A small-signal approach to temporal modulation transfer functions with exposure-rate dependence and its application to fluoroscopic detective quantum efficiency

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The detective quantum efficiency (DQE) is a metric widely used in radiography to quantify system performance and as a surrogate measure of patient “dose efficiency.” It has been applied previously to fluoroscopic systems with the introduction of a temporal correction factor. Calculation of this correction factor relies on measurements of the temporal modulation transfer function (MTF). However, the temporal MTF is often exposure-rate dependent, violating a necessary Fourier linearity requirement. The authors show that a Fourier analysis is appropriate for fluoroscopic systems if a “small-signal” approach is used. Using a semitransparent edge, a lag-corrected DQE is described and measured for an x-ray image intensifier-based fluoroscopic system under continuous (non-pulsed) exposure conditions. It was found that results were equivalent for both rising and falling-edge profiles independent of edge attenuation when effective attenuation was in the range of 0.1–0.6. This suggests that this range is appropriate for measuring the small-signal temporal MTF. In general, lag was greatest at low exposure rates. It was also found that results obtained using a falling-edge profile with a radiopaque edge were equivalent to the small-signal results for the test system. If this result is found to be true generally, it removes the need for the small-signal approach. Lag-corrected DQE values were validated by comparison with radiographic DQE values obtained using very long exposures under the same conditions. Lag was observed to inflate DQE measurements by up to 50% when ignored. © 2009 American Association of Physicists in Medicine.

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I. INTRODUCTION

Fluoroscopy is used to visualize internal patient anatomical movement using x rays to produce a time series of images. Typical exposure rates are 20–50 mGy/min (potentially more for larger patients) and interventional procedures lasting 60–90 min are not uncommon, resulting in potentially large patient doses. The risks from ionizing radiation must always be weighed against the benefit of the fluoroscopic procedure, and it is imperative that the benefit-to-risk ratio for a given patient dose be maximized for a given system. The detective quantum efficiency (DQE) is a surrogate metric of “dose efficiency” widely used in radiography. Systems with small DQE values require larger doses to patients than systems with large DQE values for the same image quality. The DQE was derived from image quality concepts as described through the noise-equivalent quanta (NEQ) and can be expressed for linear and shift-invariant systems as

$$DQE(u,v) = \frac{\overline{d^2} MTF^2(u,v)}{\overline{q NPS}(u,v)},$$

where \(u\) and \(v\) are spatial-frequency variables in the \(x\) and \(y\) directions, \(MTF\) is the modulation transfer function describing spatial resolution, and \(NPS\) is the Wiener noise power spectrum calculated from open-field and dark-subtracted images corresponding to \(\overline{q}\) incident quanta per mm\(^2\) and average pixel value \(\overline{d}\). To provide a meaningful description of dose efficiency, the DQE must be measured under clinically relevant conditions, including beam half-value layer (HVL), kVp, and typical exposures and exposure rates incident on the detector.

Fluoroscopic systems add an additional complication due to the temporal averaging of image noise caused by phosphor lag and possibly the temporal properties of other system components. Phosphor lag causes a reduction in image noise as described by Swank in 1974 for both a \(\text{Gd}_2\text{O}_2\text{S/P-20}\) and...
a CsI/P-20 x-ray image intensifier (XRII). In 1984, Rowlands' used a temporal MTF to describe temporal resolution and noise reduction in video-camera-based XRII systems. The Fourier-based linear-system approach was also used by Wilson and co-workers' to describe human performance in noise-limited spatio-temporal detection tasks.

More recently, the effect of lag has been incorporated into descriptions of DQE for fluoroscopic systems. Granfors et al. used a time-domain-based method to compensate for the effect of temporal averaging on the NPS. Their approach assumes that lag acts as a deterministic linear filter independent of exposure rate and other exposure conditions, similar to Swank. Cunningham, Siewerdsen, and co-workers made the same assumption using a temporal-frequency-based approach. These methods are consistent with each other and use a correction factor to describe the NPS that would be achieved if lag were not present. In the Fourier-based approach, the correction factor is given by

\[ \beta = a_i \int_{-\infty}^{\infty} \text{MTF}_t^2(v) dv = \frac{a_i}{a_L} \]

and where MTF is the temporal MTF given as a function of temporal frequency \( v \), \( a_L \) is the effective system temporal aperture defined as 1 over the integral of MTF\(_t^2\), similar to the bandwidth integral introduced by Wagner and Brown, and \( a_i \) is the frame-integration time of each image, giving 0 \( \leq \beta \leq 1 \).

