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A method for the determination of the two-dimensional MTF of digital radiography systems using only the noise response

Andrew Kuhls-Gilcrist^{*}, Daniel R. Bednarek, and Stephen Rudin

University at Buffalo (State University of New York), Toshiba Stroke Research Center, 3435 Main St., Buffalo, NY USA 14214

Abstract

We present a new method that enables the determination of the two-dimensional MTF of digital radiography systems using the noise response measured from flat-field images. Unlike commonly-used methods that measure the one-dimensional MTF, this new method does not require precision-made test-objects (slits/edges) or precise tool alignment. Although standard methods are dependent upon data processing that can result in inaccuracies and inconsistencies, this method based on the intrinsic noise response of the imager is highly accurate and less susceptible to such problems. A cascaded-linear-systems analysis was used to derive an exact relationship between the noise power spectrum (NPS) and the presampled MTF of a generalized detector system. The NPS was then used to determine the two-dimensional MTF for three systems: a simulated detector in which the “true” MTF was known exactly, a commercial indirect flat-panel detector (FPD), and a new solid-state x-ray image intensifier (SSXII). For the simulated detector, excellent agreement was observed between the “true” MTF and that determined using the noise response method, with an averaged deviation of 0.3%. The FPD MTF was shown to increase on the diagonals and was measured at 2.5 cycles/mm to be 0.086 ± 0.007 , 0.12 ± 0.01 , and 0.087 ± 0.007 at 0, 45, and 90°, respectively. No statistically significant variation was observed for the SSXII as a function of angle. Measuring the two-dimensional MTF should lead to more accurate characterization of the detector resolution response, incorporating any potential non-isotropy which may result from the physical characteristics of the sensor, including the active-area shape of the pixel array.

Keywords

MTF; two-dimensional MTF; NPS; detector; performance; flat panel detector; SSXII; image quality

1. INTRODUCTION

The modulation transfer function (MTF) is the most widely accepted measure of the spatial resolution response of medical x-ray imaging detectors and has proved to be a valuable tool for determining and comparing detector performance. The slit¹ and edge² response methods are the two most commonly used and accepted techniques for measuring the MTF. The edge response (ER) method is presently preferred and has been adopted by the IEC for a variety of reasons.³ An edge is relatively simpler to construct than a slit (one polished edge versus two polished edges spaced parallel to each other). The ER method is also less sensitive to physical imperfections and misalignments of the edge device.² However, it is well documented that the ER method is vulnerable to a host of potential problems which could

^{*}Corresponding author: Andrew Kuhls-Gilcrist. atkuhls@buffalo.edu; Dept. of Physics; Phone: 716 829 5416.

influence the measurement and result in inaccuracies. The edge spread function must be numerically differentiated to obtain the line spread function, which results in an amplification of the noise and hinders accurate measurements at higher spatial frequencies (where the slit method's performance is superior).^{2, 4} Inaccuracies may also result from errors in the calculated edge angle, noise, influences of scattered radiation, profile misregistration and phasing errors, truncation of the LSF tails and incorrect normalization, and windowing and processing.^{2, 5-9} Difficulties also arise when comparing measurements performed at different facilities by different investigators, as slight differences in object, acquisition, and/or processing techniques could easily alter the results.^{7, 10} In one study, several research groups analyzed the same edge image using their own image analysis algorithms and the results demonstrated that significant inconsistencies exist — even under otherwise identical conditions.¹¹

Further complicating standard MTF measurement techniques, present methods rely on use of precisely machined test objects that must be carefully aligned such that the edge(s) are parallel to the x-ray beam. This alignment is often achieved with the aid of a laser beam or other iterative techniques and by using a special holder that can provide fine movement of the test object. The test object must also be oriented at a slight angle relative to the pixel matrix to provide a finely sampled response. As such, both the slit and edge response methods are inherently one-dimensional and have difficulty measuring the MTF at angles greater than a few degrees. Two measurements are often taken — one in the horizontal direction and one in the vertical direction — to “completely” quantify a detector's resolution response. Such an approach fails to provide a complete description of the detector resolution response in all directions and does not incorporate potential non-isotropy.

Others have proposed techniques to determine the two-dimensional MTF. One such method uses a “point source array” test object that contains an array of holes machined in a uniformly attenuating object.¹²⁻¹³ The center location can be determined for each spot to subpixel accuracy by fitting the signal profile with a two-dimensional Gaussian function. Each hole's center is presumably at a slightly different location within a particular pixel, and a finely sampled point spread function can be determined by registering all of the spots in the array. MTF non-isotropy was observed for a variety of different detectors, and the authors of these works have highlighted the importance of completely characterizing the MTF in all directions.¹²⁻¹⁴ Although such “point source array” methods enable measurement of the two-dimensional MTF, they likely suffer from similar technical difficulties as experienced with other methods that rely on the use of precision test objects (such as influences of physical imperfections, scattered radiation, profile misregistration, truncation and overlap of the PSF tails, etc.).

