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A method for determining the information capacity of x-ray imaging scintillator detectors by means of luminescence and modulation transfer function measurements

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Abstract—*A method to determine the information capacity of x-ray phosphor screens used in the detectors of medical imaging systems is described. Information capacity was determined via x-ray luminescence efficiency (XLE), modulation transfer function (MTF) and emission spectrum measurements. The method was applied to laboratory prepared screens from commonly employed phosphor materials. The screen coating weight varied from 50 mg cm^{-2} to 140 mg cm^{-2}. Results indicated that information capacity decreased with screen coating thickness but also depended on intrinsic phosphor properties (density, effective atomic number, intrinsic conversion efficiency, light wavelength). The Gd_2O_2S:Tb phosphor, exhibiting high density and effective atomic number, was found to be superior to La_2O_2S:Tb and Y_2O_2S:Tb.*

Keywords—*Scintillators, Phosphor screens, X-ray luminescence, Information capacity, MTF*

Med. Biol. Eng. Comput., 1999, 37, 25–30

1 Introduction

THE CONCEPT of image information capacity has been introduced within the context of Shannon's information theory in order to assess image quality [SHANNON, 1948; JONES, 1961; JONES, 1962; KANAMORI, 1968; DAINTY and SHAW, 1974; BROWN *et al.*, 1979; SHAW, 1979; WAGNER *et al.*, 1979; EVANS, 1981; KANAMORI and MATSUMOTO, 1984]. According to this theory the image information capacity C_I per unit of image area is given by the relation

$$C_I = n_P \log_2 N_S \tag{1}$$

where n_P is the number of image elements (pixels) per unit of area and N_S is the number of distinguishable signal intensity levels that can be registered in an image element. However, little work relevant to medical imaging has been published [KANAMORI, 1968; BROWN *et al.*, 1979; SHAW, 1979; WAGNER *et al.*, 1979; EVANS, 1981; KANAMORI and MATSUMOTO, 1984]. Published work has been based on the determination of the modulation transfer function (MTF) and the noise power spectra (NPS) for radiographic screen–film combinations and computed tomography (CT) systems.

In the present study, a new method is described allowing for experimentally investigating the information capacity of scintillators/phosphors used in conventional or digital X-ray imaging detectors. This is accomplished independently of the optical detector (film, photocathode, photodiode, CCD) used with the scintillator. The method relates the information capacity to intrinsic physical properties of the phosphor and is based on luminescence, emission spectrum and MTF measurements. Results obtained allow for optimal detector material and phosphor thickness selection.

2 Materials and methods

2.1 *Theory*

For the detectors used in various imaging systems, the information capacity has been described in terms of signal power spectra (SPS) and NPS [EVANS, 1981; KANAMORI and MATSUMOTO, 1984]. For the detectors used in both conventional and digital x-ray imaging, power spectra can be represented as one-dimensional functions of spatial frequency ω, $W_S(\omega)$ and $W_N(\omega)$, subscripts S and N denoting signal and noise, respectively. The information capacity is then given by [KANAMORI, 1968; SHAW *et al.*, 1974; BROWN *et al.*, 1979; SHAW, 1979; EVANS, 1981; KANAMORI and MATSUMOTO, 1984]:

$$C_I = \pi \int_0^\infty \log_2 \left[1 + \frac{W_S(\omega)}{W_N(\omega)} \right] \omega \, d\omega \tag{2}$$

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First received 3 March 1998 and in final form 16 June 1998

For x-ray phosphor screens used in radiographic, fluoroscopic or other imaging detectors, both SPS and NPS can be expressed in terms of the MTF associated with the light spread process within the phosphor. SPS and NPS are also functions of parameters describing the physical processes of x-ray absorption, x-ray to light conversion and light transmission through the screen material.

