A small-signal approach to the non-linear temporal modulation transfer function and its application to fluoroscopic detective quantum efficiency

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Fluoroscopic procedures can result in potentially large radiation doses to patients. A metric to quantify system “dose efficiency” is crucial to ensure that the benefit-to-risk ratio for a given patient dose is maximized. The detective quantum efficiency (DQE) is widely used in radiography as a surrogate measure of dose efficiency and can be applied to fluoroscopy if a temporal correction factor is used. Calculation of this correction factor relies on measurements of the temporal modulation transfer function (MTF). However, the temporal MTF is known to be exposure-rate dependent, violating a necessary Fourier requirement referred to as temporal linearity. We show that a Fourier analysis is only appropriate for fluoroscopic systems if a “small-signal” approach is used for the temporal MTF. Using a semi-transparent 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, and independent of edge attenuation when effective attenuation was in the range of 0.1 to 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 and radiopaque edge were equivalent to the small-signal results at the same exposure rates for the tested system. Use of an opaque edge generally provides better precision than a semi-transparent edge. Lag-corrected DQE values were validated by comparison with radiographic DQE values obtained using very long exposures under the same conditions. It is concluded that lag accounted for inflation to DQE measurements by up to 50% when ignored.

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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 measured through the noise equivalent quanta (NEQ) and can be expressed as:

\[
\text{DQE}(u, v) = \frac{\overline{d^2} \text{MTF}^2(u, v)}{\overline{\text{NPS}(u, v)}},
\]

where \(u\) and \(v\) are spatial-frequency variables in \(x\) and \(y\) directions, MTF is the modulation transfer function describing spatial resolution, and NPS is the Wiener noise power spectrum calculated from open-field, dark-subtracted images corresponding to \(\overline{\sigma}\) incident quanta per mm² and average pixel value \(\overline{d}\).

The DQE only provides a meaningful indication of dose efficiency when measured under clinical conditions, including beam half-value layer (HVL), kV and typical exposures incident on the detector. This is problematic for fluoroscopy, where our own attempts to measure the DQE in the past have resulted in inflated and even nonsensical values (greater than unity), indicating that it is inappropriate to use Eq. (1) to directly describe fluoroscopic systems.

Other investigators have considered the temporal as-
pect of fluoroscopic systems and its affect on measurements of performance. Rowlands,6 introduced the concept of the temporal MTF to describe temporal resolution. Wilson and colleagues7–14 developed a linear systems model predicting human performance in spatio-temporal tasks.

Applications of the DQE to fluoroscopy by accounting for the effect of lag have been previously described.15–18 Granfors et al.,15,16 used a temporal-domain-based method to compensate for the effects of lag on the NPS. Their approach assumed system linearity in both space and time, with lag acting as a deterministic linear filter, which we now know is simplistic.19 Cunningham, Siewerdsen, and colleagues17,18 made a similar assumption using a temporal-frequency-based approach. They describe the NPS that would be achieved if lag were not present through a “lag-free” NPS. Their definition of lag-free NPS assumes separability between spatial and temporal characteristics, and uses a multiplicative temporal correction factor $\beta$ where:17,19

$$\beta = a_t \int_{-\infty}^{\infty} MTF_i^2(\nu) d\nu$$

$$= \frac{a_t}{a_L}, \quad (2)$$

and where $MTF_i$ is the temporal MTF given as a function of temporal frequency $\nu$, $a_L$ is the effective system temporal aperture defined as 1 over the integral of $MTF_i^2(\nu)$, similar to the bandwidth integral introduced by Wagner and Brown,20 and $a_t$ is the frame integration time of each image, giving $0 \leq \beta \leq 1$.

Assumptions may fail when image quality is compromised by excessive additive noise, noise aliasing, or other potential considerations.19 In addition, using the example of noise in a simple phosphor-based system, Akbarpour and colleagues19 have shown that lag only scales the correlated component of noise, and does not affect the uncorrelated, such as noise resulting from a secondary quantum sink as would result from inadequate collection of light photons. This suggests that it is only appropriate to scale by $\beta$ when correlated noise is much greater than uncorrelated noise. We will restrict ourselves to correlated-noise-dominant systems, and use the “lag-corrected NPS” (previously referred to as lag-free17) to characterize fluoroscopic systems.