The assumption of deterministic lag implies that the temporal NPS scales with the squared temporal MTF according to the Wiener-Khinchin theorem. This enables a method of determining \( \beta \) in Eq. (2) without an independent measurement of MTF\(_t(v)\) by normalizing the temporal NPS (Refs. 17 and 19) and has been incorporated into an International Electrochemical Commission (IEC) standard for measurement of the fluoroscopic DQE. However, this assumption may present a problem for some systems. While lag may result from a number of different causes (e.g., phosphor decay or charge trapping), it always involves the delayed production and/or detection of image quanta. The random nature of these physical processes means that the temporal response curve is the probability distribution function describing how image quanta may be delayed. We are familiar with this distinction in the spatial domain, where the loss of resolution due to quantum scatter has a different effect on image noise than what would be predicted by a deterministic (linear filter) blur. In fact, quantum scatter is responsible for much of the decrease in the DQE with increasing spatial frequency.

The implications of nondeterministic lag were explored theoretically by Akbarpour et al. They showed that lag affects the correlated component of noise but not the uncorrelated component. As a consequence, the temporal NPS will not scale with the squared temporal MTF, and the assumption of deterministic lag may not be well satisfied when the NPS is affected by additive noise, noise aliasing, or a secondary quantum sink as would result from inadequate conversion gain and collection of secondary quanta (such as light in a phosphor).

The assumption of lag being independent of exposure conditions also presents a problem for some systems. Siewerdsen and Jaffray showed that lag between fluoroscopic image frames varied by a factor of 5 (from 2% to 10%) depending on exposure rate using a Gd_2O_2S-based flat-panel detector likely due to changes in charge trapping and other imperfect readout mechanisms in the amorphous-silicon circuitry. Our own work with a CsI-based XRII system also showed a strong exposure-rate dependence.

We believe that a meaningful assessment of performance and dose efficiency of fluoroscopic systems, particularly those that exhibit suboptimal image quality, will require the use of a spatio-temporal DQE in three dimensions (two spatial frequency and one temporal frequency). This will require direct measurements of the MTF in each dimension as well as a separate measurement of the spatio-temporal NPS. In general, Fourier methods require wide-sense stationary (WSS) noise processes, corresponding to low-contrast image structure (i.e., small changes in image exposure). For systems that show an exposure-rate dependence of lag, we propose the use of a small-signal approach to the temporal MTF measurement analogous to that used to describe the DQE of (nonlinear) film-screen radiographic systems.

This article describes the first step toward the goal of a spatio-temporal DQE by reporting on a method of measuring the small-signal temporal MTF based on the moving slanted-edge method described previously. In that work, an XRII-based bench-top system exhibited exposure-rate-dependent lag, including differences in rising and falling-edge response profiles. We show that a Fourier analysis is valid in this situation and develop a method to measure the small-signal temporal MTF under steady-state constant exposure-rate conditions based on a semitransparent moving slanted-edge method. We describe the detective quantum efficiency of fluoroscopic systems that exhibit an exposure-rate-dependent temporal MTF and measure it under fluoroscopic conditions. The lag-corrected DQE is compared with a (simulated) radiographic DQE obtained under the same exposure-rate conditions, providing the first experimental validation of the lag-corrected DQE method.

II. THEORY

Our description of the fluoroscopic DQE using the small-signal approach involves three steps: (A) Introduction of a small-signal temporal MTF, (B) correction of the (spatial) NPS to account for the effect of lag, and (C) calculation of the lag-corrected DQE.

II.A. Small-signal temporal MTF

II.A.1. Definition

The small-signal spatio-temporal MTF is exposure-rate dependent, given by

\[ \text{MTF}(u, v, \nu|q_o) \]
where \( \bar{q}_o \) is the average incident distribution of quanta (mm\(^{-2}\) s\(^{-1}\)), \( T_{\Delta}(u,v,\bar{q}_o) \) and \( p_{\Delta}(x,y,t|\bar{q}_o) \) are the normalized system spatio-temporal small-signal transfer function and point spread function (PSF), respectively, and \( \mathcal{F} \) is the Fourier transform. All components of the PSF are defined to have unity area, describing both spatial blurring and temporal lag effects, including scattering and lag exhibited in output phosphors, detector-element size, and frame-integration windows.

It will be assumed in Sec. II A 2 that spatial and temporal system characteristics are independent, implying that the spatio-temporal small-signal MTF is separable in space and time. In addition, only temporal characteristics depend on \( \bar{q}_o \), so that the spatio-temporal MTF can be expressed as

\[
\text{MTF}_2(u,v,\nu|\bar{q}_o) = \text{MTF}(u,v)\text{MTF}_v(\nu|\bar{q}_o),
\]

where \( \text{MTF}(u,v) \) is the (conventional) spatial MTF, and \( \text{MTF}_v(\nu|\bar{q}_o) \) is the small-signal temporal MTF. This expression reduces to the (spatial) MTF when \( \nu=0 \).

