Analysis of the direct x-ray absorption noise in phosphor-coupled CMOS detectors

Jong Chul Han [a], Seungman Yun [a], Ian Cunningham [b], Thorsten Achterkirchen [c], Ho Kyung Kim [a*]
[a]*School of Mechanical Engineering, Pusan National University, Busan 609-735, South Korea*
[b]*Research Labs, Robarts Research Institute, 100 Perth Drive, London, Ontario N6A 5K8, Canada*
[c]*Rad-icon Imaging Corp., 3193 Belick Street, Santa Clara, CA 95054-2404, USA*
[*]*Corresponding author:hokyung@pnu.edu*

1. Introduction

It is known that the indirect conversion detectors have an NPS (noise power spectrum), which decreases with the spatial frequency, and the direct conversion detector have a nearly constant NPS with the spatial frequency (or white NPS). This explains that when a significant amount of x rays are not absorbed in the phosphor layer, then the additional absorption of x-rays in the semiconductor layers (or the photodiodes) with their white noise contributions degrades the total NPS performance. From the fact, we investigated how the direct x-ray affects CMOS detectors in terms of NPS and DQE (detective quantum efficiency).

2. Methods and Methods

2.1 CMOS detectors

We constructed a sample detector with a commercial phosphor screen (MinR-2000™, Carestream Healthcare, Inc., USA) and a CMOS photodiode array (RadEye™, Rad-icon Imaging Corp., USA) with a format of 512 × 1024 pixels and a pitch of 48 μm. The phosphor screen is mainly made up of terbium-doped gadolinium oxysulfide (Gd_2O_2S:Tb) and a polyurethane elastomer as the phosphor and binder, respectively. The detailed physical configuration, parameters and specifications of CMOS photodiode array and phosphor screen can be seen in Ref. 1 and Ref. 2.

2.2 Experimental measurements

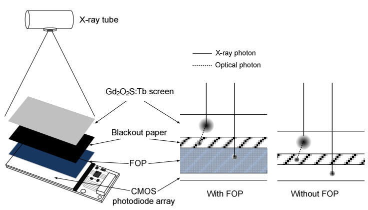

Fig. 1. A sketch describing an experimental layout for the measurement of direct x-ray signals by inserting a blackout paper between a phosphor screen and a photodiode array

Various measurement procedures were applied to the CMOS detector to isolate image noise sources by the proper introduction of FOP and blackout material. Fig. 1 shows two configurations of detectors whether a FOP layer (Incom, Inc., USA) is present or not. In the configurations, introduction of FOP may prevent direct x-rays from the absorption within the photodiode array and blackout material (Flock Paper #40, Edmond Optics Inc., Barrington, NJ, USA) is used for the measurement of direct x-ray signals while stopping the transmissions of optical photons from the phosphor layer. From the measurements, noise sources were classified with quantum, direct, scatter, and additive noises.

2.3 Cascade model analysis

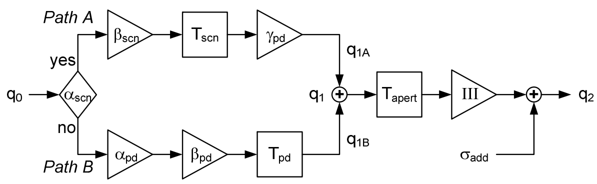

Fig. 2. Block diagram describing the cascaded model incorporating an additional parallel cascading path to account for the direct interaction of x-rays transmitted through a phosphor layer within the photodiode array.

Previously, a generalized cascaded model considering characteristic x-ray interactions and direct x-ray absorption was introduced[3]. As a K-shell photoelectric interaction of gadolinium, mainly contributing to the generation of characteristic radiation in the Gd_2O_2S:Tb phosphor, occurs for an energy of at least 50.24 keV, it can be assumed that no characteristic x-rays are produced in this study because mammographic energy, 26kVp was used. Therefore, the generalized cascaded model can be simplified as shown in Fig. 2. When q_0 interacts in a phosphor with a probability of α_{scn} (or quantum absorption efficiency), path *A* describes a conversion process of the absorbed energy within the phosphor into the generation of optical photons and an additional parallel cascading path *B* accounts for the direct interaction of x rays transmitted through the phosphor within the photodiodes.

Table 1. Physical parameters used in the cascaded model.

