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Solid-state fluoroscopic imager for high-resolution angiography: Physical characteristics of an 8 cm×8 cm experimental prototype

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Abstract

In this paper, the performance of an 8 cm×8 cm three-side buttable charge-coupled device (CCD)-based imager specially designed for high-resolution fluoroscopy and operating in fluoroscopic (30 frames/second) mode is presented in terms of the presampling modulation transfer function (MTF), noise power spectrum (NPS), and detective quantum efficiency (DQE). The 8 cm×8 cm CCD imager is coupled to a 450 μm thick CsI:Tl scintillator by nondemagnifying (straight, 1:1) fiber optics. The CCD imager has a fundamental pixel pitch of 39 μm and incorporates an optically opaque interline (data) channel. The CCD imager was operated at 156 μm pixel pitch by binning 4×4 adjacent pixels prior to readout. The fluoroscopic image lag was measured and accounted for in the DQE estimate to provide lag-corrected DQE. The measured limiting spatial resolution at 10% presampling MTF with the imager operated at 156 μm pixel pitch (Nyquist sampling limit: 3.21 cy/mm) was 3.6 cy/mm. In the pulsed fluoroscopic mode, the first-frame image lag was less than 0.9%. The lag-corrected DQE(0) of ~0.62 was achieved even at a low fluoroscopic exposure rate of 1 $\mu\text{R}/\text{frame}$. Grid phantom measurements indicate no appreciable distortion. Results from DQE and image lag measurements at fluoroscopic exposure rates combined with the high spatial resolution observed from the MTF suggest that this type of imager or its variants may be a potential candidate for high-resolution neuro-interventional imaging, cardiovascular imaging, pediatric angiography, and small animal imaging. Since the CCD is three-side buttable, four such CCD modules can be joined to form a 2×2 matrix providing a field of view of 16 cm×16 cm.

Keywords

fluoroscopy; angiography; charge-coupled devices (CCD); presampling modulation transfer function (MTF); detective quantum efficiency (DQE)

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I. INTRODUCTION

Image intensifiers coupled to video pickup tubes or charge-coupled devices (CCDs) are the current standard in fluoroscopic imaging technology. While the quality of these devices have improved gradually, several limiting factors such as degradation of image quality at the periphery of the image, degradation with time, and geometric distortion, persist. Hence, solid-state flat-panel based technology such as amorphous silicon and amorphous selenium have been proposed and developed to overcome some of these limitations. We have developed an alternate approach based on the charge-coupled device concept.

Objective measures such as the modulation transfer function (MTF), noise power spectrum (NPS) and the detective quantum efficiency (DQE) have been used to characterize the performance of imaging systems. Such objective measures detailing the performance of imaging systems developed for mammography^{1–4} and radiography^{5–12} have been reported. Similar measures of image quality for fluoroscopic imaging systems based on image intensifiers, ^{13–17} amorphous silicon, ^{18–22} amorphous selenium, ^{7,23–26} and CCDs coupled to scintillator using fiberoptic tapers^{27,28} have also been reported.

Imager description

The imaging system under development for fluoroscopic applications consists of a 2×2 array of three-side buttable, 8 cm×8 cm large area CCDs, coupled to a structured CsI:Tl scintillator by a straight (nontapering) fiberoptic plate. The proposed design allows for all or any of the CCDs to be operated at different resolution modes by combining adjacent pixels (binning) prior to readout to achieve pixel pitch modes of 78, 156, and 234 μm . As an initial step to study the image quality of such a device, the imager was populated with a single 8 cm×8 cm CCD with fixed 4×4 binning to provide a pixel pitch of 156 μm , and the experimental characterization performed at 30 frames/second (fps) pulsed fluoroscopy with this single module is reported in this work. The 8 cm×8 cm CCD module has a 2048×2048 pixel matrix with a fundamental pixel pitch of 39 μm and has eight readout ports as shown in Fig. 1. Each port is used to readout 2048 rows×256 columns of pixels. Frame rate of up to 30 fps is achieved by incorporating a data line (interline channel) and by readout of all eight ports in parallel. The interline architecture allows readout of the previous frame, while the CCD is integrating the current frame as the interline channel is opaque to light. This results in reduction of the fill factor. The width of the interline channel is 19- μm and traverses the entire length of each 39 μm pixel, resulting in a fill factor of 0.513. It is relevant to note that the fill factor remains constant irrespective of the pixel pitch mode. After integration of a frame in the active area of the pixel, charges are transferred to the interline channel. Vertical binning of four pixels is achieved by transferring four rows of charges from the interline channel to the vertical summing well. Horizontal binning of four pixels is achieved by transferring four columns of charges in the vertical summing well to the horizontal summing well, resulting in 4×4 binning and 156 μm pixel pitch. While thermoelectric coolers (TECs) are provided to reduce the CCD operating temperature and hence reduce thermally generated dark charge, the experimental prototype imager used in these measurements were operated at room temperature with air-circulation by fans and does not employ TECs or liquid circulation, so that the imager performance can be measured at relatively adverse

