A Method to Measure the Temporal MTF to Determine the DQE of Fluoroscopy Systems

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ABSTRACT

Fluoroscopic procedures can result in significant radiation exposures to patients. To maximize the patient benefit-to-risk ratio, systems must be designed to produce the highest possible image quality for a given patient exposure, and quality assurance programs must be designed to ensure these standards are maintained. While the detective quantum efficiency (DQE) is often used in radiography to quantify “dose efficiency,” attempts to measure the DQE of fluoroscopic systems have produced incorrect results due to system lag reducing measured noise power spectrum (NPS) values and artificially inflating DQE values. Methods involving the use of the system temporal modulation transfer function (MTF) have been proposed to remove this effect. However, measurements of the temporal MTF from acquired image data is problematic, as a direct measure of the system decay curve from images acquired at the image frame rate of 30 Hz is seriously undersampled. As a result, the DQE of fluoroscopic systems is rarely measured.

We have developed a novel method to measure system temporal MTF using a “moving slanted-edge” method. Image data is acquired while an attenuating edge is translated across the detector with constant velocity. Pixel values from fluoroscopic images are mapped to a new spatiotemporal coordinate based on the distance and time from passage of the edge at that pixel. Both the presampling spatial MTF and presampling temporal MTF are determined from three images: an open image (with no edge) for normalization; an image of a stationary edge; and an image of a moving edge (of order 45 cm/s).

The method has been demonstrated using a bench-top image-intensifier-based fluoroscopic system using detector exposures representative of clinical procedures. Image data was acquired by digitizing the fluoroscopic video signal. The method was validated by comparison with a direct measure of the optical decay curve of the image intensifier sampled at 2.5 kHz. After correction for the temporal effects of video integration time, excellent agreement was obtained between the two methods. It is concluded that the moving slanted-edge method provides a practical method for measuring the presampling temporal MTF of a fluoroscopic system.

Keywords: x-ray imaging, fluoroscopy, modulation transfer function, MTF, detective quantum efficiency, DQE, temporal MTF, detector lag

1. INTRODUCTION

Fluoroscopic procedures typically result in adult patient skin dose rates of 20-50 mGy/min and interventional procedures can involve 60 to 90 minutes of fluoroscopy. This large dose necessitates that the benefit-to-risk ratio of the procedure be maximized, and systems must therefore be designed to produce the highest possible image quality for a given patient exposure and quality assurance programs must be designed to ensure that these standards are maintained. The detective quantum efficiency (DQE) is often used to quantify the “efficiency”
of an imaging system for producing images with the best possible signal-to-noise ratio (SNR) for a specified detector exposure in non-fluoroscopic radiography. The radiographic DQE in one dimension is given by

\[ \text{DQE}(u) = \frac{\bar{q}_o \text{MTF}^2(u)}{\bar{q}_o \text{NPS}(u)} \]  

(1)

where \( \bar{q}_o \) is the average incident number of x-ray quanta per unit area on the detector, \( \bar{d} \) is the corresponding average dark-subtracted pixel value, \( \text{MTF}(u) \) and \( \text{NPS}(u) \) are the MTF and noise power spectrum (NPS) respectively and \( u \) is the spatial frequency.

However, attempts in our laboratory to measure the DQE of fluoroscopic systems have produced nonsensical results often with DQE values greater than unity. This is because system lag results in a “frame averaging” effect that reduces image noise (NPS) in individual fluoroscopic images, thereby incorrectly inflating DQE values given by Eq. (1). Granfors et al.,\(^4\) Cunningham\(^5\) and others have suggested the use of quantities that remove this effect. These methods all require a measurement of the temporal response of the fluoroscopic system. The “lag-free” DQE, suggested by Cunningham et al., requires the system temporal modulation transfer function, \( \text{MTF}_t(u) \),\(^6\) and is given by:

\[ \text{DQE}_{\text{lf}}(u) = \frac{\bar{q}_o \text{MTF}^2(u)}{\bar{q}_o \text{NPS}_m(u)} \times \int_{-\infty}^{\infty} \text{MTF}_t^2(\nu) \, d\nu, \]  

(2)

where \( \bar{q}_o \) is the incident rate of x-ray quanta per unit area, \( \text{NPS}_m(u) \) is the NPS measured from individual fluoroscopic images and includes the effect of lag-induced noise averaging, and \( \nu \) is temporal frequency. In a linear-systems model, the lag-free DQE, determined using fluoroscopic data, should be numerically equivalent to the more conventional radiographic DQE under quantum-noise-limited conditions.

