PERGAMON

Applied Radiation and Isotopes 52 (2000) 119–126

Applied Radiation and Isotopes

www.elsevier.com/locate/apradiso

Assessing the information content of phosphor produced medical images: application to Zn_2SiO_4:Mn phosphor

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Received 12 April 1999; accepted 30 May 1999

Abstract

In this study a method to assess the information content of medical images produced by phosphors is described. The optical signal emitted by the phosphor after X-ray excitation, the detective quantum efficiency (DQE), expressing the signal-to-noise ratio (SNR) transfer efficiency, and the information capacity were experimentally determined. The method was based on light flux and modulation transfer function (MTF) measurements and was used to assess the imaging performance of the Zn_2SiO_4:Mn phosphor. The latter was employed in the form of laboratory prepared phosphor layers (test screens). Results showed that high values for optical signal emission and DQE were obtained for medium thickness phosphor layers (56 and 89 mg/cm^2) at 20 kVp X-ray tube voltage. The information capacity was found to decrease continuously with phosphor coating weight.

Keywords: Medical phosphors; Phosphor screens; MTF; Signal-to-noise ratio

1. Introduction

The performance of medical image receptors may be assessed by the amount of diagnostic information displayed by the images produced. The image information content may be estimated by various image quality metrics quantifying either the level of output signal or the output-signal-to-noise ratio (SNR) (Dainty and Shaw, 1974, Motz and Danos, 1978). In the present study, an experimental method was developed for assessing the information content of images produced by means of phosphors used in medical imaging radiation detectors. The method comprised the following three steps:

1. Determination of the output optical signal of the phosphor as a function of spatial frequency. This signal depends on the light fluence emitted by an X-ray excited phosphor and on the modulation transfer function (MTF). The latter describes the transfer of signal through an imaging system and provides an objective estimation of image contrast and spatial resolution (Dainty and Shaw, 1974; ICRU, 1986).

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0969-8043/00/$ - see front matter
PII: S0969-8043(99)00116-5

2. Determination of the output SNR as a function of spatial frequency. SNR is often expressed by the detective quantum efficiency (DQE) (Dainty and Shaw, 1974; Shaw, 1979; Shaw and Van Metter, 1984), which describes the transfer of SNR through an imaging system. DQE depends on the output optical signal and on the noise power spectrum (NPS), also called the Wiener spectrum, expressing the noise power in the spatial frequency domain (Dainty and Shaw, 1974; Shaw and Van Metter, 1984; Van Metter, 1992; Bunch et al., 1987).
3. Determination of the information capacity which is as a function of the number of distinguishable output signal intensity levels in the final image. Information capacity has been expressed (Dainty and Shaw, 1974; Shaw, 1979) as an integral of the phosphor's SNR properties over the spatial frequency domain and, thus, it assesses the overall imaging performance of an image receptor by a single value.

The proposed method was based on experimental techniques of light fluence and MTF measurements and was employed to assess the imaging performance of Zn_2SiO_4:Mn phosphor. This material emits green light well within the spectral sensitivity of most optical detectors (films, photocathodes, photodiodes) (Kandarakis et al., 1999b) but, to our knowledge, it has never been employed for medical applications.

2. Materials and methods

2.1. Theory and definitions

The response of a phosphor layer to an input X-ray signal may be expressed by the contrast transfer function (CTF) (Bunch et al., 1987; Van Metter, 1992). The output optical signal S_o in the spatial frequency domain is as follows:

$$S_o(u, w, E) = \Phi_Q \mathrm{CTF}(u, w) = \Phi_\lambda(u, w, E) \quad (1)$$

where u is the spatial frequency, w is the phosphor coating weight, Φ_Q is the mean incident X-ray quantum fluence (input signal), E is the mean energy of the X-ray quanta, and Φ_λ is the mean emitted optical quantum fluence (quanta per unit area). CTF is defined as the product of MTF and slope ($d\Phi_\lambda/d\Phi_Q$) of the phosphor's characteristic curve. The latter expresses the conversion of input X-ray quanta into output optical quanta by a phosphor layer at zero frequency. Hence, relation (1) may be written as:

$$S_o(u, w, E) = \Phi_Q \left[\frac{d\Phi_\lambda}{d\Phi_Q}\right] \mathrm{MTF}(u, w) \quad (2)$$

or

$$S_o(u, w, E) = \Phi_\lambda(w, E) \mathrm{MTF}(u, w) \quad (3)$$

where Φ_λ (w,E) is the mean output optical quantum flux at zero frequency.

