UTILIZATION OF MONOENERGETIC X-RAY BEAMS TO EXAMINE
THE PROPERTIES OF RADIOGRAPHIC INTENSIFYING SCREENSC.E. Dick and J.W. Motz
National Bureau of Standards
Washington, D.C. 20234Summary

Monoenergetic x-ray beams, produced by the direct electron excitation of characteristic K x rays in elemental targets, are important for measuring the response of different components of radiologic imaging systems. Previous studies have investigated the energy dependence of the scatter produced as an x-ray beam traverses the object to be radiographed¹ and the efficacy of anti-scatter grids in reducing this unwanted component of the image signal.² Presently, these beams are being utilized to examine the image information transfer properties of x-ray intensifying screens conventionally used in screen-film imaging systems. The technique of single photon counting is being employed to determine the relative probability distribution of the number of optical photons emitted from the screen after absorption of an incident x ray. These data can be used to determine the average number of light quanta emitted per absorbed x ray. In addition, the shape of these distributions can be used to determine the image information transfer properties of a particular screen. Results of these measurements for a typical calcium tungstate screen and one of the new rare-earth phosphor screens are presented.

Introduction

In an ideal radiography system, the image information content in the final image is determined by the incident exposure (number of x rays per unit area) received by the patient. In practice, however, this ideal is never realized due to the introduction of noise by the various components of the system. In the typical system shown in Fig. 1 for example, the signal is affected by the scatter of the x-ray beam as it passes through the patient, the transmission properties of the antiscatter grid used to eliminate this scatter component, and the detection properties of the film screen system used to record the image. There are other noise sources as well, such as off focus radiation and so on but these are not included in the present discussion. We have been investigating these various phenomena as a function of the incident x-ray energy and have previously reported on the amount of scatter produced¹ and the efficacy of the antiscatter grids in removing this unwanted scatter component of the image signal.²

In the conventional system depicted in Fig. 1 the x-ray image is recorded by a film-screen system consisting of a photographic emulsion tightly coupled to either one or two x-ray intensifying screens in a light tight cassette. Although photographic film is sensitive to x rays, the sensitivity of the system is increased by the use of the intensifying screens to convert the incident x-ray energy to energy in the optical wavelength region (300-600 nm). The capability of the screen to transfer information to the film depends on the following four independent parameters: (1) The attainable spatial resolution, (2) the efficiency for the absorption of the incident x-ray quanta, (3) the spectrum of photons emitted, and (4) the statistical distribution of the photons emitted per absorbed x ray. In this paper, we provide no data on the first of these parameters and we will assume that this parameter has a negligible effect on the image information properties of the screen since the size of the picture element (pixel) required to transfer the information for typical diagnostic procedures is usually

much larger than the attainable spatial resolution of the screens. The relationship between the remaining three parameters and the ability of the screen to transfer information is developed in the following discussion.

Figure 1. Components of a typical radiography system

As pointed out by Motz and Danos³ the image information content in an x-ray image is quantitatively expressed in terms of the signal-to-noise ratio per resolution element. Therefore, in order to evaluate the image information transfer properties of a given intensifying screen, it is necessary to compare the signal-to-noise ratios at the input and output of the screen. In particular, the information transfer efficiency of the screen may be defined by the transfer ratio R , or alternatively by the Detective Quantum Efficiency DQE as

$$R = \sigma / \sigma_0 \quad (1)$$

or

$$DQE = (\sigma / \sigma_0)^2 = R^2$$

where σ is the output signal-to-noise ratio and σ_0 is the input signal-to-noise ratio for a given screen. For an ideal screen $\sigma = \sigma_0$ and there is no loss of information. It can be shown^{4,5} that the output signal-to-noise ratio, σ , may be expressed as

$$\sigma = [\alpha \eta N I]^{\frac{1}{2}} \quad (2)$$

where α is the area of a spatial resolution element, N is the incident x-ray fluence at a given point in the plane of the screen, and η is the x-ray detection efficiency of the screen. The quantity I is a statistical factor arising from the fluctuations in the number, m , of light photons emitted from the screen per absorbed x ray and is defined by:

$$I = M_1^2 / M_0 M_2 \quad (3)$$

where the n th moment of the light photon distribution is given as

$$M_n = \sum_m p(m) m^n \quad (4)$$

and where the fluctuations in m are given by the probability distribution, $p(m)$. The input signal-to-noise ratio σ_0 can be expressed as⁴

$$\sigma_0 = [\alpha N]^{1/2} \quad (5)$$

so that the transfer parameter R and the DQE for a screen can be expressed as

$$\begin{aligned} R &= [\eta I]^{1/2} \\ \text{or} \\ DQE &= R^2 = \eta I \end{aligned} \quad (6)$$