The moving slanted-edge method was developed to enable temporal MTF measurements from image data using continuous fluoroscopy and requires a radiopaque moving edge to extract system temporal information.21 Measurements on an x-ray image intensifier-based bench-top system showed that temporal characteristics are exposure-rate dependent, an effect that is also observed through differences in rising and falling-edge profiles. We refer to exposure-rate independence of lag as “temporal linearity,” and these results suggested that the requirement is violated within the system.21

Similar to the small-signal approach used to describe the DQE of (non-linear) film-screen radiographic systems,22 we adopt a small-signal approach in the time domain to address temporal non-linearity. In general, Fourier methods require wide-sense stationary (WSS) noise processes, which result in low contrast and small temporal changes. If a detector is confirmed to be linear, measurements of the MTF using large signal changes can be used, such as the opaque slanted-edge technique.23,24 For systems exhibiting linearity over only small changes in incident exposure, a small-signal Fourier approach must be used.

We address the issue of temporal linearity in this paper and show that a Fourier analysis is appropriate if a small-signal approach is taken for temporal MTF measurements. We develop a method to measure the small-signal temporal MTF under steady-state constant exposure-rate conditions based on a semi-transparent moving slanted-edge method. We describe the detection quantum efficiency of fluoroscopic systems that exhibit temporal non-linearity and measure it under fluoroscopic conditions. The lag-corrected DQE is validated by comparison with radiographic DQE measurements under similar conditions.

II. THEORY

A. Small-signal temporal MTF

1. Definition

The small-signal spatio-temporal MTF is exposure-rate dependent, given by $MTF_\Delta(u, v, \nu|\tilde{q}_o)$:

$$MTF_\Delta(u, v, \nu|\tilde{q}_o) = |T_\Delta(u, v, \nu|\tilde{q}_o)|$$

$$= |F\{p_\Delta(x, y, t|\tilde{q}_o)\}|, \quad (3)$$

where $\tilde{q}_o$ is the average incident distribution of quanta [mm$^{-2}$s$^{-1}$], and $T_\Delta(u, v, \nu|\tilde{q}_o)$ and $p_\Delta(x, y, t|\tilde{q}_o)$ are normalized system spatio-temporal small-signal transfer and point spread functions (PSF), respectively. 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 the next section 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 $\tilde{q}_o$, so that the spatio-temporal
MTF can be expressed as:

$$\text{MTF}_{\Delta}(u, v, \nu) = \text{MTF}(u, v)\text{MTF}_{\Delta}(\nu),$$  \hspace{1cm} (4)

where MTF$(u, v)$ is the (conventional) spatial MTF, and MTF$_{\Delta}(\nu)$ is the small-signal temporal MTF. This expression reduces to the (spatial) MTF when $\nu = 0$.

2. **Semi-transparent moving slanted-edge method**

Based on the moving slanted-edge method\textsuperscript{21,25} and the conventional (stationary) slanted-edge method\textsuperscript{23,24} we now derive the “semi-transparent moving slanted-edge method” to measure the small-signal temporal MTF\textsuperscript{26}.

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 presampling signal corresponding to a uniform open-field distribution of incident quanta $q_o$ is given by:

$$d_o(x, y, t) = \bar{q}_o = kq_o,$$  \hspace{1cm} (5)

where $k$ is a constant of proportionality.

The semi-transparent 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:

$$\bar{q}_E(x, y, t) = \bar{q}_P(x, y, t) + \bar{q}_S(x, y, t).$$  \hspace{1cm} (6)

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

$$\bar{q}_P(x, y, t) = \bar{q}_o(1 - A_P) + \bar{q}_o A_P H_\theta(x, y, t),$$  \hspace{1cm} (7)

where $A_P$ represents attenuation of the primary beam, and

$$H_\theta(x, y, t) = \begin{cases} 1 & x - y \tan \theta - vt > 0 \\ 0 & \text{otherwise.} \end{cases}$$  \hspace{1cm} (8)

The scatter component is described similar to Neitzel \textit{et al.}\textsuperscript{27} 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, $S = \bar{q}_o/\bar{q}_E$ giving:

$$\bar{q}_S(x, y, t) = \bar{q}_o S[1 - H_\theta(x, y, t)] *_{x,y,t} p_S(x, y)\delta(t),$$  \hspace{1cm} (9)

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 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:

$$d_E(x, y, t|\bar{q}_o) = \frac{d_P(x, y, t) + d_S(x, y, t)}{d_o(x, y, t)} = \frac{d_c + d_\Delta(x, y, t|\bar{q}_o)}{d_o(x, y, t)},$$ \hspace{1cm} (10)

where $d_P(x, y, t)$ and $d_S(x, y, t)$ are the presampling output functions resulting from the primary and scatter components $\bar{q}_P(x, y, t)$ and $\bar{q}_S(x, y, t)$, respectively.

