Characterization of imaging performance of a large-area CMOS active-pixel detector for low-energy X-ray imaging

Chang Hvy Lim a, Seungman Yun a, Jong Chul Han a, Ho Kyung Kim a,b,*, Michael G. Farrier c, Thorsten Graeve Achterkirchen c, Mike McDonald b, Ian A. Cunningham b

a School of Mechanical Engineering, Pusan National University, Jangjeon-dong, Geumjeong-gu, Busan 609-735, Republic of Korea
b Imaging Research Laboratories, Robarts Research Institute, 100 Perth Drive, London, Ontario, Canada N6A 5K8
b Rad-icon Imaging, DALSA Corporation, Sunnyvale, CA 94085, USA

1. Introduction

A novel large-area (49.2 × 98.3 mm²) photodiode array with a pixel-to-pixel distance of 96 μm (RadEye™100, Rad-icon Imaging, DALSA Corporation, Sunnyvale, CA, USA) was developed recently using complementary metal-oxide-semiconductor (CMOS) active-pixel sensor (APS) technology, whose source-follower circuit enables voltage (instead of charge) signal readout from a pixel [1]. Most of the design architecture is shared with a previous version that featured a smaller 48 μm-sized pixel arranged in a 512 × 1024 format [2]. Although a single panel is not enough for full-size mammographic imaging, the panel can be tiled using three transistors, and the pixel pitch is 96 μm. The imaging characteristics of the detector have been investigated in terms of modulation-transfer function (MTF), noise-power spectrum (NPS), and detective quantum efficiency (DQE). From the measured results, the MTF at the Nyquist frequency is about 20% and the DQE around zero-spatial frequency is about 40%. Simple cascaded linear-systems analysis has showed that the FOP prevents direct absorption of X-ray photons within the CMOS photodiode array, leading to a lower NPS and consequently improved DQE especially at high spatial frequencies.

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2. Materials and methods

2.1. Fourier-based metrics describing detector performance

The concept of DQE is now universally adopted as a primary metric to characterize the imaging performance of X-ray imaging systems [5] and the measurement procedure has been standardized [6]. A practical expression for use when measuring the DQE of a linear system is given by [7]

\[
\text{DQE}(\rho) = \frac{C^2 \text{MTF}^2(\rho)}{\text{NPS}(\rho)} = \frac{\bar{q}_0^2 C^2 \text{MTF}^2(\rho)}{\text{NPS}(\rho)}
\]  

(1)

where \( \rho \) is a vector-form variable in the Fourier domain, \( \bar{q}_0 \) the average input X-ray quantum distribution and \( C \) the detector gain relating \( \bar{q}_0 \) to the average pixel output \( \bar{d} \). As seen in Eq. (1), the DQE includes the signal correlation in space (MTF) as well as the second-moment statistics in noise (NPS).

2.2. Measurements of imaging performance

To mimic mammography conditions, we used a 28 kV tungsten-target spectrum (Ultrabright™, Oxford Instruments X-ray Technology, Inc., USA) with 0.5-mm-thick added aluminum filtration. The measured half-value layer was 0.52 mm of aluminum. A source-detector distance of 500 mm was used and the detector-entrance exposure was measured by replacing the aluminum. A source-detector distance of 500 mm was used and the detector-entrance exposure was measured by replacing the detector with a calibrated electrometer (Piranha™R&F/M 605, RTL Electronics AB, Sweden).

The detector response as a function of exposure was analyzed in a central 256 × 256 pixel region for 20 images at each exposure level. The MTF was estimated from a finely sampled line-spread function, obtained by using the slanted slit method [8] with the 10-μm-width slit camera (L.E. GmbH, Aachen, Germany). The NPS was determined using a two-dimensional (2-D) Fourier analysis of 70 realizations having 256 × 256 size for each exposure level. In the NPS analysis, second-order polynomial surface detrending was applied and Hamming windowing was employed to reduce spectral leakage [9]. The one-dimensional (1-D) NPS was extracted from the 2-D NPS in the radial direction. The detector was operated at 1 fps during all measurements and the typical gain-offset correction procedure was applied to all images before analysis.