conditions. This 8 cm×8 cm CCD was coupled to a 450 μm thick (148 mg/cm²) structured CsI:Tl scintillator deposited on an amorphous carbon substrate (Hamamatsu Corporation, Bridgewater, NJ) by a straight (nontapering) 2.54 cm (1 inch) thick fiberoptic plate (Type 47A, Schott Fiberoptics, Southbridge, MA). A photograph of this single module imager is shown in Fig. 2.

II. METHODS AND MATERIAL

The x-ray system comprised of an x-ray generator (Indico 100, CPI Inc., Canada) capable of radiographic, continuous fluoroscopic and pulsed fluoroscopic exposure modes coupled to an x-ray tube (B-150 housing with A-192 tube insert, Varian Medical System, Salt Lake City, UT) with 0.6 and 1.2 mm nominal focal spot sizes and 12° anode angle. All measurements reported in this work were performed with the small focal spot size (nominal) of 0.6 mm using the pulsed fluoroscopic exposure mode. In the pulsed fluoroscopic mode, it was possible to control independently the peak applied tube voltage (kVp), the tube current (mA) and the pulse width (ms). This allowed independent control of the exposure rate ($\mu\text{R}/\text{frame}$) without affecting the half-value layer (HVL) of the detector entrance beam. Granfors¹⁸ used a 70 to 80 kVp x-ray beam with a HVL of 7 mm of aluminum (Al) to characterize the performance of an amorphous silicon based cardiac imager. We opted to use similar beam quality for our measurements. This beam quality, in general, is approximately in the range used in several studies.^{29–34} The HVL of approximately 7 mm of Al was achieved at 72 kVp by adding 2.54 cm (1 inch) of 1100 alloy of Al at the tube port. The inherent filtration of the x-ray tube specified by the manufacturer was 0.7 mm of Al at 75 kVp. The detector entrance spectrum was simulated using the software provided by IP³⁵ and included the inherent filtration of the x-ray tube and collimator. The simulation yielded a first HVL of 7.19 mm of Al compared to the experimentally measured value of 7.02 mm of Al (~2.4% difference). The fluence per μR of exposure (q_0/X) for this simulated x-ray spectrum was calculated to be 293 x-ray photons/(mm² μR) based on the definition of Roentgen provided by Johns and Cunningham³⁶ and the technique described by Siewerdsen *et al.*³⁷

II. A. Sensitivity

Contiguous dark-frame subtracted, flat-field corrected, fluoroscopic (pulsed) sequences of 500 frames each were acquired at measured exposure rates of 1, 2.5, 4, 5.25, and 10.5 $\mu\text{R}/\text{frame}$, by varying the pulse width and tube current, while maintaining a constant source-to-imager distance of 192.5 cm. Exposure measurements were performed at a distance of 30 cm from the detector entrance with a calibrated dosimeter and scaled to the detector entrance using the inverse square law. Precision in exposure measurement was improved by averaging five such measurements for each pulse width and tube current setting. Detector entrance exposure rates of 1.5 to 2.5 $\mu\text{R}/\text{frame}$, 3 to 6 $\mu\text{R}/\text{frame}$ and 10 to 15 $\mu\text{R}/\text{frame}$ are typical of entrance exposures used for normal, high-dose and cine-film fluoroscopy for a 23–25 cm FOV image intensifier based system without a grid at 80 kVp.³⁸ The detector entrance exposure rates used in this study are also, in general, in the range of exposure rates surveyed in clinical practice.^{39–41} The mean and the variance in the central 256×256 region-of-interest (ROI) of each image were computed. The average signal in digital units

