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# On the choice of scintillators for "scintillator-photodiode" detectors for digital radiography

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As market proposal of various scintillators with different characteristics is rapidly increasing, it becomes more and more difficult to assess them from the viewpoint of the effects of this or that scintillator property upon parameters of digital X-ray radiography systems. Therefore, optimum choice of scintillators for "scintillator-photodiode" (S-PD) type detectors is a very important aspect in the development and design of new radiographic systems. We propose a simple procedure for making this choice, which uses linear matrices of S-PD detectors. It allows evaluation of changes in the relative sensitivity of a radiographic system with variation of the movement speed of the inspected object and the radiation energy on the basis of amplitude-time characteristics of scintillators (decay time and afterglow, light output). Amplitude-time characteristics are presented for scintillators ZnSe(Te), CsI(Tl), $CdWO_4$. On the basis of these data, it is proposed to use ZnSe(Te) in the 20–100 keV range at object movement speed up to 10 cm/s, CsI(Tl) — 90—500 keV up to 10 cm/s, $CdWO_4$ → 150 keV at the speeds up to 500 cm/s.

В связи с увеличением количества предложений на рынке сцинтилляторов с различными характеристиками, трудно оценить их по влиянию той или иной характеристики сцинтиллятора на параметры цифровой рентгенографической системы. Поэтому актуален подбор сцинтиллятора для детекторов типа сцинтиллятор-фотодиод (СЦ-ФД) при проектировании и создании рентгенографических систем. Нами предлагается простая методика выбора сцинтилляторов для цифровой радиографии, использующих линейные матрицы детекторов типа СЦ-ФД. Она позволяет на основе амплитудно-временных характеристик сцинтиллятора (временные зависимости высвечивания и послесвечения, световыход) оценивать изменение относительной чувствительности радиографической системы в целом при изменении скорости перемещения объекта и энергии ионизирующего излучения. Приводятся амплитудно-временные характеристики сцинтилляторов ZnSe(Te), CsI(Tl), $CdWO_4$. На основании этих данных предлагается использовать ZnSe(Te) в диапазоне 20–100 кэВ при скорости объекта не более 10 см/с, CsI(Tl) — 90–500 кэВ до 10 см/с, $CdWO_4$ → 150 кэВ при скорости до 500 см/с.

Choosing the best scintillator for each specific case is one of the main problems to be solved in the development of instruments and equipment based on scintillation detectors. From the other side, requirements to scintillator characteristics, which very often cannot be adequately met by scintillator producers, constitute the "inverse" problem. These requirements are often contradictory and ambiguous. In principle, the ideal scintillator should possess the following properties: high density, high atomic number, high scintillation efficiency, short emission decay time, low afterglow, good spectral matching with a photoreceiver, and low price. However, such "ideal" scintillators do not exist, and in each specific case a compromise should be looked for, choosing the best suitable material among the available scintillators. In using the linear matrix for detectors and the radiation source, the relevant characteristics can be listed in the following order according to their relative importance:

— low afterglow-less than 1 % after 3 ms;
— high chemical, temperature and radiation stability;
— high density (>6 g/cm$^2$);
— luminescence range 500–1000 nm;
— high scintillation efficiency >15 000 ph/MeV [1, 2].

We endeavored to solve this problem for digital radiography that uses a linear matrix of "scintillator-photodiode" (S-PD) type detectors. As the principal characteristics of a radiographic system are sensitivity (detecting ability) and spatial resolution, we propose the following expression for relative sensitivity as criterion for efficiency of the scintillator used:

$$(\delta/d)_V \approx \frac{1}{1-\sum\limits_{i=1}^{n} A_i \cdot e^{-\frac{\delta}{V\cdot(Q_i+\tau)}}} \cdot \frac{\Delta S}{S} \times$$
$$\times \frac{\int\limits_0^{h\nu_{\max}} \alpha(h\nu)\cdot e^{-\mu_{eq}(h\nu)\cdot d_{eq}} \cdot B(h\nu)d(h\nu)}{\int\limits_0^{h\nu_{\max}} \alpha(h\nu)\cdot e^{-\mu_{eq}(h\nu)\cdot d_{eq}} \cdot \mu(h\nu)d(h\nu)}, \qquad (1)$$