2.3. Cascaded model analysis

To assess signal and noise propagation through the scintillator, FOP, and CMOS APS, a theoretical linear-systems approach was applied [4,7,10]. Neglecting the generation of characteristic radiation in the detector, which is a reasonable assumption as X-ray energies were less than 30 keV, a simple cascaded model can be constructed as depicted in Fig. 1 [4] showing the conversion of \( \bar{q}_0 \) (average \( \bar{q}_0 \) quanta/mm² incident X-ray photons to the pixel signal \( \bar{d} \) (average \( \bar{d} \)). This model is an improvement over previous models as it includes parallel cascades to include the effect of direct X-ray interactions in the CMOS detector. In our model, the overhead bar indicates a random variable and the overhead bar or Greek character without an overhead bar indicates a mean value, and boldface indicates a vector. Photons incident on the detector can contribute to the output signal through two different mechanisms as described by the parallel paths. Path A describes X-ray photons that interact in the scintillator (probability \( z_{\text{scn}} \)) with subsequent conversion into optical quanta with an average amplification factor \( \beta_{\text{scn}} \) followed by optical scatter according to the normalized point-spread function \( p(r) \), transmittance of optical quanta through the FOP with probability \( \kappa \), and interaction of optical quanta and conversion to an electric charge in the photodiode with probability \( \eta \). Alternatively, incident photons may be transmitted through the scintillator (probability \( 1-z_{\text{scn}} \)) and subsequently interact in the photodiode after attenuated by the FOP layer with probability \( \beta_{\text{pd}} \) and direct conversion into electric charges with an average amplification factor \( \beta_{\text{pd}} \). These two paths represent independent processes, so we can neglect cross-correlation terms in signal and noise expressions [11]. The average number of charges generated along the paths is realized into measurable signals by aperture integration and scaling into detector units followed by the sampling process with a pixel pitch \( p \). Readout electronic noise is assumed to be uncorrelated (white noise in the Fourier domain).

Referring to Eq. (1), the cascaded model analysis gives the detector gain as

\[
\mathcal{G} = \alpha \left[ z_{\text{scn}} \beta_{\text{scn}} \kappa \eta + (1-z_{\text{scn}}) \beta_{\text{pd}} \right]
\]  

(2)

The detector system MTF is expressed as multiplication of the MTF describing the scatter of optical quanta in the scintillator/FOP and the “sine cardinal” function describing the pixel aperture integration

\[
\text{MTF}(\rho) = T(\rho) \sin(\pi \alpha \rho)
\]  

(3)

Our cascaded model analysis gives the total NPS of the detector as the sum of three terms: correlated noise resulting from X-ray quanta that interact in the scintillator, uncorrelated noise corresponding to direct X-ray interactions in the CMOS detector, and uncorrelated additive readout noise

\[
\text{NPS}(\rho) = \text{NPS}_{\text{cor}}(\rho) + \text{NPS}_{\text{uncor}}(\rho) + \text{NPS}_{\text{read}}(\rho)
\]  

(4)

where

\[
\text{NPS}_{\text{cor}}(\rho) = \bar{q}_0^2 \sigma^2 \alpha^4 z_{\text{scn}} \beta_{\text{scn}} \kappa \eta \sum_{j=0}^{\infty} \left\{ 1 + \kappa \eta \left( \frac{\beta_{\text{scn}}}{1-\beta_{\text{scn}}} - 1 \right) T^2 \left( \rho + \frac{j}{p} \right) \right\} \sin^2\left\{ \pi \alpha \left( \rho + \frac{j}{p} \right) \right\}
\]  

(5a)

\[
\text{NPS}_{\text{uncor}}(\rho) = \bar{q}_0^2 \sigma^2 \left[ 1-z_{\text{scn}} \right] \alpha^2 \beta_{\text{pd}}^2
\]  

(5b)

\[
\text{NPS}_{\text{read}}(\rho) = p^2 \sigma_{\text{read}}^2
\]  

(5c)

![Fig. 1. Block diagram describing the cascade model of CMOS APS detector. Path A describes the subsequent conversion processes of the absorbed energy within the scintillator into the secondary optical and electric quanta. Path B describes the conversion process of the absorbed energy within the photodiode from direct X rays transmitted through the scintillator into the electric quanta. Symbols depicted as mathematical integration and delta functions, respectively, denote the aperture integration and the sampling processes.](image-url)
3. Results

Linearity of the detector response, a required assumption for the use of Fourier methods, was assessed by measuring the detector output signal as a function of exposure and the results are plotted in Fig. 2. Least-squares regression analysis showed that more than 99.97% of the measured data could be described by a first-order polynomial. However, this analysis also showed a negative offset of 72 DN (digital number) with no X-ray exposure, which is not physical. As illustrated in Fig. 2 by the regression analysis with a higher-order polynomial, the detector is more correctly described as having a nonlinear response at low exposure levels. Careful, separate measurements with reduced X-ray power revealed that the nonlinear response is restricted to exposure levels less than ~8 mR. As such, results reported here apply to operation above 8 mR and the low-exposure performance will be addressed in a subsequent article.

