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Section A

An experimental method for the determination of spatial-frequency-dependent detective quantum efficiency (DQE) of scintillators used in X-ray imaging detectors

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Abstract

The spatial-frequency-dependent detective quantum efficiency (DQE) of imaging scintillators was studied independently of the optical detector (film, photocathode, or photodiode) employed in medical imaging devices. A method was developed to experimentally determine the scintillator DQE in terms of its luminescence efficiency (LE), quantum detection efficiency, modulation transfer function, and light emission spectrum. $Gd_2O_2S:Tb$, $La_2O_2S:Tb$, $Y_2O_2S:Tb$ and $ZnSCdS:Ag$ scintillating screens were prepared in laboratory and were excited to luminescence by a medical X-ray tube. Maximum DQE values varied between 0.13 and 0.33 depending on the scintillator material, the screen coating weight, and the tube voltage; $Gd_2O_2S:Tb$ was superior to $La_2O_2S:Tb$ followed by $ZnSCdS:Ag$ and $Y_2O_2S:Tb$. This ranking was maintained at frequencies up to 100 cycles/cm. Considering the same material, DQE of thin screens was found superior to DQE of thicker screens at medium-to-high frequencies. The proposed method allows for the comparison of imaging characteristics of scintillating materials without the inclusion of optical detector imaging properties.

1. Introduction

The performance of scintillators employed in radiation detectors of medical imaging systems is assessed by several parameters related to the intensity of the signal produced at the detector output and to the quality

of the final diagnostic image. Among these parameters the following are of most importance [1–4]: (1) The quantum detection efficiency (QDE), which approximately equals the efficiency of absorption of radiation quanta from the incident beam. (2) The X-ray luminescence efficiency (LE) that gives the fraction of energy of the incoming ionizing radiation which is converted into emitted optical energy [1]. (3) The modulation transfer function (MTF) that describes the variation of the output signal modulation or image contrast, as

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a function of spatial frequency, as well as the limiting spatial resolution of an imaging system. (4) The noise power spectrum (NPS) expressing the noise content in the final image with respect to spatial frequency and (5) the detective quantum efficiency (DQE) which is the efficiency with which the signal-to-noise ratio (SNR) propagates from the input to the output of an imaging component, defined as [4]

$$\text{DQE} = \left[\frac{\text{SNR}_O}{\text{SNR}_I} \right]^2,$$

where SNR_O , SNR_I are the output and input SNR, respectively. DQE may also be evaluated as a function of spatial frequency being described as a quantity proportional to the ratio MTF^2/NPS [5–7]. In previous studies, the DQE of radiographic film–scintillating screen systems has been experimentally determined by measuring the MTF and NPS of the combined screen–film system [7].

In this study, we propose a method allowing for the determination of a scintillator's DQE in terms of four parameters: the QDE, the LE, the MTF and the spectrum of the emitted optical photons. The method was employed to experimentally evaluate the spatial-frequency-dependent DQE of imaging scintillators ($\text{Gd}_2\text{O}_2\text{S}:\text{Tb}$, $\text{La}_2\text{O}_2\text{S}:\text{Tb}$, $\text{ZnSCdS}:\text{Ag}$, $\text{Y}_2\text{O}_2\text{S}:\text{Tb}$) independently of the presence of radiographic film or other kind of optical detector (photocathode or photodiode).

2. Material and methods

The scintillators employed in this study had the form of fluorescent layers (scintillating screens) of various thicknesses. They consisted of small phosphor grains embedded in a binding material. This form simulates phosphor screens used in conventional or digital X-ray imaging. Random scattering, which affects the efficiency of light propagation through the material and the spatial distribution of the output signal, is the dominant optical effect in these scintillators. The amount of optical scattering depends on the size and distribution of scatterers (phosphor grains), on the wavelength of the generated light and on the index of refraction discontinuities within the layer. Luminescence efficiency and modulation transfer function

depend strongly on scattering effects and thus, DQE is similarly affected.