Parameters	Description
q_0	Incident x-ray fluence
α_{scn}	Quantum detection efficiency in the scintillator
β_{scn}	Quantum amplification factor in the scintillator
γ_{pd}	Light quantum efficiency in the photodiode
α_{pd}	Quantum efficiency in the photodiode
β_{pd}	Quantum amplification factor in the scintillator
T_{scn}	MTF of the scintillator
T_{apert}	MTF due to the aperture integration
σ_{add}	Additive electronic noise
III	Sampling process

Physical parameters for the cascade model are summarized in the Table 1. From the cascaded linear-systems theory, the theoretical DQE can be expressed as [3]

$$\mathrm{DQE}(\boldsymbol{\rho}) = \frac{\bar{q}_0 \left[a^2 \left\{\alpha_{scn}\beta_{scn}\gamma_{pd} + (1-\alpha_{scn})\alpha_{pd}\beta_{pd}\right\}\right]^2 T_{scn}^2(\boldsymbol{\rho}) T_{apart}(\rho)}{W_Q(\boldsymbol{\rho}) + W_U + W_{add}} \quad (1)$$

In the equation (1), $W_Q(\rho)$ is optical quantum noise term, $W_U(\rho)$ is NPS due to direct x-ray absorption, and $W_{add}(\rho)$ is NPS due to the additive electronic noise charges.

3. Results

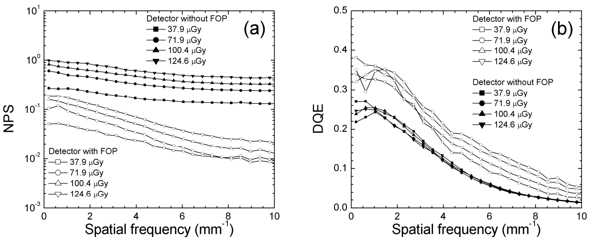

Fig. 3. Measured NPSs (a) and DQEs(b) of two different detector configurations with respect to various doses.

Measured NPSs with respect to various doses are shown in Fig. 3(a). The overall level of noise spectral densities is cranked up as the dose increases. The use of FOP largely reduces the overall noise spectral densities over the entire spatial frequency regions. Fig. 3(b) shows the calculated DQEs based on the measured NPSs. Inserting the FOP greatly improves the DQE performance because it effectively prevents direct x-ray photons from the absorption within the photodiode.

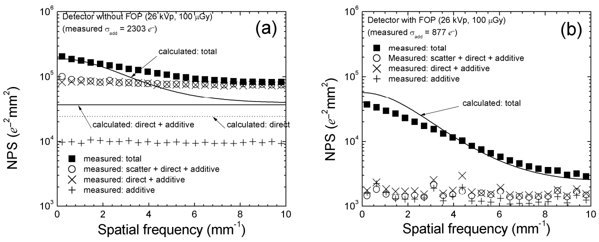

Fig. 4. Componential analysis of noise spectral densities for various image noise sources (a) Noise spectral densities of the detector without FOP. (b) Noise spectral densities of the detector with FOP.

Componential measurement results of image noise sources are shown in Fig. 4 for two different detector configurations. Estimation based on the developed cascaded models is also plotted. From these measurements and analyses, FOP effectively prevents the direct x-rays from absorption within the photodiode. While the direct x-ray absorption noise and scatter noise are significant in the detector without the FOP layer, it is negligible in the detector employing the FOP layer.

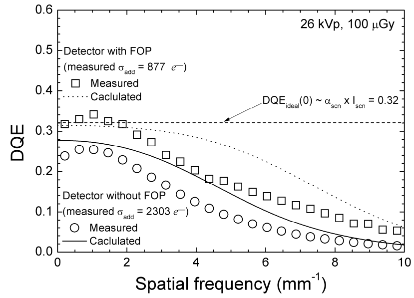

Fig. 5. DQE comparisons between the measurements and theoretical calculations

For a dose of 100 μGy, the measured DQE results were analyzed with the cascade models as shown in Fig. 5. Although the models slightly overestimate the measurements, they reasonably compliment the measurements.

4. Conclusions

Image noise sources including direct x-ray, which affects in the CMOS detectors significantly, are isolated by proper introduction of the FOP and the blackout paper. From the measurement and cascaded model analysis, direct x-ray degrades the total NPS performance. This effect is more significant at higher spatial frequencies where the optical photon absorption noise in the phosphor lessens. This degradation in NPS would be higher with a thinner phosphor layer and higher x-ray energies when the contribution of the direct x-ray absorption is relatively higher to the optical photon absorption. Although the introduction of the FOP layer reduces the sensitivity and MTF (modulation transfer function) of the detector, it largely enhances the DQE performance because it plays as an efficient stopper for the direct x-rays.

ACKNOWLEDGEMENT

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