Several investigators have measured the temporal MTF of individual components in an imaging chain. For example, Rowlands\(^6\) measured the temporal MTF of an image intensifier using a rotating “chopper disk” to create a temporal square-wave input of x-ray exposure and measured the resulting optical response. His method therefore did not measure the true temporal performance of the entire imaging system. Attempts to measure system response using a video signal are generally limited by the video frame rate which imposes a maximum temporal sampling frequency of 30 samples/sec (in North America). For these reasons, temporal MTF measurements are rarely attempted in a clinical setting, and measurements of DQE under fluoroscopic conditions have not been possible.

The goal of our research is to develop a method of measuring the temporal MTF to be used in Eq. (2) for the lag-free DQE. Measurements must be made using the entire imaging system and under conditions appropriate for clinical fluoroscopy so that the lag-free DQE can be used to characterize the “dose efficiency” of these systems. It would be particularly useful to be able to measure the temporal MTF in a clinical setting with minimal disruption to the system or its use. Only then will it be possible to use quantitative metrics such as the DQE to ensure acceptable performance of fluoroscopic systems on an on-going basis and ensure patients are exposed to only the minimum necessary radiation risks.

2. THEORY

Direct measurement of the system temporal response is made difficult by aliasing artifacts caused by the 30 Hz sampling rate (in North America) of the video system. This limitation can only be removed by developing a method that provides a much greater effective sampling rate. Similar to use of the “slanted edge” method for MTF measurements in radiography to give an over-sampled line-spread function,\(^7,8\) we describe a “moving slanted edge” method that gives both an over-sampled edge-spread function in one spatial direction and an over-sampled temporal decay curve in time representing the system response to the abrupt termination of x-ray exposure. From this data, both the spatial MTF and temporal MTF are extracted.

A simple linear-systems model of a “generic” fluoroscopic system can be written as:

\[ d(x, y) = q(x, y) * p(x, y) \]  

(3)
where \(d(x, y)\) represents the “presampling” detector signal, \(q(x, y)\) is the (expected) incident x-ray image, \(p(x, y)\) is the system point-spread function (PSF), and \(*\) is the two-dimensional convolution operator. This equation gives the output image from an imaging system with the exception of potential sampling artifacts when system temporal effects can be ignored.

When the system presents temporal effects that cannot be ignored, such as the decay time of a phosphor, or the frame integration time of a video system, it is necessary to use a spatiotemporal model:

\[
d(x, y, t) = q(x, y, t) * p(x, y, t).
\]

Figure 1 illustrates a hypothetical spatiotemporal point-spread function that includes both spatial and temporal blurring functions. While spatial blur may or may not be spatially symmetric, temporal blur is always asymmetric due to the causal nature of temporal events. We define the normalized spatiotemporal point spread function, \(p(x, y, t)\), to represent the average spatial and temporal blurring of the system. Because spatial and temporal blurring are caused by different physical phenomena, separability between spatial and temporal events is assumed. Thus the spatiotemporal PSF may be expressed as

\[
p(x, y, t) = p_{x,y}(x, y) \delta(t) * p_t(t) \delta(x, y),
\]

where \(p_{x,y}(x, y)\) is the normalized 2D spatial PSF and \(p_t(t)\) is the normalized temporal PSF. All include the effect of the aperture integration time as applicable, and \(\delta\) represents a Dirac delta function.

### 2.1. Moving Slanted Edge Method

The moving slanted-edge method involves a sheet of tungsten, with a straight edge at a small angle \(\theta\) with respect to the \(y\)-axis, being translated across the detector with a known velocity \(v\) as illustrated in Fig. 2. In this section, we describe the moving slanted-edge method for determining the spatiotemporal MTF as an extension of the more conventional stationary slanted-edge method.