The constant component is independent of space and
time, and thus is not affected by blurring, giving:
\[ d_c = 1 - A_P. \]  

(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 XRII systems.\textsuperscript{29} 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:

\[ p_\Delta(x, y, t \| \bar{q}_0) = p(x, y) \delta(t) * p_\Delta(t \| \bar{q}_0) \delta(x, y), \]  

(12)

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

\[ d_\Delta(x, y, t \| \bar{q}_0) = A_P H_\theta(x, y, t) * p_\Delta(t \| \bar{q}_0) \]
\[ + S[1 - H_\theta(x, y, t)] * p_\Delta(t \| \bar{q}_0), \]

(13)

where it is crucial that the edge material be sufficiently radiotranslucent that \( A_P \) is sufficiently small so that our 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,\textsuperscript{21}

\[ d_E^Y(x, t \| \bar{q}_0) \]
\[ \approx (1 - A_P) + A_P H(x, t) * \text{lsf}_x(x) * t \]
\[ + S[1 - H(x, t)] * \text{lsf}_x(x) * t \]

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

\[ H(x, t) = \begin{cases} 1 & x - vt > 0 \\ 0 & \text{otherwise}. \end{cases} \]  

(15)

The approximation in Eq. (14) is valid for \( \theta \) of a few degrees.\textsuperscript{21,23,24}

We now follow a derivation similar to that outlined in a description of the (radiopaque) moving slanted-edge method.\textsuperscript{21} Estimating distance and time from passage of the edge moving with velocity \( \nu \) using the relationships \( x_\xi = x - \Delta x \) and \( t_\xi = \frac{x - \Delta x}{v} \), 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:\textsuperscript{21}

\[ d_\xi(x_\xi \| \bar{q}_0) = (1 - A_P) + [A_P H(x_\xi + \Delta x) \]
\[ * x_\xi \text{lsf}_x(x_\xi + \Delta x) * t_\xi \]
\[ + S[1 - H(x_\xi + \Delta x)] * t_\xi \]
\[ + \frac{1}{v} \text{lrn}(t_\xi \| \bar{q}_0), \]  

(16)

where

\[ H(x_\xi) = \begin{cases} 1 & x_\xi > 0 \\ 0 & \text{otherwise}. \end{cases} \]  

(17)

Taking the derivative of Eq. (16) with respect to \( x_\xi \) gives:

\[ d_\xi(x_\xi \| \bar{q}_0) = \frac{d(1 - A_P) + A_P H(x_\xi + \Delta x)}{dx_\xi} \]
\[ \times x_\xi \text{lsf}_x(x_\xi + \Delta x) * t_\xi \]
\[ + S[1 - H(x_\xi + \Delta x)] * t_\xi \]
\[ * x_\xi \text{lsf}_x(x_\xi + \Delta x) * t_\xi \]
\[ + \frac{1}{v} \text{lrn}(t_\xi \| \bar{q}_0), \]  

(18)

where

\[ T_\xi(u \| \bar{q}_0) = \left[ T(u)e^{i2\pi \Delta xu} \right]_v = \nu \]
\[ = A_P T(u)e^{i2\pi \Delta xu} \]
\[ - S T_S(u)e^{i2\pi \Delta xu} \]
\[ \times T(u)e^{i2\pi \Delta xu} \]
\[ \times \left[ T(u)T_\Delta(\nu \| \bar{q}_0) \right]_v = v \]
\[ = A_P - S T_S(u)e^{i2\pi \Delta xu} \]
\[ \equiv e^{i2\pi \Delta xu}, \]  

(19)

For a non-zero edge velocity, \( v \), the Fourier transform of Eq. (18) is the moving-frame characteristic function, describing perceived spatial blur of a system moving with velocity \( v \):

\[ A_E(u) = |A_P - S T_S(u)e^{i2\pi \Delta xu}|, \]  

