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Evaluation and Comparison of High-Resolution (HR) and High-Light (HL) Phosphors in the Micro-Angiographic Fluoroscope (MAF) using Generalized Linear Systems Analyses (GMTF, GDQE) that include the Effect of Scatter, Magnification and Detector Characteristics

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Abstract

In this study, we evaluated the imaging characteristics of the high-resolution, high-sensitivity micro-angiographic fluoroscope (MAF) with 35-micron pixel-pitch when used with different commercially-available 300 micron thick phosphors: the high resolution (HR) and high light (HL) from Hamamatsu. The purpose of this evaluation was to see if the HL phosphor with its higher screen efficiency could be replaced with the HR phosphor to achieve improved resolution without an increase in noise resulting from the HR's decreased light-photon yield. We designated the detectors MAF-HR and MAF-HL and compared them with a standard flat panel detector (FPD) (194 micron pixel pitch and 600 micron thick CsI(Tl)). For this comparison, we used the generalized linear-system metrics of GMTF, GNNPS and GDQE which are more realistic measures of total system performance since they include the effect of scattered radiation, focal spot distribution, and geometric un-sharpness. Magnifications (1.05-1.15) and scatter fractions (0.28 and 0.33) characteristic of a standard head phantom were used. The MAF-HR performed significantly better than the MAF-HL at high spatial frequencies. The ratio of GMTF and GDQE of the MAF-HR compared to the MAF-HL at 3(6) cycles/mm was 1.45(2.42) and 1.23(2.89), respectively. Despite significant degradation by inclusion of scatter and object magnification, both MAF-HR and MAF-HL provide superior performance over the FPD at higher spatial frequencies with similar performance up to the FPD's Nyquist frequency of 2.5 cycles/mm. Both substantially higher resolution and improved GDQE can be achieved with the MAF using the HR phosphor instead of the HL phosphor.

Keywords

MTF; DQE; GMTF; GDQE; NPS; GNNPS; MAF; FPD; MAF-HR; MAF-HL

1. Introduction

Standard objective parameters such as modulation transfer function (MTF), noise power spectrum (NPS), and detective quantum efficiency (DQE) have been widely used for evaluating x-ray imaging systems. But these parameters only provide useful information about the intrinsic detector performance separate from the effect of the realistic clinical environment which includes scatter due to the patient and geometric unsharpness due to the finite size of the focal spot – factors that play a major role in image quality. The effects of focal spot unsharpness, object magnification, and scatter due to the object have been already studied by many authors.^[1-5] We have been evaluating the complete system with the inclusion of scatter due to objects, object magnification, and geometric unsharpness due to the finite size focal spot using generalized system parameters: generalized modulation transfer function (GMTF), generalized normalized noise power spectrum (GNNPS), and generalized detective quantum efficiency (GDQE).^[6-11]

The columnar structured CsI(Tl) phosphor has been widely used as the imaging phosphor for indirect x-ray imaging detector systems because it provides higher spatial resolution as compared to other phosphors. Two types of 300 micron thick CsI(Tl) phosphor are commercially available in the market from Hamamatsu Corp.: HR for high resolution but with lower light output and HL for high light output but with somewhat compromised resolution.^[12,13] Jain et. al. already reported on the 2D generalized linear system analysis for a micro-angiographic fluoroscope (MAF) detector that is used in this study.^[14] In the present study, we use generalized linear system metrics to evaluate the performance of the newly-developed, high sensitivity and high resolution MAF (35-micron active pixel size) with each of the phosphor types. We designate the combinations as MAF-HR and MAF-HL depending on the types of imaging phosphor used, HR and HL respectively, and we also provide a comparison with a commercially available flat panel detector (FPD) system (194-micron pixel size). The purpose of this work is to see if the increased gain capability of the MAF achieved by increasing the gain of the light image intensifier (LII) could enable improved spatial resolution in the case of MAF-HR without a substantial increase in noise that might characterize the decreased light photon yield per absorbed x-ray photon for the HR phosphor, potentially resulting in a degradation of the GDQE.