(DU) for the 156 μm pixel pitch mode at each exposure rate of $X \mu\text{R}/\text{frame}$ was computed as the average of the mean computed from each of the 500 ROIs and represented as S_X . Plotting the average signal versus the detector entrance exposure rate generated the linearity of signal response plot. The slope of the linearity plot provided the sensitivity of the imager in units of $\text{DU}/\mu\text{R}$ for the 156 μm pixel pitch. The sensitivity of the system was also calculated in units of $\text{electrons}/(\text{mm}^2\mu\text{R})$, based on the conversion gain in $\text{electrons}/\text{DU}$ provided by the manufacturer and the pixel area.

II. B. Presampling modulation transfer function

The presampling modulation transfer function (MTF) was determined using the technique described by Fujita *et al.*⁴² A detailed description of the measurement technique has been described by Dobbins *et al.*⁶ and has been applied to evaluate the spatial resolution properties of mammographic imagers.^{3,4} Specifically, a long pulsed fluoroscopic sequence consisting of dark-subtracted, flat-field corrected image frames was acquired using a 72 kVp x-ray beam with a 10 μm slit (Model: 07-624, Cardinal Health, Cleveland, OH) placed on top of the imager at a slight angle to the detector matrix. The source-to-imager distance (SID) was sufficiently large (192.5 cm) compared to the distance between the slit and the CsI:Tl scintillator (~ 1.5 cm), so that magnification effects could be ignored. The fluoroscopic frames were converted from the original 14-bit digitization to floating point values. An average of 100 consecutive frames was used to compute the finely sampled line-spread function (LSF), so that the tails of the LSF were not overtly affected by noise. The finely sampled LSF was normalized to the peak value and had equally spaced data points 4 μm apart. The finely sampled LSF was Fourier transformed and deconvolved of the finite width of the slit [$\text{sinc}(10 \mu\text{m})$], to provide the pre-sampling MTF. Measurements of the presampling MTF were performed along two orthogonal directions and represented as $T_{\text{pre}}(u,0)$ and $T_{\text{pre}}(0,v)$.

II. C. Electronic noise

The electronic noise was measured as the spatial mean of the temporal standard deviation image obtained from a sequence of 500 dark images, prior to any correction. The imager was operated in the 30 fps fluoroscopic mode. These measurements were performed at discrete time points from the initialization of the imager at room temperature, to study the time (and temperature) dependence of the electronic noise. These measurements provided the electronic noise in DU for the 156 μm pixel, which were scaled by the manufacturer provided conversion gain.

The technique for measurement of the spatial frequency-dependent two-dimensional NPS has been addressed in detail by Dobbins *et al.*⁶ and has been applied to evaluate the noise characteristics of mammographic imagers.^{3,4} Specifically, a dark sequence of 500 images was acquired with the imager operating at 30 fps after the imager reached temperature stabilization. All images were converted to floating point numbers. The central 256×256 region-of-interest (ROI) from each image, represented as $\text{DROI}_i(x, y)$, was extracted and the average amplitude of the ROI, represented as $\overline{\text{DROI}_i(x, y)}$ was subtracted. The ensemble average of the magnitude of the Fourier transform of these ROIs scaled as shown below⁶ provided the two-dimensional (2D) electronic NPS, represented as $W_E(u, v)$,

$$W_E(u, v) = \frac{\langle |\text{FT}[\text{DROI}_i(x, y) - \overline{\text{DROI}_i(x, y)}]|^2 \rangle}{N_x \cdot N_y} \Delta x \cdot \Delta y, \quad (1)$$

where N_x and N_y represent the number of elements in the ROI ($N_x=N_y=256$), and Δx and Δy are the pixel pitch along the x and y directions, respectively ($\Delta x = \Delta y = 0.156$ mm). From the $W_E(u, v)$, the 1D electronic NPS along the u and v axes were determined as $W_E(u, 0)$ and $W_E(0, v)$. The NPS determined through the above technique also includes any structural electronic noise component (also referred to as fixed-pattern noise in literature) that may be present in the imager.