(20)

describing the edge attenuation including the effect of the spatial-frequency dependent edge scattering in the
Fourier domain. Taking the modulus of Eq. (19) and rearranging, we can isolate the exposure-rate dependent small-signal temporal modulation transfer function:

\[
|T_\Delta(\nu|\vec{q}_o)| = \frac{|T_\xi(\nu|\vec{q}_o)|}{A_E(\nu)|T(\nu)|}\Bigg|_{\nu=v_o,u}.
\]  

(21)

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

\[
d_\xi(x_\xi)|_{\nu \rightarrow 0} = \lim_{\nu \rightarrow 0} A_P \left| \text{lsf}_\xi(x_\xi + \Delta x) \ast \frac{1}{\nu} \text{p}_\xi(t_\xi|\vec{q}_o)|_{t_\xi = x_\xi/v} \right. \\
- \lim_{\nu \rightarrow 0} S \text{lsf}_\xi(x_\xi + \Delta x) \ast x_\xi \text{lsf}_\xi(x_\xi + \Delta x) \\
\left. \ast \frac{1}{\nu} \text{p}_\xi(t_\xi|\vec{q}_o)|_{t_\xi = x_\xi/v} \right| \\
= A_P \text{lsf}_\xi(x_\xi + \Delta x) - S \text{lsf}_\xi(x_\xi + \Delta x) \\
\ast x_\xi \text{lsf}_\xi(x_\xi + \Delta x).
\]  

(22)

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

\[
|T_\xi(u)|_{\nu \rightarrow 0} = A_E(u)|T(u)|.
\]  

(23)

Combining Eqs. (21) and (23), we can express the exposure-rate dependent small-signal temporal MTF, \(\text{MTF}_\Delta(\nu|\vec{q}_o)\), as

\[
\text{MTF}_\Delta(\nu|\vec{q}_o) = |T_\Delta(\nu|\vec{q}_o)| = \frac{|T_\xi(\nu|\vec{q}_o)|}{|T_\xi(\nu)|} \Bigg|_{\nu = v_o,u}.
\]  

(24)

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

### B. Lag-corrected NPS

The (spatial) NPS of a spatio-temporal system will be underestimated if calculated without accounting for temporal noise-averaging effects due to lag.\textsuperscript{15-19} Similar to previous definitions of lag-free NPS,\textsuperscript{17,26} we define the 2D lag-corrected NPS, \(\text{NPS}_\beta(u,v)\), 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:

\[
\text{NPS}_\beta(u,v) = \frac{1}{\beta(\vec{q}_o)} \text{NPS}(u,v),
\]  

(25)

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

#### C. Lag-corrected DQE

We adapt a previous definition of “lag-free” DQE,\textsuperscript{17} an expression of the (spatial) system performance as measured from image frames by modifying Eq. (1) using the lag-corrected NPS, and now refer to it as the “lag-corrected DQE,” \(\text{DQE}_\beta(u,v)\), where:\textsuperscript{26}

\[
\text{DQE}_\beta(u,v) = \frac{d^2 \text{MTF}^2(u,v)}{t_o \beta(\vec{q}_o) \text{NPS}_\beta(u,v)},
\]  

(26)

and where \(t_o\) is the time between subsequent images (1/frame rate).

We expect measurements of \(\text{DQE}(u,v)\) and \(\text{DQE}_\beta(u,v)\) 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 Dunlee x-ray image intensifier (XRII) (model TH715-3N:91 01 2693), Prosilica digital CCD camera (model EC1350), operated in frame-transfer mode\textsuperscript{31} at 29.97 frames per second with a frame integration time of \(a_t = 32.0\) ms. Pixel size in the image plane was 0.28 mm x 0.28 mm. Measurements were made using a 50 kV beam with 0.8 mm Cu filter, and repeated for an RQA-5 beam (70 kV, half value layer of 7.1 mm, additional 21 mm Al filter).\textsuperscript{32} All images were dark-field subtracted and corrected for geometric distortions.\textsuperscript{33} 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 servo-motor control at a constant edge velocity of \(v_o = 37\) cm/s. The output frame that contained the edge closest to the center of the XRII was used for analysis and a Hann window\textsuperscript{34} was applied to all slanted-edge data before calculating the fast Fourier transform (FFT). All calculations of \(\beta\) from the temporal MTF used numerical integration with limits of ±100 Hz, previously found to be acceptable.\textsuperscript{21} The NPS was calculated without use of a Hann window.
A. Small-signal temporal MTF

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 μR/frame using a (hardened) 50 kV beam and 3.9 μR/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 section V).