Thus the image information transfer properties of an intensifying screen can be obtained from a determination of the x-ray detection efficiency η and the statistical factor I which depends on the distribution of the light photons emitted from the screen per absorbed x ray.

Experimental Arrangement and Procedures

The two quantities η and I have been determined experimentally at x-ray energies of 18, 22, 32, 49, 51, 58, and 69 keV. The incident x-ray flux is provided by nearly parallel and nearly monoenergetic K x-ray beams produced as described elsewhere.^{1, 2} In the present report, data are presented for two different screen types identified as a conventional calcium tungstate screen (HiPlus) and a rare earth oxysulfide screen (Min-R).⁶

The x-ray detection efficiency, η , is determined by the arrangement shown in Fig. 2. The pulse height spectrum of the x-ray beam is measured with a scintillation spectrometer both with and without a given x-ray screen in position behind the lead collimator. The quantity η can then be determined from the attenuation ratio both with and without the screen if every x ray that is absorbed or scattered out of the beam causes the emission of a burst of light photons from the screen. This would not occur if some of the x rays were absorbed in non-phosphorescent materials such as the binder or protective coatings. This equivalence was approximately confirmed from a measurement of the number of light bursts emitted from the screens as described below.

In order to determine the statistical factor I , both the number, m , and the number distribution $p(m)$ of light pulses emitted from the screen per absorbed x ray were determined with the setup shown in Fig. 3.

In this setup which is similar to that shown in Fig. 2, the x-ray intensifying screen is viewed by an RCA-8850 photomultiplier tube (PMT).⁶ After absorption of an incident x ray in the screen, the individual optical photons emitted from the screen are detected with a certain efficiency by the PMT and appear at the output as a train of pulses. The separation time of the successive pulses in the train increases in a manner which depends on the decay time of the phosphor. In order to count all of the pulses belonging to a given pulse train, the input to the counting circuitry is gated open for a time interval which is long (10 ms) compared to the decay time of the phosphors under study. The opening of this gate is triggered by the occurrence of two successive pulses which are detected within a time interval from 10 ns (the resolving time of the circuitry) to 10 μ s. This upper limit of 10 μ s was chosen in order to avoid interference with the dark current pulses which have an average separation of 20 ms. In order that there be no overlap of x ray initiated pulse trains, the incident x-ray flux is adjusted to provide approximately 20 absorbed x rays per second so that the average separation time between x-ray absorption events is 50 ms. In addition, the reliability of the detection circuitry to detect successive x-ray events was checked by comparing the number of pulse trains detected with the number of events expected for a known x-ray flux and the value of η measured previously. In all cases, these two numbers agreed to $\pm 10\%$, indicating the reliability of the circuitry and confirming the assumption that few x rays are absorbed in non-phosphorescent portions of the screen. As an additional check, the value of the incident x-ray flux was increased by an order of magnitude, and these numbers exhibited the same agreement as before.

After passage through the gate the number of pulses in a pulse train are stored in a computer memory. After the accumulation of approximately 10^4 x-ray absorption events, the computer sorts the data into a format which gives the statistical distribution of the number of counts per x ray absorbed in the screen.

Figure 2. The experimental apparatus for the determination of the x-ray absorption efficiency, η .

Figure 3. The experimental arrangement for the determination of the number distribution, $p(m)$, of photons emitted from a screen per absorbed x ray.