The aim of this work was to develop a new and simple method for measuring the two-dimensional MTF of digital radiography systems, termed the noise-response (NR) method. Unlike commonly-used methods that measure the one-dimensional MTF, the new NR method does not require precision-made test objects (slits, edges, point source arrays, etc.) or precise tool alignment. Although standard methods are dependent upon data processing that can result in inaccuracies and inconsistencies, this method based on the intrinsic noise response of the imager is highly accurate and less susceptible to such problems. A theoretical cascaded-linear-systems analysis was used to derive an exact relationship between the noise power spectrum (NPS) and the presampled MTF of a generalized detector system. The NPS was then used to determine the two-dimensional MTF, as described below.

2. MATERIALS AND METHODS

2.1 Theory

Cascaded-linear systems analysis models a detector as a set of fundamental interaction stages. At each stage, quanta undergo one of the following processes: amplification, blurring, additive noise, or aliasing. The output of one stage is the subsequent input to the next stage. Parallel processes may occur due to K-flourescence in the x-ray absorbing material.¹⁵ The affect these processes have on signal and noise is well described and excellent agreement has been observed between calculated and measured results for a wide variety of detector technologies over the past several decades.^{16–21}

A theoretical cascaded-linear systems analysis was used to develop an exact relationship between the two-dimensional noise power spectrum (NPS) and the presampled MTF for a generalized detector system as described by²²

$$NPS(u, v) = \Delta x \Delta y \left[\tilde{g} \frac{T_{sys}^2(u, v)}{A_s(u, v)} + \frac{g_4}{F_p} \right] \Phi_4 + NPS_{ADD}(u, v) \quad (1)$$

where u and v are the spatial frequencies in the horizontal and vertical directions, Δx and Δy are the pixel width in the horizontal and vertical directions, $\tilde{g}$ is the effective system gain in units of digital number (DN) per absorbed x-ray photon, $A_s(u, v)$ is the frequency-dependent Swank noise,²³ T_{sys} is the system MTF, g_4 is the electron-to-digital-number conversion factor, F_p is the pixel fill factor, Φ_4 is the average digital detector signal, and $NPS_{ADD}(u, v)$ is the additive electronic noise. The NPS consists of additive contributions from quantum noise (primary quantum, secondary quantum, and Poisson excess noise), which scale with the detector entrance exposure (or similarly, Φ_4) and additive electronic noise, which is independent of exposure.²⁴ Structure noise, which scales with the squared exposure has been omitted, as the images are assumed to have been corrected for gain and offset. The form of Eq. (1) is generic for a wide range of detector technologies. From Eq. (1), it is evident that the presampled detector MTF is inherently included in the NPS and can be isolated by separating the various noise components.

The quantum noise terms that scale proportionally with detector entrance exposure (or similarly, with Φ_4) can be separated from the additive instrumentation noise by determining the slope of a linear fit of the two-dimensional NPS plotted versus mean signal (Φ_4), at each spatial frequency u and v , which can be written as

$$Slope(u, v) = \frac{\Delta x \Delta y \tilde{g}}{A_s(u, v)} T_{sys}^2(u, v) + \frac{\Delta x \Delta y g_4}{F_p}. \quad (2)$$

The presampled detector MTF (T_{SYS}) can be determined from this two-dimensional slope data, which is representative of the quantum noise per unit signal. Using a simple fitting technique, $T_{SYS}(u, v)$ can be extracted from this data by choosing a functional form of T_{SYS} . For the analysis presented in this work, a one-dimensional Gaussian function was used to fit radial slices of the two-dimensional slope, taken at half-degree intervals. This approach generally provided an excellent fit of the data. The fitting function used was

$$F_{\text{Gaussian Mixture},\theta}(f) = \frac{h_{1,\theta}}{A_S(f)} \left[h_{2,\theta} \exp\left(\frac{(f - h_{3,\theta})^2}{h_{4,\theta}}\right) \right]^2 + h_{5,\theta} \quad (3)$$

where $h_{i,\theta}$ corresponds to the i th fitting parameter for the radial slice taken at angle θ . Derivation and calculation of $A_S(f)$ has been described by Hadjok et al., demonstrating good agreement with Monte Carlo and measured results.²³ The one-dimensional MTF obtained from this fit can then be written as

$$T_{\text{SYS},\theta}(f) = \frac{\exp\left(-\frac{(f - h_{3,\theta})^2}{h_{4,\theta}}\right)}{\exp\left(-\frac{h_{3,\theta}^2}{h_{4,\theta}}\right)}. \quad (4)$$

