Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2013 March 6; 8668: 86685U-. doi:10.1117/12.2006217.

Theoretical performance analysis for CMOS based high resolution detectors

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Abstract

High resolution imaging capabilities are essential for accurately guiding successful endovascular interventional procedures. Present x-ray imaging detectors are not always adequate due to their inherent limitations. The newly-developed high-resolution micro-angiographic fluoroscope (MAF-CCD) detector has demonstrated excellent clinical image quality; however, further improvement in performance and physical design may be possible using CMOS sensors. We have thus calculated the theoretical performance of two proposed CMOS detectors which may be used as a successor to the MAF.

The proposed detectors have a 300 μm thick HL-type CsI phosphor, a 50 μm -pixel CMOS sensor with and without a variable gain light image intensifier (LII), and are designated MAF-CMOS-LII and MAF-CMOS, respectively. For the performance evaluation, linear cascade modeling was used. The detector imaging chains were divided into individual stages characterized by one of the basic processes (quantum gain, binomial selection, stochastic and deterministic blurring, additive noise). Ranges of readout noise and exposure were used to calculate the detectors' MTF and DQE.

The MAF-CMOS showed slightly better MTF than the MAF-CMOS-LII, but the MAF-CMOS-LII showed far better DQE, especially for lower exposures.

The proposed detectors can have improved MTF and DQE compared with the present high resolution MAF detector. The performance of the MAF-CMOS is excellent for the angiography exposure range; however it is limited at fluoroscopic levels due to additive instrumentation noise. The MAF-CMOS-LII, having the advantage of the variable LII gain, can overcome the noise limitation and hence may perform exceptionally for the full range of required exposures; however, it is more complex and hence more expensive.

Keywords

MTF; DQE; CMOS; MAF; Linear Cascade Model; interventional imaging; x-ray image detector

INTRODUCTION

High resolution imaging capabilities are essential for an efficient and successful endovascular interventional procedure.¹ Due to their inherent limitations, present state of the

art detectors do not fulfill the criteria as optimum imaging detectors. The present state-of-the-art detectors have limited performance due to low spatial resolution (<3 lp/mm) and high additive noise.²⁻⁴ Our group has developed a CCD based region-of-interest detector, the micro-angiographic fluoroscope (MAF), which can provide high resolution imaging and high sensitivity.⁵ The MAF was tested in clinical settings and received excellent reviews from the clinicians.^{6, 7} In this study we have carried out the theoretical performance estimation for two proposed CMOS detector designs which can be used as the successor of the MAF.

METHOD AND MATERIALS

The present MAF is comprised of a CCD detector with 12 micron pixels coupled to a light image intensifier through a 2.88:1 fiber optic taper, resulting in an effective pixel size of 35 μm . The new proposed CMOS detector will have a larger pixel size CMOS sensor (50 μm) without the need for the fiber optic taper. The proposed detectors will have 300 μm thick HL-type CsI, the same phosphor that was previously described for the MAF.⁵ We propose two different MAF-CMOS detector designs: 1) with LII and 2) without LII. The specifications used for the simulations are summarized in table 1, some of which are the same as a previously described 50 μm pixel CMOS detector.⁸

For both proposed detector designs, 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).⁹ For all the stages, signal and noise were calculated and the MTF and DQE for the detectors were estimated for various situations (different noise levels and incident exposures). Schematic diagrams for both detector designs are shown in figure 1 where FOP indicates fiber optic plate.

The linear cascade diagrams are shown in figures 2 and 3. In figure 2, the linear cascade model for the MAF-CMOS without LII consists of 12 stages. The MAF-CMOS with LII has a total of 19 stages as shown in the linear cascade diagram of figure 3.

For the theoretical performance estimation, three different readout noise values were used to evaluate their effect on performance since the specifications for different commercially available detectors quote a range of values. The MTF and DQE for a range of exposures were also calculated. For the MAF-CMOS with LII, the incident exposure and LII gain were taken in such a combination so that the number of electrons in the CMOS sensor is always 90% of the full well capacity of the sensor.

The MTF for the 300 μm thick CsI was measured and the MTF for the K-fluorescence was simulated using the method given by Que et. al.¹⁰

For the simulation calculation, a Gen 2 dual micro-channel plate (MCP) LII (Model PP0410K, 40 mm diameter)¹¹ similar to the one that is being used for the original MAF is assumed. The LII gain and the MTF were provided by the manufacture (Delft Electronic Products B.V., Roden, The Netherlands).