where $A_i$ is the contribution of the $i$-th component of the scintillator X-ray luminescence, $\delta$ is diameter of the wire, cm, $Q_i$ are exponential components of the scintillator X-ray luminescence, $s$, $\tau$ is the time constant of the amplifying circuit, $s$, $d_{eq}$ is the object thickness, cm, $V$ is the object movement speed, cm/s, $\alpha(E)$ is the dose contribution of a specified energy in the X-ray radiation spectrum, $\mu_{eq}(E)$, $\mu(E)$ are linear attenuation coefficients of the object and background object, $B(E)$ is absorption factor of the scattered radiation from the object, $\Delta S/S$ is the threshold contrast of the system (signal to noise ratio for the detector with the amplifying circuit) [3].

The expression was obtained under conditions that the defect is much smaller than the inspected object, which is the main point of radiography. This expression can be divided into three parts. The first part describes the amplitude-time characteristic of the system. It is determined by kinetic characteristics of the scintillator and the amplifying circuit. As the time constant of the amplifying circuit can be varied, the limiting factor is the scintillator characteristics. The second part is described by amplitude-noise characteristics, i.e., the signal to noise ratio of the system. As noises coming from the scintillator and photodiode-preamplifier connection are statistically independent, we can deduce from this expression the ratio of the detector sensitivity to the scintillator noise.

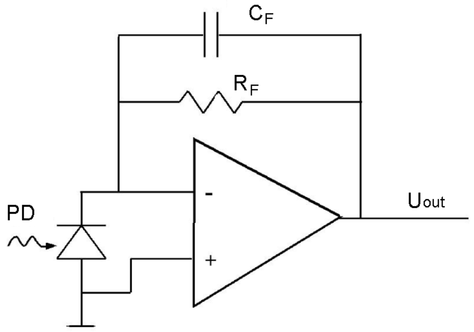

Fig. 1. Electric scheme.

$$\frac{\Delta S}{S} \sim \frac{N_{noiseS\text{-}PD}}{S_{S\text{-}PD}} =$$
$$= \frac{\sqrt{\int\limits_0^{E_{\max}} C(E)^2 \cdot n(E)dE}}{\sqrt{q_{SC}\cdot q_{PH}} \int\limits_0^{E_{\max}} C(E)\cdot n(E)dE},$$

$$C(E) = (1 - e^{-\mu_{SC}\cdot d_{SC}}) \cdot \frac{\gamma_{SC}}{\mu_{SC}} \cdot R_{light} \cdot K_{SC},$$

where $q_{SC}$, $q_{PD}$ are quantum efficient of the scintillator and the photodiode; $\mu_{SC}$ is the linear attenuation coefficient of the scintillator, cm$^{-1}$; $\gamma_{SC}$ is linear coefficients of electronic conversion of the scintillator, cm$^{-1}$; $d_{SC}$ is the scintillator thickness; $R_{light}$ is the light collection coefficient in the scintillator to the photodiode, $K_{SC}$ is the spectral matching coefficient of the scintillator luminescence spectrum and the photodiode sensitivity.