The average spatiotemporal distribution of x rays incident on the detector can be written as \(\bar{q}_o H_s(x, y, t)\) where the Heaviside function \(H_s(x, y, t)\) is restricted to values of 0 or 1, representing presence or absence of tungsten respectively. We define the edge to be at position \((x, y, t) = (0, 0, 0)\) at time \(t = 0\), and therefore \(H_s(x, y, t)\) can be expressed as

\[
H_s(x, y, t) = \begin{cases} 
1 & x - y \tan \theta - vt > 0 \\
0 & \text{otherwise}.
\end{cases}
\]
Figure 2. A sheet of tungsten, slanted at a small angle $\theta$, is translated across the detector with a known velocity $v$.

Linear-systems theory allows the output “spatiotemporal” image, $d(x, y, t)$, created using the tungsten sheet, to be expressed as

$$d(x, y, t) = \bar{q}_o H_s(x, y, t) * p(x, y, t),$$

$$= \bar{q}_o H_s(x, y, t) * p_{x,y}(x, y) \delta(t) * p_t(t) \delta(x, y),$$

where $d(x, y, t)$ describes the two-dimensional image that would be obtained at any given time $t$. A single video frame obtained at $t = 0$ can be expressed as the “snapshot” $d(x, y, t)|_{t=0}$.

We make use of the “synthesized slit” method to calculate the MTF in the $x$ direction.$^8, 9$ This is normally accomplished by integrating the image signal over a distance $Y$ in the $y$ direction, thus removing the $y$ dependence, where $Y$ is much greater than the resolving distance in the $x$ direction. In the limit of $\theta \to 0$:

$$d^Y(x, t) = \lim_{\theta \to 0} \frac{1}{Y} \int_Y R_{-\theta}\{d(x, y, t)\}dy$$

$$\approx \frac{1}{Y} \int_Y \bar{q}_o R_{-\theta}\{H_s(x, y, t) * p_{x,y}(x, y) \delta(t) * p_t(t) \delta(x, y)\}dy$$

$$= \frac{1}{Y} \int_Y \bar{q}_o H_s(x, y, t) * R_{-\theta}\{p_{x,y}(x, y)\} \delta(t) * p_t(t) \delta(x, y)dy,$$

where $R_{-\theta}\{ \}$ represents a rotation operator by $-\theta$ and

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

(9)

Using the convolution property that $\int a * b = \int a \int b^{10}$ gives

$$d^Y(x, t) = \bar{q}_o H(x, t) * \frac{1}{Y} \int_Y R_{-\theta}\{p_{x,y}(x, y)\}dy \delta(t) * p_t(t) \delta(x)$$

$$\approx \bar{q}_o H(x, t) * \text{lsf}_x(x) \delta(t) * p_t(t) \delta(x)$$

(10)

where $\text{lsf}_x(x)$ is the system line-spread function in the $x$ direction and
The quantities \( \text{lsf}_x(x)\delta(t) \) and \( p_t(t)\delta(x) \) are illustrated in Fig. 3.

Equation (10) is valid as long as the integral through \( p_{x,y}(x,y) \) parallel to the edge is approximately equal to the integral along the \( y \) axis. It can be simplified by expansion of the convolution integrals. The first convolution expands to

\[
\bar{q}_o H(x, t) = \frac{1}{\bar{q}_o} \int \int H(x', t')\text{lsf}_x(x - x')\delta(t - t')dx'dt'
\]

Therefore,

\[
d^Y(x, t) = \bar{q}_o H(x, t) * \text{lsf}_x(x - x') * p_t(t)\delta(x)
\]

It is convenient at this point to introduce a new “\( \chi \)-space,” illustrated in Fig. 4, with axes \( x_\chi \) and \( t_\chi \) representing distance from the edge and time from passage of the edge respectively for any image location.
Figure 4. The function $d^Y(x,t)$ is mapped onto a line, $\xi$, in $\chi$-space based on distance from the edge, $x_\chi$, and time from passage of the edge, $t_\chi$. All points in $d^Y(x,t)$ along a line parallel to the edge get mapped to a single point on $\chi(x_\chi,t_\chi)$.

