Appl. Phys. A 78, 915–919 (2004)
DOI: 10.1007/s00339-003-2089-5

**Applied Physics A**
**Materials Science & Processing**

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# Optical gain signal-to-noise ratio transfer efficiency as an index for ranking of phosphor-photodetector combinations used in X-ray medical imaging

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**Received: 6 August 2002/Accepted: 23 December 2002**
**Published online: 27 June 2003 •** 

**ABSTRACT** Phosphor materials are used in medical imaging combined with radiographic film or other photodetectors. A parameter for choosing a phosphor material is the number of light photons produced per absorbed X-ray energy $E$, i.e. phosphor gain. Traditionally, a parameter for choosing the best photodetector for a phosphor material is the spectral matching factor, which denotes the percentage of the optical photons detected by the photodetector. However, this factor does not account for the phosphor gain neither in terms of signal strength nor in terms of noise. In this paper a new factor is introduced which evaluates phosphor-photodetector combinations in terms of optical gain signal-to-noise ratio matching. The proposed factor was implemented to some phosphor-photodetector combinations. It was found that for the narrow band emitting phosphors studied the results of the new factor and the matching factor were numerically the same. However, when not narrow bandwidth emitting phosphors were considered the results were numerically different. Additionally, for the case of CsI:Na phosphor different results were obtained in combinations ranking.

**PACS** 78.65; 42.80

## 1 Introduction

Phosphor materials are used in medical imaging, combined with radiographic film or other photodetectors. A critical parameter for choosing a phosphor material is its gain; that is, the number of light photons produced per absorbed X-ray of energy $E$ [1, 2]. The phosphor gain per absorbed X-ray is affected by phosphor properties such as the intrinsic conversion efficiency and the energy of the emitted light photons [1–4]. Additionally, these properties affect the contribution of the gain to total system noise [5, 6].

When a phosphor material in conjunction with a photodetector is irradiated with X-ray photons of energy $E$, the gain of the phosphor–photodetector combination differs from the inherent phosphor gain. This occurs because the phosphor light photon energy distribution is affected by the spectral response of the photodetector.

Traditionally, phosphor–photodetector efficiency is measured by the spectral matching factor [7], which denotes quantitatively the percentage of the optical photons detected by the image receptor [7–9]. However, this spectral matching factor does not account for the phosphor gain, neither in terms of signal strength nor in terms of noise [7]. Therefore, the use of this factor limits phosphor–photodetector combinations ranking, since it accounts only for optical photon detection.

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In this paper, a new factor is introduced for ranking phosphor–photodetector combinations used in X-ray medical imaging. The factor accounts for the optical gain signal-to-noise ratio transfer efficiency, overcoming the limitations of the spectral matching factor. In an effort to demonstrate the applicability of the proposed factor, it is used in ranking some phosphor–photodetector combinations.

## 2 Method and materials

### 2.1 *Method*

If one X-ray photon of energy $E$ is absorbed in the phosphor, light photons will be produced. The inherent mean gain, $\overline{m}_i(E)$, of the screen (i.e. the number of light photons produced per absorbed X-ray of energy $E$) is defined as [1, 6]:

$$\overline{m}_i(E) = \frac{n_c E}{\overline{E}_{i\lambda}}\,, \tag{1}$$

where $n_c$ is the intrinsic conversion efficiency of the X-ray energy to light photon energy of the phosphor and $\overline{E}_{i\lambda}$ is the average energy of the optical spectrum, defined by the following equation [10, 11]:

$$\overline{E}_{i\lambda} = \left(\int_{\lambda_{min}}^{\lambda_{max}} E_\lambda S_p(E_\lambda)\,dE_\lambda\right)\left(\int_{\lambda_{min}}^{\lambda_{max}} S_p(E_\lambda)\,dE_\lambda\right)^{-1}\,, \tag{2}$$

where $E_\lambda$ is the energy of the optical photons and $S_p(E_\lambda)$ is the phosphor inherent optical photon energy distribution. $\lambda_{min}$ and $\lambda_{max}$ are the minimum and maximum optical wavelengths of the energy distribution, respectively.