The output signal to noise ratio, associated with the number of emitted quanta, is given by:

$$\mathrm{SNR_o}(u, w, E) = \frac{\Phi_\lambda(w, E)\mathrm{MTF}(u, w)}{N_\lambda(u, w)} \quad (4)$$

where N_λ (u,w) is a function describing output quantum noise in the spatial frequency domain. N_λ is equal to the square root of the quantum noise power spectrum (Wiener spectrum) of the emitted optical quanta (Shaw and Van Metter, 1984; Hillen et al., 1987).

The SNR of an imaging system is often represented in terms of the detective quantum efficiency (DQE) defined by the ratio:

$$\mathrm{DQE}(u, w) = \left[\frac{\mathrm{SNR_o}(u, w, E)}{\mathrm{SNR_I}}\right]^2 \quad (5)$$

where $\mathrm{SNR_I}$ is the input SNR related to the X-ray quanta incident on the phosphor. $\mathrm{SNR_I}$ may be written as follows:

$$\mathrm{SNR_I} = \frac{\Phi_Q}{\sigma(\Phi_Q)} \quad (6)$$

where σ is the statistical standard deviation associated with the incident X-ray quantum fluence fluctuations. The denominator in Eq. (6) represents an expression of input quantum noise. Considering that the incident quanta follow Poisson statistical distribution (Shaw and Van Metter, 1984):

$$\sigma(\Phi_Q) = \sqrt{\Phi_Q} \quad (7)$$

and hence from Eqs. (4)–(7) it follows that

$$\mathrm{DQE}(u, w) = \frac{[\Phi_\lambda(E, w)\mathrm{MTF}(u, w)]^2}{\Phi_Q W_\lambda(u, w)} \quad (8)$$

where, W_λ in Eq. (8) is the Wiener spectrum of the emitted optical quanta. W_λ has been previously described (Shaw and Van Metter, 1984) in terms of emitted optical quantum fluence Φ_λ by relation (9) (See Appendix):

$$W_\lambda(u, w) = \Phi_\lambda(E, w)\left[m(E, \lambda)\left\{1 + \frac{\varepsilon}{m_o}\right\}\mathrm{MTF}^2(u, w) + 1\right] \quad (9)$$

where $m(E,\lambda)$ is the mean number of optical quanta emitted per X-ray quantum absorbed, m_o is the mean number of optical quanta created within the phosphor layer per X-ray absorbed, ε is a parameter accounting for the excess of the variance in m_o with respect to the Poisson distribution, given by $\varepsilon = \frac{\sigma^2(m_o)}{m_o} - 1$ (Shaw and

Van Metter, 1984). Following previous studies (Nishikawa and Yaffe, 1990; Shaw and Van Metter, 1984) it was assumed that m_o follows Poisson distribution, then $\sigma^2(m_o) = m_o$ and hence $\varepsilon = 0$. Thus, using Eq. (9), DQE can be written as:

$$\mathrm{DQE}(u, w) = \frac{\Phi_\lambda(E, w)\mathrm{MTF}^2(u, w)}{\Phi_Q\left[m(E, \lambda)\mathrm{MTF}^2(u, w) + 1\right]} \tag{10}$$

The information capacity (C_I) has been defined (Dainty and Shaw, 1974, Shaw, 1979) by the relation:

$$C_I = n_P \log_2 n_G \tag{11}$$

where n_P is the number of image elements (pixels) per unit of image area and n_G is the number of distinguishable optical signal intensity levels in the output image. It has been previously shown (Dainty and Shaw, 1974; Shaw, 1979) that C_I can also be expressed as a function of SNR_o by the following relation:

$$C_I(w) = \pi \int_0^\infty \log_2\left[1 + \mathrm{SNR}_0^2(u, w, E)\right] u \, \mathrm{d}u \tag{12}$$

Using relations (4) and (9), C_I may be expressed as follows:

$$C_I(w) = \pi \int_0^\infty \log_2\left[1 + \frac{\Phi_\lambda(E, w)\mathrm{MTF}^2(u, w)}{m(E, \lambda)\mathrm{MTF}^2(u, w) + 1}\right] u \, \mathrm{d}u \tag{13}$$

Relations (3), (4), (8), (9), and (13) indicate that the information content of a phosphor produced medical image may be experimentally assessed by determining Φ_λ, Φ_Q, MTF and m.