2.1. Theory

The mean number of light photons $\bar{m}_0(E_0)$ produced within the scintillator material per X-ray quantum absorbed in the screen may be calculated by the relation:

$$\begin{aligned} \bar{m}_0(E_0) &= \eta_C \frac{\int_0^{E_0} S_X(E)E \, dE / \int_0^{E_0} S_X(E) \, dE}{\int_{E_{\lambda_1}}^{E_{\lambda_2}} S_P(E_\lambda)E_\lambda \, dE_\lambda / \int_{E_{\lambda_1}}^{E_{\lambda_2}} S_P(E_\lambda) \, dE_\lambda} \\ &= \eta_C [\bar{E}/\bar{E}_\lambda], \end{aligned} \quad (1)$$

where η_C is the intrinsic X-ray to light conversion efficiency giving the fraction of X-ray energy flux that is converted into light energy flux within the material of the scintillator. $S_X(E)$ and $S_P(E_\lambda)$ are the X-ray spectral distribution and the emitted light spectral distribution, respectively. \bar{E} , \bar{E}_λ are the corresponding mean energies of the incident X-ray quanta and emitted light quanta. E_0 is the maximum energy in the spectrum of the incident X-ray quanta. E_0 is numerically equal to the X-ray tube voltage. λ_1 and λ_2 are the lower and upper limits in the spectrum of optical photons.

The mean number N_L of light photons emitted by a fluorescent layer excited by N_X X-ray quanta incident per unit of area and time is given by the following relation [3,6,7]:

$$N_L = N_X(E_0)\eta_Q(E_0, t)\bar{m}_0(E_0)G(a, s, r, E_0, t), \quad (2)$$

where $\eta_Q(E_0, t)$ denotes the X-ray quantum detection efficiency of the fluorescent layer of thickness t at X-ray energy E_0 . $G(a, s, r, E_0, t)$ is the light transmission efficiency giving the fraction of produced light photons that are transmitted through the material and are emitted from the surface of the fluorescent layer s , a , r , are coefficients of optical scattering (s), optical absorption (a) within the scintillator material, and of optical reflection (r) at the boundaries of the layer [1–3].

The luminescence efficiency of a fluorescent layer (η_ϕ) is defined [1–3] as the ratio of the light energy flux Ψ_L emitted by the layer over the X-ray energy flux Ψ_X incident on the layer

$$\eta_\phi(E_0, t) = \Psi_L(E_0, t)/\Psi_X(E_0), \quad (3a)$$

where

$$\Psi_L(E_0, t) = N_L \bar{E}_\lambda \quad \text{and} \quad \Psi_X(E_0) = N_X(E_0) \bar{E}. \quad (3b)$$

From relations (1)–(3) it is obtained that

$$\begin{aligned} N_L &= N_X(E_0) \eta_Q(E_0, t) \eta_C[\bar{E}/\bar{E}_\lambda] G(s, a, r, E_0, t) \\ &= N_X(E_0) \eta_\phi(E_0, t) [\bar{E}/\bar{E}_\lambda], \end{aligned} \quad (4)$$

which is in accordance with the expression [1] of the efficiency of a phosphor as the product of QDE, intrinsic conversion efficiency and light transmission efficiency (i.e. $\eta_\phi(E_0, t) = \eta_Q(E_0, t) \eta_C G(s, a, r, E_0, t)$).

The spatial-frequency-dependent DQE of a fluorescent layer has been previously described [5–7] in terms of the MTF $T_S(E_0, t, \omega)$ and the NPS $W_Q(E_0, t, \omega)$ as follows:

$$\text{DQE}(E_0, t, \omega) = N_X(E_0) [dN_L/dN_X]^2 \frac{T_S^2(E_0, t, \omega)}{W_Q(E_0, t, \omega)}, \quad (5)$$

where ω is the spatial frequency and t is the thickness of the layer. $T_S(E_0, t, \omega)$ is the MTF of the fluorescent layer determined independently of the optical detector's MTF (film, etc.). Considering Poisson statistics for m_0 , $W_Q(E_0, t, \omega)$ may be expressed [6–9] as a function of T_S and N_L by

$$\begin{aligned} W_Q(E_0, t, \omega) &= N_X(E_0) \eta_Q(E_0, t) [\bar{m}_0(E_0) G(s, a, r, E_0, t)]^2 \\ &\quad \times T_S^2(E_0, t, \omega) + N_L(E_0, t). \end{aligned} \quad (6)$$

