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Solid-state fluoroscopic imager for high-resolution angiography: Parallel-cascaded linear systems analysis

Srinivasan Vedantham, Andrew Karellas^a, and Sankararaman Suryanarayanan

Department of Radiology, Emory University School of Medicine, 1364 Clifton Road NE, Atlanta, Georgia 30322

Abstract

Cascaded linear systems based modeling techniques have been used in the past to predict important system parameters that have a direct impact on image quality. Such models are also useful in optimizing system parameters to improve image quality. In this work, detailed analysis of a solid-state fluoroscopic imaging system intended for high-resolution angiography is presented with the use of such a model. The imaging system analyzed through this model uses four 8×8 cm three-side buttable interlined charge-coupled devices (CCDs) specifically designed for high-resolution angiography and tiled in a seamless fashion to achieve a field of view (FOV) of 16×16 cm. Larger FOVs can be achieved by tiling more CCDs in a similar manner. The system employs a CsI:Tl scintillator coupled to the CCDs by straight (nontapering) fiberoptics and can potentially be operated in 78, 156, or 234 μm pixel pitch modes. The system parameters analyzed through this model include presampling modulation transfer function, noise power spectrum, and detective quantum efficiency (DQE). The results of the simulations performed indicate that DQE(0) in excess of 0.6 is achievable, with the imager operating at 156 μm pixel pitch, 30 frames/s, and employing a 450- μm -thick CsI:Tl scintillator, even at a low fluoroscopic exposure rate of 1 μR /frame. Further, at a nominal fluoroscopic exposure rate of 2.5 μR /frame there was no noticeable degradation of the DQE even at the 78 μm pixel pitch mode suggesting that it is feasible to perform high-resolution angiography hitherto unattainable in clinical practice.

Keywords

fluoroscopy; angiography; charge-coupled devices; cascaded linear systems analysis; detective quantum efficiency (DQE)

I. INTRODUCTION

A cascaded linear-systems-based model was used to analyze the processes that govern the output image quality of the solid-state high-resolution fluoroscopic system. With the assumptions that the proposed system is linear and shift-invariant, the model was used to describe the output image quality in terms of the objective measure, detective quantum efficiency (DQE). Cascaded linear-systems-based modeling techniques have been used to predict imaging performance of systems developed for x-ray imaging.^{1–5} Such models have

^aAuthor to whom correspondence should be addressed; electronic mail: akarell@emory.edu.

been used to investigate key objective parameters of image quality such as the Wiener spectrum or noise power spectrum (NPS),^{6–8} noise equivalent quanta,^{7,9} and detective quantum efficiency (DQE).^{7,9,10} Over the past several years, many aspects detailing the development of the theory, modeling techniques and its application have been described.^{11–17} Theoretical calculations based on the cascaded model for evaluating charge-coupled device (CCD)-based imagers with slightly varying design and application have been published.^{10,18,19}

The imaging chain is represented as a cascade of amplifying and scattering mechanisms,¹³ with the assumption that the system is linear and shift invariant.^{7,12} While the assumption of linearity can be largely supported, as CCD-based imaging systems exhibit linear signal dependence with incident exposure over most of their dynamic range, the assumption that the system is spatially stationary can be made only in a wide sense as detector nonuniformities exist. For fluoroscopic applications, image lag also limits the validity of such an assumption in the temporal domain.²⁰ Hence, the description of image noise in terms of the spatiotemporal NPS, which incorporates the image lag, has been sought.²⁰ Cunningham *et al.*²⁰ have shown experimentally and theoretically that “the spatial component of the spatiotemporal DQE of a system operating in the fluoroscopic mode is the same as the conventional DQE of the same system operating in the radiographic mode under quantum-noise-limited conditions.” Analysis of the system parameters in the fluoroscopic mode was performed using this finding so that a single fluoroscopic frame is considered as essentially a radiographic acquisition with an exposure level corresponding to that typically used in fluoroscopy.

II. METHODS AND MATERIAL

The system analyzed through the cascaded linear systems-based approach consists of four, three-side buttable, 8×8 cm large-area interlined CCDs specifically designed for high-resolution fluoroscopy, coupled to a structured CsI:Tl scintillator by a straight (nontapering) fiberoptic plate. Each CCD has a 2048×2048 pixel matrix with a fundamental pixel pitch of 39 μm . The CCDs can potentially be operated in three different pixel pitch modes of 78, 156 and 234 μm , resulting in Nyquist sampling limits of 6.4, 3.2, and 2.1 cycles/mm, respectively. The variable pixel pitch is achieved by grouping (binning) 2×2, 4×4, and 6×6 adjacent pixels, respectively. This CCD with a unique architecture using interline channel (hereafter referred to as the interline CCD) was specifically designed for high-resolution fluoroscopic imaging. The interline channel is opaque to light resulting in degradation of the fill factor. The width of the interline channel is 19 μm and traverses the length of the pixel, resulting in an active area of 20×39 μm for each fundamental pixel. This results in a fill factor of ~51%, independent of the pixel pitch mode. Thallium-doped cesium iodide (CsI:Tl) has been selected as the scintillator of choice, as it has the capability to maintain high spatial resolution due to its structured columnar arrangement. CsI:Tl scintillator thickness of 300–525 μm were considered in this analysis. Optical coupling between the CCD and the CsI:Tl scintillator is achieved by using a 1 in. (2.54 cm) thick nontapering (1:1) fiberoptic plate.