In order to determine the number of optical photons, m , emitted for a given incident x-ray photon absorbed, it is necessary to correct the measured number of counts by a factor which takes into account the detection efficiency of the PMT for a given optical photon energy, k_L . If the number of photons emitted from the screen with energy k_L is given by $\eta(k_L)$, and the detection efficiency of the PMT at energy k_L is given by $\epsilon(k_L)$ then the average detection efficiency for a given screen is given by:

$$\epsilon = \frac{\sum_0^{k_{\max}} \epsilon(k_L) \eta(k_L)}{\sum_0^{k_{\max}} \eta(k_L)} \quad (7)$$

The evaluation of Eq. 7 was done by utilizing the manufacturers data for the PMT efficiency data, $\epsilon(k_L)$ and for the spectral distribution of the optical photons emitted from the phosphors, $\eta(k_L)$. The values of ϵ for the two screens included in this study are given in Table 1. These values which are derived on the assumptions that the optical output spectrum from the screen does not depend on the incident x-ray energy or on the number of the incident photons have an estimated uncertainty of $\pm 20\%$.

Table 1: Values of the average detection efficiency, ϵ , for optical photons emitted from a HiPlus and a Min-R screen

Screen	ϵ
HiPlus	0.22
Min-R	0.09

In addition, several other sources of error in the values of η were investigated and are covered in detail elsewhere.⁴ These include counting losses due to pulse pileup and insufficient resolving time of the counting circuitry, optical interface effects between the face of the PMT and the intensifying screen, direct x-ray response of the PMT, and uncertainties in the published values of the PMT efficiency. For the screens studied, these effects were found to be negligible and their effects are included in the $\pm 20\%$ uncertainty quoted above.

Results

From the measurements described above, data were obtained for the various quantities necessary to de-

termine the image information transfer properties of the two different screen types presented here, a calcium tungstate (HiPlus) and a rare-earth oxysulfide (Min-R) screen. These data and some interesting comparisons of the screens with regard to image information transfer are given below.

1. The x-ray detection efficiency, η

The dependence of the x-ray detection efficiency, η , is shown by the curves of Fig. 4 for the HiPlus and Min-R screens. The data for HiPlus are in good agreement with the values calculated for calcium tungstate for a 60 mg/cm^2 screen using the tables of McMaster, et al.⁷ For the Min-R screen, the values of η are in good agreement with those of Wagner.⁸ A comparison of these two screens indicates that for the region below 50 keV, the HiPlus screen has a higher x-ray detection efficiency while for the region above 50 keV, the gadolinium oxysulfide in the Min-R screen increases the η value so that the two screens are approximately equal in x-ray absorption efficiency.

Figure 4. The values of the x-ray detection efficiency, η , are plotted as a function of the incident x-ray energy.

2. The light photon distributions, $p(m)$

Figure 5 shows the light photon probability distributions, $p(m)$, for the number of photons, m , emitted from the two screens as a function of the x-ray energy. The results for the HiPlus screen show distributions which are approximately symmetrical about a given value of m which increases monotonically as a function of the x-ray energy. For the Min-R screen, the distributions are somewhat broader but show similar behavior up to x-ray energies of 50 keV. For energies above this value, the data show a peak shift due to the escape of gadolinium K-x rays from the screen. It should also be noted that the Min-R screen produces significantly larger numbers of optical photons per absorbed x ray throughout the x-ray energy range as discussed below.

Figure 5. The probability distribution, $p(m)$, for producing m photons per absorbed x ray is plotted as a function of the incident x-ray energy.

3. The average optical photon number, m , per absorbed x ray.

The average number of light photons produced per absorbed x ray was determined from the probability distributions $p(m)$ shown in Fig. 5 in the usual way as

$$\bar{m} = \frac{\sum_m m p(m)}{\sum_m p(m)} \quad (8)$$

The results of these calculations are shown by the curves in Fig. 6 which indicate a general increase in the value of m with increasing x-ray energy except for structure effects in the region of the K absorption edge in the rare-earth screen. A comparison of these data indicates that the Min-R screen produces at least a factor of two more light throughout most of the x-ray region studied. For approximately 60 keV radiation, a value of approximately 550 was obtained by Colman et al⁹ for a calcium tungstate screen. This value is in good agreement with the value of approximately 500 obtained from the present measurements.

