APPLICATION OF THRESHOLD DETECTORS FOR INCREASING OF THE CONTRAST IN X-RAY IMAGES

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Efficiency in the use of detectors with threshold energy discrimination of radiation ("threshold detectors") for improvement of contrast in X-ray images in quasimonochromatic X-rays is considered. The threshold detectors would allow to eliminate registration of X-rays with energy below of the energy of incident monochromatic X-ray beam. Therefore, incoherent scattered photons will not be registered and contrast will be increased and/or total dose may be reduced.

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1. INTRODUCTION

In X-ray imaging, one of the topical problems is the improvement of image contrast. A high-contrast X-ray image can be obtained by excluding from the image a part of photons scattered by the irradiated object, which represent an interfering background in the formation of the image and necessitate an increase in the radiation dose.

One of the possible ways of decreasing the portion of scattered photons in X-ray imaging lies in the use of detectors with threshold energy discrimination of radiation ("threshold detectors"). This possibility stems from the fact that the photon incoherently scattered by free electrons gives a part of its energy to the electron. Therefore, if the initial quantum beam is monochromatic, then the incoherently scattered photons arriving at the detector will have the energy lower than the energy of ballistic (unscattered) photons, and the part of these scattered photons will be cut off by the threshold detector. A certain part of incoherently scattered photons will also be cut off through energy discrimination in the case, where the primary X-ray beam is quasimonochromatic. These quasimonochromatic X-ray beams may be produced, for example, by using the parametric X-ray radiation (PXR) or the coherent bremsstrahlung (CB).

Below we give the estimated percentage of X-ray quanta scattered in the irradiated sample that may be eliminated from the X-ray image owing to their energy discrimination. Numerical calculations were performed for different initial X-ray beam energies as functions of quantum energy spread in the initial beam, and also, of the accuracy of energy discrimination (energy resolution of the detector).

2. ESTIMATION OF THE NUMBER OF INCOHERENTLY SCATTERED PHOTONS ELIMINATED FROM THE X-RAY IMAGE

The cross section for incoherent scattering of photons by atomic electrons is generally presented as a product of two multipliers [1]. As a first multiplier, we use the Klein-Nishina cross section. The second multiplier is called the incoherent scattering function $S \approx 1 - \exp(-5v)$ [1, 2]. Take into account value of ν [1], the differential cross section of incoherent scattering by the atomic electron can be approximately estimated by the formula:

$$\frac{d\sigma_s}{d\Omega} \approx \frac{d\sigma_s^{KN}}{d\Omega}\left[1 - \exp\left(-456 \cdot \frac{\alpha}{Z^{2/3}} \cdot \sin\frac{\theta}{2}\right)\right]. \quad (1)$$

If the photon is scattered through the angle θ from the initial direction, then its energy varies by the following value:

$$\Delta E_\gamma = E_\gamma\left[1 - 1/[1 + \alpha(1 - \cos\theta)]\right]. \quad (2)$$

The ratio of the number of primary photons scattered through the range of angles $\theta_S < \theta < 90^\circ$ to the total number of photons incoherently scattered to the forward semisphere will equal the ratio of the corresponding integral cross sections:

$$B = \frac{\Sigma(\theta_s \le \theta \le \pi/2)}{\Sigma(0 \le \theta \le \pi/2)} = \frac{\int_{\theta_s}^{\pi/2} \frac{d\sigma_s}{d\Omega} 2\pi \sin\theta d\theta}{\int_0^{\pi/2} \frac{d\sigma_s}{d\Omega} 2\pi \sin\theta d\theta}. \quad (3)$$

If the energy resolution of the threshold detector (accuracy of energy discrimination) permits the separation between photons of energy E_γ and photons of energy $E_\gamma - \Delta E$, then formula (3) with the lower limit of integration θ_S equal to

$$\theta_s = \arccos\left[1 - \Delta E \cdot m_e c^2 / [E_\gamma \cdot (E_\gamma - \Delta E)]\right], \quad (4)$$

will determine the percentage of incoherently scattered photons having the initial (monochromatic) energy E_γ, which will be cut off from the X-ray image by the threshold detector having the energy resolution *ΔE*.

