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Experimental and theoretical performance analysis for a CMOS-based high resolution image detector

Amit Jain, Daniel R. Bednarek, and Stephen Rudin

Toshiba Stroke and Vascular Research Center, University at Buffalo, Buffalo, NY, 14214

Abstract

Increasing complexity of endovascular interventional procedures requires superior x-ray imaging quality. Present state-of-the-art x-ray imaging detectors may not be adequate due to their inherent noise and resolution limitations. With recent developments, CMOS based detectors are presenting an option to fulfill the need for better image quality. For this work, a new CMOS detector has been analyzed experimentally and theoretically in terms of sensitivity, MTF and DQE.

The detector (Dexela Model 1207, Perkin-Elmer Co., London, UK) features 14-bit image acquisition, a CsI phosphor, 75 μm pixels and an active area of 12 cm $\times$ 7 cm with over 30 fps frame rate. This detector has two modes of operations with two different full-well capacities: high and low sensitivity. The sensitivity and instrumentation noise equivalent exposure (INEE) were calculated for both modes. The detector modulation-transfer function (MTF), noise-power spectra (NPS) and detective quantum efficiency (DQE) were measured using an RQA5 spectrum. For the theoretical performance evaluation, a linear cascade model with an added aliasing stage was used.

The detector showed excellent linearity in both modes. The sensitivity and the INEE of the detector were found to be 31.55 DN/ μR and 0.55 μR in high sensitivity mode, while they were 9.87 DN/ μR and 2.77 μR in low sensitivity mode. The theoretical and experimental values for the MTF and DQE showed close agreement with good DQE even at fluoroscopic exposure levels.

In summary, the Dexela detector's imaging performance in terms of sensitivity, linear system metrics, and INEE demonstrates that it can overcome the noise and resolution limitations of present state-of-the-art x-ray detectors.

Keywords

Linear Cascade Model; DQE; MTF; Aliasing; CMOS; X-Ray Imager

1. INTRODUCTION

Endovascular interventional procedures are getting more and more complex with advancing technologies. High resolution imaging capabilities are crucial for an efficient and successful endovascular interventional procedure [1]. Present state of the art detectors do present a reasonable solution but often, these detectors do not fulfill the criteria as optimum imaging

detectors due to their inherent performance limitations. Low spatial resolution (<3 lp/mm) [2, 3] and high additive noise [4] are the primary limitations of the present detectors. In recent years, our group presented many CCD based detectors [1]. Other than CCD based detectors, newly developed CMOS-based detectors are gaining notice for improved image quality and low noise operations. In this study we have carried out the experimental and theoretical performance evaluation of a commercially available CMOS detector whose design may be used as the successor to present state-of-the-art detectors.

2. METHOD AND MATERIALS

The detector evaluated here is the Dexela Model 1207 (Dexela Limited London, UK). It has 14-bit image acquisition, a CsI phosphor, $75\text{ }\mu\text{m}$ pixels and an active area of $12\text{ cm} \times 7\text{ cm}$ with a frame rate of over 30 fps. The specifications for the CMOS x-ray detector are available from Perkin-Elmer [5] and are summarized in Table 1. The basic design has active pixel sensor (APS) architecture. For this detector, each pixel has the special feature of two different full well capacities. The high full well capacity mode or low sensitivity mode has a full well capacity of 1.4 M electrons and noise around 400 electrons, while the high sensitivity mode has a full well capacity of 0.36 M electrons and 200 electrons noise.

For the detector, all the stages for the imaging chain were identified and characterized by one of the elementary processes (stochastic blurring, deterministic blurring, gain/amplification, binomial selection or additive noise) [6]. For all stages, signal and noise were calculated and the MTF and DQE were estimated for different exposures. The diagram for the linear cascade model is shown in Figure 1. For this detector we also included an aliasing stage (stage # 10) [7].

For the theoretical performance estimation, values of different parameters were estimated based on the experimental data taken with the detector. The MTF for the 600 micron thick CsI was measured and the MTF for the K-fluorescence was simulated using the method given by Que et. al. [8].