2. Methods and Materials

2.1 X-ray imaging detectors and experimental setup

For this study, we used a commercially available FPD (Varian PaxScan 2020 FPD Palo Alto, CA, USA) and the MAF, both mounted on a C-arm gantry (Infinix, Toshiba Medical Systems Corporation). The FPD uses 600 micron thick CsI(Tl) as the imaging phosphor at the front end and has a 1024x1024 array of 194 micron pixels. The MAF is a region-of-interest x-ray imaging detector with a small field of view ($3.6 \times 3.6 \text{ cm}^2$), low instrumentation noise, high sensitivity, and large variable gain.^[14] Figure 1 shows the schematic of the components inside the MAF and figure 2 is the picture of MAF. At the front end, a CsI(Tl) (Hamamatsu Corp., Bridgewater, NJ) imaging phosphor is coupled to a generation 2 dual light image intensifier (LII) (Model PP0410K, DEP Inc., Dwaziewegen 2, NL-9300 AB Roden, The Netherlands) through a fiber optic plate. The LII is coupled to a

CCD camera (Model Pantera TF-1M30, Dalsa Corp., Waterloo, ON, Canada) through a 2.88:1 ratio fiber optic taper (FOT). Two MAFs, MAF-HR and MAF-HL, were constructed using the HR and HL CsI(Tl) imaging phosphors, respectively. The LII is the key component in the imaging chain that provides a large variable gain, and enables the MAF to be used both in high exposure x-ray imaging (angiography) and low exposure x-ray real time imaging (fluoroscopy). The MAF operates in the quantum noise limited region even at very low exposures because of the LII. Compared to the FPD, the MAF has higher spatial resolution because of its small active pixel size of 35 micron as, while the thickness of its imaging phosphor is 300 micron.

The experimental set up is shown in figure 3. The detector was at a distance of 105cm from the x-ray tube. The FPD was used with a grid of grid ratio 13:1, whereas no grid was used in the case of the MAF. The x-ray beam was collimated to the field of view of the detector. The scatter fractions were measured using the standard lead beamstop method keeping the phantom in the x-ray beam at fixed air-gaps (2.5 cm and 5cm) with respect to the detector, and the detector entrance exposure was measured by replacing the detector with an ionization chamber, using the same set up. A small focal spot of nominal size 0.3 mm was used in this study. The object magnifications (1.05-1.15) were defined as the three different positions inside the phantom, while keeping the phantom at a fixed air-gap with respect to the detector. The RQA 5 spectrum is used with a 74 kVp x-ray beam and added filtration of 21mm aluminum.

2.2 CsI(Tl) Imaging Phosphor

There are two types of CsI(Tl) phosphors of 300 micron thickness available: high resolution (HR) and high light (HL).^[12,13] In the HL phosphor, there is a reflective layer at the end towards the x-ray tube. When an x-ray is absorbed in the phosphor, it produces light photons proportional to the absorbed x-ray energy. As these light photons can travel in any direction, those that travel toward the x-ray tube (away from the detector) are reflected back from the reflecting layer, and redirected toward the detector. There is an increase in light photons that results in an increase in light output, and consequently a decrease of noise in the detector. As light photons spread with distance during travel, the spatial resolution degrades in the case of the HL phosphor. Therefore, the HL phosphor produces high light output with somewhat less spatial resolution. In the case of the HR phosphor, there is no reflective layer at the back end. Hence, it produces high spatial resolution and low light output as compared to the HL phosphor.

2.3 Measurement of Intrinsic Detector Performance Parameters

To evaluate the total system performance in terms of generalized parameters, we need to measure the MTFs for focal spot, scatter, and the detectors as well as the scatter fraction and the NNPS for the detectors. Measurement of each of these parameters is described briefly in the following subsections.