2.2. Experiments and calculations

The proposed method was employed to assess the performance of Zn_2SiO_4:Mn phosphor. This phosphor was supplied by Derby Luminescents Ltd in powder form with mean grain size of 7 μm. Fluorescent layers (phosphor screens) with coating weights 18–153 mg/cm^2, were prepared by sedimentation of the phosphor powder on fused silica substrates as described in previous studies (Cavouras et al., 1996; Kandarakis et al., 1997a,b, 1999a,b; Cavouras et al., 1999a). Φ_λ was determined by measuring the light intensity emitted after X-ray excitation of the phosphor, using 20 kVp X-ray tube voltage. Since Φ_λ is expressed in quanta per unit area, the light intensity was divided by the mean energy ($hc/\bar{\lambda}$) of the optical quanta. This energy was found by performing emission spectrum measurements in order to determine the mean optical wavelength $\bar{\lambda}$. Using relation $\bar{\lambda} = \int S_P(\lambda)\lambda \mathrm{d}\lambda / S_P(\lambda)\mathrm{d}\lambda$, where $S_P(\lambda)$ is the measured emission spectrum forming a narrow band centered around 525 nm. Φ_Q was found from X-ray exposure measurements (Hendee, 1970; Greening, 1985). The measuring instrumentation used comprised an EMI 9558 QB photomultiplier coupled to a Cury 401 electrometer for light intensity determination, an Oriel 7242 spectrometer for emission spectrum measurements and a PTW dosemeter (ionization chamber type No. 23333) for X-ray exposure measurements. Φ_λ was determined for both the front and rear sides of each phosphor layer (Cavouras et al., 1996; Kandarakis et al., 1997a). Rear side emission simulates the input screens of image intensifiers, the front screen of double coated radiographic cassettes, as well as the detectors of digital radiography, computed tomography and nuclear medicine systems. Front side emission simulates the rear screen of double coated radiographic cassettes and the single coated mammographic cassettes. Light intensity measurements were corrected taking into account the following: (1) the spectral matching factor, which expresses the compatibility between the phosphor emission spectrum and the spectral sensitivity of the photomultiplier's photocathode (extended S-20). This sensitivity was obtained from manufacturer's data. (2) The geometric efficiency, which expresses the effects of geometric parameters like the phosphor-photocathode distance, the angular distribution of light etc., on light measurements (Cavouras et al., 1999).

MTF was determined by the square wave response function (SWRF) method (Barnes, 1979; ICRU, 1986). SWRF was measured using a test pattern (MTF pattern typ-53 of Nuclear Associates) comprising lead line pairs with spatial frequencies from 0.25 to 10 lp/mm. The pattern image was formed on a radiographic film (Agfa Curix Ortho GS) by the light emitted from the excited phosphor layers. Measurements were performed using both rear and front phosphor side emission to simulate all types of X-ray imaging detectors. Details of the measurements are given in previous studies (Cavouras et al., 1996; Kandarakis et al., 1997b, 1999a; Cavouras et al., 1998). MTF was finally calculated from SWRF data employing the Coltman's formula (Barnes, 1979; ICRU, 1986; Cavouras et al., 1998)

The number $m(E,\lambda)$ of emitted optical quanta per X-ray absorbed was determined by dividing Φ_λ by the absorbed fraction of Φ_Q. This fraction was calculated using the X-ray absorption coefficient of Zn_2SiO_4:Mn, calculated from data on Zn, Si, O as given by Storm and Israel, and considering exponential X-ray absorption (Storm and Israel, 1967).