The inherent gain noise factor is a measure of the contribution of the inherent phosphor gain to the total noise, denoted hereafter as $GNF_i(E)$, and is given by [1, 5, 6]:

$$GNF_i(E) = \left[\frac{var[m_i(E)]}{\overline{m}_i^2(E)} - \frac{1}{\overline{m}_i(E)} + 1\right]\,, \tag{3}$$

where $\mathrm{var}[m_i(E)]$ is the variance of the inherent phosphor gain.

The term $\mathrm{var}[m_i(E)]/\overline{m}_i^2(E)$ has been found to be equal to [6]:

$$\frac{\mathrm{var}[m_i(E)]}{\overline{m}_i^2(E)} = \frac{\mathrm{var}[E_{i\lambda}]}{\overline{E}_{i\lambda}^2} + \frac{\beta E_\mathrm{g}}{E}\frac{1-n_\mathrm{c}\beta}{n_\mathrm{c}\beta}, \tag{4}$$

where $\mathrm{var}[E_{i\lambda}]$ is the variance of the inherent optical photon energy distribution. The term $E_\mathrm{g}$ in (4) is the energy gap of the phosphor material and $\beta$ is a parameter whose theoretical value is 1.5 [12], although experimentally its value has been found to be higher [3, 4, 12].

The variance, $\mathrm{var}[E_{i\lambda}]$, can be calculated as [10, 11]:

$$\mathrm{var}[E_{i\lambda}] = \left(\int_{\lambda_\mathrm{min}}^{\lambda_\mathrm{max}} \left(E_\lambda - \overline{E}_{i\lambda}\right)^2 S_\mathrm{p}(E_\lambda)\,\mathrm{d}E_\lambda\right) \times \left(\int_{\lambda_\mathrm{min}}^{\lambda_\mathrm{max}} S_\mathrm{p}(E_\lambda)\,\mathrm{d}E_\lambda\right)^{-1}. \tag{5}$$

By combining (1) and (3), the inherent optical signal-to-noise ratio of the phosphor material, denoted as $\mathrm{OSNR}_i(E)$, can be found to be:

$$\mathrm{OSNR}_i(E) = \frac{\overline{m}_i(E)}{\mathrm{GNF}_i(E)}. \tag{6}$$

If a photodetector is placed in conjunction with a phosphor material, the detected optical photon energy distribution is affected by the optical response of the detector. In order to evaluate the detector effect on the phosphor optical energy distribution, the detector sensitivity spectrum, $w(E_\lambda)$, can be utilized [7, 8]. If $w(E_\lambda)$ is the detector sensitivity spectrum, then the effective optical photon energy distribution is equal to [7]:

$$\Lambda(E_\lambda) = \int_{\lambda_1}^{\lambda_2} w(E_\lambda) S_\mathrm{p}(E_\lambda)\,\mathrm{d}E_\lambda, \tag{7}$$

where $\lambda_1 = \min\{\lambda_\mathrm{w}, \lambda_\mathrm{s}\}$ and $\lambda_2 = \max\{\lambda_\mathrm{w}, \lambda_\mathrm{s}\}$, where $\lambda_\mathrm{w}$ is the photodetector response wavelength, while $\lambda_\mathrm{s}$ corresponds to the phosphor inherent emission spectrum. $\Lambda(E_\lambda)$ is normalized to unity.

The effective mean gain of the phosphor–photodetector combination, $m_e(E)$, is different than $m_i(E)$ for the following reasons. First, the mean energy of the detected optical photons, $\overline{E}_{e\lambda}$, which is affected by $\Lambda(E_\lambda)$, may be different than $\overline{E}_{i\lambda}$. Second, the number of detected optical photons is less than $\frac{n_\mathrm{c}E}{\overline{E}_{e\lambda}}$, where $\overline{E}_{i\lambda}$ is replaced by $\overline{E}_{e\lambda}$ in (1). The latter occurs due to the effect of the photodetector sensitivity spectrum, $w(E_\lambda)$. Therefore, the effective mean gain of the phosphor–photodetector combination can be defined as:

$$\overline{m}_e(E) = \frac{n_\mathrm{c}E}{\overline{E}_{e\lambda}} a_\mathrm{s}, \tag{8}$$

where, the term $a_\mathrm{s}$ accounts for the spectral matching factor, which express the percentage of the emitted optical photons that are detected. $\overline{E}_{e\lambda}$ corresponds to the mean energy of the optical photons of the effective optical photon energy distribution and is given by [10, 11]:

$$\overline{E}_{e\lambda} = \left(\int_{\lambda_1}^{\lambda_2} E_\lambda \Lambda(E_\lambda)\,\mathrm{d}E_\lambda\right)\left(\int_{\lambda_\mathrm{min}}^{\lambda_\mathrm{max}} \Lambda(E_\lambda)\,\mathrm{d}E_\lambda\right)^{-1}. \tag{9}$$

The effective optical signal-to-noise ratio of the phosphor–photodetector combination, $\mathrm{OSNR}_e(E)$, can be found from the following relation:

$$\mathrm{OSNR}_e(E) = \frac{\overline{m}_e(E)}{\mathrm{GNF}_e(E)} \tag{10}$$

where $\mathrm{GNF}_e(E)$ is the gain noise factor of the effective spectrum and can be calculated by an equation similar to (3). The corresponding ratio of $\mathrm{var}[m_e(E)]/\overline{m}_e^2(E)$ can be obtained by an equation similar to (4). The variance, $\mathrm{var}[E_{e\lambda}]$ of the effective optical photon energy distribution, which is necessary for the $\mathrm{var}[m_e(E)]/\overline{m}_e^2(E)$ calculation, can be found if the inherent optical photon energy distribution of the phosphor, $S_\mathrm{p}(E_\lambda)$, is replaced by the effective optical photon energy distribution of the phosphor–photodetector combination, $\Lambda(E_\lambda)$, in (5).

Finally, by combining (6) and (10) the ratio of $\mathrm{OSNR}_e(E)$ over $\mathrm{OSNR}_i(E)$ provides the optical gain signal-to-noise ratio transfer efficiency, denoted hereafter as OGTE. That is:

$$\mathrm{OGTE}(E) = \frac{\mathrm{OSNR}_e(E)}{\mathrm{OSNR}_i(E)}. \tag{11}$$

By combining (1) and (4)–(11), we obtain:

$$\mathrm{OGTE}(E) = a_\mathrm{s}\frac{\overline{E}_{i\lambda}}{\overline{E}_{e\lambda}}\frac{\frac{\mathrm{var}(E_{i\lambda})}{\overline{E}_{i\lambda}^2} + \frac{\beta E_\mathrm{g}}{E}\frac{1-n_\mathrm{c}\beta}{n_\mathrm{c}\beta} - \frac{\overline{E}_{i\lambda}}{n_\mathrm{c}E} + 1}{\frac{\mathrm{var}(E_{e\lambda})}{\overline{E}_{e\lambda}^2} + \frac{\beta E_\mathrm{g}}{E}\frac{1-n_\mathrm{c}\beta}{n_\mathrm{c}\beta} - \frac{\overline{E}_{e\lambda}}{n_\mathrm{c}E} + 1}. \tag{12}$$

A perfect phosphor–photodetector combination should have a $\mathrm{OGTE}(E)$ factor equal to unity.

### 2.2 *Materials*

In order to demonstrate the applicability of the proposed factor, $\mathrm{OGTE}(E)$, in phosphor–photodetector combinations ranking, several types of phosphors with different dopant materials ($Y_2O_3{:}Eu^{3+}$, $YVO_4{:}Eu^{3+}$, $Gd_2O_2S{:}Tb$, $La_2O_2S{:}Tb$ and $Y_2O_2S{:}Tb$) were prepared by sedimentation in 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 emission spectra were measured with an Oriel 7240 grating monochromator [7, 13, 14]. The data were corrected for the optical response of the monochromator and the background in order to diminish any systematic errors. The frequency distribution of the inherent optical photon energy is demonstrated in Fig. 1. It may be observed from Fig. 1 that of the phosphors studied, CsI:Na exhibits a broad inherent optical photon