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 to 16 μR/frame for the (hardened) 50 kV and RQA-5 beams. Small signal measurements were made using a semi-transparent edge with effective edge attenuation of approximately 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.

B. Lag-corrected DQE

Calculation of the lag-corrected DQE defined in Eq. (26) is summarized in the following steps:

1. Measure the flat-field dark-subtracted average pixel value from image data, $\overline{q}$, and calculate the average density rate of incident x rays, $\overline{q}_o$, 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 semi-transparent edge. The same semi-transparent 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. (26)

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 was acquired during continuous x-ray exposures four seconds in length with incident exposure rates of 1.9 μR/frame using a (hardened) 50 kV beam and 3.9 μR/frame using the RQA-5 beam. The radiographic data was simulated by summing all fluoroscopic frames during the exposure, as well as frames acquired one second 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 semi-transparent edge with an effective edge attenuation of approximately 0.4, and at the appropriate exposure rates. Additional (conventional) DQE measurements were made using the fluoroscopic data and Eq. (1) with $\overline{q} = t_0\overline{q}_o$. These results were compared to lag-corrected DQE results to measure the inflation on the (conventional) DQE due to lag.

The first two second after turn-on of fluoroscopic data was 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

A. Small-signal temporal MTF

Figure 2(a) shows the spatial transfer function determined using a semi-transparent edge (3.9 μR/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 2(b) shows the characteristic functions $|T_\xi|$ for moving and stationary edges, and the small-signal temporal MTF from
values appear to be greater. We believe this is due to
pendent of edge attenuation except at an effective edge
observed due to reduced edge contrast, and measured
is equal to the ratio of the moving-frame and stationary char-
acteristic functions, $|T_\xi(\nu)|_{\nu \to 0}$ and $|T_\xi(0)|_{\nu \to 0}$ respectively.

Eq. (24), for the same test condition. Both char-
acteristic functions have the same zero-frequency value,
$A_E(0) = |A_p - S| = 0.39$, resulting in the temporal MTF
being correctly normalized with a zero frequency value
close to unity as predicted by Eq. (24).

1. Dependence on edge attenuation

Figure 3 shows values of $\beta$ using Eq. (2) for both rising
and falling-edge profiles. Falling-edge $\beta$ values are inde-
pendent of edge attenuation except at an effective edge
attenuation of $A_E(0) \approx 0.1$, 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 section V. This inde-
pendence 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 attenu-
ation.

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. 3, an effective edge attenuation $\lesssim 0.6$
resulted in agreement with falling-edge $\beta$ values in all test
cases, suggesting that the small-signal MTF can be mea-
sured with an effective edge attenuation $\sim 0.5$ on the test
system.

2. Dependence on exposure rate

Figure 4(a) shows measured values of $\beta$ using both
the small-signal and large-signal temporal MTF (effective
edge attenuation $A_E(0) = 0.40$ and 1.0 respectively)
over exposure rates of 0.4 to 16 $\mu R$/frame using the
hardened 50 kV 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.

B. Lag-corrected DQE

Figure 5 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. (26) suc-
cessfully compensated for inflation due to lag. In this ex-
ample, lag would be responsible for a $\sim 50\%$ increase in
DQE values at all frequencies, unless correctly accounted
for through the use of $\beta$.

V. DISCUSSION

A. Small-signal temporal MTF

The semi-transparent moving slanted-edge method
provides measurements of the presampling small-signal
temporal MTF. It requires access to (linearized) image
data, but does not require any system disassembly or
modification. Thus, it can be potentially implemented in
both laboratory and clinical environments. As with the
moving slanted-edge method, all results have been ob-
tained using a continuous (non-pulsed) fluoroscopic sys-
tem. In principle, results could be extended to pulsed-
exposure systems by modeling the system input as a  
cyclostationary process.\textsuperscript{4,21}

1. Dependence on edge attenuation

Agreement between rising and falling-edge $\beta$ values,  
independent of edge attenuation, is indicative of exposure-  
rate independence over the measured range, a result that  
we refer to as temporal linearity. This criterion was used  
to confirm that measurements were in the small-signal  
regime, and an effective edge attenuation of $A_{E}(0) \lesssim 0.6$  
produced the small-signal temporal MTF in the test sys-  
tem. Edges outside this range were not sufficiently ra-  
diotranslucnt to correspond to small signals. Values of  
$\beta$ obtained for $A_{E}(0) \lesssim 0.3$ have less precision and show  
an upward trend. The upward trend is likely due to in-  
creased quantum noise in the measured edge profiles, re-  
sulting in positively biased high-frequency noise in the  
temporal MTF, and inflated $\beta$ values. To maximize pre-  
cision and accuracy, the most attenuating edge, consist-  
tent with small-signal measurements, should be used.