The same dark sequence was used to determine the electronic NPS without the structured (fixed-pattern) noise component. The central 256×256 ROI from each image, represented as $\text{DROI}_i(x, y)$, was extracted and the average image from these ROIs, represented as $\langle \text{DROI}(x, y) \rangle$, subtracted to provide the ROI without the presence of structured-noise component. These ROIs were Fourier transformed and scaled as shown below to obtain the electronic NPS without the presence of any structured-noise component represented as $W_E^{\text{NS}}(u, v)$.

$$W_E^{\text{NS}}(u, v) = \frac{\langle |\text{FT}[\text{DROI}_i(x, y) - \langle \text{DROI}(x, y) \rangle]|^2 \rangle}{N_x \cdot N_y} \Delta x \cdot \Delta y. \quad (2)$$

The resultant $W_E^{\text{NS}}(u, v)$ was scaled by a factor of $\frac{500}{499}$ to account for the loss in variance¹¹ due to the subtraction of the average dark ROI, $\langle \text{DROI}(x, y) \rangle$. From the $W_E^{\text{NS}}(u, v)$, the 1D electronic NPS along the u and v axes were determined in a manner similar to that addressed previously. The structured-noise component along the u axis [$W_E^S(u, 0)$] can be estimated by⁴³

$$W_E^S(u, 0) = W_E(u, 0) - W_E^{\text{NS}}(u, 0). \quad (3)$$

Similarly, the structured-noise along the v axis can also be estimated.

II. D. Fluoroscopic noise power spectrum

A dark-image subtracted, flat-field corrected fluoroscopic sequence of 500 images was acquired with the imager operating at 30 fps after the imager reached temperature stabilization at exposure rates of 1, 2.5, 4, 5.25, and 10.5 $\mu\text{R}/\text{frame}$. All images were converted to floating point numbers. The central 256×256 region-of-interest (ROI) from each image, represented as $\text{ROI}_i(x, y)$, was extracted and the average amplitude of the ROI, represented as $\overline{\text{ROI}_i(x, y)}$, was subtracted. The ensemble average of the magnitude of the Fourier transform of these ROIs scaled as shown below⁶ provided the two-dimensional (2D) NPS at an exposure rate of X $\mu\text{R}/\text{frame}$, represented as $W_X(u, v)$,

$$W_x(u, v) = \frac{\langle |FT[ROI_i(x, y) - \overline{ROI_i(x, y)}]|^2 \rangle}{N_x \cdot N_y} \Delta x \cdot \Delta y, \quad (4)$$

where N_x and N_y represent the number of elements in the ROI ($N_x=N_y=256$), and Δx and Δy are the pixel pitch along the x and y directions, respectively. From the $W_x(u, v)$, the 1D electronic NPS along the u and v axes were determined as $W_x(u, 0)$ and $W_x(0, v)$. The NPS determined through the above technique also includes any structural noise component (electronic or due to x rays) that may be present in the imager.

The same fluoroscopic sequences were used to determine the fluoroscopic NPS without the structured-noise (fixed-pattern) component. The central 256×256 ROI from each image, represented as $ROI_i(x, y)$, was extracted and the average image from these ROIs, represented as $\langle ROI(x, y) \rangle$, was subtracted to provide the ROI without the presence of structured-noise component. These ROIs were Fourier transformed and scaled as shown below 6 to obtain the fluoroscopic NPS without the presence of any structured-noise component at an exposure rate of $X \mu R/\text{frame}$, represented as $W_x^{NS}(u, v)$,

$$W_x^{NS}(u, v) = \frac{\langle |FT[ROI_i(x, y) - \langle ROI(x, y) \rangle]|^2 \rangle}{N_x \cdot N_y} \Delta x \cdot \Delta y. \quad (5)$$

The resultant $W_x^{NS}(u, v)$ was scaled by a factor of $\frac{500}{499}$ to account for the loss in variance¹¹ due to the subtraction of the average ROI, $\langle ROI(x, y) \rangle$. From the $W_x^{NS}(u, v)$, the 1D electronic NPS along the u and v axes were determined in a manner similar to that addressed previously.