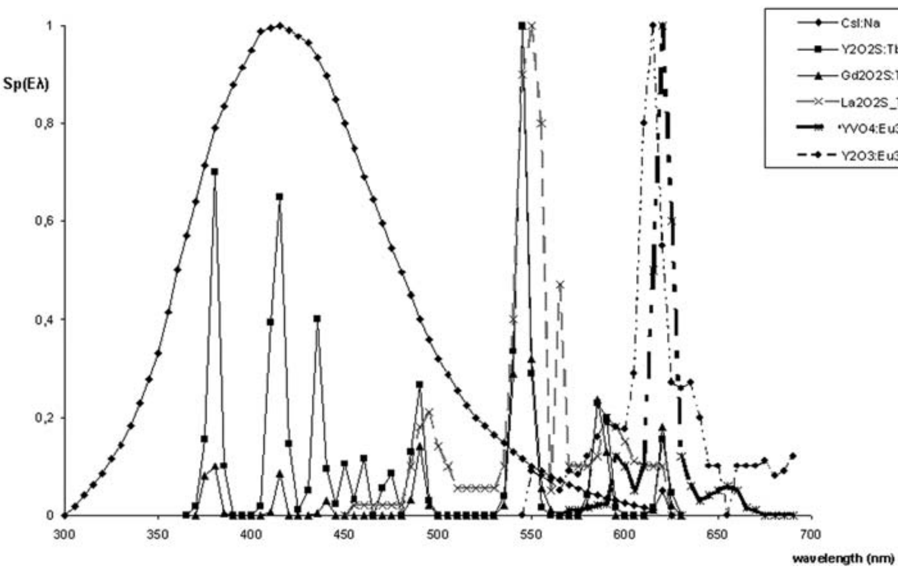


**FIGURE 1** The frequency distribution functions of the inherent optical photon energies for CsI:Na, $Y_2O_2S$:Tb, $Gd_2O_2S$:Tb, $La_2O_2S$:Tb, $YVO_4:Eu^{3+}$ and $Y_2O_3:Eu^{3+}$ phosphors

energy frequency distribution, $Y_2O_2S$:Tb, $Gd_2O_2S$:Tb and $La_2O_2S$:Tb exhibit several peaks in their corresponding inherent optical photon energy distribution and finally $Y_2O_3:Eu^{3+}$ and $YVO_4:Eu^{3+}$ exhibit a narrow inherent optical photon energy distribution. All the aforementioned materials were examined in combination with several photodetectors (GaAs, Si, S9, ES-20, Fuji-LH, Fuji-UM, Agfa-GS, Kodak-GR). The normalized response functions of the above photodetectors, as well as the values of $n_c$ and $E_g$ used in (6) were obtained from the literature [3, 6–9, 13–21]. The value of $\beta$ was considered to be 1.5 [4, 6, 12].

| Phosphors | $n_c$ | $E_g$ (eV) | $CV(E_{i\lambda})$ | $\overline{E}_{i\lambda}$ (eV) |
|---|---|---|---|---|
| $Y_2O_3:Eu^{3+}$ | 0.10 | 5.6 | 0.05 | 2.02 |
| $YVO_4:Eu^{3+}$ | 0.07 | 8.0 | 0.02 | 2.00 |
| $Y_2O_2S$:Tb | 0.18 | 4.4 | 0.15 | 2.66 |
| $Gd_2O_2S$:Tb | 0.19 | 4.6 | 0.14 | 2.46 |
| $La_2O_2S$:Tb | 0.18 | 4.5 | 0.06 | 2.26 |
| CsI:Na | 0.11 | 6.4 | 0.42 | 2.94 |

**TABLE 1** The intrinsic conversion efficiency ($n_c$), energy gap ($E_g$), relative fluctuations of the inherent optical photon energy distribution ($CV(E_{i\lambda})$) and the inherent mean optical photon energy ($\overline{E}_{i\lambda}$), of the phosphors studied