3. Results and discussion

Fig. 1 shows the variation of MTF with spatial frequency for various Zn_2SiO_4:Mn phosphor coating

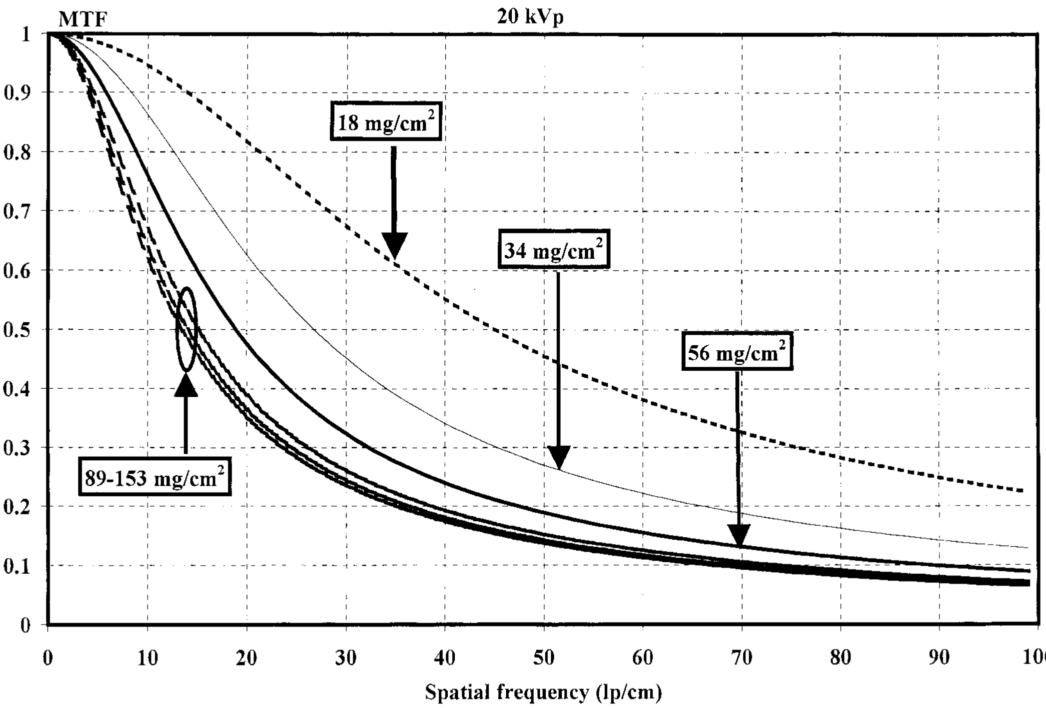

Fig. 1. Variation of MTF with spatial frequency for Zn_2SiO_4:Mn phosphor screens of various coating weights.