### II.A.2. Semitransparent moving slanted-edge method

Based on the moving slanted-edge method\(^{26,28} \) and the conventional (stationary) slanted-edge method,\(^{29,30} \) we now derive the “semitransparent moving slanted-edge method” to measure the small-signal temporal MTF.\(^{31} \)

The output of a fluoroscopic system is a time sequence of two-dimensional (2D) images, determined from detector-element signals \( d_i \) that are interpreted as samples in \( x, y \), and \( t \) of a presampling output function \( d(x,y,t) \). This presampling function describes expected detector-element values for an element centered at position \((x,y)\) with integration time ending at \( t \). Values \( d_i \) are samples of \( d(x,y,t) \) at actual detector-element positions and readout times. The average presampling signal corresponding to a uniform open-field distribution of incident quanta \( \bar{q}_o \) is given by

\[
d_{av}(x,y,t) = \bar{q}_o = k\bar{q}_o,
\]

where \( k \) is a constant of proportionality.

The semitransparent edge is formed using a thin sheet of material (Cu is used here) moving with constant velocity \( v \). As illustrated in Fig. 1(a), x rays incident on the edge material may result in forward scatter that is incident on the detector in addition to the transmitted primary beam. We therefore express the average incident quanta distribution \( \bar{q}_E(x,y,t) \) as a sum of primary and scatter components, \( \bar{q}_p(x,y,t) \) and \( \bar{q}_S(x,y,t) \) respectively, giving

\[
\bar{q}_E(x,y,t) = \bar{q}_p(x,y,t) + \bar{q}_S(x,y,t).
\]

The transmitted primary beam is expressed using a spatio-temporal Heaviside function (where 1 represents full transmission of the primary beam) as

\[
\bar{q}_p(x,y,t) = \bar{q}_p(1 - A_P) + \bar{q}_p A_P H_\delta(x,y,t),
\]

where \( A_P \) represents attenuation of the primary beam and

\[
H_\delta(x,y,t) = \begin{cases} 
1, & x - y \tan \theta - vt > 0 \\
0, & \text{otherwise}.
\end{cases}
\]

The scatter component is described similar to Neitzel et al.\(^{32} \) in terms of the scatter PSF \( p_S(x,y) \) and the ratio of the average distribution of scatter quanta generated in the edge material and incident on the detector to quanta incident on the material, \( S = \bar{q}_S/\bar{q}_o \), giving

\[
\bar{q}_S(x,y,t) = \bar{q}_o S [1 - H_\delta(x,y,t)] *_{x,y} p_S(x,y) \delta(t),
\]

where * indicates convolution over the dimensions indicated by the subscript, and \( \delta \) is the Dirac delta function.

For our special case where \( d(x,y,t) \) exhibits only small changes with \( t \), the presampling open-field normalized\(^{33} \) output edge function \( d_E(x,y,t|\bar{q}_o) \) can be described as the sum of constant and small changing components, \( d_c \) and \( d_\Delta(x,y,t|\bar{q}_o) \), respectively, giving
\[
\frac{d_\xi(x, y; t \tilde{\sigma}_0)}{d_\xi(x, y, t)} = d_\xi + d_\xi(x, y; t \tilde{\sigma}_0),
\]
(10)

where \(d_\rho(x, y, t)\) and \(d_\xi(x, y, t)\) are the presampling output functions resulting from the primary and scatter components \(\tilde{\sigma}_p(x, y, t)\) and \(\tilde{\sigma}_s(x, y, t)\), respectively.

The constant component is independent of space and time, and thus is not affected by blurring, giving

\[
d_\xi = 1 - A_p.
\]
(11)

The small changing component can be simplified by noting that separability of spatial blur and temporal lag is a good assumption in the P-20 phosphors used in XR1 systems. It is also likely a good assumption in all CsI-based fluoroscopic systems as lag is the delayed release of light quanta from the phosphor and blur is primarily the subsequent spatial spreading of these quanta. Separability gives

\[
p_\Delta(x, y, t \tilde{\sigma}_0) = p(x, y) \delta(t) * x, y, p_\Delta(t \tilde{\sigma}_0) \delta(x, y),
\]
(12)

where \(p(x, y)\) is the spatial PSF, and \(p_\Delta(t \tilde{\sigma}_0)\) is the exposure-rate-dependent temporal PSF. The small changing component is therefore given by

\[
d_\Delta(x, y, t \tilde{\sigma}_0) = A_p \ H_\rho(x, y, t) * x, y, p_\Delta(t \tilde{\sigma}_0) * p_\Delta(t \tilde{\sigma}_0) + S[1 - H_\rho(x, y, t)] * x, y, p_\Delta(x, y) * p_\Delta(t \tilde{\sigma}_0),
\]
(13)

where it is crucial that the edge material be sufficiently radiotranslucent that \(A_p\) is small enough to ensure the small-signal assumption is satisfied, as discussed later.