The system was considered as a cascade of discrete stages, which can be represented by one of the following processes: quantum gain, stochastic blurring, or deterministic blurring. For any given stage i , the input and output signal are represented as $\overline{q_{i-1}}$ and $\overline{q_i}$ in the spatial coordinates of (x,y) , the average input and output signal are represented as q_{i-1} and q_i , and the input and output signal are represented as $q_{i-1}(u,v)$ and $q_i(u,v)$ in its orthogonal spatial frequency coordinates of (u,v) . Similarly, for any given stage i , the input and output Wiener spectrum (NPS) are represented in the spatial frequency coordinates as $W_{i-1}(u,v)$ and $W_i(u,v)$. For any quantum gain stage i , the average quantum gain of that stage is represented as $\overline{g_i}$ and its gain variance represented as $\sigma_{g_i}^2$. The gain variance can also be expressed in terms of the Poisson excess,¹⁵ ϵ_{g_i} , or in terms of the Swank factor,²¹ A_S . For any blurring stage i , the blur is characterized by its modulation transfer function (MTF) in spatial frequency coordinates and represented as $T_i(u,v)$. The additive noise imparted by any given stage i , is represented in the spatial frequency coordinates as $W_{add_i}(u,v)$. Signal and noise transfer relationships from the input to the output for gain and blurring stages have been provided in the past.^{2,13,15,17}

The system was analyzed by modeling the imaging chain into the following elementary stages:

1. Incident image quanta
2. Attenuation of x rays by the CsI:Tl scintillator
3. Generation and emission of optical quanta by the CsI:Tl scintillator
4. Optical blurring by the CsI:Tl scintillator
5. Coupling of the optical quanta by straight (nontapering) fiber optics
6. Absorption of optical quanta by the CCD
7. Pixel presampling MTF and fill factor
8. NPS aliasing
9. Additive noise

Thus the model provides the presampling signal and the aliased NPS. DQE measurements performed on digital imaging systems are based on the presampling signal (MTF) and the aliased NPS. Hence, the effects of noise aliasing have also been included. This is of particular importance to this imager as the system can be operated in any of the three pixel pitch modes and hence, their impact on the aliased NPS need to be addressed. Analysis of system performance was performed for the three pixel pitch modes of 78, 156, and 234 μm and for 300-, 375-, 450-, and 525- μm -thick CsI:Tl scintillators.

Absorption of K -fluorescent x rays cause a spatial blur and result in spatial correlation between the primary interaction site and the reabsorption site.¹⁶ This results in parallel pathways for signal and noise transfer within the scintillator medium. Cunningham *et al.*¹⁶ used the term “parallel cascade” to describe this process in his model. Cunningham^{16,22} and Yao²³ have provided detailed descriptions of the modeling technique using parallel pathways. Zhao *et al.*²⁴ have studied the effect of characteristic x rays as applied to an

amorphous selenium based imager using parallel pathways. Recently, Ganguly *et al.*¹⁹ have analyzed the performance of a CCD-based microangiographic imager designed for neurovascular imaging using the parallel cascade approach. In this work, the parallel-cascaded linear systems-based model^{16,19,22–24} was applied to the fluoroscopic imager using a clinically representative polyenergetic x-ray spectrum with an aim of predicting system performance and with the assumption that the statistical nature of light follows the Poisson process.

Stage 0: Incident x-ray quanta

The system was analyzed using a polyenergetic 72 kVp x-ray beam filtered by 2.54 cm (1 in.) of Al from a 12° tungsten (W) target, with a first half-value layer (HVL) of 7.2 mm of Al, and is in the range of beam quality used by several investigators.^{25–31} A plot of this spectrum normalized to unit area is shown in Fig. 1. The fluence per μR of exposure ($\bar{q}_0/X$) for this beam was calculated to be 293 x-ray photons/(mm² μR) based on the definition of Roentgen provided by Johns and Cunningham³² and the technique described by Siewerdsen *et al.*²

Stage 1: Attenuation of x rays by the scintillator

This is a stochastic gain stage that follows the binomial process, where the probability that an incident x-ray photon is attenuated by the CsI:Tl scintillator is given by the average quantum efficiency, $\bar{g}_1$. The quantum efficiency, $g_1(E)$, of the CsI:Tl scintillator was computed as

$$g_1(E) = 1 - \exp \left[- \left(\frac{\mu}{\rho}(E) \right)_{\text{CsI:Tl}} \rho_s \right] \quad (1)$$

The energy-dependent mass attenuation coefficient of CsI:Tl represented as $[(\mu/\rho)(E)]_{\text{CsI:Tl}}$ was obtained from the Physical Reference Data of the National Institute of Standards and Technology.³³ The material density of CsI:Tl was assumed to be 4.51 g/cm³. The surface density (coverage), ρ_s , for each CsI:Tl scintillator thickness provided by the manufacturer (Hamamatsu Corp., Bridgewater, NJ), and shown in Table I, was used. The energy-dependent quantum efficiency was weighted by the incident spectrum to provide the average quantum efficiency, $\bar{g}_1$, as shown in the following:

$$\bar{g}_1 = \int g_1(E) q_{\text{rel}}(E) dE, \quad (2)$$

where, $q_{\text{rel}}(E)$ is the incident spectrum normalized to unit area. The calculated $\bar{g}_1$ for the four CsI:Tl thickness is provided in Table I.