Using relations (1), (4)–(6), DQE may be expressed as a function of the LE (η_ϕ) and the modulation transfer function T_S according to

$$\begin{aligned} \text{DQE}(E_0, t, \omega) &= \frac{\eta_Q(E_0, t) \eta_\phi(E_0, t) [\bar{E}/\bar{E}_\lambda] T_S^2(E_0, t, \omega)}{\eta_Q(E_0, t) + \eta_\phi(E_0, t) [\bar{E}/\bar{E}_\lambda] T_S^2(E_0, t, \omega)}, \end{aligned} \quad (7)$$

η_ϕ and T_S were determined by experimental techniques (see next section). The detection efficiency η_Q

was approximated [10] by the formula:

$$\begin{aligned} \eta_Q(E_0, t) &= \int_0^{E_0} S_X(E) [1 - \exp(-\mu(E)t)] dE / \\ &\quad \int_0^{E_0} S_X(E) dE, \end{aligned} \quad (8)$$

where $\mu(E)$ is the X-ray attenuation coefficient calculated for the scintillators employed in this study from data on coefficients for the chemical elements tabulated by Storm and Israel [11]. \bar{E} , \bar{E}_λ were determined according to relation (1). The spectrum S_X of X-rays was calculated as described in Refs. [3, 12]. The spectrum $S_p(E_\lambda)$ of the emitted light, used in calculating E_λ in Eq. (1), was experimentally determined (see next section).

2.2. Experimental procedures

2.2.1. Preparation of screens

Scintillating materials were supplied in powder form (Derby Luminescents Ltd., U.K.) with average grain size of about 7 μm . The scintillating screens were prepared by sedimentation of the material on fused silica substrates (Spectrosil B) with approximate screen coating weights of 50, 80, and 120 mg/cm^2 . A mixture of 2000 ml deionized water and 25 ml Na_2SiO_3 aqueous solution was used; Na_2SiO_3 acts as a binder between the grains of the scintillator material. The value of the index of refraction of Na_2SiO_3 , which affects the amount of optical scattering within the screen, is 1.353.

2.2.2. Luminescence efficiency measurements

The luminescence efficiency η_ϕ was measured by exposing the screens to X-rays at 90 kVp. The emitted light flux was measured by an EMI 9558 QB photomultiplier equipped with an extended sensitivity S-20 photocathode. The photomultiplier was connected to a Cary 401 vibrating reed electrometer. The exact light flux of the screen was determined by performing the following corrections on the experimental data: (i) Measurements were multiplied by the ratio of the total light flux emitted by the screen towards the side of the photomultiplier to the light flux collected by the photocathode's sensitive area. This ratio was calculated by taking into account the screen's emissive area, the

distance between the screen and the photomultiplier, the photocathode's sensitive area and the angular distribution of the emitted light; angular distribution was approximated by a Lambertian one i.e. following the $\cos \theta$ law where θ is the angle of light emission. (ii) Measurements were divided by the spectral matching factor, expressing the compatibility between the spectral sensitivity of the optical detector (photocathode) and the spectrum of the light emitted by the scintillator [13]. This factor is given by

$$a_s = \int_{\lambda_1}^{\lambda_2} S_P(\lambda) S_D(\lambda) d\lambda / \int_{\lambda_1}^{\lambda_2} S_D(\lambda) d\lambda, \quad (9)$$

where $S_D(\lambda)$ is the spectral sensitivity of the S-20 photocathode, obtained from manufacturer's data, and $S_P(\lambda)$ is the scintillator's optical emission spectrum measured in our laboratory.