2.3.1 Modulation Transfer Function (MTF)—The detector MTF was measured using the slanted edge method described by Samei et. al..^[15] In this experiment, an edge was placed at a slight angle to the image matrix directly on the detector surface to minimize the

effect of magnification and finite size of focal spot. The edge test device was a 2mm thick with machined lead edge. The edge response function of the detector was obtained from the flat field and offset corrected images of the edge and the first derivative of it was used to obtain the line spread function. Finally, a Fourier transform was performed to obtain the detector MTF from the line spread function.

2.3.2 Focal spot MTF—The focal spot MTF was measured using the standard pinhole method, keeping the pinhole close to the x-ray tube.^[16] X-ray images of the small focal spot were taken using a 10 micron pin-hole, and a high magnification of 3.12 was used to minimize the effect of detector blur. We obtained the 2D PSF from the pin-hole image and took the Fourier transform of it to get 2D focal spot MTF. We did radial averaging to calculate the 1D focal spot MTF from the 2D focal spot MTF. A scale factor based on the pin-hole magnification was used to get the images at unit focal spot magnification i.e. the focal spot plane. Focal spot MTF is a property of the x-ray tube and does not depend on detector properties; hence, we used the same focal spot MTF for all the detectors.

2.3.3 Scatter MTF—The scatter MTF was measured using the method described by Boone et. al.^[17] In this work, the scatter PSF was assumed to be Gaussian with a radial expansion term $1/r$. The scatter PSF was simulated for a uniform head equivalent phantom used in this study, and the Hankel transformation was used to get the scatter MTF from the scatter PSF. The scatter MTF is defined at the detector plane. Because the scatter MTF is a property of an object or phantom and is independent of detector properties, we can use the same scatter MTF for all the MAF's. There is an effect of air-gaps and scatter grids on the scatter MTF, but it is not considered here and we use the detectors at the same air-gap and without the scatter grids for the comparison.

2.3.4 Normalized Noise Power Spectrum (NNPS)—The detector noise power spectrum is defined as the square modulus of the Fourier transformation of the differences between the mean value and individual pixel values in a flat field image, multiplied by the pixel area with units of mm^2 .^[10,11] Several flat field images were acquired using the standard RQA5 x-ray spectrum. The two dimensional (2D) detector normalized noise power spectrum was measured using the standard Fourier transform method.^[18] In this method, several ROIs of 256×256 were selected at the center of each image with half-overlap in horizontal and vertical directions. The mean pixel value in each ROI was subtracted from each pixel value, and the differences were Fourier transformed to obtain the noise power spectrum (NPS). The NPS from all ROIs were averaged and normalized using the square of the average pixel values to get the NNPS. As the 2D NNPS of the detectors is quite symmetric in the Fourier domain, the one dimensional (1D) NNPS was obtained by radial averaging of the 2D NNPS. This method does not involve scatter in the calculation as it treats primary and scatter photons equally.

2.3.5 Scatter Fraction—The scatter fractions for a uniform head equivalent phantom were measured using the lead beamstop technique, keeping the phantom at different air-gaps from the detector.^[19] The phantom consists of 12 inch $\times$ 12 inch square, 3.2mm thick aluminum, 6 inches thick PMMA and was shown to be equivalent to an average human

head.^[9] Lead disks of 2mm thickness and of different diameters were placed in the x-ray beam between the x-ray tube and phantom, blocking the primary radiation. The scatter fraction was calculated for each disc diameter using the equation 2 and plotted against the disc diameter. The scatter fraction due to the phantom was estimated by extrapolating the above plot to zero diameter disc. Scatter fractions for two different air gaps of 2.5cm and 5cm were found to be 0.33 and 0.28, respectively for the MAF detector. The same scattering fraction was used in the case of the FPD for comparison i.e. assuming the field of view of the FPD is collimated to the field of view of the MAF.