Stage 2: Generation and emission of optical quanta by scintillator

Following the work of Cunningham^{16,22} and Yao,²³ paths A, B, and C correspond to local light emission when a *K*-fluorescent x ray is not produced, local light emission when a *K*-fluorescent x ray is produced, and remote (*K*-fluorescent x-ray absorption site) light emission when a *K*-fluorescent x ray is produced as shown in Fig. 2. With the assumption

that the statistical nature of light follows the Poisson process, the NPS at the output of stage 2 along paths A, B, and C can be determined using the transfer relationship¹³ as

$$\begin{aligned} W_2^A &= t_f \bar{q}_0 g_1 (1 - \zeta \omega) \bar{m}_A (\bar{m}_A + 1), \\ W_2^B &= t_f \bar{q}_0 g_1 \zeta \omega \bar{m}_B (\bar{m}_B + 1), \\ W_2^C &= t_f \bar{q}_0 g_1 \zeta \omega f_K \bar{m}_C (\bar{m}_C + 1), \end{aligned} \quad (3)$$

where t_f is the x-ray transmission factor of the cover plate (detector enclosure), ζ is the probability of K -shell photoelectric interaction, ω is the fluorescence yield, f_K is the fraction of K -fluorescent x rays reabsorbed in the scintillator, and $\bar{m}_A$, $\bar{m}_B$, and $\bar{m}_C$ are the mean gains along paths A, B, and C, respectively. If the statistical nature of light is ignored,^{16,22} then the NPS at the output of stage 2 along paths A, B, and C can be determined using the transfer relationship¹³ as

$$\begin{aligned} W_2^A &= t_f \bar{q}_0 g_1 (1 - \zeta \omega) \bar{m}_A^{-2}, \\ W_2^B &= t_f \bar{q}_0 g_1 \zeta \omega \bar{m}_B^{-2}, \\ W_2^C &= t_f \bar{q}_0 g_1 \zeta \omega f_K \bar{m}_C^{-2}. \end{aligned} \quad (4)$$

It is relevant to note that for large values of $\bar{m}_A$, $\bar{m}_B$, and $\bar{m}_C$, the terms $\bar{m}_A(\bar{m}_A + 1)$, $\bar{m}_B(\bar{m}_B + 1)$, and $\bar{m}_C(\bar{m}_C + 1)$ approximate $\bar{m}_A^2$, $\bar{m}_B^2$, and $\bar{m}_C^2$, respectively, which indicate that the statistical nature of light can be ignored. However for completeness, equations for the case that include the statistical nature of light in the theoretical model are presented. The measured t_f of the cover plate (detector enclosure) for the specified spectrum was 0.944 and the values for ζ and ω were obtained as 0.85 and 0.89, respectively, from Cunningham *et al.*²²

In order to determine the mean gains along each of the three paths, the scintillator was considered to be made of fractional layers of thickness t as shown in Fig. 3. Given a layer at a distance z from the output surface of the phosphor (surface of phosphor coupled to the fiberoptic plate), then the incident x rays are attenuated by a factor $e^{-\mu(t-z)}$ before it reaches the fractional layer of interest. Within this layer of thickness t , a fraction corresponding to $(1 - e^{-\mu t})$ is absorbed and converted to optical quanta. The linear attenuation coefficients were determined from the mass attenuation coefficients by taking into account the density of CsI:Tl and packing fraction. Holl *et al.*³⁴ measured 50 000 optical quanta per MeV and more recently as high as 64 000 optical quanta per MeV³⁵ have been reported. We chose to use the average of 58 000 optical quanta per MeV (58 optical quanta per keV) for m_0 . Thus the absorbed fraction within the layer of thickness t generates $(1 - e^{-\mu t}) E m_0$ optical quanta. However, only a fraction of the generated optical quanta from a fractional layer located at a distance z from the output surface escape the scintillator in the direction of the CCD and this fraction is represented as $\eta_{\text{esc}}(z)$. The escape efficiency $\eta_{\text{esc}}(z)$, was determined by fitting the result of Hillen *et al.*³⁶ with a first-order exponential decay function of the form $\eta_{\text{esc}}(z) = y_0 + a_1 e^{-z/t_1}$, with the assumption that the maximum escape efficiency occurs at the output surface of the scintillator. Hence, the mean gain along paths A, B, and C, represented as $\bar{m}_A$, $\bar{m}_B$, and $\bar{m}_C$ were determined as

$$\begin{aligned}\overline{m}_A &= \frac{\int q_0(E) [\int_{z=t}^0 e^{-\mu(t-z)} (1 - e^{-\mu\Delta t}) \eta_{\text{esc}}(z) (1 - \zeta\omega) E m_0 dz] dE}{\int q_0(E) g_1(E) (1 - \zeta\omega) dE}, \\ \overline{m}_B &= \frac{\int q_0(E) [\int_{z=t}^0 e^{-\mu(t-z)} (1 - e^{-\mu\Delta t}) \eta_{\text{esc}}(z) \zeta\omega (E - E_K) m_0 dz] dE}{\int q_0(E) g_1(E) \zeta\omega dE}, \\ \overline{m}_C &= \frac{\int q_0(E) [\int_{z=t}^0 e^{-\mu(t-z)} (1 - e^{-\mu\Delta t}) \eta_{\text{esc}}(z) \zeta\omega f_K E_K m_0 dz] dE}{\int q_0(E) g_1(E) \zeta\omega f_K dE},\end{aligned}\quad (5)$$