We now consider how the energy spread in the X-ray beam influences the scattered-photon cutoff efficiency by the threshold detector. Let the X-ray beam not be monochromatic, while the quantum energy distribution in the beam is uniform from the minimum energy $E_{\gamma\min}$ to the maximum energy $E_{\gamma\max} = E_{\gamma\min} + \Delta E_\gamma$. The energy threshold of the X-ray detector is tuned to the energy $E_{sd} = E_{\gamma\min} - \Delta E$, where *ΔE* is the energy resolution of the detector.

Let us denote the number of quanta incoherently scattered to the forward semisphere and having the energy $E_\gamma^{sc} < E_{sd}$ by $N_\gamma^{sc}(E_\gamma^{sc} < E_{sd})$ and the total number of photons incoherently scattered to the forward semisphere by $N_{\gamma total}^{sc}(\theta < 90^0)$. The ratio of these values

$$B_s = N_\gamma^{sc}(E_\gamma^{sc} < E_{sd}) \Big/ N_{\gamma total}^{sc}(\theta < 90^\circ) \qquad (5)$$

determines the percentage of incoherently scattered photons excluded from X-ray imaging by the threshold detector having the energy resolution *ΔE*, when the primary X-ray beam has the energy spread from $E_{\gamma\min}$ to $E_{\gamma\min} + \Delta E_\gamma$. The B_s values can be calculated by integrating the numerator and the denominator in formula (3) over E_γ with a variable limit of integration θ_S (4).

The results of numerical calculations of $B_s\left(\Delta E, \Delta E_\gamma, E_{\gamma\min}\right)$ for three values of the initial X-ray beam quantum energy (25.5, 50 and 120 keV) and for different beam energy widths ΔE_γ are shown in Fig. 1. In our calculations we have used Z=8 in formula (4), this corresponding to the basic weighting factor in different tissues, blood and cerebrum of man [3].

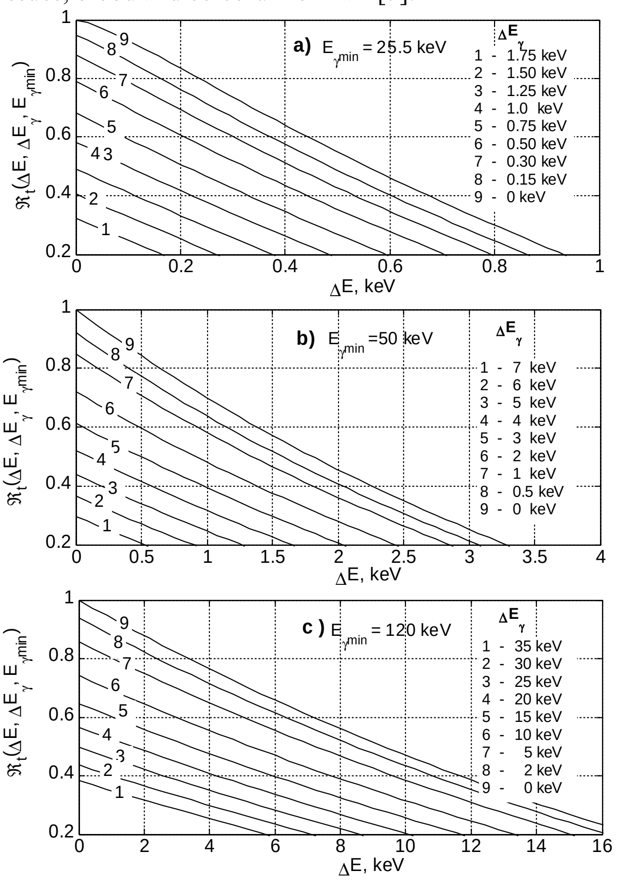

Fig. 1. The relative number of incoherently scattered photons cut off from the X-ray image versus the energy resolution ΔE of the detector. The plots are given for different energy spread values in the initial X-ray beam ΔE_γ: a) $E_{\gamma min}$ = 25.5. keV, b) $E_{\gamma min}$= 50 keV, c) $E_{\gamma min}$= 120 keV

The analysis of data presented in the figure shows the application of threshold detectors for X-ray imaging to be most efficient in the case of using the X-ray radiation beams of energies higher than 50 keV. The detector that forms the X-ray image must have the energy threshold close to the initial photon beam energy. For example, in the digital radiography with the application of CCD matrices it appears possible to image only with the use of those photons registered, whose energy exceeds a certain threshold value. For threshold detectors with the 2.5 keV energy resolution and for X-ray beams with an energy spread of ± 1 keV, about 85% of background (Compton) photons will be rejected from the image.