II. E. Fluoroscopic image lag

The experimental procedure for measuring image lag was similar to that used by Granfors.¹⁸ A pulsed fluoroscopic sequence (30 fps) consisting of 100 frames was acquired, with the x-ray exposure terminated at the end of the 50th frame. The average signal of the central 256×256 ROI of each frame was used to represent the mean signal amplitude of that frame. Image lag in the n th frame was computed as the fraction of the residual signal in the n th frame after the termination of the x-ray exposure (S_n) to that prior to the termination of the x-ray exposure (S_0) as¹⁸

$$\text{Lag}_n = \frac{|S_n - S_f|}{|S_0 - S_f|}, \quad (6)$$

where S_f is the equilibrium signal in the final frame. Image lag measurements were performed at each exposure rate, to study the signal dependence on image lag. Three such measurements were performed and averaged to improve the estimate. The lag-correction factor (LCF) was computed according to the technique of Granfors and Aufrichtig⁴⁴ as

$$LCF = (1 - \text{Lag}_1)^2 + \sum_{n=2}^{\infty} (\text{Lag}_{n-1} - \text{Lag}_n)^2. \quad (7)$$

II. F. Lag-corrected noise power spectrum

The lag-corrected fluoroscopic NPS at an exposure rate of $X \mu\text{R}/\text{frame}$ along the u axis represented as $W_X^{LC}(u, 0)$ was obtained by 34,44

$$W_X^{LC}(u, 0) = W_E^{NS}(u, 0) + \frac{W_X^{NS}(u, 0) - W_E^{NS}(u, 0)}{LCF}, \quad (8)$$

where $W_E^{NS}(u, 0)$ was determined according to Sec. II C, and $W_X^{NS}(u, 0)$ was determined according to Sec. II D. Similarly, the lag-corrected fluoroscopic NPS along the v axis was determined.

II. G. Lag-corrected detective quantum efficiency

The lag-corrected DQE of the imaging system at an exposure rate of $X \mu\text{R}/\text{frame}$ along the u axis represented as $DQE_X^{LC}(u, 0)$ was obtained by 18,44

$$DQE_X^{LC}(u, 0) = \frac{S_X^2 \cdot T_{\text{pre}}^2(u, 0)}{X \cdot \left(\frac{q_0}{X}\right) \cdot W_X^{LC}(u, 0)}, \quad (9)$$

where S_X is the mean signal determined according to Sec. II A, $T_{\text{pre}}(u, 0)$ is the presampling MTF along the u axis determined according to Sec. II B, $W_X^{LC}(u, 0)$ is the lag-corrected fluoroscopic NPS determined according to Sec. II F, and (q_0/X) was calculated to be 293 x-ray photons/(mm² μR). The lag-corrected DQE along the v axis was estimated in a similar manner.

II. H. Qualitative measures of image quality

Qualitative measures of fluoroscopic systems such as resolution measurements using bar-pattern tool (Model: 07-501, Gammex RMI, Middleton, WI) and distortion measurements using wire-mesh grid (Model: 141, Gammex RMI, Middleton, WI) are often performed in clinical setting to monitor image quality. Similar measurements were performed with the prototype imager to study in particular any geometric distortion, if present.

III. RESULTS AND DISCUSSION

The imager response curve obtained by plotting the detector entrance exposure on a single fluoroscopic image frame versus the mean signal amplitude is shown in Fig. 3. The error bars at each exposure rate represents the rms standard deviation computed as the square-root of the rms variance. The imager demonstrated a linear behavior within the tested exposure range. The sensitivity of the imager computed from the slope of the imager response curve was 360.14 DU/ μR for the 156 μm pixel pitch. Based on the conversion gain of 2.2

electrons/DU determined by the manufacturer through photon-transfer curve, and the pixel pitch of $156\text{ }\mu\text{m}$, the measured sensitivity translates to 792 electrons/ μR for the $156\text{ }\mu\text{m}$ pixel or 3.26×10^4 electrons/($\text{mm}^2\text{ }\mu\text{R}$). The increase in the rms standard deviation observed with increasing exposure is due to the increased quantum noise.