where E_K is the K edge of CsI:Tl and approximated as 33 keV. The K -fluorescent x-ray absorption factor, f_K , was determined using the technique of Chan and Doi³⁷ with the assumption that the x-ray beam is normally incident. The average energy of the characteristic x rays was determined by weighting the $K\alpha_1$, $K\alpha_2$, and $K\beta_1$ emission lines of cesium and iodine with their relative intensities.³⁸ The photoelectric and total mass attenuation coefficients corresponding to the average energy (30 keV) were obtained from NIST database.³⁹ The calculated f_K for the four CsI:Tl thicknesses are shown in Table I. The frequency-dependent signal along path C can be determined as

$$q_2^C(u, v) = t_f \overline{q_0 g_1} \zeta\omega f_K \overline{m}_C T_K(u, v), \quad (6)$$

where $T_K(u, v)$ is the characteristic transfer function (stochastic blur of K -fluorescent x rays). $T_K(u, v)$ was determined using the technique of Metz and Vyborny.⁴⁰ The point spread function of K -fluorescent x-ray absorption (characteristic spread function) was determined using Monte Carlo simulation⁴¹ and with absorption and scattering coefficients of CsI:Tl determined at 30 keV.

Since paths B and C are correlated and all quanta are real, the cross-spectral density can be written as^{16,23,24}

$$W_2^{BC} + W_2^{CB} = 2t_f \overline{q_0 g_1} \zeta\omega f_K \overline{m}_B \overline{m}_C T_K(u, v). \quad (7)$$

The summed mean signal at the output of stage 2 is given by

$$\overline{q_2} = t_f \overline{q_0 g_1 g_2}, \quad (8)$$

where the mean gain of stage 2, $\overline{g_2} = (1 - \zeta\omega) \overline{m}_A + \zeta\omega \overline{m}_B + \zeta\omega f_K \overline{m}_C$ and is identical to m^- stated in Ref. 20. The NPS at the output of stage 2 can be written as

$$\begin{aligned}W_2(u, v) &= t_f \overline{q_0 g_1} [(1 - \zeta\omega) \overline{m}_A^2 + \zeta\omega \overline{m}_B^2 + \zeta\omega f_K \overline{m}_C^2 \\ &\quad + \overline{g_2} + 2\zeta\omega f_K \overline{m}_B \overline{m}_C T_K(u, v)].\end{aligned}\quad (9)$$

Stage 3: Optical blurring by the scintillator

The stochastic blur due to the random displacement of optical quanta, represented as $T_3(u, v)$, was approximated from measurement of the scintillator MTF (obtained by deconvolving the pixel presampling MTF from the measured presampling MTF) at energy levels below the K

edge of CsI:Tl. Specifically, the measurement was performed with a mammographic x-ray source at 32 kVp using a rhodium (Rh) target and rhodium (Rh) filtration. Alternatively, $T_3(u,v)$ can be obtained by Monte Carlo modeling⁴² or by weighting of the measured presampling MTF as performed by Cunningham *et al.*²² Based on the transfer relationship, 13 the NPS at the output of stage 3 can be written as

$$W_3(u, v) = t_f \overline{q_0 g_1} [((1 - \zeta \omega) \overline{m_A}^2 + \zeta \omega \overline{m_B}^2 + \zeta \omega f_K \overline{m_C}^2 + 2\zeta \omega f_K \overline{m_B} \overline{m_C} T_K(u, v)) T_3^2(u, v) + \overline{g_2}]. \quad (10)$$

Stage 4: Coupling of optical quanta by fiberoptics

This is a stochastic gain stage that follows the binomial process, where the probability that an incident quantum is coupled to the CCD is given by the average fiberoptic coupling efficiency, $\overline{g_4}$. The fiberoptic transmission efficiency, calculated using the technique of Hejazi and Trauernicht,¹⁸ was determined to be 0.495. Based on the transfer relationship,¹³ the NPS at the output of stage 4 can be written as

$$W_4(u, v) = t_f \overline{q_0 g_1 g_4} [\overline{g_4} A(u, v) T_3^2(u, v) + \overline{g_2}], \quad (11)$$

where $A(u, v) = (1 - \zeta \omega) \overline{m_A}^2 + \zeta \omega \overline{m_B}^2 + \zeta \omega f_K \overline{m_C}^2 + 2\zeta \omega f_K \overline{m_B} \overline{m_C} T_K(u, v)$.