The signal spectrum can be evaluated by considering the following: an x-ray quantum fluence $N_X(E)$ impinges on the detector. The detected fraction of N_X is expressed by the corresponding probability of x-ray detection depending on material density and atomic number. A fraction of the x-ray energy detected is converted into optical photons, but only a fraction of those photons is emitted. The emitted fraction depends on the light attenuation properties of the phosphor material and on the spatial frequencies contained in the imaged object. The higher the frequency the lower is the visibility of the corresponding small details due to lateral light spread and scattering. Thus, the fraction of emitted photons is frequency modulated and this can be expressed by the MTF of the screen. In accordance with the aforementioned description of physical processes and phosphor material properties, the signal spectrum may be expressed as:

$$S_L(\omega) = \bar{\eta}_Q(E, t)\bar{N}_X(E)\bar{m}_0(E)\bar{G}(\omega, t) \tag{3}$$

where, η_Q is the quantum detection efficiency (QDE) expressing the probability of an x-ray quantum being detected by the phosphor screen, $m_0(E)$ is the number of optical photons produced within the phosphor material by an x-ray quantum, $G(\omega, t)$ is the spatial frequency dependent light transmission efficiency giving the fraction of produced optical quanta that escape from the phosphor material as a function of frequency ω and screen thickness t, and E is the energy of an x-ray quantum. Barred parameters $\bar{\eta}_Q$, $\bar{m}_0$, $\bar{G}$ represent mean values over detector area of corresponding stochastic variables and $\bar{N}_X$ represents the mean value of incident x-ray quanta over the measuring time. All these variables were considered to be independent of each other.

The MTF of a screen, expressing the image degradation due to light spread within the screen material, may be defined as the ratio of the signal spectrum to the zero frequency signal spectrum value:

$$\begin{aligned} MTF(\omega, t) &= T_S(\omega, t) \\ &= \frac{\bar{\eta}_Q(E, t)\bar{N}_X(E)\bar{m}_0(E)\bar{G}(\omega, t)}{\bar{\eta}_Q(E, t)\bar{N}_X(E)\bar{m}_0(E)\bar{G}(0, t)} \\ &= \frac{\bar{G}(\omega, t)}{\bar{G}(0, t)} \end{aligned} \tag{4}$$

Thus eqn. 3 can be written as

$$S_L(\omega) = \bar{\eta}_Q(E, t)\bar{N}_X(E)\bar{m}_0(E)\bar{G}(0, t)T_S(\omega, t) \tag{5}$$

The signal power spectrum is then given by

$$\begin{aligned} W_S(\omega, t) &= SPS(\omega) \\ &= \left[\bar{\eta}_Q(E, t)\bar{N}_X(E)\bar{m}_0(E)\bar{G}(0, t)T_S(\omega, t)\right]^2 \end{aligned} \tag{6}$$

Accordingly, the noise power spectrum can be expressed [SHAW and VAN METTER, 1984] in terms of the same physical parameters used for W_S:

$$\begin{aligned} W_N(\omega, t) = {} & \bar{\eta}_Q(E, t)\bar{N}_X(E)\left[\bar{m}_0(E)\bar{G}(0, t)T_S(\omega, t)\right]^2 \\ & + \bar{\eta}_Q(E, t)\bar{N}_X(E)\bar{m}_0(E)\bar{G}(0, t) \end{aligned} \tag{7}$$

In deriving eqn. 7, the variances of η_Q, m_0, G and N_X were calculated and used to determine the variance in S_L. N_X and m_0 were assumed to follow Poisson statistics with variances equal to $\bar{N}_X$ and $\bar{m}_0$, respectively. η_Q and G follow binomial processes; an incident x-ray quantum may or may not be absorbed by the phosphor screen and an optical quantum may or may not be transmitted through the screen. Thus, the variances of η_Q and G are:

$$\mathrm{var}[\eta_Q] = \bar{\eta}_Q(1 - \bar{\eta}_Q) \qquad \mathrm{var}[G] = \bar{G}(1 - \bar{G})$$