$\Delta S/S$ will be written down for the scheme usually used in digital radiography (Fig. 1) as:

$$\frac{\Delta S}{S} \approx \left( (N_{noiseS\text{–}PD} \cdot R_F)^2 + e^2 (1 + \frac{R_F}{R_{i.d.}})^2 \cdot \Delta F + \right.$$
$$\left. + \left( I_{noise}^2 + \frac{4 \cdot k \cdot T}{R_F} \right) \cdot R_F^2 \cdot \Delta F \right)^{1/2} / \left( S_{S\text{–}PH} \cdot R_F \right)^{-1},$$

where $e$ is amplifier noise EMF spectral density, V/Hz$^{1/2}$; $R_F$ is amplifier feedback resistance, Ohm; $R_{i.d.}$ is PD inverse dark resistance, Ohm; $k$ is Boltzmann constant; $\Delta F$ is frequency band, Hz; $T$ is temperature, K; $I_{noise} = (2 \cdot q \cdot (I_d^2 + i^2))^{1/2}$; $i$ is amplifier noise current spectral density, A/Hz$^{1/2}$; $q$ is electron charge, C; $I_d = I_{i.d.} + I_{ph}$; $I_{i.d.}$ is PD inverse dark current, A; $I_{ph}$ is PD photo current, A.

The third part describes properties of the inspected object.

For modelling the detector design on the basis of (1), alongside with reference data, solution of two problems is needed — deriving a mathematical expression for the amplitude-time characteristic of the scintillator and determining the light collection coefficient. In this paper, we consider the first problem. To obtain this characteristic, as a large time range is covered, two testing boards were used: one for measurement of the decay time ($t = 0.5 \div 100$ μs), and another — for measurement of afterglow ($t$ = 1–1000 ms). Block diagrams of the testing boards are presented in Fig. 2a,b.

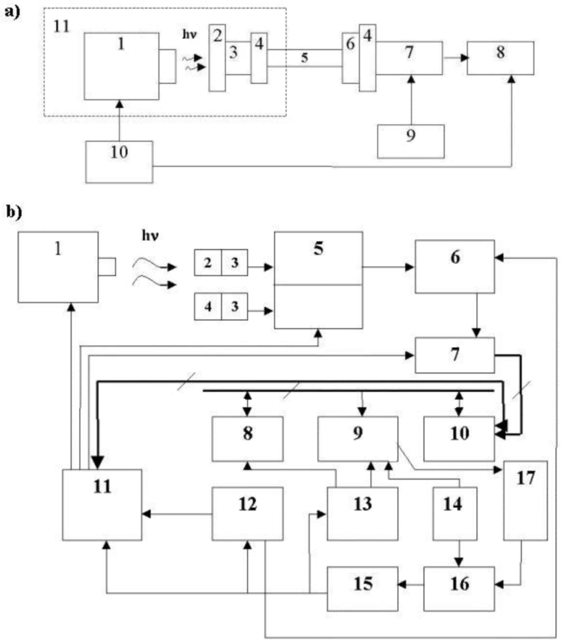

Fig. 2. a) Testing board for measurement of decay time: *1* is pulse X-ray source Mira-2D; *2* is X-ray filter; *3* is scintillator; *4* is optical collimator; *5* is fiber optics light transducer; *6* is optical attenuator; *7* is PMT; *8* is oscilloscope; *9* is PMT power supply; *10* is X-ray source control block; *11* is protection chamber. b) Testing board for measurement of afterglow: *1* is X-ray source with controlled grid; *2* is tested scintillator; *3* is photodiode; *4* is reference scintillator; *5* is preamplifiers; *6* is commutator; *7* is 15-digit ADC; *8* is memory buffer; *9* is transmitter; *10* is multiplexer; *11* is state register; *12* is decreasing step generator; *13* is memory buffer controlling device; *14* is generator; *15* is command decoder; *16* is receiver; *17* is PC.

Experimental data arrays $g_p$ are approximated by an exponentially decreasing function of the form

$$f(t) = a_1 \cdot \exp(-t/Q_1) + + a_2 \cdot \exp(-t/Q_2) + \ldots + a_i \cdot \exp(-t/Q_i). \tag{3}$$

Approximation parameters $a_i$ and $Q_i$ are determined by the least squares method, i.e., by minimization of the functional

$$\Phi = \sum [f(t_n) - g_n]^2. \tag{4}$$

The system of normal levels obtained by minimization of $\Phi$ is non-linear and can be solved numerically by iterations [4].