2.4 Generalized linear system parameters calculation

The generalized system parameter treats focal spot blurring due to the finite size of focal spot and scatter due to the object as parallel processes at the detector plane followed by the degradations due to the detector blur as the cascade in the imaging chain. The Generalized MTF (GMTF) is given by combining the MTFs for detector (MTF_D), focal spot (MTF_F), and scatter (MTF_S) using the following equation:^[9,10]

$$GMTF(f, \rho, m) = \left[(1 - \rho) MTF_F \left(\left(\frac{m-1}{m} \right) f \right) + \rho MTF_S \left(\frac{f}{m} \right) \right] MTF_D \left(\frac{f}{m} \right) \quad (1)$$

Here f is the spatial frequency, m is the object magnification of features on a plane within the object onto the detector plane, and ρ is the scatter fraction that is defined as

$$\rho = \frac{S}{S+P} \quad (2)$$

where S and P are the scatter and primary components, respectively. In this equation, the scatter fraction ρ is independent of object magnification. GMTF is defined in the object plane, whereas intrinsic detector MTF is defined in the detector plane. Therefore, a scaling factor based on the object magnification was used for all the MTFs to transfer the spatial frequency in the detector plane to the spatial frequency in the object plane. The first term in the above equation gives the primary blurring to the detector MTF that is the product of focal spot MTF and primary fraction $(1-\rho)$, whereas the second term only gives the scatter blur that is the product of scatter MTF and scatter fraction.

Similarly, the Generalized Normalized Noise Power Spectrum (GNNPS) in the object plane is defined as

$$GNNPS(f, X, m) = \frac{NPS_D \left(\frac{f}{m}, X \right)}{m^2 d^2(x)} = \frac{NNPS_D \left(\frac{f}{m}, X \right)}{m^2} \quad (3)$$

Where $NPS_D(f/m, X)$ and $NNPS_D(f/m, X)$ are defined in the object plane and X is the x-ray exposure measured at the detector entrance surface. $d(x)$ in the denominator is the averaged pixel value of the flat field image, assuming the detector is linear or linearized. A division by a factor m^2 in the denominator is used to transfer the effective pixel area from

the detector plane to the object plane. Flat field images with scatter components were used in the NNPS calculation, but there was no distinction between primary photon and scatter photon as it is assumed the detector treats them equally. Hence, it does not include any scatter term in its equation.

GNEQ represents the effective number of quanta at the object plane that is used in the final image formation. GNEQ is the absolute measure of the image quality i.e. a higher NEQ means an image with larger signal to noise ratio. GDQE represents the fraction of input quanta used in the formation of final image. Using the GMTF and GNNPS, we can define GNEQ and GDQE as follows;

$$\text{GNEQ}(f, \rho, X, m) = \frac{\text{GMTF}^2((f, \rho, X, m))}{\text{GNNPS}((f, \rho, X, m))} \quad (4)$$

$$\text{GDQE}(f, \rho, X, m) = \frac{\text{GNEQ}(f, \rho, X, m)}{m^2 \Phi_{\text{in}}(X, m)} \quad (5)$$

where $\Phi_{\text{in}}(X, m)$ is the number of input quanta per unit area at the detector entrance surface. The denominator $m^2 \Phi_{\text{in}}(X, m)$ represents the number of input quanta per unit area at the object plane. The number of input quanta per unit area at the detector entrance surface at the detector entrance is determined using the normalized x-ray spectrum as a function of energy and the measured detector entrance exposure.^[20] The detector entrance exposure was measured using the ionization chamber replacing the detector for each measurement, and using the same experimental set up.

3. Results and Discussions

Figure 4 shows the low frequency distribution of scatter MTF and focal spot MTF. The focal spot MTF shows the spatial frequency behavior for the small focal spot of nominal size 0.3mm, and the spatial frequencies are referenced to the focal spot plane after considering the pinhole magnification. The focal spot MTF is almost zero at 3 cycles/mm. The scatter MTF shows the spatial frequency behavior of scatter radiation for the uniform head equivalent phantom and drops rapidly with spatial frequency as compared to the focal spot MTF. The spatial frequencies of the scatter MTF are referenced to the detector plane.