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 ex-  
pertimentally more robust than use of a semi-transparent  
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,\textsuperscript{16,35} suggesting that this result may be  
true for a wide range of systems.
2. Dependence on exposure rate

Figure 4 shows a decrease in lag with increasing exposure rate, with the most lag present at low exposure rates. These results are consistent with previous measurements of an XRII-based system, but are not consistent with the results of other investigators using flat-panel-based systems. Furthermore, a measurable difference between lag characteristics over the fluoroscopic regime of exposure rates ($\lesssim 5 \mu R/frame$) 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.

Figure 4: Values of $\beta$ as a function of incident exposure for both small-signal (effective edge attenuation $\sim 0.4$) and large-signal (effective edge attenuation $\sim 1$) temporal MTF measurements at incident exposure within the range 0.4 to 16 $\mu R/frame$. Plotted points and error bars are the mean and standard deviation of 3 trials.

(a) 50 kV, 0.8 mm Cu

(b) RQA-5

FIG. 5: DQE calculations from Eq. (1) of a system using radiographic and fluoroscopic data ($\tilde{q} = t_0 \tilde{q}_0$), and the lag-corrected DQE of the system using Eq. (26). A small low-frequency artifact is noted in the data.

(b) RQA-5, 3.9 $\mu R/frame$

B. Lag-corrected NPS and lag-corrected DQE

General agreement between radiographic DQE results using Eq. (1) and the lag-corrected DQE results obtained using Eq. (26) verifies that meaningful DQE measurements of fluoroscopic (spatial) system performance require correction for temporal considerations, and that the semi-transparent moving slanted-edge method provides accurate measurements of the small-signal temporal MTF needed to calculate the temporal correction factor $\beta$. Ignoring temporal considerations can result in substantial inflation of DQE values ($\sim 50\%$ in the test system). Small differences between DQE curves ($\sim 1.2$ Hz for 50 kV, $\sim 0.8$ Hz for RQA-5) are due to noisy (spatial) MTFs resulting from poor contrast in the low-dose fluoroscopic image, and the radiographic results are likely more accurate. An artifact was present at low frequen-
cies for the radiographic data at both energies, however, this is common to many DQE measurements and values are often presented with these erroneous values removed.

The results presented here are valid only when uncorrelated noise in the measured NPS is negligible. Uncorrelated 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 if high-frequency noise is small compared to low frequency noise, uncorrelated noise can be ignored. In addition, the image must represent linear (or linearized) data from the detector free of post processing.

C. Spatio-temporal DQE

The work presented in this paper makes an important contribution to measuring and understanding the DQE of fluoroscopic systems, and is a crucial step to a comprehensive spatio-temporal approach, providing the method and results for spatio-temporal MTF. The restrictions described above regarding uncorrelated noise imply that the lag-corrected DQE approach may not be adequate for systems exhibiting poor dose efficiency due to secondary quantum sinks. Furthermore, the lag-corrected DQE only provides a spatial description of what are fundamentally spatio-temporal systems. We believe a spatio-temporal DQE is required for a more comprehensive description of these systems. The work described here provides a step towards 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 semi-transparent 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 semi-transparent edge with an effective edge attenuation between 0.3 and 0.6 provided accurate measurements of the small-signal MTF. Edges with larger effective attenuation provide better precision.

2. The temporal MTF is exposure-rate dependent, with more lag present at lower exposure rates for the tested system. Measurements must be made 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.

4. The lag-corrected DQE, given by Eq. (26), describes (spatial) fluoroscopic system performance and has been validated by comparison with radiographic DQE measurement taken under the same conditions.

5. Ignoring temporal considerations in Eq. (1) can result in inflated DQE values by as much as 50%.

The semi-transparent 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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