Stage 5: Absorption of optical quanta by the CCD

This is a stochastic gain stage that follows the binomial process, where the probability that the CCD absorbs an incident quantum is given by the average CCD quantum efficiency ($\overline{g_5}$). Quantum efficiency of 0.53 provided by the manufacturer of the CCD (Fairchild Imaging, Inc., Milpitas, CA) was used in the calculations. Based on the transfer relationship, 13 the NPS at the output of stage 5 can be written as

$$W_5(u, v) = t_f \overline{q_0 g_1 g_4 g_5} [\overline{g_4 g_5} A(u, v) T_3^2(u, v) + \overline{g_2}]. \quad (12)$$

Stage 6: Pixel presampling MTF and fill factor

The pixel presampling MTF represented as $T_6(u,v)$ was approximated with a sinc function, and can be stated as⁷

$$T_6(u, v) = |\text{sinc}(\pi a_x u) \text{sinc}(\pi a_y v)|, \quad (13)$$

where a_x and a_y represent the dimensions of the pixel that is sensitive to light (active dimension) in the x and y directions, respectively. The fill factor, F_f , of 0.513 was used. Based on the transfer relationship,² the mean signal at the output of stage 6 can be written as

$$\overline{q_6} = t_f \overline{q_0 g_1 g_2 g_4 g_5} a_{\text{pitch}}^2 F_f. \quad (14)$$

The frequency-dependent signal at the output of stage 6 can be written as

$$q_6(u, v) = t_f \overline{q_0 g_1 g_4 g_5} a_{\text{pitch}}^2 F_f T_3(u, v) g_2(u, v) T_6(u, v), \quad (15)$$

where $g_2(u, v) = (1 - \zeta\omega)\overline{m_A} + \zeta\omega\overline{m_B} + \zeta\omega f_K T_K(u, v)\overline{m_C}$.

Based on the transfer relationship,² the NPS at the output of stage 6 for the case where the statistical nature of light is considered can be written as

$$W_6(u, v) = t_f \overline{q_0 g_1 g_4 g_5} a_{\text{pitch}}^4 F_f^2 T_6^2(u, v) \times [\overline{g_4 g_5} A(u, v) T_3^2(u, v) + \overline{g_2}]. \quad (16)$$

If the statistical nature of light is ignored,^{16,22} then the NPS along the u axis at the output of stage 6 can be shown as

$$W_6(u, 0) = W_6(u) = t_f \overline{q_0 g_1 g_4 g_5} a_{\text{pitch}}^2 F_f T_6^2(u) [\overline{g_4 g_5} T_3^2(u) \times (A(u) - \overline{g_2}) + \overline{g_2}], \quad (17)$$

where $A(u) = (1 - \zeta\omega)\overline{m_A}^2 + \zeta\omega\overline{m_B}^2 + \zeta\omega f_K \overline{m_C}^2 + 2\zeta\omega f_K \times \overline{m_B m_C} T_K(u)$. Equation (17) is identical to Eq. (24) of Ref. 22 for the case t_f is unity, $\overline{g_1} = \eta$, $\overline{g_4 g_5}$ is unity,

$\overline{g_2} = \overline{m}$, $a_{\text{pitch}}^2 F_f = a^2$ and $T_6^2(u)$ is expressed as $\text{sinc}^2(\pi au)$.

Stage 7: NPS Aliasing

The signal and NPS represented in the above equations are the presampling signal and the presampling NPS. However, DQE measurements reported in the literature^{5,43–48} for digital imaging (sampled) systems are based either on the presampling MTF or on the expectation MTF computed from the presampling MTF, and the aliased NPS. The aliased NPS represented as $W_7(u, v)$ is expressed as^{49,50}

$$W_7(u, v) = W_6(u, v) * III(u, v), \quad (18)$$

where $III(u, v)$ is the Fourier transform of a rectangular array of δ functions representing the pixel matrix.^{49,50}

Stage 8: Additive noise

The total additive electronic noise (σ_T) associated with a CCD-based system was calculated using the technique of Hejazi and Trauernicht¹⁸ by considering a typical dark current of 15 pA/cm², measured read noise of 20 electrons rms, measured quantization step-size of 2.2 electrons/digital unit (DU) and with the imager operating at 30 fps. Additive noise levels (σ_T) thus determined for the three pixel pitch modes and included in Table I were used in the simulation. For the case where the electronic noise is “white” (independent of spatial frequency), the amplitude of the “white” noise power, W_{add8} can be estimated as⁴⁹

$$W_{\text{add8}} = \frac{\sigma_T^2}{4U_{\text{Nyq}} V_{\text{Nyq}}}, \quad (19)$$

where σ_T is the estimated electronic noise, U_{Nyq} and V_{Nyq} are the Nyquist sampling limits along the two orthogonal directions. Hence, the NPS at the output of stage 8 can be stated as

$$W_8(u, v) = W_7(u, v) + W_{\text{add8}}. \quad (20)$$

The detective quantum efficiency, which is defined as the ratio of the square of the output signal-to-noise ratio to the square of the input signal-to-noise ratio can be calculated from the above-given equations as

$$\text{DQE}(u, v) = \frac{[q_6(u, v)]^2}{X \left(\frac{q_0}{X} \right) W_8(u, v)}, \quad (21)$$

where (q_0/X) is the photon fluence per μR of incident exposure and X is the incident exposure in μR . The presampling MTF represented as MTF_{pre} along the two orthogonal axes were determined as

$$\begin{aligned} \text{MTF}_{\text{pre}}(u) &= \frac{q_6(u, 0)}{q_6(0, 0)}, \\ \text{MTF}_{\text{pre}}(v) &= \frac{q_6(0, v)}{q_6(0, 0)}, \end{aligned} \quad (22)$$

The sensitivity (Γ) of the imaging system was calculated as $\Gamma = \overline{q_6}/X$.