The presampling MTF measured along two orthogonal directions is shown in Fig. 4(A). $T_{\text{pre}}(0,v)$ corresponds to the axis where the active dimension of the pixel is $156\text{ }\mu\text{m}$ and $T_{\text{pre}}(u,0)$ corresponds to the axis where the active dimension of the pixel is reduced to $80\text{ }\mu\text{m}$ due to the interline channel. The 10% presampling MTF was between 3.6 and 4 cy/mm depending upon the axis. To verify the theoretical expectation of isotropic scintillator blur, the pixel presampling MTF represented as the sinc of the active pixel dimension corresponding to each axis was deconvolved. Figure 4(B) shows the scintillator MTF obtained along u and v axes. Almost identical scintillator MTF along the u and v axes indicate that the difference in the presampling MTF is primarily due to the pixel presampling MTF.

Figure 5 shows the time (and temperature) dependence of the electronic noise from start-up of the imager at room temperature. At $t=0$ the imager was turned on and the electronic noise was monitored at discrete time points over a period of 3.5 hours. The plot indicates that temperature stabilization is achieved in approximately 90 minutes after start-up. While such a characteristic in general may not be a desirable, it is important to note that the increase in electronic noise is ~ 3.5 electrons from start up to temperature stabilization, which may not have a significant impact on image quality. Temperature stabilization is achieved through air circulation by fans as shown in the photograph of the imager in Fig. 2. The imager is neither liquid cooled nor does it use thermoelectric coolers (TECs) for the setup used in our measurements. However, for faster stabilization of temperature, which is desirable, it would be preferable to have the TECs operational with a closed loop temperature control.

Figure 6 shows the natural logarithm of the 2D electronic NPS inclusive of the structured (fixed-pattern) noise [$W_E(u,v)$] estimated from a sequence of 500 images according to Sec. II C. The plot indicates that there is some significant noise along the u axis. This noise is due to the readout and appears as vertical lines, which can be corrected for in the signal field through the flat-field correction process as illustrated in Fig. 7. Figure 8(A) shows the 1D electronic NPS inclusive of the structured noise component along the u and v axes estimated according to Sec. II C. Significant spikes at mid- and high-spatial frequencies were observed along the u axis and at low spatial frequencies along the v axis. Figure 8(B) shows the electronic NPS without the structured (fixed-pattern) noise component along the u and v axes. The spikes seen in Fig. 8(A) are absent in Fig. 8(B) indicating that these spikes were due to the structured (fixed-pattern) electronic noise. Figure 8(C) shows the estimated structured noise along the u and v axes. This plot confirms that the spikes observed in Fig. 8(A) at mid- and high-spatial frequencies along the u axis, and at low spatial frequencies along the v axis, were due to the structured (fixed-pattern) noise.

Figure 9 shows the natural logarithm of the 2D fluoroscopic NPS inclusive of the structured-noise component at exposure rates of 1, 2.5, 4, and $10.5\text{ }\mu\text{R}/\text{frame}$. Similar measurement was also performed at $5.25\text{ }\mu\text{R}/\text{frame}$, but is not reported for the sake of conciseness. The plots

indicate the presence of increased noise along the u axis. Also, anisotropy at the low exposure rate of $1 \mu\text{R}/\text{frame}$ was observed. However, with increasing exposure the 2D NPS indicated improved radial isotropy. The source of this anisotropy at $1 \mu\text{R}/\text{frame}$ is yet to be determined. Figure 10 shows the natural logarithm of the 2D fluoroscopic NPS excluding the structured-noise component. These 2D NPS images show that noise spikes seen along the u axis is suppressed compared to Fig. 9, indicative of fixed-pattern noise.

Figure 11 shows the measured image lag of the system operating at 30 fps at exposure rate from 2.5 to $10.5 \mu\text{R}/\text{frame}$. The error bars indicate ± 1 standard deviation computed from three measurements. Measurement of image lag at $1 \mu\text{R}/\text{frame}$ did not yield reliable results as the signal in the first frame after termination of the x-ray pulse dropped to electronic noise levels. Within the range of exposure rates tested the imager exhibited minimal exposure (and signal) dependence. The measured first-frame image lag was 0.9%, which illustrates excellent temporal imaging characteristics. From these measurements, the lag-correction factor (LCF) was calculated to be 0.984.