By averaging along the \(y\) direction over a distance \(Y\), we remove the \(y\) dependence creating the 2D output:

\[
d_\xi^Y(x, t \tilde{\sigma}_0) = d_\xi^Y(x, t \tilde{\sigma}_0) = (1 - A_p) + A_p H_\xi(x, t) * \text{lsf}_\xi(x) * p_\Delta(t \tilde{\sigma}_0) + S[1 - H_\xi(x, t)] * \text{lsf}_\xi(x) * \text{lsf}_\xi(x) * p_\Delta(t \tilde{\sigma}_0),
\]
(14)

where \(\text{lsf}_\xi(x)\) and \(\text{lsf}_\xi(x)\) are the 1D line spread functions describing spatial blur and scatter blur, respectively, and

\[
H_\xi(x, t) = \begin{cases} 
1, & x - u t > 0 \\
0, & \text{otherwise}.
\end{cases}
\]
(15)

The approximation in Eq. (14) is valid for \(\theta\) of a few degrees. We now follow a derivation similar to that outlined in a description of the (radiopaque) moving slanted-edge method. Estimating distance and time from passage of the edge moving with velocity \(v\) using the relationships \(x_\xi = x - \Delta x\) and \(t_\xi = (x - \Delta x) / v\), respectively, where \(\Delta x\) represents a potential error in determining the edge location, enables Eq. (14) to be expressed as a function of \(x_\xi\) and \(t_\xi\) in what we called \(\xi\) space.
\[ T_\Delta(v|\tilde{q}_o) = \left| \frac{T_{\xi}(v|\tilde{q}_o)}{A_\xi(v)|T(v)|} \right|_{v_{\text{max}}} . \]  

(21)

It is very important to note at this stage that \( T_\Delta(v|\tilde{q}_o) \) is not expected to have unity value at \( v=0 \) due to the effective edge attenuation \( A_\xi \). Correct normalization of the temporal MTF is only achieved by using the same semitransparent material to form the stationary edge, where only spatial blurring is present. Under these conditions, Eq. (18) becomes

\[
d'_\xi(x_\xi)|_{v=0} = \lim_{v \to 0} A_p \text{lsf}_s(x_\xi + \Delta x)* \frac{1}{x_\xi} \Delta(t_{\xi}(\tilde{q}_o))_{x_{\xi} \rightarrow x_{\xi}}^v - \lim_{v \to 0} S \text{lsf}_s(x_\xi + \Delta x)* x_\xi \Delta(t_{\xi}(\tilde{q}_o))_{x_{\xi} \rightarrow x_{\xi}}^v = A_p \text{lsf}_s(x_\xi + \Delta x) - S \text{lsf}_s(x_\xi + \Delta x) * x_\xi \Delta .
\]

(22)

Moving into the Fourier domain and taking the modulus gives the stationary characteristic function

\[ |T_{\xi}(u)|_{v=0} = A_\xi(u)|T(u)| . \]

(23)

Combining Eqs. (21) and (23), we express the exposure-rate-dependent small-signal temporal MTF, \( MTF_\Delta(v|\tilde{q}_o) \), as

\[ MTF_\Delta(v|\tilde{q}_o) = \left| T_\Delta(v|\tilde{q}_o) \right| = \frac{|T_{\xi}(v|\tilde{q}_o)|_{v_{\text{max}}}}{|T_{\xi}(v)|_{v=0,v_{\text{max}}}} . \]

(24)

Equation (24) shows that the small-signal temporal MTF is given by the ratio of the spatial characteristic function obtained using the moving semitransparent edge, based on Eq. (19) with a variable substitution, to the characteristic function obtained using the same semitransparent edge when stationary.