For fluoroscopic applications, in addition to the spatial characteristics, the temporal characteristics of the imager also need to be addressed. Of particular importance is image lag, which is a result of a fraction of the generated signal from a particular frame being released into subsequent frames. Primary sources that contribute to image lag in pulsed fluoroscopic systems include the decay characteristics of the scintillator, decay characteristics of the x-ray source primarily due to the capacitance of the high-tension cables, and charge traps within the CCD. Measurements of the CsI:Tl scintillator decay characteristics at room temperature by Valentine *et al.*⁵¹ have found two primary decay time constants of 679 ± 10 ns and 3.34 ± 0.14 μs , which contribute to 63.7% and 36.1% of the emission. The system is designed to include a delay of 2 ms after the termination of the x-ray pulse, which is sufficient to allow for almost complete integration of the emitted optical quanta within a particular frame. Also, scientific-grade CCDs are routinely used for fast-framing applications. Hence, image lag is not expected to be significant with this system. The companion paper⁴⁸ confirms this theoretical expectation, where first-frame image lag of 0.9% was measured with the system operating at 30 fps.

The model was implemented using IDL (Version 5.5, Research Systems, Inc., Boulder, CO) and all simulations were performed with the imager operating at 30 fps. The effect of CsI:Tl thickness on the presampling MTF [$\text{MTF}_{\text{pre}}(u)$], NPS after aliasing [$W_8(u, 0)$], and

frequency-dependent DQE[DQE(u)], were studied for all the three pixel pitch modes at a nominal fluoroscopic exposure rate of 2.5 $\mu\text{R}/\text{frame}$. The effect of pixel size on the DQE(u) of the system employing a 450 μm CsI:Tl scintillator was performed at an exposure rate of 2.5 $\mu\text{R}/\text{frame}$. The effect of incident exposure on the frequency-dependent DQE was studied for all pixel pitch modes and for various thickness of the CsI:Tl scintillator by varying the incident exposure rate from 1 to 10.5 $\mu\text{R}/\text{frame}$.

All computations of the frequency-dependent DQE addressed so far are along the u axis in the spatial frequency domain, which corresponds to the active dimension that is unaffected by the fill factor in the spatial domain. However, along the v axis there is degradation of the active dimension due to interline channel. Hence, it is pertinent to compare the presampling MTF, aliased NPS and DQE performance along the two orthogonal axes. Simulations of the presampling MTF, aliased NPS and DQE along the u and v axes, were performed with the imager using a 450 μm CsI:Tl and operating at 30 fps, 156 μm pixel-pitch mode and an exposure rate of 2.5 $\mu\text{R}/\text{frame}$.

III. RESULTS AND DISCUSSION

Table I provides a summary of the parameters used or estimated from the model. Since the values of $\overline{m}_A$, $\overline{m}_B$, and $\overline{m}_C$, were large, the terms $\overline{m}_A(\overline{m}_A+1)$, $\overline{m}_B(\overline{m}_B+1)$, and $\overline{m}_C(\overline{m}_C+1)$ may be approximated to $\overline{m}_A^{-2}$, $\overline{m}_B^{-2}$, and $\overline{m}_C^{-2}$, respectively, which indicate that the statistical nature of light generation can be ignored with this imager. However, for completeness all calculations were performed without the approximation. The experimentally measured sensitivity of a prototype imager addressed in the companion paper was 360 DU/ μR for 156 μm pixel pitch mode and when scaled by quantization step size of 2.2 electrons/DU, yields 792 electrons/ μR , which is in good agreement with the theoretical estimate of 810 electrons/ μR for 156 μm pixel pitch mode.

Figure 4 shows the presampling MTF along the u axis computed for each thickness of the CsI:Tl scintillator considered with the imager operating at the 78, 156, and 234 μm pixel pitch modes. The plots indicate that limiting MTF (10% of presampling MTF) in excess of 5 cycles/mm can be achieved in the high-resolution 78 μm pixel pitch mode with the imager employing a 450 μm CsI:Tl scintillator. For the 156 and 234 μm pixel pitch modes, presampling MTF of 0.21 and 0.36 were predicted at Nyquist sampling limits of 3.21 and 2.14 cycles/mm for the system employing a 450 μm CsI:Tl scintillator. Such high-spatial resolution may be beneficial in many fluoroscopic procedures such as cardiovascular imaging and interventional neuroangiography.

Figure 5 shows the aliased NPS along the u axis computed for each thickness of the CsI:Tl scintillator considered with the imager operating at the 78, 156, and 234 μm pixel pitch modes and at a nominal fluoroscopic exposure rate of 2.5 $\mu\text{R}/\text{frame}$. The faster roll-off of the NPS with increasing thickness of CsI:Tl scintillator is due to the combination of increased optical blur [degraded $T_0(u,v)$] and increased K -fluorescent x-ray absorption fraction (f_K) with increasing CsI:Tl thickness.