Figures 12(A) and 12(B) show the lag-corrected fluoroscopic NPS along the u and v axes represented as $W_x^{LC}(u, 0)$ and $W_x^{LC}(0, v)$ calculated according to Sec. II F for the five exposure rates considered. The electronic NPS [W_E^{NS}] corresponding to the axes are also plotted to facilitate easy comparison. Faster roll-off of the NPS along the v axis at $1 \mu\text{R}/\text{frame}$ was noticed, consistent with the anisotropy observed in Figs. 9 and 10.

Figures 13(A) and 13(B) show the lag-corrected DQE along the u axis and v axis respectively, at each of the exposure rates. The plots indicate along the u axis that there was no significant dependence with exposure rate. However, along the v axis there was a noticeable increase in the DQE at the low exposure rate of $1 \mu\text{R}/\text{frame}$ at mid to high-spatial frequencies due to the faster roll-off of the NPS as observed in Fig. 12(B). With increasing exposure rates ($2.5 \mu\text{R}/\text{frame}$ and above), no appreciable exposure dependence in the frequency-dependent DQE along the v axis was observed. The imager exhibits a DQE of ~ 0.62 at zero frequency.

Images of a bar-pattern test tool and a wire-mesh phantom were acquired to provide qualitative (visual) measure of image quality. The acquired images of these test tools are shown in Fig. 14. The limiting high-contrast spatial resolution perceived from the bar-pattern test tool was $3.19 \text{ lp}/\text{mm}$, which compares well with the Nyquist sampling limit of $3.21 \text{ cy}/\text{mm}$. In comparison, the 10% presampling MTF was between 3.6 and $4 \text{ cy}/\text{mm}$ depending upon the axis. While some of the bars at $3.54 \text{ lp}/\text{mm}$ could be resolved, aliasing effects were observed. Image of the wire-mesh phantom indicates no appreciable geometric distortion.

The measured 10% presampling MTF of $3.6 \text{ cy}/\text{mm}$ of this prototype imager was in general better than x-ray image intensifier-based systems (XRII) operating in the nonzoom mode and coupled to video pickup tubes^{15,16} or charge-coupled devices.^{14–17,20} However, when XRII-based systems are operated in the zoom mode and depending on the video capture device used, ^{20,45} 10% MTF comparable to that with this prototype imager is observed. In image-intensifier/video pickup tube-based systems image lag is signal

dependent, 18,46,47 which makes it difficult to incorporate temporal filtering algorithms. The DQE performance of the imager is comparable with that achieved by image intensifier based fluoroscopic systems at low spatial frequencies^{13–16,18,20} and show a significant improvement at mid- to high-spatial frequencies.^{14–16,18}

The limiting resolution of this prototype imager is either comparable^{19–21,48} or slightly better²² than that reported with amorphous silicon-based flat-panel fluoroscopy devices depending on the implemented pixel pitch and the scintillator used. In comparison to amorphous selenium-based fluoroscopic devices, the limiting resolution of this prototype imager is either comparable²⁵ or inferior^{49,50} depending on the implemented pixel pitch. First frame image lag in the range of 1.8% to 10% have been reported^{18,19,21,51} with amorphous silicon-based fluoroscopy systems. Luhta and Rowlands⁴⁵ have discussed the factors influencing lag in amorphous selenium based large area x-ray sensitive vidicon. First frame image lag of ~3% to 5% have also been reported with amorphous selenium-based fluoroscopic devices.^{23,50} Depending on the CsI:Tl scintillator thickness used and the pixel pitch, DQE performance of amorphous silicon-based fluoroscopy devices are either superior or comparable to that of the prototype imager.^{18–22,34} It is possible to improve the DQE performance of this prototype imager by incorporating thicker scintillators, however at the expense of degraded spatial resolution.