**II.A.3. Practical limitations on edge velocity**

The semitransparent moving slanted-edge method shares restrictions on edge velocity similar to the moving slanted-edge method.\(^{26} \) The minimum edge velocity, \( v_{\text{min}} \), is restricted by Eq. (24) where care must be taken to avoid dividing by small values of the spatial transfer function. This is ensured by limiting the maximum spatial frequency to \( u_{5\%} \), defined such that the stationary characteristic function \( |T_{\xi}(u_{5\%})|_{v=0} \) is equal to 0.05. Thus, for any specified maximum frequency of importance in the small-signal temporal MTF, \( v_{\text{max}} \), the minimum acceptable edge velocity is\(^{26} \)

\[ v_{\text{min}} = \frac{v_{\text{max}}}{u_{5\%}} . \]

(25)

Similarly, the maximum edge velocity, \( v_{\text{max}} \), is restricted by the need to measure \( p_\Delta(t_{\xi}q_o) \) in a limited spatial ROI. For example, to measure \( p_\Delta(t_{\xi}q_o) \) until \( r_{5\%} \) where it decays to 5\% of the peak value with an ROI of size \( X \), the maximum accepted velocity is\(^{26} \)

\[ v_{\text{max}} = \frac{X}{r_{5\%}} . \]

(26)

For our conditions, these velocities correspond to 7 cm/s \( \leq v \leq 56 \) cm/s.\(^{26} \)

An error in the calculation of \( v_o \) affects \( MTF_\Delta(v|\tilde{q}_o) \) by a scaling along the \( v \) axis according to \( v=v_ou \).\(^{26} \) In addition, the velocity should be uniform over the time interval \( \tau_o \) during which the edge position may influence pixel values in the ROI. This includes frame-integration time, \( a_o \), width of the temporal PSF to the point at which it is slowly varying, \( \Gamma_v \), and the corresponding width of the spatial LSF, \( \Gamma_x \), divided by the velocity. Thus:

\[ \tau_o = a_o + \Gamma_v + \frac{1}{v_o} \Gamma_x . \]

(27)

The sum \( \Gamma_x/(1/v_o)\Gamma_v \) is the corresponding width of \( d'_\xi(x_\xi|\tilde{q}_o) \) in Eq. (18). For our conditions, that results in \( \Gamma_x/(1/v_o)\Gamma_v = 42 \) ms and \( \tau_o = 33 \) ms + 42 ms = 75 ms.

**II.B. Lag-corrected NPS**

Similar to previous definitions of lag-free NPS,\(^{17,31} \) we define the 2D lag-corrected NPS, \( NPS_{\beta}(u,v) \), describing the image NPS that would be obtained if temporal effects on noise were negligible. If a system is correlated-noise dominant with negligible additive noise (e.g., electronic), we can define the 2D lag-corrected NPS as

\[ NPS_{\beta}(u,v) = \frac{1}{\beta(\tilde{q}_o)} NPS(u,v) , \]

(28)

where the (spatial) NPS is measured using fluoroscopic frames, \( \beta(\tilde{q}_o) \) is a temporal correction factor defined by Eq. (2), and we have explicitly indicated the exposure-rate dependence of \( \beta \).

**II.C. Lag-corrected DQE**

Consistent with previous works,\(^{15,17,20} \) we express the lag-corrected DQE, \( DQE_{\beta}(u,v) \), as\(^{31} \)

\[ DQE_{\beta}(u,v) = \frac{d^2MTF^2(u,v)}{t_o\beta(\tilde{q}_o)NPS_{\beta}(u,v)} , \]

(29)

where \( t_o \) is the time between subsequent images (1/frame rate). We expect measurements of DQE\(_u\) and DQE\(_v\) to have the same values for a system operated in radiographic and fluoroscopic modes, respectively, under the same conditions.

**III. METHODS**

All results were obtained using a laboratory fluoroscopic system operated in continuous fluoroscopy mode and consisting of a 6-year-old Thales x-ray image intensifier (model TH9432 XQH304VR, P20 output phosphor with a thickness between 4 and 8 \( \mu \)m according to the manufacturer)\(^{28} \) and Prosilica digital CCD camera (model EC1350), operated in frame-transfer mode\(^{27} \) at 29.97 frames/s with a frame-
integration time of \( t_0 = 32.0 \) ms. Pixel size in the image plane was \( 0.28 \times 0.28 \) mm\(^2\). Measurements were made using a 50 kVp beam with 0.8 mm Cu filter (half-value layer of 4.6 mm Al), and repeated for an RQA-5 beam (70 kVp, half-value layer of 7.1 mm, additional 21 mm Al filter). All images were dark-field subtracted and corrected for geometric distortions. Only \( x \)-direction analyses are considered, but similar analyses for the \( y \) direction can be performed.

All metal sheets used to form the edges were precision machined, mounted in a custom-made assembly, placed against the detector surface, and moved under servomotor control, as illustrated in Fig. 2. Edge velocity in the image plane was calculated from image data by noting the change in position between subsequent frames. A velocity of \( v = 37 \pm 1 \) cm/s (mean and standard deviation from six independent trials) was used. Uniformity was verified by ensuring the same velocity in each adjacent frame over a four-frame interval. This corresponds to 99 ms and satisfies Eq. (27). The frame that contained the edge closest to the center of the ROI was used for analysis and a Hann window was applied to all slanted-edge data after differentiation and before calculating the fast Fourier transform (FFT). All calculations of \( \beta \) from the temporal MTF used numerical integration with limits of \( \pm 100 \) Hz, previously found to be acceptable. The NPS was calculated without use of a Hann window.

