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Evaluating optical spectral matching of phosphor-photodetector combinations

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ABSTRACT: Phosphor materials are used in medical X-ray imaging combined with various photodetectors suitable for conventional and digital radiography and fluoroscopy. A prerequisite for these combinations is good optical spectral matching, which results in patient dose minimization. In the present work, a recently introduced factor, named OGTE, which accounts for optical gain signal-to-noise ratio transfer efficiency, is utilized for the evaluation of various phosphor-photodetector combinations. The optical photon spectrum of the phosphor materials studied was either determined experimentally, or obtained from literature. These phosphors were examined in conjunction with various photodetectors, which may be suitable for digital imaging. The corresponding optical response functions of the photodetectors were obtained from literature. It was found that there are numerous combinations exhibiting OGTE values above 0.80, which contribute to patient dose minimization.

KEYWORDS: X-ray detectors; X-ray radiography and digital radiography (DR)

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Contents

1 Introduction

Phosphor materials in conjunction with various photodetectors are extensively used in medical X-ray imaging. Phosphors exhibit the ability to transform X-ray photons into optical photons. Since currently used photodetectors (films in conventional radiography and photocathodes in fluoroscopy) are more sensitive to optical than to X-ray photons, the use of phosphor materials leads to considerable patient dose reduction. With the development and wide use of digital imaging detectors into hospital practice, additional types of photodetectors are introduced [1].

A prerequisite for a phosphor-photodetector combination is adequate optical spectral matching between the optical photon spectrum emitted by the phosphor and the spectral response function of photodetector. Good optical spectral matching results in patient dose minimization. Optical spectral matching has been previously evaluated by the spectral matching factor [2]. Recently an alternative factor, the optical gain signal-to-noise ratio transfer efficiency, OGTE, has been introduced [3], to rank phosphor-photodetector combinations. OGTE derivation is based on the knowledge of optical gain variations, affecting phosphor-photodetector noise, and on the spectral matching factor affecting phosphor-photodetector speed. Hence OGTE accounts for both image quality and patient dose [2–5].

In this work, additional phosphor-photodetector combinations for digital X-ray imaging applications are ranked, by using the OGTE factor.

2 Materials and methods

The recently introduced optical gain signal-to-noise ratio transfer efficiency [3] has been defined as:

$$OGTE(E) = a_s\left(E_{i\lambda}/E_{e\lambda}\right)\left[F\left(E_{i\lambda},E,n_c,E_g\right)/F\left(E_{e\lambda},E,n_c,E_g\right)\right] \tag{2.1}$$

where a_s is the spectral matching factor, which expresses the fraction of the emitted optical photons detected by the photoreceptor [2], n_C is the intrinsic x-ray to light conversion efficiency of the phosphor material [5], [6] $E_{e\lambda}$ is the mean energy of the effective optical photon energy distribution [4], i.e. the optical photon energy distribution, altered by the photodetector optical spectral response distribution. $\overline{E}_{i\lambda}$ is the mean energy of the optical photons of the inherent optical photon energy distribution. The term $F(E_{i\lambda},E,n_c,E_g)$ is the contribution of the process of optical photon production in the scintillator to the detector total noise. It is a function of the X-ray energy and the intrinsic optical properties of the scintillator [3], [4], however for X-ray energies greater than 17000 eV, depends mainly upon the spectral distribution of the emitted light photons and can be practically simplified as:

$$F(E_\lambda, E, n_c, E_g) \approx \left[var[E_\lambda]/E_\lambda^2\right] + 1 \tag{2.2}$$

Where $var[E]_\lambda$ is the statistical variance of the emitted light photon spectrum [3], [4], hence OGTE is, practically, affected only by the inherent and effective optical photon energy distributions.

In order to demonstrate the applicability of the proposed factor, OGTE, in phosphor-photo-detector combinations ranking, several types of phosphors with different dopands (Y_2O_3:Eu^{3+}, YVO_4:Eu^{3+}, Gd_2O_2S:Tb, La_2O_2S:Tb, Y_2O_2S:Tb) were prepared by sedimentation on fused silica substrates in our laboratory. Additionally, a CsI:Na phosphor screen was prepared by evaporation. The phosphors were excited with a UV light source. Their inherent optical photon energy distribution, i.e. their emission spectrum was measured with an Oriel 7240 grating monochromator [7]. These data were corrected for the optical response of the monochromator and the background in order to diminish any systematic errors. Additional inherent optical photon energy distributions for various phosphors ($LaCl_3$:Ce with dopand concetration 0.1%, CdS:In, CdS:In, Te, CdS:Te, HiLight^{TM}), where obtained from literature [8–10]. The corresponding values of, $E_{e\lambda}$ $var[E]_{e\lambda}$, $E_{i\lambda}$ and $var[E]_{i\lambda}$ were calculated according to previous studies [3, 4]. Finally, data for the optical response function of the photodetectors used in this study, was obtained from literature [1, 3].

3 Results and discussion

In table 1 the OGTE values for the various phosphor-photodetector combinations studied are presented. Additionally, the OGTE value of every phosphor with GaAs is again presented, since GaAs has been reported to be suitable for digital imaging [11].