The X-ray energy flux was determined from X-ray exposure rate measurements at the screen's position, using a PTW simplex dosimeter. These measurements were converted into energy flux using the appropriate conversion factor $a(E) = \Psi_X / \dot{X}$ [14].

2.2.3. Emission spectra measurements

The spectrum $S_P(E_i)$ of the light emitted by the scintillator materials was measured using an Oriel 7240 grating monochromator. From these measurements the mean energy \bar{E}_i and the matching factors a_s were determined.

2.2.4. MTF measurements

For the experimental determination of MTF scintillating screens were combined with an Agfa Curix Ortho GS radiographic film, which is a green sensitive film compatible with the emission spectrum of the four scintillators. Images of a Typ-53 MTF test bar pattern (Nuclear Associates Inc., Carle Place, NY) were obtained by X-raying the screen–film–test pattern combination at 90 kVp. The test pattern images were digitized by a MICROTEC Scanmaker II SP (24-bit color, 1200 × 1200 dpi) CCD scanner. The MTF was determined following the Square Wave Response Function (SWRF) method as described in previous studies [2,3,15]. Screen–film nonlinearities were corrected via the H and D characteristic curve determined by bootstrap sensitometry technique [15]. 64 successive image traces transverse to the pattern bars were

selected and averaged to obtain a low-noise SWRF. Trace amplitudes were normalized to the image contrast at 2.5 lp/cm. MTF was calculated by Coltman's formula:

$$\text{MTF}(\omega) = \frac{\pi}{4} \left[\frac{\text{SWRF}(\omega)}{\omega} + \frac{\text{SWRF}(3\omega)}{3\omega} - \frac{\text{SWRF}(5\omega)}{5\omega} + \dots \right]. \quad (10)$$

In order to obtain the screen MTF, the MTF found in Eq. (10) was divided by the combined MTF of the acquisition system (radiographic film, CCD scanner). The combined MTF was determined by scanning the test pattern alone and considering the radiographic film MTF approximately equal to 1 for frequencies lower than 100 lp/cm [8].

3. Results and discussion

Table 1 shows the values of LE measured at 90 kVp for screens of coating weight 50, 80 and 120 mg/cm². Gd₂O₂S : Tb screens are most efficient followed by the La₂O₂S : Tb screens. These results are in accordance with the high effective atomic numbers and X-ray attenuation coefficients of these two materials giving increased QDE (η_Q) at the X-ray energy considered in this study. η_Q was found to vary from 0.41 to 0.66 for the Gd₂O₂S : Tb screens and from 0.23 to 0.46 for the La₂O₂S : Tb screens. In the case of La₂O₂S : Tb, ZnSCdS : Ag and Y₂O₂S : Tb, the thicker screens of 120 mg/cm² showed a saturation effect expressed by the equal values of LE for both 80 and 120 mg/cm² screens. For Gd₂O₂S : Tb the LE was found to decrease at thick screens. In all cases this is due to the higher light attenuation caused by the increased probability of both optical scattering and absorption. This may be attributed to the longer average distance traveled by the optical quanta within the fluorescent layer, since light is mostly generated at points close to the exposed screen surface. This light attenuation seems to overbalance the higher X-ray capture capabilities (η_Q) of thick screens.

An example of MTF results is shown in Fig. 1 for three Gd₂O₂S : Tb screens. The MTFs of the other materials are lower, following the same order of magnitude as with the LE results. This is in agreement with the inherent properties of Gd₂O₂S : Tb such as