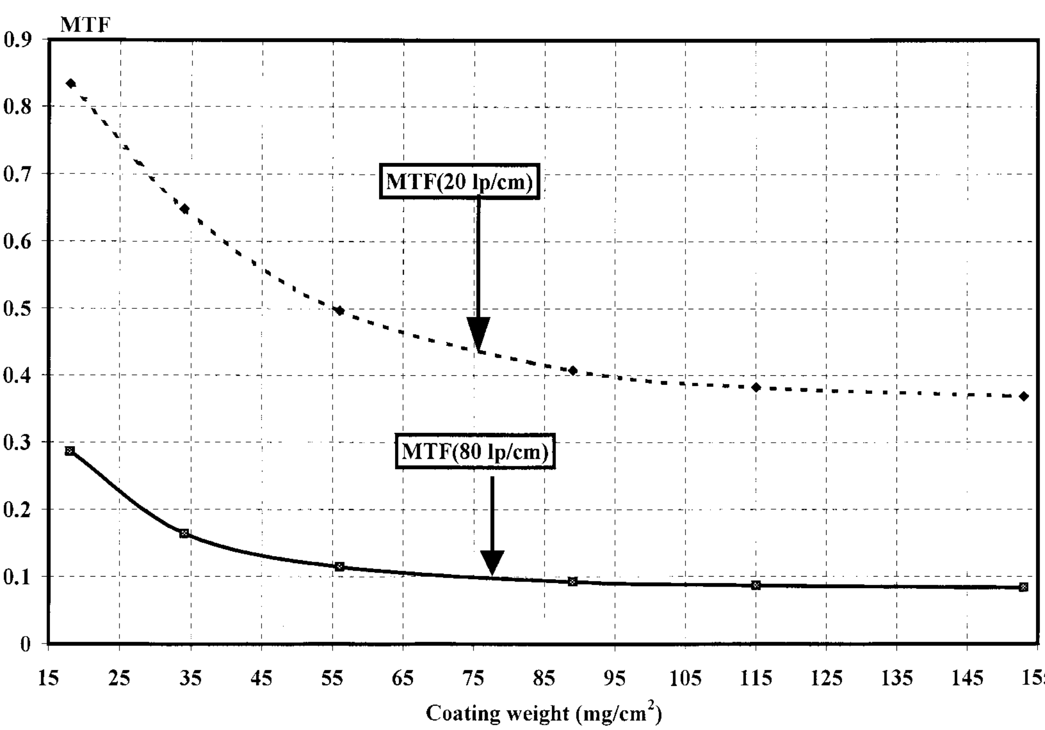

Fig. 2. Variation of MTF at 20 lp/cm and at 80 lp/cm with coating weight.

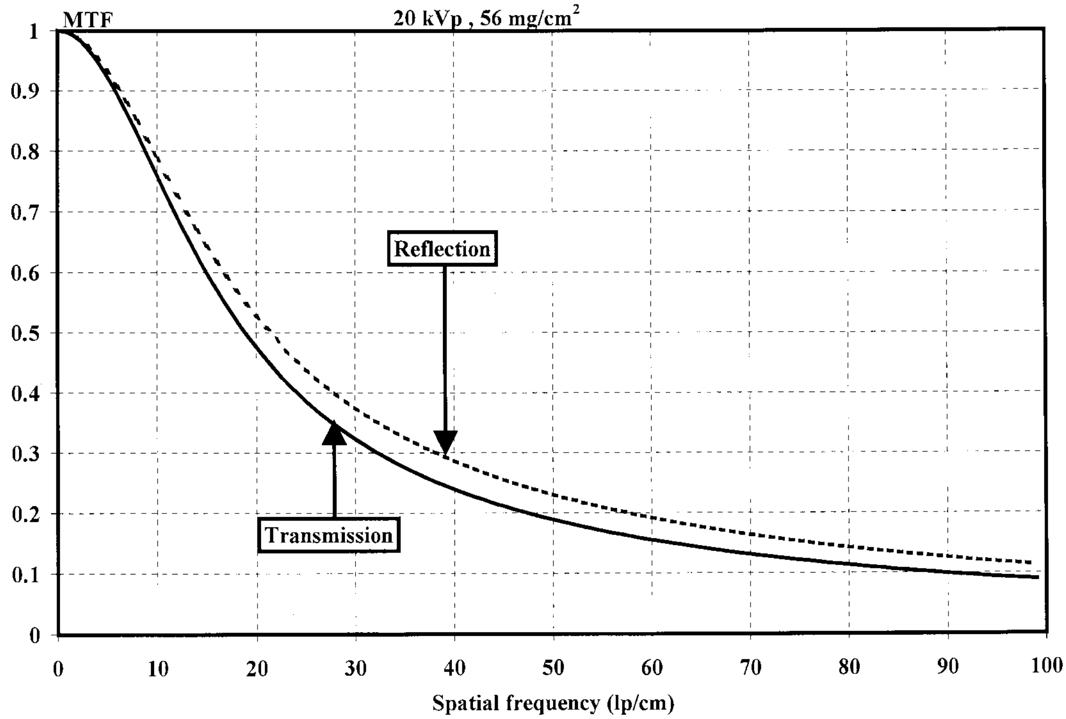

Fig. 3. Comparison of the rear and front screen configuration MTFs of the 56 mg/cm^2 phosphor layer.

weights. MTF decreases significantly with increasing coating weight for phosphor layers up to 89 mg/cm^2, while for thicker layers the corresponding decrease is minimal. This behaviour may be explained by considering the spatially isotropic creation of optical quanta within the phosphor mass. In thick phosphor layers, laterally directed optical quanta travel long distances to escape the phosphor and, hence, they spread over a large area at the emitting surface of the phosphor layer. Additionally, optical scattering on phosphor grains increases with thickness. Thus, image sharpness and contrast degrade resulting in lower SWRF and MTF. However, for very thick phosphors the probability of absorption of the laterally directed optical quanta along their trajectories increases. This phenomenon tends to reduce the area of light spread at the phosphor's surface and this may explain the minimal MTF decrease for phosphor layers thicker than 89 mg/cm^2.