If $LaCl_3$:Ce phosphors are considered the best photodetector is GaAs with an OGTE value over 0.90. CdS:In demonstrates high OGTE values (above 0.80) if combined with Hybrid CMOS with BLUE AR coating and CCD BI with Broadband AR coating. CdS:In, Te phosphor demonstrates high OGTE values (above 0.80) if combined with Hybrid CMOS with BLUE AR coating, Hybrid CMOS with NIR AR coating, CCD with ITO gates and μlens and CCD BI with IR AR coating. CdS:Te demonstrates high OGTE values (above 0.80) if combined with Hybrid CMOS with BLUE AR coating, CCD with ITO gates and μlens and Hybrid CMOS with NIR AR coating. HiLight^{TM} demonstrates high OGTE values (above 0.80) combined with Hybrid CMOS with NIR AR coating, Hybrid CMOS with BLUE AR coating, CCD with ITO gates and μlens and CCD BI with IR AR coating. CsI:Na phosphor demonstrates high OGTE values (above 0.80) if combined with CCD BI with Broadband AR coating and Hybrid CMOS with BLUE AR coating. Y_2O_2S:Tb phosphor demonstrates good OGTE values (above 0.60) if combined with Hybrid CMOS with BLUE AR coating, CCD BI with Broadband AR coating, CCD with ITO gates and μlens, Hybrid CMOS with NIR AR coating, Monolithic 0.25μ CMOS-Image sensor and CCD BI with IR AR coating. Gd_2O_2S:Tb phosphor demonstrates high OGTE values (above 0.80) if combined with Hybrid CMOS with BLUE AR coating, CCD BI with Broadband AR coating, CCD with ITO gates and μlens and Hybrid CMOS with NIR AR coating. La_2O_2S:Tb phosphor demonstrates

Table 1. The optical gain signal-to-noise ratio transfer efficiency, OGTE, of the phosphor-photodetector for digital imaging combinations studied.

	$LaCl_3$:Ce	CdS(In)	CdS(In,Te)	CdS(Te)	HiLight^{TM}	Csi:Na	Y_2O_2S:Tb	Gd_2O_2S:Tb	La_2O_2S:Tb	Y_2O_3:Eu	YVO_4:Eu
CMOS 0.5μm Pgate	0.07	0.15	0.16	0.16	0.15	0.07	0.11	0.16	0.16	0.16	0.16
CCD FF-no LOD	0.10	0.30	0.33	0.34	0.32	0.13	0.21	0.34	0.33	0.32	0.32
CCD Ffwith LOD	0.07	0.21	0.27	0.27	0.27	0.09	0.15	0.23	0.23	0.27	0.27
Hybrid CMOS with NIR AR Coating	0.53	0.78	0.87	0.86	0.87	0.67	0.69	0.84	0.81	0.88	0.88
Hybrid CMOS with BLUE AR Coating	0.65	0.88	0.87	0.88	0.86	0.82	0.79	0.91	0.88	0.87	0.87
Monolithic 0.25μ CMOS-Image sensor	0.41	0.66	0.67	0.70	0.66	0.53	0.66	0.68	0.67	0.66	0.66
CCD BI with Broadband AR coating	0.67	0.83	0.79	0.79	0.78	0.86	0.79	0.85	0.81	0.78	0.78
CCD BI with IR AR coating	0.44	0.07	0.80	0.79	0.81	0.56	0.60	0.75	0.73	0.82	0.81
CCD with ITO gates	0.33	0.51	0.63	0.70	0.61	0.42	0.46	0.57	0.56	0.63	0.62
CCD with poly gates	0.10	0.28	0.35	0.37	0.35	0.12	0.20	0.33	0.32	0.36	0.34
CCD with ITO gates&μlens	0.54	0.78	0.85	0.87	0.85	0.69	0.70	0.84	0.81	0.86	0.87
Si	0.29	0.53	0.95	0.62	0.59	0.31	0.44	0.58	0.57	0.66	0.66
GaAs	0.91	0.91	0.64	0.95	0.87	0.86	0.93	0.99	0.94	0.96	0.96

high OGTE values (above 0.80) if combined with Hybrid CMOS with BLUE AR coating, CCD BI with Broadband AR coating, CCD with ITO gates and μlens and Hybrid CMOS with NIR AR coating. Y_2O_3:Eu^{3+} phosphor demonstrates high OGTE values (above 0.80) if combined with Hybrid CMOS with NIR AR coating, Hybrid CMOS with BLUE AR coating, CCD with ITO gates and μlens and CCD BI with IR AR coating. YVO_4:Eu^{3+} phosphor demonstrates high OGTE values (above 0.80) if combined with Hybrid CMOS with NIR AR coating, Hybrid CMOS with BLUE AR coating, CCD with ITO gates and μlens and CCD BI with IR AR coating. A point worth mentioning is that GaAs photocathode seems to be an excellent choice for all combinations studied, from the point of view of optical spectral matching, except for the case of CdS:In, Te, as in all other cases the OGTE value is higher than 0.85.

Summarizing, a factor recently introduced, named OGTE, which accounts for the optical gain signal-to-noise ratio transfer efficiency is utilized for evaluation of various phosphor-photodetector combinations capable for digital imaging. It was found that numerous combinations exhibited high OGTE value (over 0.80), permitting their utilization in indirect flat panel detectors.

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