## 3 Results and discussion

In Table 1, some inherent properties of the phosphor materials studied are presented. These properties are: the intrinsic conversion efficiency $n_c$, the energy gap of the phosphor material, $E_g$ and the relative fluctuations, $CV(E_{i\lambda})$, of the inherent optical photon energy distribution. $CV(E_{i\lambda})$ equals to $\sqrt{\text{var}[E_{i\lambda}]/\overline{E}_{i\lambda}^2}$ and corresponds to the coefficient of variation of the inherent photon energy distribution. Finally, in Table 1 the inherent mean optical photon energy, $\overline{E}_{i\lambda}$, which is calculated with (2), is demonstrated. It can be observed from Table 1 that the phosphors with $CV(E_{i\lambda})$ values are $YVO_4$:Eu, $Y_2O_3$:Eu and $La_2O_2S$:Tb, with values 0.02, 0.05 and 0.06, respectively, while $Gd_2O_2S$:Tb, $Y_2O_2S$:Tb and CsI:Na have values 0.14, 0.15 and 0.42, respectively. In Table 2, the relative fluctuations $CV(E_{e\lambda})$ of the effective optical photon energy distribution for the phosphor–photodetector combinations studied is presented. $CV(E_{e\lambda})$ equals to $\sqrt{\text{var}[E_{e\lambda}]/\overline{E}_{e\lambda}^2}$ and corresponds to the coefficient of variation of the effective optical photon energy distribution.

In Table 3, the effective mean optical photon energy, $\overline{E}_{e\lambda}$, for the phosphor–photodetector combinations studied, is presented.

It is observed that the presence of the photodetector may significantly alter $CV(E_{i\lambda})$ values. So, if CsI:Na phosphor is considered, the inherent value of its coefficient of variation equals 0.42, while in conjunction with the photodetectors it was found ranging from 0.03 to 0.12. If the phosphors, whose inherent optical photon energy distribution exhibits several peaks, are considered, then for $Gd_2O_2S$:Tb the inherent value is 0.14, while in conjunction with the photodetectors it ranges from 0.03 to 0.14. For $Y_2O_2S$:Tb the inherent value is 0.15, while in conjunction with the photodetectors it ranges from 0.03 to 0.16, and for $La_2O_2S$:Tb the inherent value is 0.06,

| | CsI:Na | $Y_2O_2S$:Tb | $Gd_2O_2S$:Tb | $La_2O_2S$:Tb | $Y_2O_3:Eu^{3+}$ | $YVO_4:Eu^{3+}$ |
|---|---|---|---|---|---|---|
| GaAs | 0.12 | 0.16 | 0.13 | 0.06 | 0.04 | 0.02 |
| Si | 0.11 | 0.15 | 0.09 | 0.06 | 0.04 | 0.02 |
| S9 | 0.12 | 0.15 | 0.13 | 0.06 | 0.04 | 0.02 |
| Kodak-GR | 0.10 | 0.14 | 0.13 | 0.05 | 0.01 | N.A. |
| Fuji-LH | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.02 |
| Fuji-UM | 0.10 | 0.14 | 0.13 | 0.05 | 0.03 | N.A. |
| Agfa-GS | 0.10 | 0.14 | 0.13 | 0.03 | 0.01 | N.A. |
| ES-20 | 0.04 | 0.15 | 0.14 | 0.06 | 0.04 | 0.02 |

**TABLE 2** The relative fluctuations of the effective optical photon energy distribution, ($CV(E_{e\lambda})$), of the phosphor–photodetector combinations studied. (The initials N.A. mean that the combination is not applicable)