Fig. 2 shows the variation of MTF at 20 lp/cm and at 80 lp/cm with coating weight. The 20 lp/cm and 80 lp/cm curves may provide an indication as to how image contrast and spatial resolution vary with coating weight. As depicted, image quality initially degrades rapidly with thickness but remains practically constant at thick coating weights. This is in accordance with findings of Fig. 1.

In Fig. 3 the rear and front screen configuration MTFs of the 56 mg/cm^2 phosphor layer are compared. The difference between the two curves may be explained by considering that distances traveled by optical quanta to escape the phosphor from its irra-

Table 1
Optical fluence (Φ_λ) measurements in front and rear screen configurations

Coating weight (mg/cm^2)	Φ_λ (front screen set-up) $\times 10^6$ (quanta/cm^2)	Φ_λ (rear screen set-up) $\times 10^6$ (quanta/cm^2)
18	61.98	92.00
34	95.45	139.97
56	111.85	165.70
89	101.30	173.79
115	83.54	174.66
153	59.93	174.83

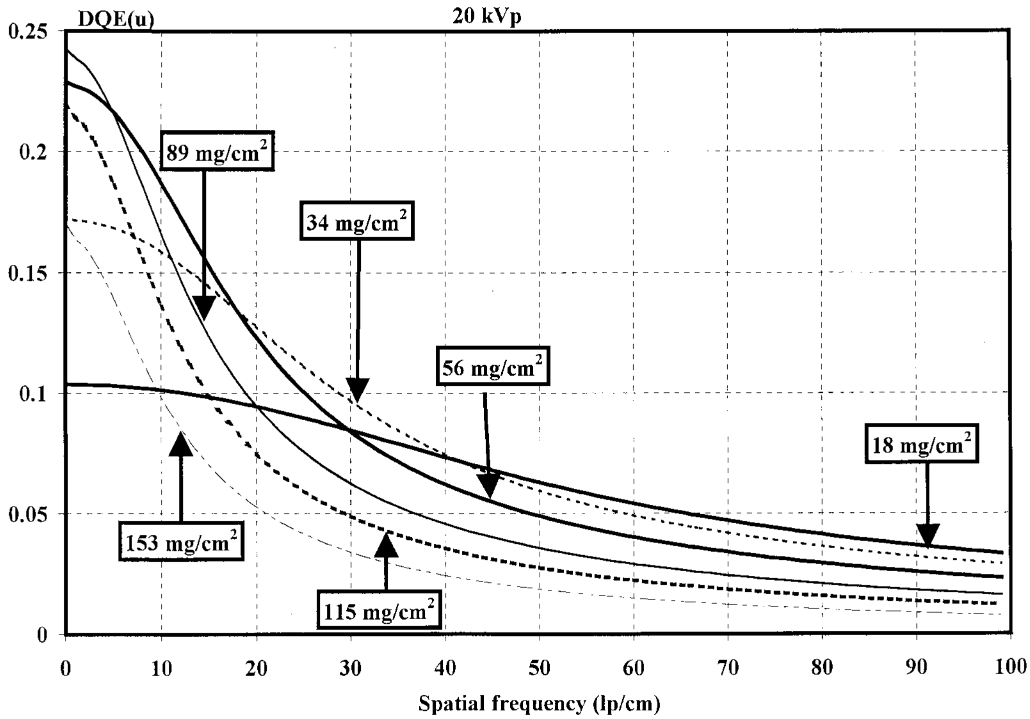

Fig. 4. Variation of DQE with spatial frequency for the 18, 34, 56, 89, 115, and 153 mg/cm^2 phosphor layers.