### III.A. Small-signal temporal MTF

#### III.A.1. Dependence on edge attenuation

The temporal MTF was calculated using both copper and lead sheets with a range of edge thicknesses listed in Table I. Measurements were made with input exposure rates of 1.9 and 10.7 \( \mu R/\text{frame} \) using a 50 kVp beam with 0.8 mm added Cu filtration, hereafter referred to as a (hardened) 50 kVp beam, and 3.9 \( \mu R/\text{frame} \) using the RQA-5 beam, resulting in the effective edge attenuations, \( A_E(0) \), listed in the table. Agreement between rising and falling-edge profiles was tested to determine if the small-signal temporal MTF was obtained (criterion discussed further in Sec. V).

#### III.A.2. Dependence on exposure rate

The effect of exposure rate on the temporal MTF was tested by calculating \( \beta \) from both small-signal and large-signal rising and falling-edge profile results over the exposure-rate range 0.4–16 \( \mu R/\text{frame} \) for the (hardened) 50 kVp and RQA-5 beams. Small-signal measurements were made using a semitransparent edge with effective edge attenuation of approximately \( A_E(0)=0.4 \), and large-signal measurements were made with a more radiopaque edge with an effective edge attenuation of approximately 1. Measurements were made from small to large exposure rates to minimize any possible ghosting effects.

### III.B. Lag-corrected DQE

Calculation of the lag-corrected DQE defined in Eq. (29) is summarized in the following steps:

1. Measure the flat-field dark-subtracted average pixel value from image data \( \bar{d} \) and calculate the average density rate of incident x rays, \( \bar{q} \), from the measured exposure.
2. Measure the (spatial) MTF using the slanted-edge technique. Measurements should be made using an opaque edge and open-field normalization without subsequent normalization by the zero-frequency value to ensure accuracy of the results.
3. Measure the image NPS in the \( x \) direction (perpendicular to the edge) for conditions corresponding to step (1).
4. Measure the small-signal temporal MTF given by Eq. (24) using the moving slanted-edge method with a semitransparent edge. The same semitransparent edge must be used for both moving and stationary edge profiles. Calculate \( \beta \) using Eq. (2).
5. Calculate the lag-corrected DQE using the relationship given in Eq. (29).

The lag-corrected DQE was measured using fluoroscopic data and validated by comparison with (conventional) DQE measurements, calculated using Eq. (1), and radiographic data on the same system under similar conditions. The fluoroscopic data were acquired during continuous x-ray exposures 4 s in length with incident exposure rates of 1.9 \( \mu R/\text{frame} \) using a (hardened) 50 kVp beam and 3.9 \( \mu R/\text{frame} \) using the RQA-5 beam. The radiographic data were simulated by summing all fluoroscopic frames dur-

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**Table I.** The temporal MTF was measured using edges of varying types and thicknesses corresponding to effective edge attenuations, \( A_E(0) \), outlined below (see Sec. III A 1).

| Material, mm | Effective edge attenuation, \( A_E(0) = |A_P - S| \) |
|--------------|-----------------------------------------------|
| Cu, 0.025    | 0.14                                           |
| Cu, 0.127    | 0.40                                           |
| Cu, 0.203    | 0.54                                           |
| Cu, 0.254    | 0.61                                           |
| Cu, 0.381    | 0.73                                           |
| Cu, 0.508    | 0.82                                           |
| Cu, 0.635    | 0.87                                           |
| Pb, 1.3      | 1.0                                            |

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**Fig. 2.** Schematic of the XRII-based laboratory fluoroscopic system during a semitransparent moving slanted-edge experiment. Covering the detector with the edge material corresponds to a falling-edge profile, while uncovering the detector corresponds to a rising-edge profile.
ing the exposure, as well as frames acquired 1 s both prior and after the exposure to produce a single image, and it was confirmed that the integrated electronic noise was negligible. Values of $\beta$ were calculated using a semitransparent edge with an effective edge attenuation of approximately 0.4, and at the appropriate exposure rates. Additional DQE measurements were made using the fluoroscopic data and Eq. (1) with $\bar{q}=t_{\bar{q}}$, without lag correction. These results were compared to lag-corrected DQE results to measure the inflation on the uncorrected DQE.