Figure 6 shows the DQE along the u axis computed for each thickness of the CsI:Tl scintillator considered with the imager operating at the 78, 156, and 234 μm pixel pitch modes and at a nominal fluoroscopic exposure rate of 2.5 $\mu\text{R}/\text{frame}$. The plots indicate that DQE(0) in excess of 0.6 can be achieved with a 450 μm CsI:Tl scintillator even at a high-resolution pixel pitch mode of 78 μm . In the 78 μm pixel pitch mode, while increasing the CsI:Tl scintillator thickness improved the DQE(0), at higher spatial frequencies there was degradation of the DQE, with the transition occurring at ~ 2.7 cycles/mm. With increasing CsI:Tl thickness, the faster roll-off of the square of the presampling MTF relative to the aliased NPS resulted in this transition. Such a trend has been observed with an α -Si based imager.²⁵ However for the 156 and 234 μm pixel pitch modes, increasing the CsI:Tl scintillator thickness resulted in improved DQE up to their corresponding Nyquist sampling limit. Extrapolation of the DQE plots for the 156 and 234 μm pixel pitch modes beyond their corresponding Nyquist sampling limits indicate that such a transition would have occurred, however the DQE is not defined beyond the Nyquist sampling limit.

Figure 7 shows the DQE along the u axis computed for the system using a 450 μm CsI:Tl scintillator and at an exposure rate of 2.5 $\mu\text{R}/\text{frame}$ for the three pixel pitch modes. This plot indicates that there is a minimal degradation of the DQE(0) with the 78 μm pixel pitch mode compared to that with the 156 μm pixel pitch mode due to relatively larger contribution from the electronic noise to the total NPS with the 78 μm pixel pitch mode. It is also seen that at 156 and 234 μm pixel pitch modes, faster roll-off of the DQE occurs due to the combined effects of reduced presampling MTF and increased noise aliasing. Figure 8 shows the exposure dependence of DQE(u) for each thickness of CsI:Tl scintillator and with the imager operating at the high-resolution 78 μm pixel pitch mode. The plots indicate that for exposure rates of 2.5 $\mu\text{R}/\text{frame}$ and above, there is minimal degradation of the DQE at low spatial frequencies. Further the plots indicate that DQE(0) of ~ 0.7 is achievable with a 525 μm CsI:Tl scintillator at exposure rates of 2.5 $\mu\text{R}/\text{frame}$ and above.

Figure 9 shows the exposure dependence of DQE(u) for each thickness of CsI:Tl scintillator and with the imager operating at the 156 μm pixel pitch mode. The plots indicate that the DQE performance had minimal dependence with exposure rate within the range considered and DQE(0) of ~ 0.64 is achievable with a 450 μm CsI:Tl scintillator even at a low fluoroscopic exposure rate of 1 $\mu\text{R}/\text{frame}$. To facilitate direct comparison with the experimentally determined DQE addressed in a companion paper,⁴⁸ DQE(u) of the system using the 450- μm -thick CsI:Tl and operating in the 156 μm pixel pitch mode at exposure rates of 1 and 10.5 $\mu\text{R}/\text{frame}$ are also presented. Experimental data are provided only for this configuration, as this version of the prototype imager operates at a fixed 4×4 pixel binning resulting in a 156 μm pixel pitch and uses a 450- μm -thick CsI:Tl. The model shows excellent agreement with experimentally determined DQE. It is important to note that the several of the parameters used in the model related to the scintillator are either approximated or averaged, such as the K edge of CsI:Tl, fluorescence yield of CsI:Tl, characteristic emission energy of CsI:Tl, optical blur of CsI:Tl, and the mean number of optical quanta generated per absorbed 1 keV photon. More accurate information and appropriate treatment of these parameters may yield better accuracy in the theoretical estimates of performance. Further, the model does not include Lubberts effect,⁵² thus limiting its applicability to large

CsI:Tl thickness. Simulations of the exposure dependency for each thickness of CsI:Tl scintillator considered with the system operating at the 234 μm pixel pitch mode, yielded similar trends to that observed with the system operating at the 156 μm pixel pitch mode, and hence are not reported.

All computations addressed so far are along the u axis, which corresponds to the active dimension that is unaffected by the fill factor in the spatial domain. However, along the v axis there is degradation of the active dimension due to interline channel. Figure 10 shows the comparison of the pre-sampling MTF, aliased NPS, and DQE along the u and v axes performed with the imager using a 450 μm CsI:Tl and operating at 156 μm pixel-pitch mode and an exposure rate of 2.5 $\mu\text{R}/\text{frame}$. While noticeable differences between the u and v axes are observed in the presampling MTF and the aliased NPS, the DQE performance remains relatively unchanged. To facilitate direct comparison with the experimentally determined DQE addressed in a companion paper,⁴⁸ DQE of the system using the 450- μm -thick CsI:Tl and operating in the 156 μm pixel pitch mode at exposure rates of 2.5 $\mu\text{R}/\text{frame}$ along the u and v axes are also presented.

IV. CONCLUSIONS

The physical characteristics of a solid-state fluoroscopic imaging system developed for high-resolution angiography were analyzed with a parallel-cascaded linear systems-based model^{16,19,22–24} that takes into account the polyenergetic nature of the incident x-ray beam and the stochastic nature of the generated optical quanta. Good agreement between the model and the experimental results indicate that this modeling technique can serve as a valuable tool for predicting and optimizing system performance. For the fluoroscopic exposure rates considered and with the imager operating at 156 μm pixel pitch mode, minimal or no dependence with exposure rate was observed suggesting quantum noise-limited mode of operation. Results indicate that it is feasible to obtain DQE(0) in excess of 0.6, while attaining limiting spatial resolution (10% presampling MTF) in excess of 5 cycles/mm, even at a nominal fluoroscopic exposure rate of 2.5 $\mu\text{R}/\text{frame}$.