Joining the solution segments together was carried out under conditions of monotonous and continuous amplitude-time characteristic of the scintillator. The respective expressions for these scintillators can be written down as: for ZnSe(Te)-fast

$$I(t) = 63.1 \cdot \exp(-t/3.18) + 31.1 \cdot \exp(-t/19.61) + + 3.59 \cdot \exp(-t/106) + 2 \cdot \exp(-t/500) + + 0.2 \cdot \exp(-t/4100) + 0.01\exp(-t/795000)$$

for ZnSe(Te)-slow

$$I(t) = 94.9 \cdot \exp(-t/10.2) + 3 \cdot \exp(-t/19) + + 0.03 \cdot \exp(-t/87860) + 2.07 \cdot \exp(-t/2800)$$

for CsI(Tl)

$$I(t) = 91.91 \cdot \exp(-t/0.96) + 4.7 \cdot \exp(-t/794) + + 2.7 \cdot \exp(-t/5731) + 0.41 \cdot \exp(-t/43153) + + 0.28 \cdot \exp(-t/1016711)$$

for $CdWO_4$

$$I(t) = 49.868 \cdot \exp(-t/1.9) + 49.868 \cdot \exp(-t/16.5) + + 0.25 \cdot \exp(-t/2546) + 0.014 \cdot \exp(-t/629184).$$

Amplitude-time characteristics have been obtained for industrially produced scintillators used in radiography — CsI(Tl),

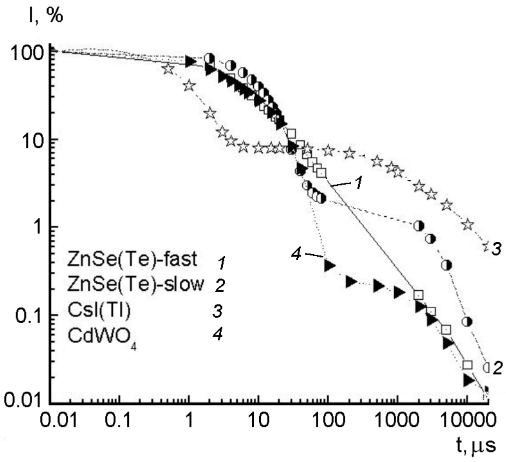

Fig. 3. Amplitude-time characteristics of scintillators.

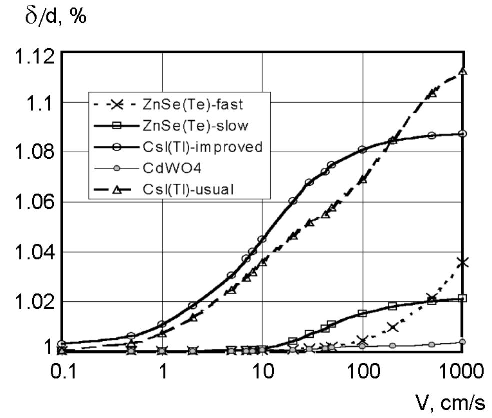

Fig. 4. Dependence of relative sensitivity on speed of moving the object at initial sensitivity of 1 % and thickness of a delay of phantom 0.01 cm for SC.

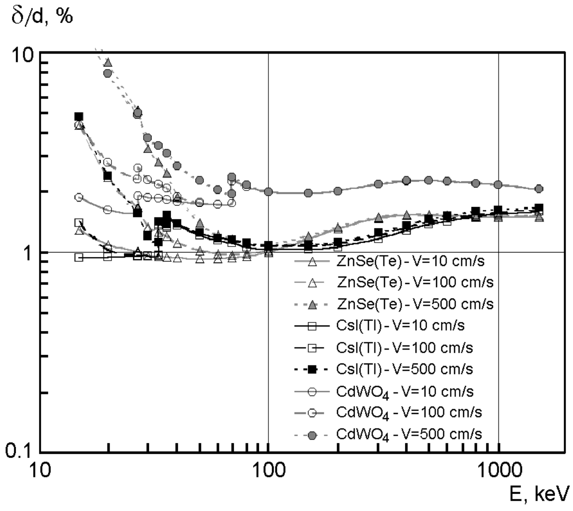

Fig. 5. Relative sensitivity of the detecting system using ZnSe(Te), CsI(Tl), $CdWO_4$ → based detectors as function of radiation energy at different speed of the object movement.