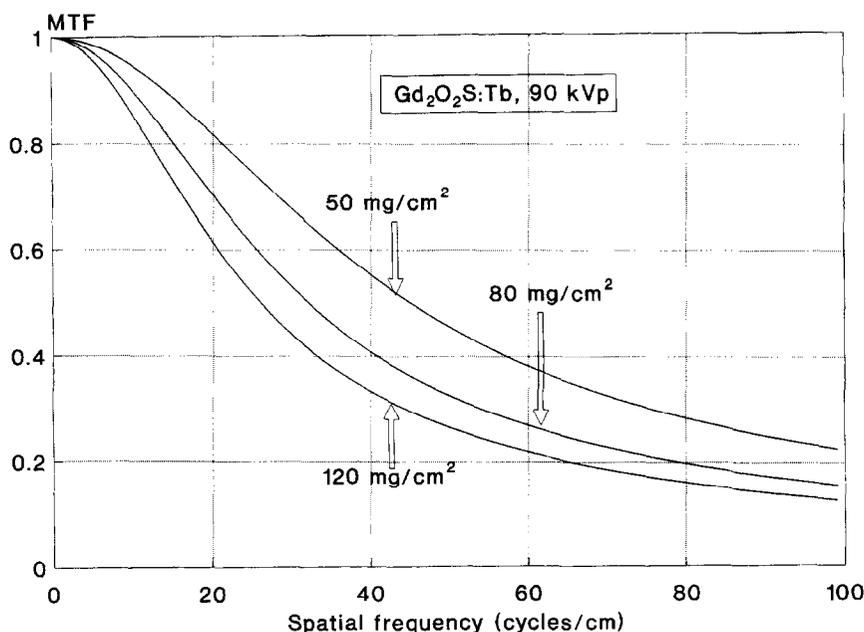


Fig. 1. MTF of three $\text{Gd}_2\text{O}_2\text{S}:\text{Tb}$ scintillating screens.

Table 1
Luminescence efficiency of scintillators

Scintillators	Screen coating weight		
	50 mg/cm ²	80 mg/cm ²	120 mg/cm ²
$\text{Gd}_2\text{O}_2\text{S}:\text{Tb}$	0.029	0.028	0.021
$\text{La}_2\text{O}_2\text{S}:\text{Tb}$	0.016	0.018	0.018
$\text{ZnSCdS}:\text{Ag}$	0.012	0.014	0.014
$\text{Y}_2\text{O}_2\text{S}:\text{Tb}$	0.011	0.013	0.013

higher X-ray absorption (η_Q), higher intensity of emitted fluorescent light (N_L), and higher volume density (g/cm^3), resulting in thinner screens for the same coating weight (mg/cm^2). The latter imposes shorter trajectories to the optical quanta from their creation point to the point of their emission. This results in lower light spread and thus better, spatial resolution and MTF.

Fig. 2 shows the emission spectra of the four scintillators as measured by the Oriel monochromator. All spectra are centered in the green region of the visible light spectrum. The spectral data were used to determine the mean energy (\bar{E}_i) of the emitted optical photons and the matching factors (a_S). The specific

value of \bar{E}_i is of importance since, given the values of η_C and E , it determines the number m_0 of the optical photons produced within the scintillator material and, consequently, the number N_L of the emitted photons. The lower the value of \bar{E}_i the higher the values of m_0 and N_L , resulting in lower quantum noise and thus promoting SNR_O and DQE. Additionally, the optical scattering coefficient s , which affects the light transmission efficiency $G(s, a, r, E_0, t)$, the number N_L as well as the MTF, is strongly influenced by the wavelength (λ) or the energy of the optical photons ($E_i \propto \lambda^{-1}$). However, the measured values \bar{E}_i of the scintillators employed in this study were found very close to each other. Thus, their role in DQE variation among the materials was not significant.

The spatial-frequency-dependent DQE of the three $\text{Gd}_2\text{O}_2\text{S}:\text{Tb}$ screens is presented in Fig. 3. The thicker screen of $120 \text{ mg}/\text{cm}^2$ shows reduced DQE values because although it captures more efficiently the input signal, expressed by the incident X-ray energy flux (higher η_Q), it presents reduced light transmission efficiency. Thick screens are characterized by increased probability of random optical scattering per optical photon created, which induces output signal degradation expressed by low values of LE and of MTF.