Additionally, it must be taken into account that the η_Q process will take place $\bar{N}_X$ times, that there will be $\bar{\eta}_Q\bar{N}_X$ different processes of m_0 optical quanta production and that the G process will happen $\bar{\eta}_Q\bar{N}_X\bar{m}_0$ times. Hence, the variances of η_Q, m_0 and G must be divided by the number of times each process occurs, N_X, $\bar{\eta}_Q\bar{N}_X$ and $\bar{\eta}_Q\bar{N}_X\bar{m}_0$, respectively. The output noise was thus expressed by a variance in S_L having two terms; one term expressing the correlated noise component, affected by the MTF of the imaging system (analogous to the first term in eqn. 7), and one term expressing the uncorrelated noise, which is unaffected by MTF [SHAW and VAN METTER, 1984]. Combining eqns. 2, 6 and 7 the information capacity can be expressed as:

$$C_I = \pi \int_0^\infty \log_2\left[1 + \frac{\bar{\eta}_Q(E, t)\bar{N}_X(E)\bar{m}_0(E)\bar{G}(0, t)T_S^2(\omega, t)}{\bar{m}_0(E)\bar{G}(0, t)T_S^2(\omega, t) + 1}\right]\omega\, d\omega \tag{8a}$$

The number of optical photons $\bar{m}_0(E)$ is computed by the product $\bar{\eta}_C\varepsilon(E, E_\lambda)$, where $\bar{\eta}_C$ is the mean intrinsic conversion efficiency, defined as the fraction of absorbed x-ray energy converted into light, and $\varepsilon(E, E_\lambda)$ is the ratio of the energy of an absorbed x-ray quantum over the energy of an optical photon $E_\lambda(E/E_\lambda)$. $\varepsilon(E, E_\lambda)$ is the number of emitted photons in the case of a perfect screen ($\eta_Q = \eta_C = G(0, t) = 1$). Thus, W_S and W_N can be expressed as functions of the product $\eta_Q\eta_C G(0, t)$ [LUDWIG, 1971], defined as the x-ray luminescence efficiency (XLE) giving the emitted light flux over the incident x-ray energy flux.

Using XLE and eqns. 6 and 7, the information capacity may be expressed as a function of parameters related to intrinsic phosphor properties as:

$$C_I = \pi \int_0^\infty \log_2\left[1 + \frac{\bar{\eta}_\Phi(E, t)\bar{N}_X(E)\varepsilon(E, E_\lambda)T_S^2(\omega, t)}{\bar{\eta}_C\bar{G}(0, t)\varepsilon(E, E_\lambda)T_S^2(\omega, t) + 1}\right]\omega\, d\omega \tag{8b}$$

where, $\bar{\eta}_\Phi$ denotes the mean XLE. Parameters η_Φ, ε, η_C, G and T_S depend on intrinsic phosphor properties as follows:

1. η_Φ increases with density and effective atomic number. η_Φ also increases with intrinsic conversion efficiency (η_C) and phosphor transparency (G).
2. ε increases with optical wavelength.
3. η_C depends on the material's fundamental electronic band gap [ALIG and BLOOM, 1977], crystal site symmetry and type of activator (Tb^{3+}).
4. G decreases with optical scattering and absorption effects within the phosphor. These effects are expressed by the relevant attenuation coefficients [LUDWIG, 1971; CAVOURAS *et al.*, 1996; KANDARAKIS *et al.*, 1997*a*].
5. T_S decreases with optical scattering coefficient. However, absorption of the laterally directed optical photons may contribute to amelioration of the point spread function and MTF. In any event, T_S is a function of the optical properties of the phosphor.

2.2 *Measurements and calculations*

Using eqn. 8*b*, the image information capacity was determined for a number of test screens prepared in the laboratory from Gd_2O_2S:Tb, La_2O_2S:Tb, and Y_2O_2S:Tb, often used in commercial radiographic cassettes or digital radiography detectors. These materials were in powder form with a mean grain size of 7 μm. The screens were developed by sedimentation [CAVOURAS *et al.*, 1996; KANDARAKIS *et al.*, 1997*a*] with coating weights from 50 to 150 $mg\,cm^{-2}$. They were of granular form with packing densities slightly over 50%, like those commercially available, but with no light absorption dyes or reflecting backings sometimes used in commercial screens. X-ray exposures were performed at 90 kVp.