The two-dimensional MTF was then obtained by combining the radial MTFs ($T_{\text{SYS},\theta}$) at all angles. Care must be exhibited to insure that the chosen functional form of T_{SYS} provides a good fit of the measured data at all spatial frequencies. The use of other function forms and techniques to extract T_{SYS} have been discussed elsewhere.²² As the fitting process takes very little computational time, a variety of fitting functions using different functional forms can be used and the one providing the best fit can then be selected for subsequent determination of the MTF. Additional noise sources that have not been implicitly included in Eq. (1) would likely not change the form of this equation and would be absorbed in the fit parameters $h_{1,\theta}$ and $h_{5,\theta}$, shown in Eq. (3).²²

2.2 Image Simulations

To assess the accuracy of the NR method, images were simulated for a simple high-resolution indirect detector model, using MATLAB (version 7.9.0, Mathworks, Natick, MA). The simulated detector was comprised of six interaction stages: x-ray absorption, x-ray-to-light conversion, light blur, light-to-electron conversion, electron-to-digital number conversion, and additive electronic noise. The image matrix contained 1000×1000 , $32 \mu\text{m}$ square pixels and images were generated according to the following prescription. First, a number of incident x-ray photons were generated per pixel using a random number generator from the Poisson distribution with a mean value of λ . Six different detector entrance exposures were considered, 4.4, 7.0, 11, 14, 17, and 21 nC/kg, corresponding to a λ of 5, 8, 13, 16, 20, and 25 incident x-ray photons per pixel with the RQA 5 x-ray spectrum, respectively. The number of absorbed x-ray photons was then determined using binomial selection with a success rate of 0.77. The absorbed x-ray photons were then converted to light using a conversion gain of 500 (assumed for simplicity to be Poisson distributed). The blur associated with this conversion process was taken to be a single Gaussian with a full width half maximum of two pixels (corresponding to a standard deviation of $28 \mu\text{m}$). Light photons were then converted to electrons using binomial selection with a success rate of 0.5. Electrons were subsequently “digitized” using an electron-to-digital number conversion factor of 0.8 electrons per DN. Finally electronic noise was added (Gaussian with zero-mean) with a standard deviation of 10 DN. The “true” MTF of this simulated detector system was known exactly, and is given by

$$T_{\text{“TRUE”}}(u, v) = \exp\left\{-\frac{1}{2}[(2\pi\sigma\Delta xu)^2 + (2\pi\sigma\Delta yv)^2]\right\} \frac{\sin(\pi\Delta xu)}{\pi\Delta xu} \frac{\sin(\pi\Delta yv)}{\pi\Delta yv} \quad (5)$$

where τ is the standard deviation of the Gaussian blurring function. Thirty images were generated at each of the six detector entrance exposures used. The MTF was then measured from these flat-field images, using the NR method, as described in Sec. 2.1. Accuracy of the NR method was then investigated relative to the known truth.

Similarly, edge images were also generated for this simulated detector model, using methods similar to those described by others.⁷ The edge was placed at the center of the image matrix and oriented at an angle of 2° relative to the pixel rows. The transmission of the edge was taken to be 0.05. To reduce the noise content in the images, an average of ten frames was used for further analysis. The averaged edge image was then analyzed using standard techniques, with no image processing (i.e., no smoothing of the ESF or use of a windowing function for suppression of high-frequency noise) as such processing would inherently alter the results.

2.3 Experimental Measurements

For further investigation, the two-dimensional MTF was measured for two detector systems, a clinical Varian Paxscan 2020+ flat panel detector (FPD) (Palo Alto, CA) and a high-resolution, high-sensitivity solid state x-ray image intensifier (SSXII).^{21, 25–26} The FPD implements a 600 μm -thick CsI(Tl) phosphor and has a pixel pitch of 194 μm . The x-ray scatter reduction grid was removed and all image processing was disabled. The SSXII is a prototype detector based on electron multiplying CCDs (EMCCDs) that employs a 375 μm -thick CsI(Tl) phosphor and has an effective pixel size of 32 μm .