Results from the DQE calculations and the high spatial resolution capabilities combined with its unique feature for a CCD-based imager to provide multiple resolution modes suited to the imaging requirement suggest that this type of technology or its variants can be a good candidate for high-resolution neuro-interventional imaging including region-of-interest fluoroscopy,^{19,53–55} cardiac and pediatric angiography.

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Fig. 1.
Plot of the 72 kVp x-ray spectrum (7.2 mm of Al HVL) incident on the imager and used in the model. The spectrum is normalized to unit area.

Fig. 2. Illustration of the parallel pathways (Refs. 16, 22, and 23) in optical quanta generation and blurring within the CsI:Tl scintillator.

Fig. 3. Schematic of the model used for determining optical quanta generation and emission from the CsI:Tl scintillator.

Fig. 4.

Presampling MTF along the u axis computed for each thickness of the CsI:Tl scintillator considered with the imager operating at the (a) 78, (b) 156, and (c) 234 μm pixel pitch modes. Also, the sinc of pixel pitch for the 78, 156, and 234 μm pixel pitch modes has been included.

Fig. 5. Aliased NPS along the u axis computed for each thickness of the CsI:Tl scintillator considered at an exposure rate of $2.5 \mu\text{R}/\text{frame}$ with the imager operating at the (a) 78, (b) 156, and (c) 234 μm pixel pitch modes.

Fig. 6. Spatial frequency-dependent DQE along the u axis computed for each thickness of the CsI:Tl scintillator considered at an exposure rate of $2.5 \mu\text{R}/\text{frame}$ with the imager operating at the (a) 78, (b) 156, and (c) 234 μm pixel pitch modes.

Fig. 7.

The effect of pixel pitch on the DQE performance is illustrated by the plot of $DQE(u)$ computed for the system using a $450\ \mu\text{m}$ CsI:Tl scintillator and at an exposure rate of $2.5\text{-}\mu\text{R/frame}$ for the three pixel pitch modes.

Fig. 8.

Exposure dependence of $DQE(u)$ with the imager operating at the high-resolution $78\ \mu\text{m}$ pixel pitch mode for (a) $300\ \mu\text{m}$ CsI:Tl, (b) $375\ \mu\text{m}$ CsI:Tl, (c) $450\ \mu\text{m}$ CsI:Tl, (d) $525\ \mu\text{m}$ CsI:Tl scintillator. The exposure levels indicated in the legend are exposure per frame with the imager operating at 30 fps. The plots are in the same order as in the legend.

Fig. 9.

Exposure dependence of $DQE(u)$ with the imager operating at the 156 μm pixel pitch mode for (a) 300 μm CsI:Tl, (b) 375 μm CsI:Tl, (c) 450 μm CsI:Tl, (d) 525 μm CsI:Tl scintillator. The exposure levels indicated in the legend are exposure per frame with the imager operating at 30 fps. The plots are in the same order as in the legend. To facilitate direct comparison with experimental results (Ref. 48), $DQE(u)$ at 1 (boxes) and 10.5 μR / frame (triangles) are presented in (c).

Fig. 10.

Comparison of the (a) presampling MTF, (b) aliased NPS, and (c) DQE along the u and v axes performed with the imager using a $450\ \mu\text{m}$ CsI:Tl and operating at $156\ \mu\text{m}$ pixel-pitch mode and an exposure rate of $2.5\ \mu\text{R}/\text{frame}$. The exposure levels indicated in the legend are exposure per frame with the imager operating at 30 fps. To facilitate direct comparison with experimental results (Ref. 48), MTF, NPS, and DQE along u and v axes are also presented.

Table I

Summary of parameters used in the model or estimated from the study.

Parameter	Notation	Pixel pitch (μm)	Scintillator thickness (μm)				
			300	375	450	525	
Fluence [photons/($\text{mm}^2 \mu\text{R}$)]	q_0/X		293.1				
CsI:TI coverage [mg/cm^2]	ρ_s		103	126	148	175	
Quantum efficiency	$\overline{g_1}$		0.663	0.730	0.779	0.827	
Detector enclosure (cover) transmission factor	t_f		0.944				
Probability of K -shell interaction ^a	ς		0.85				
Fluorescence yield ^a	ω		0.89				
K -absorption probability	f_K		0.583	0.630	0.666	0.701	
Mean gain path A	$\overline{m_A}$		1608.3	1475.8	1358	1250.1	
Mean gain path B	$\overline{m_B}$		592.2	549.3	510	473.8	
Mean gain path C	$\overline{m_C}$		1023.5	933.5	854.5	782.5	
Mean quantum gain	$\overline{g_2}$		1290.8	1219.6	1146.9	1077.8	
Fiber optic coupling efficiency	$\overline{g_4}$		0.495				
CCD quantum efficiency	$\overline{g_5}$		0.53				
Fill factor	F_f	78	0.513				
Additive noise [e^- rms]	σ_T	156	24.3				
		234	34.1				
			45.9				
Sensitivity [$e^-/\mu\text{R}$]	Γ	78	193.1	201.5	202.4	201.8	
		156	775.7	806.1	809.7	807.3	
		234	1745.2	1813.8	1821.8	1816.5	

^aReference 22.