ZnSe(Te), $CdWO_4$ (Fig. 3). These expressions are convenient for choosing the object movement speed or the scintillator. Fig. 4 shows relative sensitivity of the scintillators studied as function of the object movement speed.

The choice of scintillator for a necessary energy range requires optimization of the values of detector sensitivity and afterglow level, reflected in the minimum $\delta/d$. Assuming equal absorption of the full energy beam in the detector, putting scintillator length to be 20 mm and substituting $A_i$, $Q_i$ (obtained from afterglow measurements) and the known relative sensitivity for $E = 100$ keV and steel thickness 20 mm (for ZnSe(Te) — 1 %, CsI(Tl) — 1 %, $CdWO_4$ — 2 %), we have calculated $\delta/d$ as function of the object movement speed for different scintillators and energies of ionizing radiation used (Fig. 5). As it is seen from this plot, preliminary selection of scintillators for specific inspection systems is possible.

Thus, in this work, a method has been proposed for efficiency evaluation of scintillators used in "scintillator-photodiode" type detectors for digital radiography. The method is based on expressing the relative sensitivity as function of scintillator characteristics. Mathematical expressions have been obtained for amplitude-time characteristics of scintillators CsI(Tl), ZnSe(Te), $CdWO_4$, which can be used in designing radiographic systems. Basing on these data, it is proposed that ZnSe(Te) should be used in the 20–100 keV range at object movement speeds up to 10 cm/s, CsI(Tl) — 90–500 keV, up to 10 cm/s, $CdWO_4$ → 150 keV at speeds up to 500 cm/s.

## References

1. W.W.Moses, SCINT99, Moscow (1999), p.11.
2. L.V.Atroschenko, S.F.Burachas, L.P.Gal'chinetskii et al., Crystals of Scintillators and Detectors of Ionizing Radiations on their Base, Naukova Dumka, Kiev (1998) [in Russian].
3. V.Ryzhikov, D.Kozin, B.Grinev et al., *Nucl. Instr. Meth.*, **A505**, 58 (2003).
4. V.Ryzhikov, N.Starginskii, D.Kozin et al., *Materials of Electronic Engineering*, No.3, 37 (2000).

# Вибір сцинтилятора до детекторів типу сцинтилятор-фотодіод до цифрової радіографії

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У зв'язку з підвищеною кількістю пропозицій на ринку сцинтиляторів з різними характеристиками, важко оцінити їх за впливом тієї чі іншої характеристики сцинтилятору на параметри цифрової рентгенографічної системи. Тому підбір сцинтилятора до детектора типу сцинтилятор-фотодіод (СЦ-ФД) при проектуванні та створенні рентгенографичних систем є актуальним. Нами пропонується проста методика вибору сцинтиляторів до цифрової радіографії, що використовують лінійну матрицю детекторів типу СЦ-ФД. Вона дозволяє на підставі амплітудно-часової характеристики сцинтилятора (часова залежність висвітлення та післясвітіння, світловихід) оцінювати зміну відносної чутливості радіографічної системи у цілому при зміні швидкості переміщення об'єкту та енергії іонізуючого випромінення. Наводяться амплітудно-часові характеристики сцинтиляторів ZnSe(Te), CsI(Tl), $CdWO_4$. На підставі цих даних пропонується застосовувати ZnSe(Te) в діапазоні 20–100 кеВ при швидкості об'єкту не більш ніж 10 см/с, CsI(Tl) — 90–500 кеВ до 10 см/с, $CdWO_4 \to 150$ кеВ при швидкості до 500 см/с.