Figure 6. The average number of photons produced per absorbed x ray is plotted as a function of the incident x-ray energy.

4. The statistical factor I

From the probability distribution data shown in Fig. 5, the statistical factor I was calculated using Eqs. 3 and 4. The results of these calculations are shown in Fig. 7. An analysis of this data indicates

Figure 7. The statistical factor, I, associated with variations in the screen light output is plotted as a function of the incident x-ray energy.

that for these screens, the I values are clustered in the region from 0.6 to 0.9 and are not strongly dependent on the incident x-ray energy except in the region of the K absorption edges of the Min-R screen. For this reason, the information transfer efficiency cannot be substantially increased by reducing the statistical fluctuations of the light emitted from the screen.

5. The Detective Quantum Efficiency, DQE

From the values M and I presented in Figs. 4 and 7, the Detective Quantum Efficiency for the two screens was calculated and the results are plotted in Fig. 8 and given in Table 2 for the seven x-ray energies. These results indicate that for energies below 50 keV, the calcium tungstate screen is somewhat more efficient in transferring the image information than the Min-R screen. The results for the Min-R screen are in reasonable agreement with the results of Wagner and Muntz¹⁰ who determined a DQE value of 0.34 for an average x-ray energy of 22.4 keV.

Table 2. Values of the Detective Quantum Efficiency, DQE, for a Single HiPlus and Min-R Screen as a Function of the Incident X-Ray Energy

X-Ray Energy	L	DQE	
		HiPlus	Min-R
18		.75	.58
22		.71	.44
32		.42	.19
49		.18	.07
51		.17	.18
58		.17	.14
69		.11	.07

Figure 8. The values of the Detective Quantum Efficiency, DQE, are shown as a function of the incident x-ray energy.

Conclusions

The use of single photon counting techniques enables the determination of the number distribution of light photons emitted from radiographic intensifying screens upon absorption of incident x rays. These data allow a quantitative assessment of the image information transfer properties of the screen. As shown elsewhere,⁴ other properties of the screens can also be

determined from these data. Presently, measurements are underway on a variety of intensifying screens being used in medical and industrial radiography.

Acknowledgments

The authors would like to acknowledge the assistance of Dr. Hans Roehrig who participated in the early measurements, Dr. Robert Wagner who graciously lent us some of the screens studied, and Dr. M. Danos who provided helpful suggestions on the analysis and interpretation of the data.

References

1. C.E. Dick, C.G. Soares, and J.W. Motz, X-Ray Scatter Data for Diagnostic Radiology, Phys. Med. Biol. **23**, 1076 (1978).
2. C.E. Dick and J.W. Motz, A New Method for the Experimental Evaluation of X-Ray Grids, Med. Phys. **5**, 133 (1978). A.F. Jacobson, C.E. Dick, and J.W. Motz, Effectiveness of Antiscatter Grids for Low Energy X-Ray Beams, Med. Phys. **5**, 333 (1978).
3. J.W. Motz and M. Danos, Image Information Content and Patient Exposure, Med. Phys. **5**, 8 (1978).
4. C.E. Dick and J.W. Motz, Image Information Transfer Properties of X-Ray Intensifying Screens, submitted for publication to Med. Phys.
5. R.K. Swank, Absorption and Noise in X-Ray Phosphors, Journal Appl. Phys. **9**, 4199 (1973).
6. Certain trade names and products are identified to adequately specify the experimental procedures or facilitate comparisons with other measurements. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the products are necessarily the best available for the purpose.
7. W.H. McMaster, N. Kerr Del-Grande, J.H. Mallett, and J.H. Hubbell, Compilation of X-Ray Cross Sections, Univ. of Calif., Lawrence Livermore Laboratory Report 50174, May 1969. (Available from the National Technical Information Service, Springfield, VA 22151.)
8. R.F. Wagner, private communication.
9. J.W. Coltman, E.G. Ebbighausen, and W. Altar, Physical Properties of Calcium Tungstate X-Ray Screens, Journal Appl. Physics, **18**, 530 (1947).
10. R.F. Wagner and E.P. Muntz, DQE Analysis of Electrostatic Imaging and Screen Film Imaging, Proc.