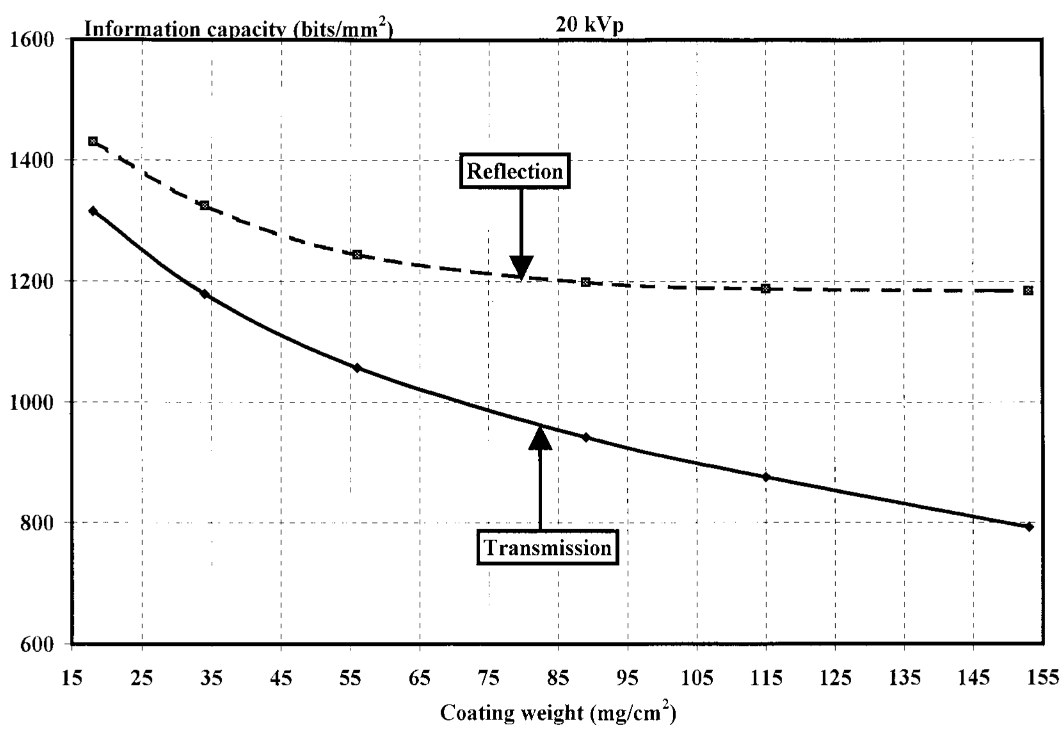

Fig. 5. Variation of information capacity with coating weight.

diated side (rear screen configuration) are shorter. Furthermore, the exponential absorption of the incoming X-ray beam, imposes higher probabilities of X-ray absorption and light creation nearby the irradiated phosphor surface. Thus, the extent of light spread at the phosphor's output is less than in the case of front screen measurements, resulting in higher MTF values in rear screen configuration. Similar differences were also observed in the case of emitted optical fluence (Φ_λ) measurements (Table 1).

Fig. 4 shows the variation of DQE with spatial frequency for all phosphor layers employed in our measurements. At zero spatial frequency, the 89 mg/cm^2 layer showed the highest DQE value, while at the medium and high frequency range, the DQE of the 18 mg/cm^2 layer was found highest. Very low DQE values were obtained for the thickest phosphor layer of 153 mg/cm^2 at medium and high frequencies. DQE variation with coating weight and frequency is determined by the corresponding variations of Φ_λ and m, affected by coating weight, and MTF, affected by both frequency and coating weight. Thus, DQE is clearly decreasing with spatial frequency affected by a similar MTF behaviour. However, at low spatial frequencies, MTF values are close to unity and hence the influence of the emitted optical quantum fluence Φ_λ on DQE is more evident. This explains the high DQE(0) found for the 89 and 56 mg/cm^2 layers, which exhibited highest Φ_λ (Table 1). On the other hand, the thin layer of 18 mg/cm^2 displayed better DQE at medium and high frequencies because of its very high MTF as shown in Fig. 1. Furthermore, the low DQE(0) of this layer is explained by its weak emission efficiency as shown by the low Φ_λ value in Table 1. The curves concerning front phosphor side emission were found similar to those of Fig. 4.