2.4 Procedure

Thirty flat-field images were acquired at six different detector entrance exposure levels, spanning a majority of the dynamic range of the detectors. NPS measurements were done as prescribed by the IEC, using a standardized x-ray spectrum (RQA 5) and measurement geometry.³ Frequencies were sampled at an interval spacing of $f_N/128$ (i.e., an ROI of 256×256 was used to determine the NPS), where f_N represents the Nyquist frequency of the detector. A linear regression fitted to a plot of NPS versus signal was used to separate the quantum and additive noise with the slope representing the quantum noise per unit signal [Eq. (1)]. This was done at each spatial frequency u and v , providing a two-dimensional distribution of the quantum noise component of the NPS. The two-dimensional MTF was then determined using the quantum noise component of the NPS and the fitting technique described in Sec. 2.1, using Eq. (3) and (4). The “directional” MTF was also determined by taking radial slices at 5° intervals, ranging from 0 to 180° relative to the pixel rows. For comparison, edge images were also acquired and analyzed using standard methods to determine the ER MTF in the horizontal and vertical directions. Results were then compared between the one-dimensional MTFs measured using the new NR and the established ER methods. Three separate measurements were done in each instance, the standard deviation of which was used to represent the experimental uncertainty.

3. RESULTS AND DISCUSSION

3.1 Image Simulations

The presampled MTF obtained using the NR and ER methods for the simulated detector system are shown in Fig. 1. Also shown in this plot is the “true” MTF, which was known exactly. The MTF determined using the NR method was in very good agreement with the “true” MTF with an averaged percent deviation of 0.3% (mean difference of 0.001) and a maximum of 1.1% at the Nyquist frequency. The MTF obtained using the ER method was shown to deviate from the “true” MTF at higher spatial frequencies with an averaged deviation of 35%, beyond 12.5 cycles/mm (i.e., between $0.8 f_N$ and f_N). Error is evident in

the ER method even under these simplified imaging conditions (e.g., the edge angle was known exactly, influences of scattered radiation from the edge device were not included, etc.). These simulation results demonstrate that the NR method can accurately determine the MTF, whereas the ER method was shown to have difficulties at higher spatial frequencies.

Fig. 2 shows the MTF measured using the NR method plotted as a function of angle for five different spatial frequencies (5, 7.5, 10, 12.5, and 15 cycles/mm). Although largely constant, a slight increase was observed on the diagonal (e.g., 45° and 135°) as compared to the horizontal or vertical directions (0, 90, and 180°) of ~4% at 15 cycles/mm. This is in general agreement with the expected behavior of a two-dimensional square aperture function (i.e., from a two-dimensional sinc function).²⁷

3.2 Experimental Measurements

The measured presampled MTF using the NR and ER methods for the FPD and SSXII are shown in Fig. 3 and Fig. 4, respectively. The error bars, which represent the variation in the measurements, were substantially larger for the ER method. This is likely in part due to slight differences in the edge alignment relative to the x-ray beam and the detector. The error bars with the NR method were less than the thickness of the curves, demonstrating excellent reproducibility. The MTFs largely exhibit agreement within experimental uncertainty. However, at higher spatial frequencies, the MTF obtained using the ER method was larger, on average, at higher spatial frequencies. The averaged percent difference was 32% (mean difference of 0.05) for the FPD and 27% (mean difference of 0.005) for the SSXII for spatial frequencies ranging from $0.8 f_N$ to f_N . These discrepancies are similar to those observed in the simulation results presented above, suggesting that these differences are a result of the inherent error of the ER method.

Fig. 5 and Fig. 6 show the two-dimensional presampled MTF for the FPD and the SSXII, respectively, obtained using the NR method. Non-isotropy is evident in the FPD MTF and is more clearly illustrated in Fig. 7, where the MTF is plotted as a function of angle (relative to the pixel rows) for five different spatial frequencies (0.5, 1, 1.5, 2, and 2.5 cycles/mm). The FPD MTF at 0, 45, and 90° was measured to be 0.086 ± 0.007 , 0.12 ± 0.01 , and 0.087 ± 0.007 at 2.5 cycles/mm, where the relative difference was most pronounced. Fig. 8 shows the SSXII MTF plot as a function of angle at spatial frequencies of 0.5, 1, 1.5, 2, 2.5, 5, and 10 cycles/mm. No statistically significant variation in measured MTF was observed as a function of angle with values at 0, 45, and 90° of 0.021 ± 0.005 , 0.019 ± 0.003 , and 0.018 ± 0.006 at 10 cycles/mm, respectively.