Accounting for the conversion factors of 0.18 μV/e– and 0.25 mV/DN [1], the detector gain for the 28 kV spectrum is estimated to be ~6 × 10¹⁰ e–/mR/pixel. The charge capacity, therefore, covers the wide range of air kerma considerably below and above the typical mammographic detector exposure range of 25–240 μGy [12], which alternatively corresponds to 3–27 mR assuming the conversion factor of 8.73 mGy/R. Error bars in each measurement denote the averaged standard deviation of 256² pixel values for 20 images. Each standard deviation value was confirmed to be equal to the spatial integration of the 2-D NPS.

Fig. 3 shows MTF curves obtained from a finely sampled line-spread function in two perpendicular directions: pixel photodiode-addressing row direction and signal-readout column direction. MTF curves in both directions are very similar, implying that the pixel geometry is likely symmetric. Accounting for the pixel pitch of 96 μm, the Nyquist spatial frequency is approximately 5 cycles/mm at which the MTF value is about 20%.

A 2-D analysis of the NPS showed the noise-power spectrum to be rotationally symmetric. The extracted 1-D NPS along the radial direction is plotted in Fig. 4. For comparison, the theoretically calculated NPS is also included. While the theoretical NPS overestimates the measured NPS in the low frequency band at lower exposure levels, it underestimates the NPS at higher frequencies at higher exposure levels. However, the calculated results describe the measured data reasonably well for the exposure ranges investigated.

A detailed cascaded model analysis of the NPS for the CMOS detector at the exposure level of 8.28 mR, with and without the FOP layer, is illustrated in Fig. 5. While introduction of the FOP layer decreases the level of $W_{cor}(p)$ because of the transmittance characteristics of the FOP layer, the dependency on spatial frequency is unchanged. This effect may not improve the DQE. Rather it degrades the DQE if the detector is operated at lower exposure levels, in which case, the additive readout noise becomes dominant. The FOP layer, however, effectively reduces $W_{uncor}(p)$ by an order of magnitude, whose effect on the total NPS $W_{total}(p)$ is apparent in the high-frequency region. Therefore, it is expected that use of the FOP improves the DQE in the high-frequency region.

Comparison of the empirical DQE with the theoretical one for the exposure level of 8.28 mR is illustrated in Fig. 6, and shows very good agreement. The DQE at zero-spatial-frequency, $DQE(0)$, can be determined by multiplication of quantum absorption efficiency and the Swank noise factor, which were estimated from the Monte Carlo simulations of the scintillator to be 0.59 and 0.68, respectively, giving $DQE(0)=0.4$. According to both the measured and theoretical DQE, the CMOS APS and the FOP layer do not

Fig. 2. Mean pixel values of the detector as a function of exposure. Error bars indicate the average standard deviation of the measured pixel values for an exposure. Solid and dashed lines denote the least-squares regression analyses with the first-order and third-order polynomials, respectively.

Fig. 3. MTF measured in two perpendicular directions: address row and readout column directions.

Fig. 4. Empirical and theoretical 1-D NPS with respect to various exposure levels. Cascaded model analyses give reasonable agreement with the measurements.
degrade the value of DQE(0) of the scintillator itself. Rather, the absence of the FOP layer, as shown in Fig. 6, degrades the DQE at higher spatial frequencies due to absorption within the CMOS APS array of X-ray photons transmitted through the scintillator. Since this absorption noise is spatially uncorrelated as demonstrated in Fig. 5, degradation of DQE values is more severe at high frequencies [13]. Since it is expected that, however, the transmission efficiency and MTF of an FOP are degraded as the thickness increases, the optimal thickness of FOP should be selected with respect to specific imaging tasks or the choice of scintillators.

Fig. 7 shows the measured DQE near zero-spatial-frequency (~0.1 cycles/mm) as a function of exposure. From the cascaded model analysis, the use of FOP enhances DQE(0) above the exposure level of ~1.5 mR.

4. Conclusion

Feasibility of the recently developed large-area CMOS APS for use in digital mammography has been empirically and theoretically evaluated using an X-ray spectrum of 28 kV. For the evaluation, the CMOS APS was mechanically combined with thin Gd_2O_2S:Tb phosphor screen through the fiber-optic faceplate. Measurements showed that the MTF at the Nyquist frequency (approximately 5 cycles/mm) was more than 20% and the DQE(0) was about 40%, which corresponds to the theoretical limit of the Gd_2O_2S:Tb phosphor screen used. For the exposure range above ~1 mR, which was estimated by the cascaded model analysis, the use of an FOP enhances the DQE performance slightly due to the effective reduction in direct X-ray absorption-induced noise. The DQE performance of the developed detector is comparable to that of commercial digital mammographic detectors [14,15]. If the detector design is optimized, for example, by employing CsI:Tl scintillator, further improvement in the DQE value is expected.

Acknowledgment

This work was supported by the Korea Research Foundation (KRF) Grant funded by the Korea government (MEST) (Grant no. KRF-2008-313-D01339).

References