| | CsI:Na | $Y_2O_2S$:Tb | $Gd_2O_2S$:Tb | $La_2O_2S$:Tb | $Y_2O_3:Eu^{3+}$ | $YVO_4:Eu^{3+}$ |
|---|---|---|---|---|---|---|
| GaAs | 2.90 | 2.66 | 2.34 | 2.26 | 2.01 | 2.00 |
| Si | 2.77 | 2.50 | 2.27 | 2.25 | 2.01 | 2.00 |
| S9 | 2.92 | 2.70 | 2.37 | 2.28 | 2.03 | 2.00 |
| Kodak-GR | 3.04 | 2.76 | 2.43 | 2.32 | 2.24 | N.A. |
| Fuji-LH | 2.09 | 2.07 | 2.07 | 2.09 | 2.00 | 2.00 |
| Fuji-UM | 2.88 | 2.76 | 2.43 | 2.30 | 2.21 | N.A. |
| Agfa-GS | 2.87 | 2.80 | 2.43 | 2.52 | 2.23 | N.A. |
| ES-20 | 2.94 | 2.71 | 2.38 | 2.27 | 2.02 | 2.00 |

**TABLE 3** The effective mean optical photon energy ($\overline{E}_{e\lambda}$), of the phosphor–photodetector combinations studied. (The initials N.A. mean that the combination is not applicable)

| | CsI:Na | $Y_2O_2S$:Tb | $Gd_2O_2S$:Tb | $La_2O_2S$:Tb | $Y_2O_3:Eu^{3+}$ | $YVO_4:Eu^{3+}$ |
|---|---|---|---|---|---|---|
| GaAs | 0.92 | 0.93 | 0.94 | 0.94 | 0.95 | 0.96 |
| Si | 0.31 | 0.41 | 0.53 | 0.57 | 0.66 | 0.66 |
| S9 | 0.88 | 0.83 | 0.76 | 0.76 | 0.50 | 0.48 |
| Kodak-GR | 0.94 | 0.83 | 0.71 | 0.62 | 0.03 | 0.00 |
| Fuji-Lh | 0.01 | 0.09 | 0.17 | 0.18 | 0.81 | 0.90 |
| Fuji-UM | 0.75 | 0.80 | 0.71 | 0.69 | 0.06 | 0.00 |
| Agfa-GS | 0.80 | 0.82 | 0.67 | 0.63 | 0.04 | 0.00 |
| ES-20 | 0.93 | 0.88 | 0.78 | 0.77 | 0.63 | 0.62 |

**TABLE 4** The spectral matching factor of the phosphor–photodetector combinations studied.

| | CsI:Na | $Y_2O_2S$:Tb | $Gd_2O_2S$:Tb | $La_2O_2S$:Tb | $Y_2O_3:Eu^{3+}$ | $YVO_4:Eu^{3+}$ |
|---|---|---|---|---|---|---|
| GaAs | 0.86 | 0.93 | 0.99 | 0.94 | 0.96 | 0.96 |
| Si | 0.31 | 0.44 | 0.58 | 0.57 | 0.66 | 0.66 |
| S9 | 0.84 | 0.82 | 0.78 | 0.75 | 0.49 | 0.48 |
| Kodak-GR | 0.86 | 0.81 | 0.72 | 0.60 | 0.03 | 0.00 |
| Fuji-Lh | 0.01 | 0.12 | 0.21 | 0.19 | 0.82 | 0.90 |
| Fuji-UM | 0.73 | 0.77 | 0.72 | 0.67 | 0.06 | 0.00 |
| Agfa-GS | 0.78 | 0.80 | 0.68 | 0.57 | 0.04 | 0.00 |
| ES-20 | 0.88 | 0.86 | 0.81 | 0.76 | 0.63 | 0.62 |

**TABLE 5** The Optical Gain Signal-to-Noise Ratio Transfer Efficiency, (OGTE($E$)), of the phosphor–photodetector combinations studied

while in conjunction with the photodetectors it ranges from 0.03 to 0.06.

Finally, if the phosphors with a narrow-band inherent optical photon energy distribution are considered, then for both $YVO_4:Eu^{3+}$ and $Y_2O_3:Eu^{3+}$ the inherent and the photodetector-modified values are almost equal. Similar conclusions for $\overline{E}_{e\lambda}$ may be obtained by observing Table 3.