Fig. 5 shows the variation of information capacity with phosphor coating weight for rear and front screen emission measurements. Although thick phosphor layers absorb larger quantities of incident X-ray quanta (Φ_Q), which is the input information to an imaging system, the information capacity decreases with increasing coating weight. This is mainly due to the type of variation of MTF with phosphor thickness (shown in Fig. 3), which is affected by the isotropic light production and the optical scattering effects within the phosphor. Additionally, the total quantity of light transmitted through phosphor mass towards the output decreases with phosphor thickness thus reducing output information. As it was expected from the MTF and Φ_λ data, front side emission showed higher information capacity values.

In conclusion, DQE and information capacity data showed that at high frequencies and thick phosphor layers noise passes more easily to the output than useful information.

4. Summary

A method to assess the information content of medical images produced by phosphor layers (screens) is presented. The method is based on the determination of the detective quantum efficiency and the information capacity by performing light fluence and modulation transfer function measurements under X-ray excitation. Zn_2SiO_4:Mn phosphor layers were prepared in laboratory and were excited by 20 kVp X-rays corresponding to mammographic imaging. DQE, which expresses signal to noise ratio, decreased with spatial frequency. However, the rate of DQE decreases and the zero frequency DQE value were found to depend strongly on phosphor thickness. Information capacity was also found to decrease with phosphor thickness, due to MTF and emitted light fluence variation with thickness.

Acknowledgements

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.

Appendix A

Relation (9) for Wiener spectrum has been developed (Shaw and Van Metter, 1984) by considering the following:

The emitted light fluence Φ_λ may be expressed as the product of the following parameters

$$\Phi_\lambda = \Phi_Q \eta m_o G_\lambda \tag{A1}$$

where η is the X-ray absorption efficiency of the phosphor and G_λ is the efficiency for transmission of the optical quanta m_o through the phosphor material. Quantum noise may be expressed by the variance in the number Φ_λ var[Φ_λ]. The latter may be calculated by determining and adding the fractional variances in Φ_Q, η, m_o, and G_λ. For this η and G_λ were considered to follow binomial statistical distribution while Φ_Q follows Poisson statistical distribution. Since Φ_λ is a cascade of the four physical events represented by Φ_Q, η, m_o, G_L, the fractional variance of Φ_λ (var[Φ_λ]/Φ_λ^2]) may be calculated by the relation:

$$\frac{\mathrm{var}[\Phi_\lambda]}{\Phi_\lambda^2} = \frac{\mathrm{var}[\Phi_Q]}{\Phi_Q^2} + \frac{\mathrm{var}[\eta]}{\eta^2 \Phi_Q} + \frac{\mathrm{var}[m_o]}{m_o^2 \Phi_Q \eta} + \frac{\mathrm{var}[G_\lambda]}{G_\lambda^2 \Phi_Q m_o \eta} \tag{A2}$$

and finally:

$$\mathrm{var}[\Phi_\lambda] = \Phi_Q \eta (m_o G_\lambda)^2 \left\{ 1 + \frac{\varepsilon}{m_o} \right\} + \Phi_Q \eta m_o G_\lambda \tag{A3}$$

where ε is the excess of the variance of m_o with respect to the variance corresponding to Poisson distribution. According to previous studies (Nishikawa and Yaffe, 1990; Shaw and Van Metter, 1984), the distribution in m_o may be assumed to follow Poisson statistics.

The first term of Eq. (A3) corresponds to the so called correlated quantum noise component (Shaw and Van Metter, 1984). This noise component expresses the effects of light diffusion processes (scattering, etc.) within the phosphor. These processes affect the spatial correlation of optical quanta emerging at the phosphor's output surface and, in the space domain, are expressed by the point spread function (PSF). The second term of Eq. (A3) was considered to express the so called uncorrelated quantum noise component which is unaffected by the light diffusion process (scattering, etc.) within the phosphor. Hence, to describe quantum noise in the spatial frequency domain, only the first term of Eq. (A3) was expressed through MTF, which describes light diffusion effects in the frequency domain. Thus, finally it is obtained:

$$W_\lambda(u, w) = \Phi_Q \eta (m_o G_\lambda)^2 \left\{ 1 + \frac{\varepsilon}{m_o} \right\} [\mathrm{MTF}]^2 + \Phi_Q \eta m_o G_\lambda \tag{A4}$$

Relation (9) was found by taking into account (A1) and placing $m_o G_\lambda = m$.

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