The first 2 s of fluoroscopic data after turn-on of x rays were discarded to ensure steady-state operation for NPS calculations. While radiographic images are typically obtained using short x-ray exposures, long exposures were used here in order to acquire fluoroscopic and radiographic data under similar exposure conditions, and we emphasize this difference by referring to the data as “simulated.”

### IV. RESULTS

#### IV.A. Small-signal temporal MTF

Figure 3(a) shows the spatial transfer function determined using a stationary semitransparent edge (3.9 $\mu$R/frame, 0.37 mm Cu edge, RQA-5 spectrum). The zero-frequency value is less than unity, as predicted by Eq. (23), equal to the effective attenuation $A_E(0)$. Figure 3(b) shows the characteristic functions $|T_s(u)|$ for moving and stationary edges, and the small-signal temporal MTF from Eq. (24) for the same test condition. Both characteristic functions have the same zero-frequency value, $A_E(0)\approx0.39$, resulting in the temporal MTF being correctly normalized with a zero-frequency value close to unity as predicted by Eq. (24).

#### IV.A.1. Dependence on edge attenuation

Figure 4 shows values of $\beta$ using Eq. (2) for both rising and falling-edge profiles. Falling-edge $\beta$ values are independent of edge attenuation except at an effective edge attenuation of $A_E(0)\approx0.1$, where reduced precision is observed due to reduced edge contrast, and measured $\beta$ values appear to be greater. We believe this is due to “noise biasing,” as discussed in Sec. V. This independence was unexpected as it suggests that lag—as it applies to the falling-edge response in the test system—depends on initial exposure rate but not on edge attenuation.

In contrast, rising-edge $\beta$ values depended on both exposure rate and edge attenuation, converging to the falling-edge value as edge attenuation is decreased. As shown in Fig. 4, an effective edge attenuation $\leq0.6$ resulted in agreement with falling-edge $\beta$ values in all test cases, suggesting that the small-signal MTF can be measured with an effective edge attenuation $\leq0.5$ on the test system.

#### IV.A.2. Dependence on exposure rate

Figure 5(a) shows measured values of $\beta$ using both the small-signal and large-signal temporal MTFs (effective edge attenuations $A_E(0)=0.40$ and 1.0, respectively) over exposure rates of 0.4–16 $\mu$R/frame using the hardened 50 kVp beam. Large-signal falling-edge $\beta$ values agreed with small-signal values at all exposure rates, with large-signal results showing better precision. Large-signal rising-edge results have consistently smaller $\beta$ values (more lag). All results show a substantial change in $\beta$ (up to 30%), and hence lag characteristics, over the range of exposure rates tested. Similar results were obtained for the RQA-5 beam shown in Fig. 5(b).

#### IV.B. Lag-corrected DQE

Figure 6 shows a comparison of (i) lag-corrected DQE using fluoroscopic data and (conventional) DQE using (ii) fluoroscopic data and (iii) simulated radiographic data. Good agreement was found between lag-corrected DQE measurements using the fluoroscopic data and DQE measurements using the simulated radiographic data. This confirms that multiplication by $\beta$ in Eq. (29) successfully com-
pensated for inflation due to lag. In this example, lag would be responsible for an ~50% increase in DQE values at all frequencies, unless correctly accounted for through the use of $\beta$.

V. DISCUSSION

The semitransparent moving slanted-edge method and lag-corrected DQE were illustrated and validated on a single bench-top XRII-based fluoroscopic system. It is not yet known whether these results are indicative of other fluoroscopic systems.

V.A. Small-signal temporal MTF

The semitransparent moving slanted-edge method provides measurements of the presampling small-signal tempo-
ral MTF. It requires access to (linearized) image data but does not require any system disassembly or modification. Thus, it potentially can be implemented in both laboratory and clinical environments. As with the moving slanted-edge method, spatio-temporal separability of the system PSF is required, and results were obtained using a continuous non-pulsed fluoroscopic system. In principle, the method can be extended to pulsed-exposure systems by modeling the system input as a cyclostationary process.

V.A.1. Dependence on edge attenuation

Agreement between rising and falling-edge β values independent of edge attenuation is indicative of exposure-rate independence over the measured range. Using this criterion, it was shown that an effective edge attenuation of $\Lambda_E(0) \leq 0.6$ was required to determine the small-signal temporal MTF in the test system. Values of β obtained for $\Lambda_E(0) \leq 0.3$ have less precision and show an upward trend. This upward trend is likely due to increased quantum noise in the measured edge profiles, resulting in positively biased high-frequency noise in the temporal MTF. To maximize precision and accuracy, the most attenuating edge, consistent with small-signal measurements, should be used.