XLE was determined [CAVOURAS *et al.*, 1996; KANDARAKIS *et al.*, 1997*a,b*], by measuring (1) the light emitted from irradiated screens using a photomultiplier* coupled to a Cary 401 electrometer, and (2) the incident exposure, which was converted into energy fluence using the appropriate conversion factor [HENDEE, 1970]. To accurately determine XLE, the following parameters were considered: (1) the angular distribution of the emitted light, determined using previously described techniques [GIAKOUMAKIS and MILIOTIS, 1985]; (2) the distance between the screen and the photocathode of the photomultiplier; (3) the active screen and photocathode areas; (4) the matching between the emitted spectrum, measured in the laboratory, and the spectral sensitivity of the photocathode (extended S-20) supplied by the manufacturer. XLE experimental uncertainties were of the order of 4%. N_X was also determined from the exposure measurements using the corresponding conversion factor, giving the x-ray quantum fluence for a given exposure [HENDEE, 1970]. $\varepsilon(E, E_\lambda)$ in eqn. 8*b* was calculated from the ratio

$$\varepsilon(E_0, E_\lambda) = \frac{\int_0^{E_0} S_X(E)E\,dE \Big/ \int_0^{E_0} S_X(E)\,dE}{\int_{E_{\lambda 1}}^{E_{\lambda 2}} S_P(E_\lambda)E_\lambda\,dE_\lambda \Big/ \int_{E_{\lambda 1}}^{E_{\lambda 2}} S_P(E_\lambda)\,dE_\lambda} \tag{9}$$

where $S_X(E)$ is the spectrum of the polyenergetic incident x-ray beam and $S_P(E_\lambda)$ is the spectrum of the emitted light. $S_X(E)$ was calculated as described in previous studies [STORM, 1972; TUCKER *et al.*, 1991; CAVOURAS *et al.*, 1996], while $S_P(E_\lambda)$ was measured using a monochromator.† The numerator in formula 9 represents the mean energy of x-ray quanta. E_0 is the maximum spectrum energy determined by the tube's voltage. The denominator in formula 9 gives the mean energy of the optical quanta.

MTF was measured employing the square wave response function (SWRF) method [BARNES, 1979; KANDARAKIS *et al.*, 1996; KANDARAKIS *et al.*, 1997*b*]. A typ53MTF test pattern‡ with spatial frequencies from 0.25 to 10 $lp\,mm^{-1}$ was imaged using the screens in contact with an Agfa Curix Ortho GS film. The film images were digitised on a 1200 × 1200 dpi scanner.§ SWRFs were obtained by averaging 64 successive traces vertically directed to the pattern bars. Screen–film characteristic curves were also obtained to correct for film non-linearities [BARNES, 1979]. Final results were obtained using Coltman's formula [BARNES, 1979; ICRU, 1986]:

$$T_S(\omega, t) = \frac{\pi}{4}\sum_{k=1}^{\infty} b_K \frac{SWRF[(2k-1)\omega, t]}{(2k-1)} \tag{10}$$

*EMI 9558 QB

†Oriel 7240

‡Nuclear Associates

§Microtec Scanmaker II SP

where,

$$b_K = 0 \qquad \text{for } m<n$$

$$b_K = (-1)^n(-1)^{k-1} \qquad \text{for } m=n$$

n is the number of prime factors other than unity in $(2k-1)$ and m is the number of prime factors other than unity which appear only once in $(2k-1)$ [ICRU, 1986].

The experimental uncertainties associated with the SWRF method of measurement depend on (1) the number of terms in eqn. 10 used to determine the MTF, and (2) the spatial frequency from which the response will be linearly extrapolated to zero frequency in order to normalise the experimental data at zero spatial frequency (eqn. 4). The MTF uncertainties ranged between 0.7% at low frequencies and thin screens and 3% at high frequencies and thick screens.

$\eta_C G$ in eqn. 8 was determined by the ratio:

$$\eta_C G(0, t) = \frac{\eta_\Phi(E_0, t)}{\eta_Q(E_0, t)} \tag{11}$$

η_Q was calculated as

$$\eta_Q(E_0, t) = \frac{\int_0^{E_0} S_X(E)[1 - e^{-\mu(E)t}]dE}{\int_0^{E_0} S_X(E)dE} \tag{12}$$

$\mu(E)$ is the x-ray attenuation coefficient of the phosphors calculated from published data on chemical elements contained in phosphor materials [STORM and ISRAEL, 1967]. Since the incident x-ray beam was polyenergetic, η_Q was averaged over the x-ray spectrum $S_X(E)$.