Figure 4 shows that all points along a line parallel to the edge have equal distances and times from the edge, and are therefore all mapped to the identical point in $\chi$-space, with coordinates:

$$x_\chi = x - vt, \quad \text{and}$$

$$t_\chi = \frac{x}{v} - t,$$

which are simply shifts of space and time. This relationship results in the 2D space of $d^Y(x,t)$ being mapped to the line $\xi$ in $\chi$-space as illustrated in Fig. (4). For convenience, we set $t = 0$ meaning that we are assuming the image of the moving edge was acquired at time zero. The slope of the line, $x_\chi/t_\chi$ is therefore equal to the edge velocity. This linear relationship allows Eq. (20) to be expressed as a function of a single variable, either $x_\chi$ or $t_\chi$.

We consider two special cases, corresponding to stationary and moving edges.

2.1.1. Case I: Stationary Edge - $\xi$ Mapped to $x_\chi$ Axis

For the stationary edge, Eq. (20) is mapped on to a line parallel to the $x_\chi$ axis. Therefore,

$$H(x,t) \rightarrow H(x_\chi)$$

(23)

$$\text{lsf}_x(x) \rightarrow \text{lsf}_x(x_\chi)$$

(24)

$$p_t(t) \rightarrow \frac{1}{v}p_t(x_\chi/v).$$

(25)

Taking the limit as $v \rightarrow 0$ gives:

$$d^Y(x_\chi)|_{v \rightarrow 0} = \lim_{v \rightarrow 0} \frac{q_0}{v}H(x_\chi) \ast \text{lsf}_x(x_\chi) \ast \frac{1}{v}p_t(\frac{1}{v} \cdot x_\chi)$$

$$= \frac{q_0}{v}H(x_\chi) \ast \text{lsf}_x(x_\chi) \ast \lim_{v \rightarrow 0} \frac{1}{v}p_t(\frac{1}{v} \cdot x_\chi)$$

$$= \frac{q_0}{v}H(x_\chi) \ast \text{lsf}_x(x_\chi) \ast \delta(x)$$

$$= \frac{q_0}{v}H(x_\chi) \ast \text{lsf}_x(x_\chi)$$

(26)

(27)
The variable $x_{\chi}$ represents an arbitrary shift in the $x$ direction and can be replaced with $x$, giving

$$d^\prime Y(x)|_{v \to 0} = \frac{\partial}{\partial x} H(x) \ast \text{lsf}_x(x).$$

Differentiation with respect to $x$ gives

$$d^{\prime \prime}Y(x)|_{v \to 0} = \frac{\partial}{\partial x} H'(x) \ast \text{lsf}_x(x) = \frac{\partial}{\partial x} \delta(x) \ast \text{lsf}_x(x) = \frac{\partial}{\partial x} \text{lsf}_x(x)$$

where $H'(x)$ is the derivative of $H(x)$ with respect to $x$. Defining the Fourier transform of $d^{\prime \prime}Y(x)$ in the limit $v \to 0$ as $T_x(u)$, we have

$$T_x(u) = \mathcal{F}\{d^{\prime \prime}Y(x)\}|_{v \to 0}$$

where $u$ is the spatial-frequency variable. This gives the $x$-direction modulation transfer function, $\text{MTF}_x(u)$, as

$$\text{MTF}_x(u) = \left| \frac{T_x(u)}{T_x(0)} \right|.$$  

This result shows that in the limit of $v \to 0$, the moving slanted-edge method is equivalent to the conventional (stationary) slanted edge method for determining the system (spatial) MTF.