One of the interesting variants of threshold detector is a common X-ray film. It is just the radiation absorbed in silver halide (AgBr) that mainly forms the X-ray image. The X-ray quanta of energy slightly higher than the K-edge (13.470 keV for Br and 25.5165 keV for Ag) are absorbed nearly 2.5 times more intensively than the photons having the energy slightly lower than the K-edge. In other words, if we use a monochromatic initial X-ray beam of energy equal, e.g., to 25.52 keV, we shall automatically obtain the image on the film, where the scattered photons will be essentially suppressed.

In fact, the X-ray film is a threshold detector with an accuracy of discrimination ΔE ≈ 8.6 eV (full width at half height of K-line of silver). Therefore, if the primary X-ray beam (e.g., PXR) has the energy spread, e.g., from 25.52 to 25.82 keV, then ~ 90% of photons incoherently scattered in the sample will fall into the region of a lower absorption of photons in the photoemulsion (see Fig. 1). Considering that these 90% of photons will be absorbed in the photoemulsion by a factor of 2 worse than the remaining 10%, the percentage of incoherently scattered photons eliminated from the X-ray image is estimated to be ~ 45%.

Thus, by using quasimonochromatic X-ray quantum beams of energy slightly higher than the absorption K-edge in silver (25.52 keV) it is possible to increase the image contrast of a common X-ray film.

3. CONSIDERATION OF COHERENTLY SCATTERED QUANTA

It has been demonstrated above that the application of threshold detectors may cut off 45 to 85% (and more) of photons incoherently scattered in the sample under irradiation. However, the incoherently scattered photons make up only a part of the total number of scattered (coherently and incoherently) photons that deteriorate the X-ray image contrast. In the coherent interaction of the photon with the atom of substance it is only the direction of photon motion that changes, but the photon energy remains unchanged. Therefore, these scattered photons cannot be cut off by the threshold detector.

The B_{total} ratio of the number of incoherently scattered photons eliminated from the image to the total number of scattered (coherently and incoherently) photons is equal to

$$B_{total} = B_s N_{inc} / (N_{inc} + N_c) \ , \qquad (6)$$

where N_{inc}, N_c denote, respectively, the number of photons scattered incoherently and coherently to the forward semisphere (falling on the detector), B_s is the percentage of incoherently scattered photons excluded by the threshold detector from X-ray imaging.

Taking into account that more than three fourths of coherent scattering acts occur at angles smaller than the characteristic angle $\theta_c = 2\arcsin\left[0.026 Z^{1/3}\left(mc^2 / E_\gamma\right)\right]$

([1]) and that no less than a half of incoherently scattered photons is scattered to the forward semisphere, for the lower limit of the $N_{inc}/(N_{inc}+N_c)$ ratio we shall have

$$N_{inc}/(N_{inc}+N_c)=\sigma_{inc}/(\sigma_{inc}+2\sigma_c)\ , \qquad (7)$$

where σ_{inc}, σ_c are the total effective cross sections for incoherent and coherent scattering, respectively, for the given substance and given energy of the initial X-ray beam.

To calculate the $N_{inc}/(N_{inc}+N_c)$ ratio, we have used the database and approximation algorithms of the XCOM program [4]. Figure 2 shows the $N_{inc}/(N_{inc}+N_c)$ values versus the X-ray beam energy. The calculation was performed for different irradiated objects such as water, skeletal muscles and mamma of man, quartz, stainless steel and gold. The stoichiometric composition of skeletal muscles, the mammary gland and cortical bone adult was taken from ref. [3].