The values related to the CMOS were taken from the specification of the CMOS detector [5]. The transmission efficiency of the fiber optic plate on the CsI phosphor was assumed to be 75 % and the quantum efficiency of the CMOS sensor was assumed to be 55 %. The MTF's of the fiber optic taper and sensor were taken to be the Sine function of the fiber diameters ($6\text{ }\mu\text{m}$ for CsI FOP) and the pixel size, respectively.

The detector was operated in both high and low sensitivity modes. Flat field and offset corrected images were used for the calculation of signal (mean) and noise (standard deviation). The linearity and sensitivity of the detector were calculated using the fitted curve of the plot of the signal vs. exposure. The INEE was calculated from the slope and the intercept of the linear fit of the variance vs. exposure curve.

The MTF was measured using the slanted edge method [9]. DQE for the high sensitivity mode was calculated for three different exposures (5, 20 and $200\text{ }\mu\text{R}$)

3. RESULTS

The flat-field images were acquired for a range of exposures from 9 μR to 360 μR . Figures 2 and 4 show the sensitivity and linearity for the detector in high and low sensitivity mode, respectively. Figures 3 and 5 demonstrate the quantum noise limited operation (linear nature of variance vs. exposure curve) for both modes. The graphs for the variance vs. exposure were also used to calculate the INEE of the detector. The experimental results for various conditions are summarized below where the sensitivity and the INEE of the detector were found to be 31.55 DN/ μR and 0.55 μR in high sensitivity mode while for the low sensitivity mode they were 9.87 DN/ μR and 2.77 μR .

Figure 6 shows the experimentally measured and theoretical MTF for the detector using the RQA5 spectrum. The theoretical and experimental MTF showed good agreement. The experimentally measured DQE is shown for exposures of 5 μR , 20 μR and 200 μR in figure 7. Two different but interesting results are shown in figure 8 and 9. Figure 8 shows the comparison of theoretical and experimental DQE with an aliasing stage and we can see that the two results do not match. In figure 9, we have shown the theoretical DQE with an aliasing stage and we found that now the experimental and theoretical results are similar.

4. CONCLUSION

The performance of the Dexela CMOS detector was evaluated in terms of sensitivity, linearity, INEE, MTF and DQE. The dual sensitivity of this detector in two different modes makes it a potentially well suited choice for fluoroscopy and angiography. The MTF shows good resolution even at the Nyquist frequency. The measured DQE is nearly independent of the exposure because of low instrumentation noise. The close agreement between the theoretical DQE that included aliasing and the experimental values shows the importance of aliasing to detector performance evaluation. Aliasing is an important factor because of the high pre-sampled MTF values above the Nyquist frequency. The CMOS-based detector presents an option for better image quality with significantly improved performance in comparison to present state-of-the-art thin-film transistor (TFT) based flat panel detectors (FPDs).

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Linear Cascade Model

Figure 1.
Linear cascade model used for the CMOS detector theoretical evaluation.

Figure 2. Sensitivity for the high sensitivity mode. The mean digital numbers of the flat-field images are plotted versus detector input exposure.

Figure 3.

Variance vs. exposure for the high sensitivity mode. The intercept and the slope for this graph were used to calculate the INEE.

Figure 4.
Sensitivity curve for the low sensitivity mode.

Figure 5.
Variance vs. exposure for the low sensitivity mode.

Figure 6.

Experimentally measured and simulated MTF with RQA 5 spectrum.

Figure 7.
Experimentally measured DQE's with the RQA 5 spectrum for the high sensitivity mode.

Figure 8.
Comparison of the measured (solid) and theoretical (dashed) DQE's without the aliasing stage for the high sensitivity mode.

Figure 9.

Comparison of the measured (solid) and theoretical (dashed) DQE's with the aliasing stage for the high sensitivity mode.

Table 1

Dexela Model 1207 CMOS Detector

Pixel Size	75 micron
Image Matrix Size	1536 × 864
Full Well Capacity (FWC)	0.36 M and 1.4 M electrons
Frame Rate	60 fps (1 × 1 binning)
Noise	200 and 400 electrons
Scintillator	CsI(Tl) 600 micron HR type
Binning Mode	2 × 2, 3 × 3, 4 × 4