A difference in the shape of the two-dimensional MTF was evident between the two detector technologies. This is likely in part due to the relative importance of the isotropic blur of the phosphor and the non-isotropic blur of the detector elements. That is, for the larger pixel FPD, the blur of the detector elements is relatively more important, resulting in more non-isotropy in the MTF than for the smaller pixel SSXII for which the isotropic blur dominates. Others have also demonstrated that the active-area shape ("L" shaped for the FPD and square for the SSXII) of the pixel array contributes significantly to the behavior of the overall MTF.²⁷ Other factors, including diffusion and crosstalk, also have an effect on the overall MTF.²⁷ Measurement of the two-dimensional MTF enables a more accurate characterization of the detector resolution response, determination of the two-dimensional DQE, and may be used to improve upon detector designs and observer performance models.

The primary motivation behind this work was to provide an alternative method for measuring the presampled MTF of digital radiography detectors that simplifies the process as compared to standard methods that rely on use of precision test objects (such as slits and

edges). However, the results presented in this analysis demonstrate that the new NR method may additionally provide improved accuracy. The two-dimensional MTF is also readily obtained with the NR method, thereby better quantifying the detector resolution response by incorporating any potential non-isotropy.

Others have proposed and implemented measurement of the DQE and MTF as part of a robust QA program in a hospital setting.²⁸ Routine monitoring of these system performance metrics may provide early warning of system problems and/or failures. Further, with wide implementation of such a QA program, differences in detector performance will become more apparent to those using the equipment (with the posting of MTF's and DQE's), which may lead to more informative detector operation and decision making in the future procurement of imaging equipment. By providing a fast and simple method for measuring the MTF that uses the measured NPS and only requires flat-field images, this type of QA program becomes substantially more practical.

4. SUMMARY AND CONCLUSION

A new method for determination of the presampled MTF, the “noise response method”, has been described. Compared to current measurement methods, the noise response method simplifies the MTF determination by eliminating the need for precisely machined test objects such as edges and slits, thereby eliminating potential inaccuracies that may result from the use of such objects and subsequent analysis of the resulting images. The accuracy of this method was demonstrated using image simulations for which the “true” MTF was known exactly. Excellent agreement was obtained with the MTF determined using the noise response method, whereas significant deviations were observed at higher spatial frequencies when using the standard ER method. Additionally, the two-dimensional MTF is readily obtained with the noise response method, whereas traditional edge and slit methods are inherently one-dimensional. Differences were measured in the MTF, as a function of angle, for the FPD whereas the SSXII MTF was approximately constant. Measuring the two-dimensional MTF provides a more accurate characterization of the overall detector resolution response. The significant advantages of the noise response method indicate that this new method is a promising candidate to replace existing standard methods.

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Figure 1.

The presampled MTF for the simulated high-resolution detector system determined using the NR and ER methods averaged along the orthogonal directions, shown on a semi-logarithmic plot. The “true” MTF of the detector was known exactly and is also shown in the plot.

Figure 2. The presampled MTF as a function of angle (relative to the pixel rows) for the simulated high-resolution detector system measured using the NR method for five spatial frequencies (5, 7.5, 10, 12.5, 15), shown on a semi-logarithmic plot.

Figure 3.

The presampled MTF averaged along the orthogonal directions for the FPD measured using the NR and ER methods, plotted up to 2.5 cycles/mm. Error bars represent the standard deviation of three separate measurements and were less than the thickness of the curve for the NR method.

Figure 4.

The presampled MTF averaged along the orthogonal directions for the SSXII measured using the NR and ER methods, plotted up to 10 cycles/mm. Error bars represent the standard deviation of three separate measurements and were less than the thickness of the curve for the NR method.

Figure 5.
The two-dimensional presampled MTF of the FPD measured using the NR method, plotted up to 2.5 cycles/mm.

Figure 6.

The two-dimensional presampled MTF of the SSXII measured using the NR method, plotted up to 10 cycles/mm.

Figure 7.

The presampled MTF as a function of angle (relative to the pixel rows) for the FPD measured using the NR method for five spatial frequencies (0.5, 1, 1.5, 2, and 2.5 cycles/mm), shown on a semi-logarithmic plot. Error bars represent the standard deviation of three separate measurements. At 2 cycles/mm and below, the error bars were smaller than the thickness of the curve.

Figure 8.

The presampled MTF as a function of angle (relative to the pixel rows) for the SSXII measured using the NR method for seven spatial frequencies (0.5, 1, 1.5, 2, 2.5, 5, 10 cycles/mm), shown on a semi-logarithmic plot. Error bars represent the standard deviation of three separate measurements. At 2 cycles/mm and below, the error bars were smaller than the thickness of the curve.