Figure 5 shows the behavior of intrinsic detector MTF for the MAF-HR, MAF-HL, and FPD as a function of spatial frequency. At low frequencies up to 1.5cycles/mm, MAF-HL, MAF-HR, and FPD perform similarly. Above 1.5cycles/mm, the MAF-HL and FPD start to degrade rapidly as compared to MAF-HR. The FPD degrades even more as compared to MAF-HL, and is limited to low frequency due to its Nyquist frequency of 2.5cycles/mm (pixel size of 194micron). At higher spatial frequencies, the MAF-HR performs significantly better than the MAF-HL as expected because of the HR imaging phosphor.

Figure 6 shows the behavior of the 1D NNPS as a function of spatial frequency for MAF-HR, MAF-HL, and FPD. The exposure was found to be different for each detector during the measurement hence NNPS for all the detectors was normalized to the same exposure of

98 μR for the comparison. Zero frequency NNPS is different for all the detectors. The FPD has lower zero frequency NNPS than the MAF-HR and MAF-HL because of its larger pixel size and greater thickness of imaging phosphor. At lower frequencies up to 1.5 cycles/mm, noise for the FPD and MAF-HL is similar, whereas noise for the MAF-HR is greater almost at all spatial frequencies. The GMTF provides the resolution performance of the total imaging system including the effect of scatter due to the object and focal spot blurring due to the finite focal spot size, as calculated using the equation 1. Figure 7 shows the spatial frequency behavior of the GMTF of the MAF-HR at two different object magnifications and scatter fractions. The object magnifications of 1.05 and 1.15 refer to positions in figure 3 close to the top and bottom, respectively inside the phantom while the phantom was kept at a fixed air-gap with respect to the detector. Scatter fractions of 0.28 and 0.33 are due to the phantom for 5 cm and 2.5 cm air-gaps, respectively. We can see that the detector the GMTF is always degraded compared to the detector MTF (no scatter and no geometric unsharpness). At a higher scattering fraction, the GMTF degrades even more at lower spatial frequencies. At higher spatial frequencies, the GMTF degrades because of focal spot blur. Similarly, figure 8 shows the frequency behavior of the GMTF of the MAF-HL at two different object magnifications and scatter fractions. The effect of scatter at air-gaps of 2.5 cm and 5 cm (SF of 0.28 and 0.33) and focal spot blur on the detector GMTF is similar as in the case of the MAF-HR; however, the ratio of GMTF of the MAF-HR compared to the MAF-HL at 3(6) cycles/mm was 1.45(2.42).

Figure 9 shows the comparison of GMTFs vs. spatial frequency for the FPD, MAF-HR, and the MAF-HL at a fixed object magnification of 1.11 that corresponds to the middle position inside the phantom, and a fixed scatter fraction that corresponds to 5 cm air-gap. At low frequencies up to 1.5 cycles/mm, the GMTF for MAF-HR, MAF-HL and FPD have similar values and degrade significantly as compared to their respective detector MTFs because of scatter radiation due to the phantom. After 1.5 cycles/mm, the GMTF for the FPD and the MAF-HL start to degrade as compared to that of the MAF-HR. The FPD degrades even more than the MAF-HL and is limited to low frequencies due to its lower Nyquist frequency. The GMTF for the MAF-HR is significantly better than that for the MAF-HL at higher spatial frequencies. At higher spatial frequencies after 3 cycles/mm, the GMTF of the MAF-HR performs better than the detector MTF of the MAF-HL, despite the degradations due to the scatter and focal spot blur. At higher spatial frequencies, the GMTFs for MAF-HR and MAF-HL degrade as compared to their respective detector MTFs because of focal spot blur due to the finite size of the focal spot. The effect of focal spot blur due to the small focal spot is less severe on the FPD due to its lower Nyquist frequency, whereas the effect is more severe on both MAF-HR and MAF-HL because of their higher Nyquist frequency.