In Table 4, the spectral matching factors of the phosphor–photodetector combinations are presented. A perfect combination should have a spectral matching factor equal to unity. Combinations with spectral matching factor above 0.90 are as follows: CsI:Na-Kodak-GR, CsI:Na-ES20, CsI:Na-GaAs, $Y_2O_2S$:Tb-GaAs, $Gd_2O_2S$:Tb-GaAs, $La_2O_2S$:Tb-GaAs, $Y_2O_3:Eu^{3+}$-GaAs, $YVO_4:Eu^{3+}$-GaAs and $YVO_4:Eu^{3+}$-Fuji-LH.

In Table 5 the OGTE($E$) values, calculated by (12), are presented for the aforementioned phosphor–photodetector combinations. These values have been calculated for X-ray energies utilized in medical imaging, over 17 000 eV [22]. For X-ray energies over 17 000 eV it was found that the values of OGTE($E$) may be considered constant regarding X-ray energy $E$. This can be observed almost directly by inspecting (12), where it can be seen that the factor $\frac{\beta E_g}{E}\frac{1-n_c\beta}{n_c\beta}-\frac{E_\lambda}{n_c E}$ is proportional to $1/E$ and therefore practically not affecting the calculations of (12) for the X-ray energies under consideration.

In the phosphors studied, which have a small CV($E_{i\lambda}$) value and emit a narrow-band inherent optical photon energy distribution ($YVO_4:Eu^{3+}$, $Y_2O_3:Eu^{3+}$), the numerical values of OGTE($E$) were equal to those of the spectral matching factor. This behavior can also be observed for $La_2O_2S$:Tb phosphor, which has a small CV($E_{i\lambda}$) value, although its inherent optical photon energy distribution has more than one peak.

If the phosphors whose inherent optical photon energy distribution has several peaks and which additionally demonstrate higher CV($E_{i\lambda}$) values ($Gd_2O_2S$:Tb and $Y_2O_2$:S:Tb) are considered, then their corresponding values of OGTE($E$) were found to be different from the corresponding values of the spectral matching factor. However, the ranking of the combinations remained the same. Finally, for a wide inherent optical photon energy distribution, like that of the CsI:Na phosphor studied, the results were not the same, neither numerically nor in ranking for the case of the CsI:Na-ES20, CsI:Na-Kodak-GR and CsI:Na-GaAs combinations. Nevertheless, for the other combinations of CsI:Na with S9, Agfa-GS, Fuji-UM and Fuji-LH, the results were equivalent in ranking with the results of the spectral matching factor.

These differences in numerical values are expected when the inherent optical photon energy distribution becomes broader and the corresponding CV($E_{i\lambda}$) value becomes larger, since the effective optical photon energy distribution may vary, related to the inherent optical photon energy distribution, as was previously observed from Tables 2 and 3. Consequently, since OGTE($E$), in its calculation, incorporates in more detail the inherent and effective optical photon energy distributions, as can be observed from (12), it may be used as an extra ranking factor in addition to the spectral matching factor when phosphor materials with broad inherent optical photon energy distributions, or distributions that exhibit several peaks, are studied.

## 4 Conclusion

A new factor is introduced, OGTE($E$), for the ranking of phosphor–photodetector combinations used in X-ray medical imaging. This factor accounts for the optical gain signal-to-noise ratio transfer efficiency. The applicability of this factor in ranking was examined for some phosphor–photodetector combinations used in X-ray medical imaging and the results were compared to the corresponding results for the spectral matching factor. It was found that for phosphors with a narrow inherent optical photon energy distribution, such as $YVO_4:Eu^{3+}$ and $Y_2O_3:Eu^{3+}$, or with a small CV($E_{i\lambda}$) value, such as $La_2O_2S$:Tb, the proposed factor gives numerically the same results as the spectral matching factor. For the phosphors for which the inherent phosphor optical photon energy distribution exhibits several peaks and which additionally have larger CV($E_{i\lambda}$) values, such as $Gd_2O_2S$:Tb and $Y_2O_2$:S:Tb, the results for the OGTE($E$) factor were found to be different to the results for the spectral matching factor. These differences were found to be only numerical, without affecting the ranking of the combinations. Finally, for a wide inherent photon energy distribution, such as that for CsI:Na, differences in phosphor–photodetector combinations ranking were observed.

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