The transmission efficiency of the fiber optic plates was assumed to be 60 %.¹² The MTF's of the fiber optic plates and the sensor were taken to be Sinc functions of the fiber diameters (6 μm for CsI and CMOS FOP and 10 μm for LII FOP) and the detector elements size, respectively.¹²

RESULTS AND DISCUSSION

The MTF and DQE calculated from the linear cascade model for both detector designs under various conditions are summarized below. Figure 4 shows the MTF for the detectors. The MAF without LII shows a better MTF than the MAF with LII. This difference demonstrates the apparent degradation due to the insertion of the LII in the imaging chain.

The DQE's for both of the proposed detectors were calculated for three different readout noise values (500, 1000 and 1500 electrons) at three different exposures (5 μR , 50 μR and 200 μR) to evaluate the performance for a range of exposure covering fluoroscopy to angiography uses. For the calculation of DQE in the case of the MAF with LII, the LII gain was changed with the incident detector exposure in such a way that number of electrons at the final stage remains the same while for the MAF without LII, the number of electrons at the final stage changed in proportion to the incident detector exposure.

Figures 5, 6 and 7 show DQE's for both detectors for different noise values at 5, 50 and 200 μR detector exposure. Figure 8 presents a comparison for the performance of both detectors at three different exposures for 500 electron readout noise. The MAF with LII shows better DQE in comparison to the MAF without LII. Another important point apparent from the figures is that the DQE for the MAF with LII is nearly independent of the exposure while that for the MAF without LII depends strongly on the exposure. The degradation in the DQE for the MAF without LII gets more severe with increasing readout noise.

The MAF with LII shows nearly exposure independent DQE at low exposure. Also the DQE for the MAF with LII shows only slight variation for high noise and high exposure. The possible reason for this behavior lies in the modeling of LII gain. The LII gain was assumed to be Poisson distributed. When we calculate DQE for higher exposure, smaller LII gain was used to get the same number of electrons at the output stage. The small gain number will have relatively higher variance (because of the Poisson distribution) and the DQE is thus affected at high exposure for the MAF with LII.

CONCLUSION

This study presents the theoretical performance of two postulated CMOS-based detectors for a range of exposures with different readout noise values. The MAF-CMOS-LII has slightly degraded MTF because of the addition of the LII within the imaging chain. The DQE for the MAF-CMOS showed a strong dependence on the incident exposure and degradation increases with increasing readout noise especially at low exposure levels. On the other hand, the MAF-CMOS-LII has nearly exposure independent DQE. The DQE at very high exposures drops slightly because of the lower gain values used for the LII but it showed far better performance than the other detector. The proposed MAF-CMOS-LII represents a detector with significantly improved performance for a wide range of exposure and noise;

however, the MAF-CMOS without the LII is a simpler and hence less expensive design. It may be possible that a MAF-CMOS without LII but with lower noise and flexible full well capacity than those values assumed in this study may still be a feasible alternative to the detectors that have the LII.

This work presents the theoretical design and performance analysis of newly proposed CMOS based detectors. The theoretical performance of these proposed detectors presents them as an attractive possible successor to the present MAF. The image quality, performance and physical design of the present MAF will be substantially improved for these proposed detectors by removing the fiber optic taper and possibly the LII. The use of larger pixels in the CMOS sensors also results in a somewhat larger FOV.

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Figure 1.
Schematics for MAF-CMOS without LII (left) and MAF-CMOS with LII (right).

Figure 2.
Linear cascade model for MAF-CMOS without LII

Figure 3.
Linear cascade model for MAF-CMOS with LII

Figure 4.
MTF comparison for with and without LII configurations

Figure 5.

DQE comparison for MAF with and without LII configurations. All DQEs were calculated with linear cascade model for 5 μ R for three different noise values.

Figure 6.

DQE comparison for MAF with and without LII configurations for different readout noise levels. All DQEs were calculated with linear cascade model for $50\ \mu\text{R}$ for three different noise values.

Figure 7.

DQE comparison for MAF with and without LII configurations for different readout noise levels. All DQEs were calculated with linear cascade model for 200 μ R for three different noise values.

Figure 8.

DQE comparison for MAF with and without LII configurations for different exposures. All DQEs were calculated for 500 electron readout noise with three different exposure values.

Table 1

Proposed MAF-CMOS Detector Specifications

Pixel Size	50 micron
CMOS Quantum Efficiency	0.50
Full Well Capacity (FWC)	3.75×10^5 electrons
Dark Noise	200 electrons
Readout Noise	500, 1000 or 1500 electrons
Scintillator	CsI(Tl) 300 micron HL type