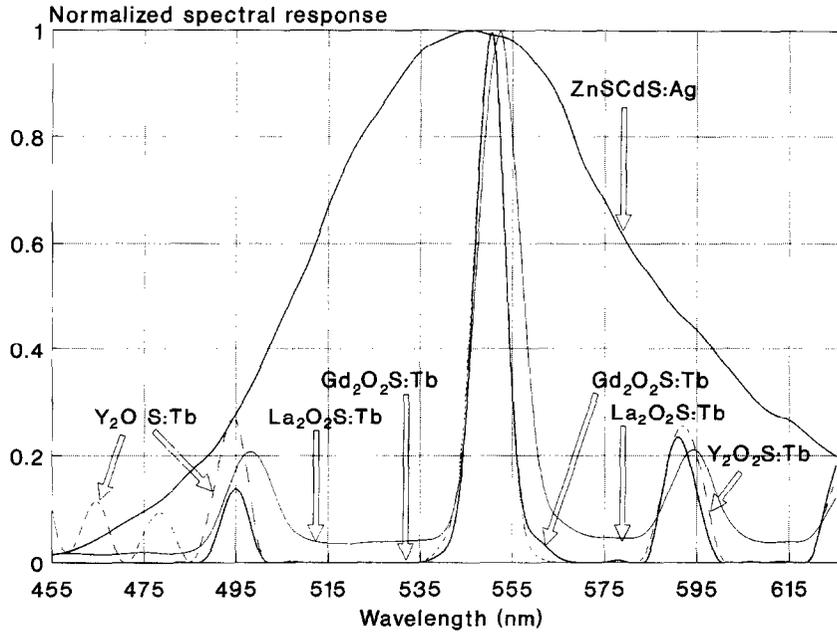


Fig. 2. Optical emission spectra of Gd₂O₃:Tb, La₂O₃:Tb, Y₂O₃:Tb and ZnSCdS:Ag scintillating screens.

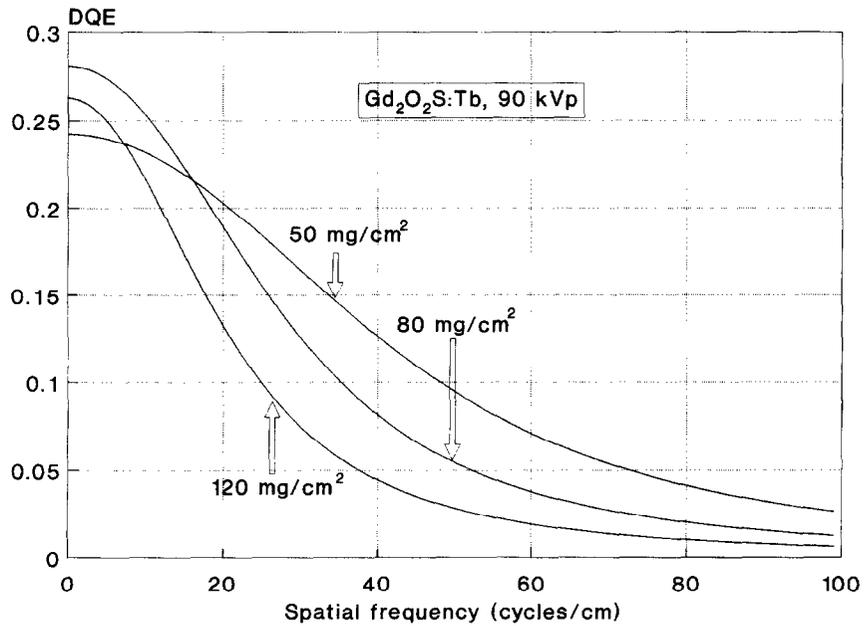


Fig. 3. Spatial-frequency-dependent DQE of three Gd₂O₃:Tb screens.