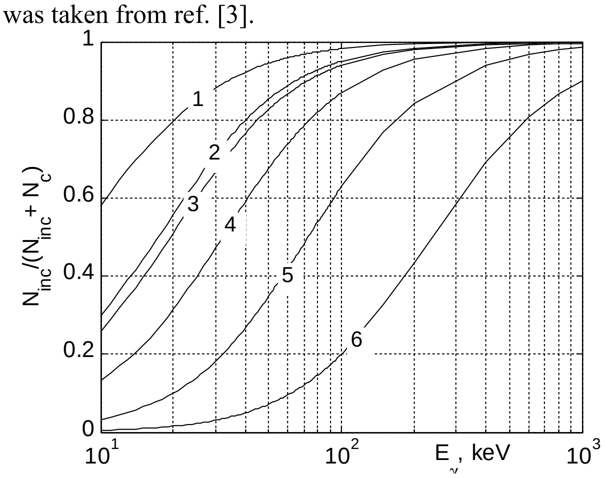

Fig. 2. The ratio of the number of photons scattered incoherently to the forward semisphere to the total number of photons scattered to the forward semisphere versus the energy of X-ray beam: 1 – water, 2 – mammary gland, 3 – skeletal muscles, 4 - cortical bone adult, 5 – stainless steel, 6 – gold

From the data presented in the figure 2 it can be seen that at a photon energy of the primary X-ray beam higher than 70 keV, more than 90% of the photons coming to the detector, which were scattered from such objects as water, skeletal muscles, or the mamma, are the incoherently scattered photons. These photons can be cut off by means of a threshold detector. For example, if the mamma is X-rayed with the X-ray beam of energy of ~ 120 keV and with an energy spread of ± 1 keV, then up to 85% of incoherent photons can be cut off from the image, if a threshold detector with the 2.5 keV accuracy of energy discrimination is used for image registration. This will make about 80% of the total number of non-ballistic photons. This result makes it possible to improve considerably the image contrast, and, as a consequence, to reduce the radiation dose for the patient. Similar estimates hold for any irradiated objects, whose main composition by weight is made up by light elements. The use of threshold detectors for imaging from substances, whose main composition by weight is determined by heavy elements, will not be so effective because of a substantial part of coherently scattered photons.

4. CONCLUSION

The use of detectors with an energy threshold discrimination of the radiation registered may substantially improve the contrast of X-ray image due to the cutoff of a part of incoherently scattered photons. The number of incoherently scattered photons eliminated from the image is determined by the energy resolution of the detector and by the characteristics of the initial X-ray beam (energy and energy resolution), and may make up to 80% of the total number of non-ballistic photons in the case of imaging from the samples, whose main composition by weight is determined by light elements. The image contrast of a common X-ray film may also be improved by applying quasimonochromatic X-ray quantum beams of energy slightly higher than the absorption K-edge in silver (25.52 keV). PXR- and CB-based sources may be used as energy-readjustable quasimonochromatic X-ray beams [5].

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ПРИМЕНЕНИЕ ПОРОГОВЫХ ДЕТЕКТОРОВ ДЛЯ УВЕЛИЧЕНИЯ КОНТРАСТНОСТИ РЕНТГЕНОВСКИХ ИЗОБРАЖЕНИЙ

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Рассматривается эффективность применения детекторов с пороговой дискриминацией регистрируемых излучений (“пороговых детекторов”) для увеличения контрастности рентгеновских изображений, получаемых с помощью квазимонохроматических рентгеновских пучков. Пороговые детекторы позволяют отсечь из формируемого рентгеновского изображения некогерентно рассеянные фотоны, и тем самым увеличить контрастность изображения и/или уменьшить дозу облучения.

ЗАСТОСУВАННЯ ГРАНИЧНИХ ДЕТЕКТОРІВ ДЛЯ ЗБІЛЬШЕННЯ КОНТРАСТНОСТІ РЕНТГЕНІВСЬКИХ ЗОБРАЖЕНЬ

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Розглядається ефективність застосування детекторів із граничною дискримінацією випромінювань (“граничних детекторів”) для збільшення контрастності рентгенівських зображень, одержуваних за допомогою квазимонохроматичних рентгенівських пучків. Граничні детектори дозволяють відітнути з формованого рентгенівського зображення некогерентно розсіяні фотони, і тим самим збільшити контрастність зображення і/або

зменшити дозу опромінення.