2.1.2. Case II: Moving Edge - $\xi$ Mapped to $t_{\chi}$ Axis

Introduction of a non-zero velocity provides temporal information, and it is convenient to express $d^\prime Y(x,t)$ from Eq. (20) as a function of $t_{\chi}$. Using similar methods to those described above gives

$$d^\prime Y(t_{\chi}) = \frac{\partial}{\partial t_{\chi}} H(t_{\chi}) \ast v \text{lsf}_x(vt_{\chi}) \ast p_t(t_{\chi})$$

for any velocity $v$. The variable $t_{\chi}$ represents an arbitrary shift in time, and can be replaced with $t$, and hence

$$d^{\prime \prime}Y(t) = \frac{\partial}{\partial t} H'(t) \ast v \text{lsf}_x(vt) \ast p_t(t) = \frac{\partial}{\partial t} \text{lsf}_x(vt) \ast p_t(t).$$

Defining $T_t(\nu)$ as the Fourier transform of $p_t(t)$ and $T_\xi(\nu)$ as the Fourier transform of $d^{\prime \prime}Y(t)/\dot{q}$ gives

$$T_\xi(\nu)|_{v=v_o} = T_x(v_o) T_t(\nu)$$

and therefore

$$T_t(\nu) = \frac{T_\xi(\nu)|_{v=v_o}}{T_x(u)|_{u=v/v_o}}.$$  

The temporal MTF is then give by

$$\text{MTF}_t(\nu) = \left| \frac{T_t(\nu)|_{v=v_o}}{T_t(0)} \right|.$$  

Thus, the temporal MTF for a wide range of temporal frequencies can be calculated from a measurement of $T_x(u)$ using a stationary slanted edge and $T_\xi(\nu)$ using a moving slanted edge at a single velocity $v_o$.

2.1.3. Summary of Steps to Obtain Temporal MTF

These results show that the temporal MTF of a system can be determined using the following process:

1. Obtain an image of a stationary slanted edge and calculate the presampling (spatial) system characteristic function $T_x(u)$ using the established “slanted-edge” method.
2. Obtain an image of a moving slanted edge at velocity $v_o$. Map all image pixels onto the $t_{\chi}$ axis of $\chi$-space where $t_{\chi}$ represents the time from passage of the edge. This results in the projection of $\chi$-space onto the $t_{\chi}$ axis directly, $d^\prime Y(t_{\chi})$.
3. Differentiate $d^\prime Y(t_{\chi})$ and take the Fourier transform to give $T_\xi(\nu)|_{v=v_o}$ for the velocity $v_o$.
4. Use Eqs. (35) and (36) to solve for the temporal MTF, $\text{MTF}_t(\nu)$.
3. METHODS

The temporal MTF of a laboratory prototype x-ray fluoroscopy system was measured using the moving slanted-edge method. In addition, the image-intensifier decay curve resulting from an abrupt termination of x-ray exposure was measured directly. This was used to provide an independent measurement of the system temporal MTF and provided validation of the moving slanted-edge method.

All data was acquired using a General Electric CT x-ray tube, model number 46-30950062, a three-year old Dunlee intensifier, model number TH715-3N:91 01 2693, a Cohu high performance CCD camera and a Data Translation Inc. video digitizer card. The camera was operated in an interline transfer, field integration mode, with each set of odd and even fields being the result of integration of the combination of two adjacent scan lines over 1/60 s. While odd and even fields are normally interlaced in the y-direction, only the odd field was used in the present analysis. The pixel size in the x-direction is 0.29 mm. The x-ray tube was operated at 50 kV and 63 mA to produce continuous x-ray exposure. The beam was hardened with 2.54 mm of Cu.

3.1. Moving Slanted-Edge Method

3.1.1. Spatial MTF

A 2-mm thick tungsten plate with a precision-machined edge was placed on the face of the x-ray image intensifier. Thirty video frames were acquired and averaged to produce a low-noise image of the edge. The image was dark-field subtracted, open-field normalized, and corrected for geometric distortions. The presampling MTF was calculated using the method described by Samei and resampled using a factor of 8 increase in the spatial sampling frequency. A Hanning window was applied before calculating all Fourier transforms.

3.1.2. Temporal MTF

The slanted tungsten edge was translated across the face of the image intensifier with constant velocity in the x-direction as video data was acquired. Two sequential frames were selected, dark-field subtracted, open-image normalized, and corrected for geometric distortions. The edge position was estimated in each image by finding the position of maximum signal change in each row and fitting a straight line to these positions as a function of row number using a least-squares method. The velocity of the edge was determined to be \( v_o = 45 \text{ cm/s} \) by noting the change in edge position between frames.