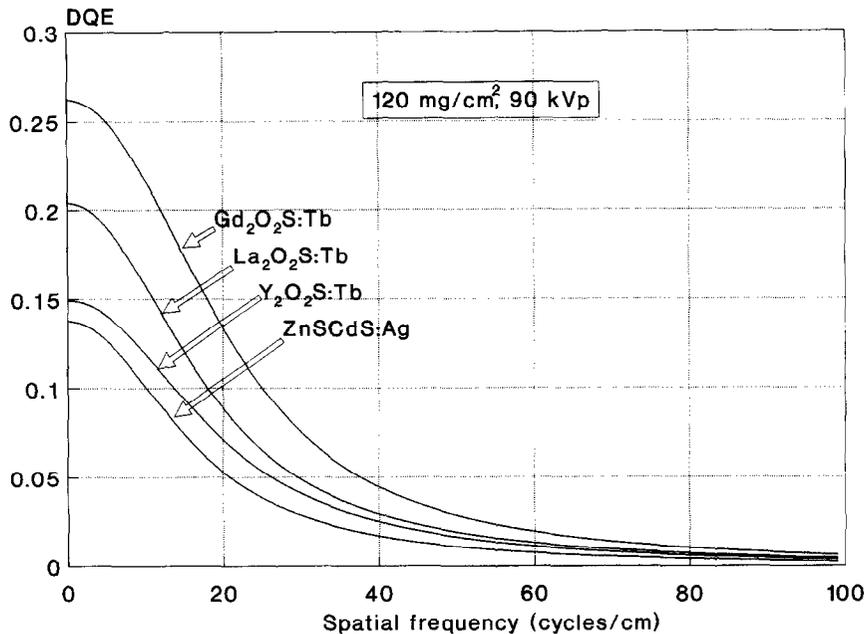


Fig. 4. Comparison of spatial-frequency-dependent DQE of Gd₂O₂S:Tb, La₂O₂S:Tb, Y₂O₂S:Tb and ZnSCdS:Ag 120 mg/cm² scintillating screens.

Additionally, optical scattering augments the statistical variations in the number of optical photons emerging at screen output for equal X-ray energy absorption. This causes increased output quantum noise thus, decreasing SNR₀ and DQE.

In Fig. 3 the thin screen of 50 mg/cm² shows increased DQE which exceeds the DQEs of the two other screens for frequencies higher than 7 lp/cm and 16 lp/cm, respectively. This is mainly due to the high MTF of this screen, which is a measure of the diagnostically useful output signal. The input signal, although not efficiently captured due to low detection efficiency, propagates easily through thin screens especially at higher frequencies corresponding to small anatomical details. At low frequencies, which correspond to objects of larger dimensions, light spread is of lower significance. In this case the principal limiting factor for DQE is the detection efficiency which is decreased in thin screens, providing lower output signal as compared to thicker screens. Fig. 4 compares DQE curves corresponding to the four scintillators studied at 120 mg/cm². Similar screen performance ranking as in luminescence efficiency, detection efficiency, or MTF was also observed here. Given that the four

scintillators exhibit similar values for \bar{E}_λ and η_C [2,16]. The most important physical properties in determining DQE results of Figs. 3 and 4 are the X-ray attenuation coefficients and the screen coating weight. Both of these parameters determine η_Q and affect MTF, $G(s, a, r, E_0, t)$ and, consequently, η_ϕ .

4. Summary

The present study proposes the determination of a scintillator DQE in terms its X-ray detection efficiency, LE, MTF, and emitted light spectrum. These parameters are strictly related to the physical properties of the scintillator material and can be found by the employment of well-known experimental techniques or be calculated by appropriate formulas [1–3,15,16]. In determining the scintillator DQE by the proposed method the influence of the optical detector (radiographic film, photocathode, photodiode) and the necessity for laborious and delicate techniques involved in screen NPS determination, required by other methods [7,17], are avoided. Our findings are in good proximity to those of previous studies [7,17–20], even

though direct comparison cannot be realistic since these authors have studied commercial screen–film combinations.

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