2}, which is the thickness range of many commercial radiographic screens. For thicker screens, MTF measurements were difficult to obtain at high frequencies due to inherent resolution limitations of the CCD camera–frame grabber system. Therefore, the variation of the screen resolution with coating thickness was assessed at MTF = 0.4. The curve of figure 8 has a hyperbolic behaviour, indicating that for screen thicknesses over 120 mg cm^{-2} the decrease in resolution is insignificant. Despite the frequency limitations, the CCD camera–frame grabber system is fast and easily accessible at user level. Similar set-ups, employing a camera interfaced to a computer, have been successfully applied in evaluating the Wiener spectrum of TV viewed fluoroscopic systems (Goldman 1992) and the MTF of on-line portal imaging screens in radiation therapy (Wowk *et al* 1994). However, the microdensitometer, although expensive and cumbersome to use, is more appropriate for applications demanding higher accuracy, especially at high frequencies (Dainty and Shaw 1974, Barnes 1979, Cunningham and Reid 1992).

4. Summary and conclusions

The absolute efficiency and spatial resolution of La_2O_2S:Tb screens were studied. The intrinsic efficiency and coefficients related to scattering and absorption of light photons within the screens were also found using a uniform screen theoretical model. The intrinsic efficiency of the La_2O_2S:Tb screens was found to be equal to that of Y_2O_2S:Tb and slightly lower than that of Gd_2O_2S:Tb. Light absorption and scattering was about the same for all three phosphors. The La_2O_2S:Tb absolute efficiency was higher in the lower and intermediate kVp range and Y_2O_2S:Tb seemed better in the very low kVp range. Screen MTF determination by CCD camera interfaced to a computer is fast and could be applied routinely.

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