Each pixel within one of the frames was mapped on to \( \chi \)-space where \( x_\chi \) is the measured distance to the edge and \( t_\chi \) is equal to

\[
\chi \chi = \frac{x_\chi}{v_o}.
\]

(37)

The \( \chi \)-space data was projected onto the \( t_\chi \) axis to give \( d^\chi(t_\chi) \) and Eqs. (34) and (36) used to determine the temporal MTF.

3.2. Direct Measurement of the System Decay Curve

The moving slanted-edge method was validated by a direct measurement of the temporal decay curve of the image intensifier to produce an independent measurement of the temporal MTF. A photodiode was used to digitize the optical intensity at the intensifier output phosphor at a sampling frequency of 2.5 kHz. A Bimba pneumatic cylinder was used to suddenly block the x-ray beam, taking approximately 0.4 ms to cover the beam width. The derivative of the optical decay curve was calculated, a Hanning window was applied and the temporal MTF calculated by taking the FFT. The effect of 1/60 s frame integration of the CCD camera was incorporated by multiplying the temporal MTF by an appropriate sinc function.
Figure 5. Illustration of measured edge profiles projected onto $x$ axis, $d'(x_\chi)$, for stationary and moving (45 cm/s) edges. The stationary edge is an average of 30 video frames while the moving edge is calculated from a single frame.

Figure 6. Illustration of: i) measured MTF$_\xi(\nu)$ evaluated with $v_o = 45$ cm/s; ii) measured MTF$_x(\frac{\nu}{v_o})$; and, iii) calculated MTF$_t(\nu)$.

4. RESULTS

Edge profiles obtained with stationary and moving edges and projected onto the $x_\chi$ axis, $d(x_\chi)$, are shown in Fig. (5). The moving edge profile shows more blur due to the motion. The stationary profile has less noise as it represents an average of 30 video frames.

Calculation of the temporal MTF, MTF$_t(\nu)$, is illustrated in Fig. (6). In this example, the velocity was high enough that the velocity-dependent spatiotemporal MTF, MTF$_\xi(\nu)$, is closely approximated by MTF$_t(\nu)$ as the spatial MTF, MTF$_x(\frac{\nu}{v_o})$, has very little effect on the measurement. While MTF$_t(\nu)$ can be measured from a wide range of $v_o$ values, it should be large enough that it has a minor influence on MTF$_\xi(\nu)$. 
Figure 7. Measured temporal decay curve of the image intensifier after abrupt termination of exposure. The normalized signal has a time constant (decreases to the value $e^{-1}$) of approximately 7 ms.

Figure 8. Comparison of the system temporal MTF obtained using the moving slanted-edge and direct decay-curve methods shows excellent agreement.

Figure (7) shows the temporal decay curve of the image as the x-ray exposure is abruptly terminated. The signal decays to a value of $e^{-1}$ after approximately 7 ms. Figure (8) shows a comparison of the temporal MTF determined by the moving slanted-edge method with the direct decay-curve method. Both show a 10% value at approximately 50 Hz and a value of 0 at approximately 60 Hz corresponding to the frame integration time of the CCD camera.

5. CONCLUSIONS

Excellent agreement was found between the temporal MTF measurements made with the moving slanted edge method and by measuring the decay curve of the intensifier. The close agreement provides direct validation of
the moving slanted-edge method.

The decay-curve method requires high-speed digitization of the optical intensity. As such, it requires a direct measurement of the optical output of the intensifier. While this is possible with a laboratory prototype intensifier-based system, it is not possible with other detectors such as active-matrix flat panel systems. In addition, it does not measure the response of the entire system. For example, it was necessary in this study to simulate the effect of the frame-integration time by scaling the measured temporal MTF by the appropriate sinc function.

The moving slanted-edge method is based on image data only. It measures the performance of the entire system without requiring disruptive measurements, and provides both the “presampling” spatial MTF and “presampling” temporal MTF. It can therefore be used to determine quantities such as the “lag-free” DQE to quantify system dose efficiency at operating parameters appropriate for fluoroscopic operation.

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