The performance characteristic of the four-module large-area device under development is expected to be similar to the single-module device, as these modules are readout independently. However, at the seam where the modules are joined, there may be some loss of information and needs to be analyzed. Since these modules are three-side buttable, seam in the order of ~40 μm (1 fundamental pixel) or less can be expected. At the same exposure rate, operating the imager in the 78 μm pixel pitch mode would result in decrease in signal by a factor of 4 compared to that in the 156 μm pixel pitch mode. This may have a negative impact on the DQE performance particularly at low exposure rates. However, given the low electronic noise levels observed, reasonable DQE performance can be expected. Theoretical estimations of DQE performance addressed in the companion paper⁵² indicate that it may be feasible to attain performance in the 78 μm pixel pitch mode similar to the 156 μm pixel pitch mode at exposure rates of 2.5 $\mu\text{R}/\text{frame}$ and above. These theoretical predictions need to be validated experimentally. While the DQE performance suggests favorable characteristics, the optimization of system parameters such as gain, dynamic range and noise, through task-dependent observer studies is a subject of on-going research.

IV. CONCLUSION

The results demonstrate high spatial resolution at 30 fps fluoroscopy, while preserving the DQE performance currently afforded by image intensifier-based fluoroscopic systems. Results from DQE and image lag measurements at fluoroscopic exposure rates combined with the high spatial resolution observed from the measured presampling MTF suggest that this type of imager or its variants may be a potential candidate for the low-dose, low-lag, and high-spatial resolution fluoroscopic applications such as region-of-interest neurointerventional imaging^{26–28,53} cardiovascular imaging, pediatric angiography, and small animal imaging.

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Fig. 1.
Pixel architecture of a single 8 cm x 8 cm CCD module.

Fig. 2.
Photograph of the imager.

Fig. 3.

The linear behavior of the imager is depicted by the imager response curve obtained by plotting the mean signal amplitude as a function of the detector entrance exposure in a single fluoroscopic image frame. The sensitivity calculated as the slope of the linearity plot was 360.14 DU/μR. The increase in the rms standard deviation observed with increasing exposure is due to the increased quantum noise.

Fig. 4.
 (A) Presampling MTF of the imager measured along two orthogonal directions. (B)
 Scintillator MTF obtained by deconvolving the pixel pre-sampling MTF corresponding to
 the axes from the measured presampling MTF along the u and v axes.

Fig. 5.

Time (and temperature) dependence of the electronic noise from start-up of the imager at room temperature. At $t=0$ the imager was turned on and the electronic noise was monitored at discrete time points over a period of 3.5 hours.

Fig. 6. 2D electronic NPS including the structured noise. Significant spikes are observed along the u axis. This noise is due to the readout and appears as vertical lines, which can be corrected for in the signal field through the flat-field correction process as illustrated in Fig. 7.

Fig. 7. Effect of dark-image subtraction and flat-field correction in signal field. (A) Image prior to dark-image subtraction and flat-field correction that shows the vertical lines. (B) After dark-image subtraction and prior to flat-field correction, where the vertical lines are corrected. (C) After dark-image subtraction and flat-field correction.

Fig. 8.

Electronic NPS along the u and v axes (A) with the structured-noise component included and (B) without the structured (fixed-pattern) noise component. (C) Structured electronic noise along u and v axes.

Fig. 9. Measured 2D fluoroscopic NPS inclusive of the structured-noise component at exposure rates of 1, 2.5, 4, and 10.5 $\mu\text{R}/\text{frame}$.

Fig. 10.
Measured 2D fluoroscopic NPS excluding the structured-noise component at exposure rates of 1, 2.5, 4, and 10.5 $\mu\text{R/frame}$.

Fig. 11.
Measured image lag of the system operating at 30 fps.

Fig. 12.

Lag-corrected fluoroscopic NPS (A) along the u axis and (B) along the v axis. The curves are in the same order as in the legend.

Fig. 13.
Lag-corrected DQE (A) along the u axis and (B) along the v axis.

Fig. 14. Qualitative measures of image quality. Acquired images of (A) a bar-pattern test tool and (B) a wire-mesh phantom to study distortion and uniformity of resolution. The limiting high-contrast spatial resolution perceived from the bar-pattern test tool was 3.19 lp/mm, which compares well with the Nyquist sampling limit of 3.21 cy/mm. While some of the bars at 3.54 lp/mm could be resolved, aliasing effects were observed. Image of the wire-mesh phantom indicates no appreciable geometric distortion.