As noted in Secs. II A 2 and IV A, scatter from a thin edge is described by $\Lambda_E$ in the Fourier domain but does not directly influence the calculated temporal MTF described by Eq. (24). If characteristic emissions from the edge contribute substantially to the measured signal, they can be attenuated with an additional thin layer of a lower-atomic number material. The thin aluminum layer and glass front of the XRII likely attenuate more than 99% of the ~8 keV emissions from the Cu edge.

The observed agreement between small-signal and large-signal falling-edge results suggests that the small-signal temporal MTF can be measured using an opaque falling-edge profile. While use of an opaque edge is experimentally more robust than use of a semitransparent edge, we do not know if this observation extends to other fluoroscopic systems. However, it should be noted that previous use of temporal correction factors have relied on large-signal falling-edge (i.e., decay response) measurements, without comparison to rising-edge results.

Standard deviation values are plotted for measurements to illustrate the precision of our technique. However, because standard deviation is determined from only three independent trials, the expected true standard deviation is within the range of $-0.5$ to $+3.4$ times the measured value with a 90% confidence interval. The measured standard deviations should only be used to give a general understanding of the potential spread of the measurements and represent a limited approximation of the true standard deviation.

V.A.2. Dependence on exposure rate

Figure 5 shows a decrease in lag with increasing exposure rate, with the most lag present at the lower rates. These results are consistent with earlier measurements on the same system but differ from the results of other investigators using flat-panel-based systems. Furthermore, a measurable difference between lag characteristics over the fluoroscopic regime of exposure rates was measured for the RQA-5 beam. This emphasizes the need to measure the temporal characteristics of each system under the specific conditions of interest.

V.B. Lag-corrected NPS and lag-corrected DQE

Ignoring temporal considerations resulted in a large (~50%) inflation of DQE values in the test system, indicating the potential importance of a lag correction. General agreement between radiographic DQE results using Eq. (1) and the lag-corrected DQE results obtained using Eq. (29) verified that lag is indeed responsible for the inflation. The agreement also shows that the small-signal temporal MTF, as determined by our method, results in the appropriate lag correction. Small differences between DQE curves (responding-
ing to values at \( \sim 1.5 \) Hz for 50 kVp and \( \sim 0.8 \) Hz for RQA-5) are due to noisy (spatial) MTFs resulting from poor contrast in the low-dose fluoroscopic image. An artifact was present at low frequencies for the radiographic data at both energies.

The results presented here are valid only when uncorrelated noise in the measured NPS is negligible. Unrelated noise may result from secondary quantum sinks, if a system has inadequate conversion gain of x rays to secondary quanta. However, uncorrelated noise is generally uniform at all frequencies, and thus since high-frequency noise was small compared to low frequency noise, it was concluded that uncorrelated noise could be ignored.

V.C. Spatio-temporal DQE

The work presented in this article contributes to our understanding of the DQE of fluoroscopic systems. However, restrictions described above regarding uncorrelated noise imply that the lag-corrected DQE may not be appropriate for use in evaluating some systems exhibiting poor dose efficiency. Furthermore, the lag-corrected DQE provides only a spatial description of what are fundamentally spatio-temporal systems. We believe the DQE of these systems should be described by a three-dimensional spatio-temporal DQE, expressed as a function of both spatial and temporal frequencies. The work described here represents only one step toward this goal.

VI. CONCLUSIONS

Application of Fourier metrics to fluoroscopic systems requires a small-signal approach to temporal resolution. A lag-corrected DQE has been defined using a small-signal MTF and lag-corrected NPS, and is applicable to fluoroscopic systems in which the uncorrelated component of the NPS is negligible. We make the following additional conclusions:

1. The semitransparent moving slanted-edge method can be used to accurately measure the small-signal temporal MTF provided that a sufficiently transparent edge is used. For the test system, a semitransparent edge with an effective edge attenuation between 0.3 and 0.6 provided accurate measurements of the small-signal MTF. Edges with greater attenuation provide better precision.

2. The temporal MTF is exposure-rate dependent, with more lag present at lower exposure rates for the test system. This emphasizes the need to make measurements at each exposure rate of interest.

3. Falling-edge large-signal temporal MTF measurements agreed with small-signal measurements over all tested exposure rates on the bench-top CsI-based XRII system. If found to be generally true, it removes the need for the small-signal approach.

4. The lag-corrected DQE, given by Eq. (29), describes (spatial) fluoroscopic system performance and has been validated by comparison with radiographic DQE measurements taken under the same conditions.

5. Ignoring temporal considerations in Eq. (1) resulted in inflated DQE values by up to 50% in the test system.

The semitransparent moving slanted-edge method enables accurate measurements of \( \beta \), the temporal correction factor required to measure the dose efficiency of fluoroscopic systems through the lag-corrected DQE.

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