The DQE is a measure of the absolute system efficiency in detecting primary photons. Figure 10 shows the behavior of intrinsic detector DQE vs. spatial frequency for MAF-HR, MAF-HL, and FPD. It is clearly seen that zero frequency DQE is different for FPD in that it has a higher DQE because of the larger pixel size and higher thickness of imaging phosphor. The DQE for the MAF-HL is similar that of the MAF-HR. At lower spatial frequencies up to 2.5 cycles/mm, both the FPD and MAF-HL have similar DQEs. After 2.5 cycles/mm, the DQE for FPD and MAF-HL start to degrade rapidly as compared to MAF-HR, whereas the degradation of DQE for the FPD is more severe. Also the FPD's DQE is limited to low

frequency due to its lower Nyquist frequency. At higher spatial frequencies, the MAF-HR clearly performs significantly better than the MAF-HL in terms of DQE.

The GDQE of a system is a measure of total system performance that is calculated combining the GMTF, GNNPS, and the number of input quanta, and calculated using the equation 5. Figure 11 shows the behavior of the GDQE for the MAF-HR vs. spatial frequency at two different object magnifications and scatter fractions. We clearly see that the GDQE degrades significantly as compared to detector MTF at lower spatial frequencies. The degradation is even more as the scatter fraction is increased. At higher spatial frequencies, the GDQE decreases due to focal spot blurring, and the degradation is even more at higher magnification. Similarly, figure 12 shows the behavior of the GDQE for the MAF-HL vs. spatial frequency at two different object magnifications and scatter fractions. The effect of scatter and focal spot blur on GDQE is similar to the case of the MAF-HR.

Figure 13 shows the comparison of the GDQEs for the FPD, MAF-HR, and MAF-HL at a fixed object magnification of 1.11, and a fixed scatter fraction of 0.28. It is clearly seen that the GDQEs for all the detectors suffer substantial drops as compared to their respective intrinsic detector DQE at lower spatial frequencies due to scatter. Both the FPD and MAF-HL have similar GDQEs at lower spatial frequencies up to 2.5cycles/mm, and a slightly better GDQE than the MAF-HR. After 2.5cycles/mm, the GDQE for FPD and the MAF-HL start to degrade rapidly as compared to the MAF-HR. The FPD degrades even more as compared to the MAF-HL and is limited to lower spatial frequencies due to its lower Nyquist frequency. The MAF-HR performs significantly better than the MAF-HL at higher spatial frequencies. Despite the degradation due to focal spot blur and scatter, the GDQE of the MAF-HR is significantly better than the detector DQE of MAF-HL. The ratio of GDQE of the MAF-HR compared to the GDQE of the MAF-HL at 3(6) cycles/mm was 1.23(2.89).

4. Conclusion

In this report, we evaluate and compare the total system performance of the FPD, MAF-HR and MAF-HL for a realistic clinical situation as compared to the intrinsic detector performance. The MAF-HR performs significantly better than the MAF-HL, especially at higher frequency in terms of GMTF and GDQE. The GDQE and GMTF for both MAFs are degraded, especially at low frequency due to the scatter from the object, and at high frequency due to the focal spot blur of the finite focal spot size. Despite the degradation, both the MAF-HR and MAF-HL perform significantly better than the commercial FPD at higher frequency.

Acknowledgments

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Figure 1.
Schematic of MAF.

Figure 2.
Picture of MAF.

Figure 3.
Experimental set up.

Figure 4.
Scatter MTF for the head phantom and focal spot MTF for small focal spot (0.3mm).

Figure 5.
Detector MTF for MAF-HR, MAF-HL, and FPD, using slanted edge method.

Figure 6.
1D NNPS (radially averaged) for MAF-HR, MAFHL, and FPD.

Figure 7.
GMTFs for MAF-HR at different magnifications and scatter fractions.

Figure 8.
GMTFs for MAF-HL at different magnifications and scatter fractions.

Figure 9.
GMTFs for MAF-HR, MAF-HL, and FPD at a fixed magnification and scatter fraction.

Figure 10.
Detector DQE for MAF-HR, MAF-HL, and FPD.

Figure 11.
GDQEs for MAF-HR at different magnifications and scatter fractions.

Figure 12.
GDQEs for MAF-HL at different magnifications and scatter fractions.

Figure 13.
GDQEs for MAF-HR, MAF-HL, and FPD at a fixed magnification and scatter fraction.