3 Results and discussion

Fig. 1 shows the variation of XLE with coating weight for Gd_2O_2S:Tb, La_2O_2S:Tb and Y_2O_2S:Tb phosphors. Measurements were performed at 90 kVp. Gd_2O_2S:Tb was found to be the most luminescent phosphor for all screens measured. The shape of the curves may be explained considering that XLE is determined by (1) the x-ray attenuation effects within the phosphor, quantitatively described by η_Q, and (2) the light attenuation effects, expressed by G. η_Q increases exponentially, with coating weight affecting XLE variation mainly at low coating weights. This determines the ascending part of the XLE curves. However, this is not the case for Gd_2O_2S:Tb. In the latter, XLE most probably increased rapidly for screen thicknesses well below 50 $mg\,cm^{-2}$, the thinnest screen used in our experiments. This behaviour of Gd_2O_2S:Tb may be explained by considering that the high density (7.43 $g\,cm^{-3}$) and high atomic number (Z(Gd) = 64) of this material are expected to highly attenuate the 90 kVp x-rays even with low thickness screen coatings. As screen thickness increases, η_Q shows a tendency to saturate towards a limit value. XLE curves are then dominated by the variation of parameter G which, for a given phosphor, decreases with coating weight. This is obvious considering that the higher the phosphor mass the higher is the probability of optical photon absorption or scattering. Thus, XLE is optimised for a particular region of screen coating weights and then it decreases more or less slowly. XLE also depends on the value of the intrinsic conversion efficiency η_C. However, η_C has previously been found to be practically equal (0.18–0.20) for the three phosphors [KANDARAKIS *et al.*, 1996].

Fig. 2 shows MTF curves of 80 $mg\,cm^{-2}$ Gd_2O_2S:Tb, La_2O_2S:Tb and Y_2O_2S:Tb screens. The performance ranking found in the XLE data was also observed in the MTF results.

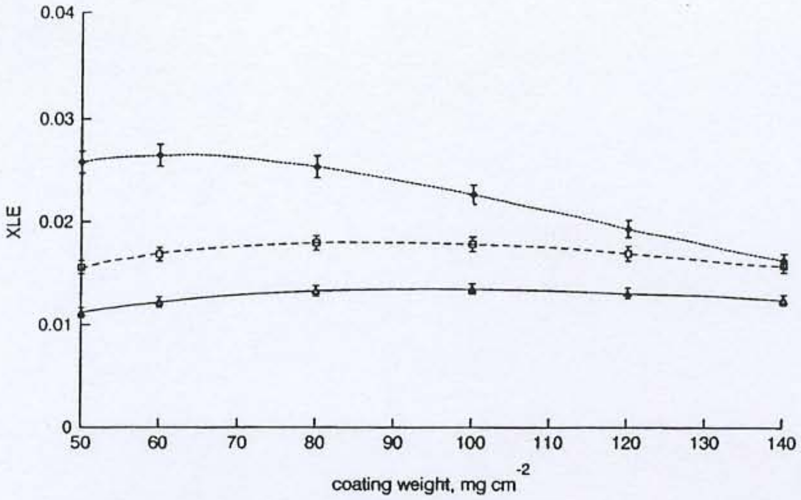

Fig. 1 *Variation of X-ray luminescence efficiency (XLE) with coating weight of Gd_2O_2S:Tb (◆), La_2O_2S:Tb (■), and Y_2O_2S:Tb (▲) phosphor screens measured at 90 kVp*

This may be explained by considering that spatial resolution and MTF decreases with lateral spread of light within the screen. The extent of light spread is determined by the screen thickness and the optical scattering within the phosphor material. The Gd_2O_2S:Tb screens are thinner than La_2O_2S:Tb and Y_2O_2S:Tb screens of the same coating weight owing to the higher density of Gd_2O_2S:Tb. For the same reason La_2O_2S:Tb screens are thinner than Y_2O_2S:Tb. Thus, for equal x-ray penetration, optical photon lateral trajectories must be shorter in Gd_2O_2S:Tb resulting in less photon spread, and MTF improvement. The same reasoning holds for La_2O_2S:Tb when compared with Y_2O_2S:Tb. However, the significance of this density effect is partially reduced by the fact that X-ray penetration is deeper in Y_2O_2S:Tb than in La_2O_2S:Tb and deeper in La_2O_2S:Tb than in Gd_2O_2S:Tb. These differences in x-ray penetration are due to corresponding differences in X-ray attenuation (η_Q). Thus, in Y_2O_2S:Tb, optical photons are generated at greater depth from the exposed screen surface and closer to the screen output inducing a slight amelioration in MTF. Optical scattering does not seriously affect the MTF differences between phosphors since it depends on the average grain size, which is equal for all screens, and on the mean optical wavelength, which does not significantly differ for the three materials.

Fig. 3 shows the MTF values at 40 cycles cm^{-1}. In the range from 50 to 100 mg cm^{-2} MTFs decrease rapidly and this decline rate slows down thereafter. Since MTF expresses the output signal modulation and image contrast, the results of Fig. 2 enable one to draw interesting conclusions concerning the dependence of contrast on screen thickness and phosphor type.

Fig. 4 shows the information capacity values of all the screens used in this study. Gd_2O_2S:Tb screens were found to be significantly better than La_2O_2S:Tb and Y_2O_2S:Tb screens, as was expected considering the XLE and MTF results. Information capacity decreased with coating weight, with the Gd_2O_2S:Tb curve exhibiting the greatest slope. The shape of the curves may be explained by considering that information capacity is affected by both XLE and MTF variation with screen thickness. MTF decreases with coating weight for all phosphors (Fig. 3) and affects C_l in a similar way. However, as shown in Fig. 1, the XLEs of La_2O_2S:Tb and Y_2O_2S:Tb phosphors were found to have a slightly increasing part in the thin-to-medium screen thickness region followed by a slightly decreasing part in thick screens (thicker than 100 mg cm^{-2}). This XLE variation slows down the rate of C_l degradation with coating weight. On the other hand, the XLE of Gd_2O_2S:Tb decreases more rapidly (Fig. 1), thus inducing a corresponding rapidly decreasing C_l curve as shown in Fig. 4. The large difference between the Gd_2O_2S:Tb C_l values and the C_l values of the other phosphors is principally due to a similar difference in corresponding XLEs (Fig. 1). Parameter $\varepsilon(E, E_\lambda)$, although important in determining information capacity, did not seriously affect the differences shown in Fig. 4, since it was found to be approximately equal for the three scintillators.

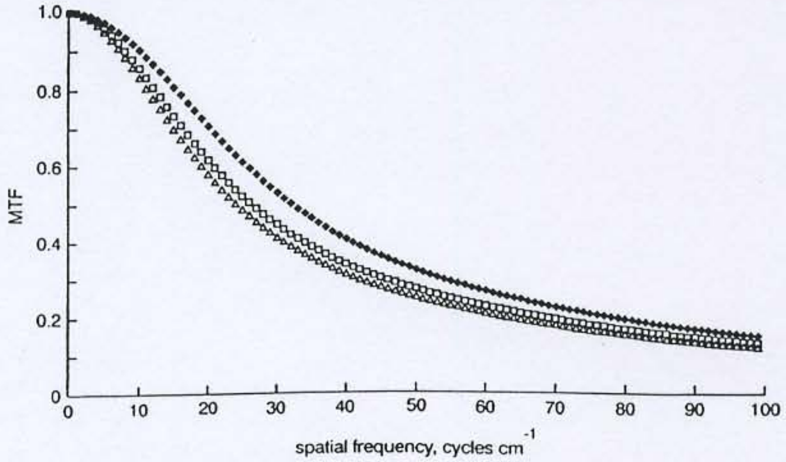

Fig. 2 *Modulation transfer functions (MTF) of 80 mg cm^{-2} Gd_2O_2S: Tb (◆), La_2O_2S: Tb (■) and Y_2O_2S: Tb (▲) phosphor screens measured at 90 kVp*

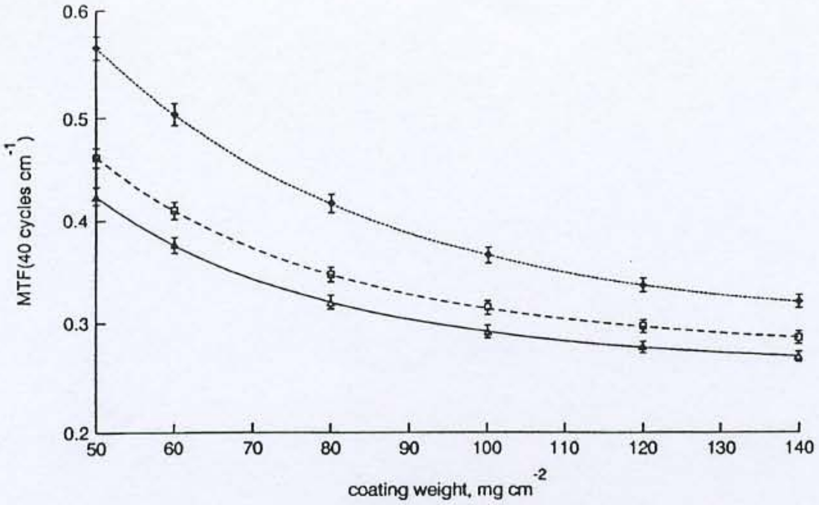

Fig. 3 *Variation of MTF (40 cycles cm^{-1}) with screen coating weight of Gd_2O_2S:Tb (◆), La_2O_2S:Tb (■) and Y_2O_2S:Tb (▲) phosphor screens measured at 90 kVp*

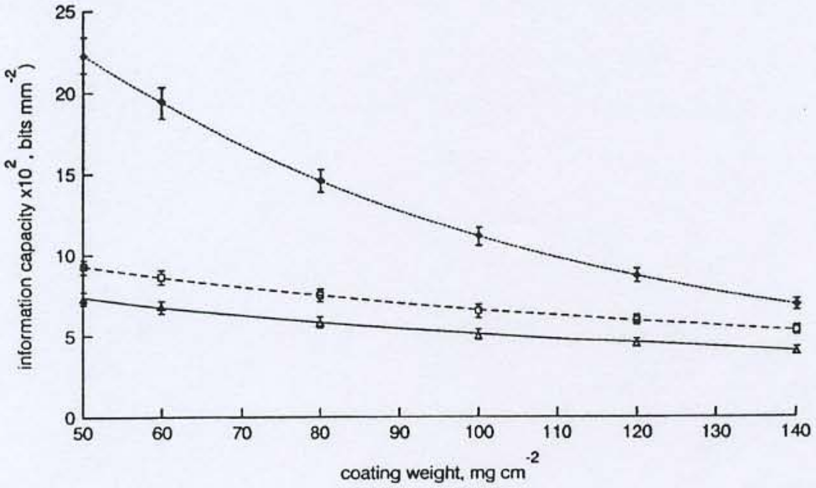

Fig. 4 *Variation of information capacity with coating weight of Gd_2O_2S:Tb (◆), La_2O_2S:Tb (■) and Y_2O_2S:Tb (▲) phosphor screens measured at 90 kVp*

4 Summary

Using the proposed method, the information capacity of phosphor screens was expressed as a function of parameters related to the intrinsic physical properties of phosphors (density, effective atomic number, emitted light wavelength, intrinsic conversion efficiency, optical scattering and absorption). These properties also determine other screen performance and image quality metrics such as MTF, NPS and QED. Among the phosphors studied, Gd_2O_2S:Tb was found to exhibit the highest C_I values owing to its high density, high effective atomic number and high intrinsic conversion efficiency (η_C), factors that govern the XLE and MTF values used to determine C_I.

Acknowledgment—This study is dedicated to the memory of Professor G. E. Giakoumakis, leading member of our team, whose work on phosphor materials has inspired us to continue.

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