Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2011 March 1; 7961(0): . doi:10.1117/12.877890.

Measuring the presampled MTF from a reduced number of flat-field images using the Noise Response (NR) method

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

^aToshiba America Medical Systems, 2441 Michelle Dr., Tustin, CA USA 92780

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

Abstract

We evaluate a new method for measuring the presampled modulation transfer function (MTF) using the noise power spectrum (NPS) obtained from a few flat-field images acquired at one exposure level. The NPS is the sum of structure, quantum, and additive instrumentation noise, which are proportional to exposure squared, exposure, and a constant, respectively, with the spatial-frequency dependence of the quantum noise depending partly on the detector MTF. Cascaded linear-systems theory was used to derive an exact and generic relationship that was used to isolate noise terms and enable determination of the MTF *directly* from the noise response, thereby circumventing the need for precision test objects (slit, edge, etc.) as required by standard techniques. Isolation of the quantum NPS by fitting the total NPS versus exposure obtained using 30 flat-field images each at six or more different exposure levels with a linear regression provides highly accurate MTFs. A subset of these images from indirect digital detectors was used to investigate the accuracy of measuring the MTF from 30 or fewer flat-field images obtained at a single exposure level. Analyzing as few as two images acquired at a single exposure resulted in no observable systematic error. Increasing the number of images analyzed resulted in an increase in accuracy. Fifteen images provided comparable accuracy with the most rigorous slope approach, with less than 5% variability, suggesting additional image acquisitions may be unnecessary. Reducing the number of images acquired for the noise response method further simplifies and facilitates routine MTF measurements.

Keywords

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

1. INTRODUCTION

The modulation transfer function (MTF) is the most widely accepted objective measure of the spatial resolution response of medical x-ray imaging detectors. The MTF has proven to

be a valuable tool for determining and comparing detector performance. To measure the MTF, the slit¹ and edge² response methods are the two most commonly used techniques with the edge response (ER) method being preferred (with adoption by the IEC)³ for reasons that include simpler construction and less sensitivity to misalignment. However, it is well documented that the ER method is also vulnerable to a host of potential problems which could influence the measurement and result in inaccuracies. Inaccuracies may result from errors in the calculated edge angle, noise, influences of scattered radiation, use of finite-element differentiation, profile misregistration and phasing errors, truncation of the LSF tails and incorrect normalization, and windowing and processing.^{2,4-8} Difficulties also arise when comparing measurements with published results of other investigators, as slight differences in object, acquisition, and/or processing techniques could easily alter the results.^{9,10} Significant variations have even been shown to occur when different individuals measured the MTF of the *same* data set.¹¹ Further, standard methods are inherently one-dimensional and cannot measure the MTF at angles larger than a few degrees relative to the pixel matrix. The aim of this work is to continue development of a new and simple method for measurement of the MTF of digital radiographic systems that is highly-accurate and less susceptible to such influences, by using the intrinsic noise response of the imager.^{12,13}

We have recently developed the noise response (NR) method, which determines the detector MTF using only flat-field images.^{12,13} The NPS is the sum of structure, quantum, and additive instrumentation noise, which are proportional to exposure squared, exposure, and a constant, respectively, with the spatial-frequency dependence of the quantum noise depending partly on the detector MTF. Cascaded linear-systems theory was used to derive a general relationship that can be used to isolate noise terms and enables determination of the MTF *directly* from the noise response, thereby circumventing the need for precision test objects (slit, edge, etc.) as required by standard techniques. Isolation of the quantum NPS by fitting the total NPS versus exposure obtained using 30 flat-field images each at six or more different exposure levels with a linear regression has been shown to provide highly accurate MTFs on a variety of indirect detector technologies.¹³ To further simplify the NR method, a subset of these images was used to investigate the accuracy of measuring the MTF from 30 or fewer flat-field images obtained at a single exposure level.

2. MATERIALS AND METHODS

A cascaded-linear systems analysis was used to develop an exact relationship between the noise power spectrum (NPS) and the presampled MTF for a generalized indirect, energy integrating detector system. This relationship was then utilized to determine the presampled MTF from the noise response alone (i.e. using no test object) as described in sections 2.1 and 2.2. The NPS has the following general form^{13,14}

$$NPS(f, X) = NPS_{STRUCTURE}(f, X^2) + [\Delta x \tilde{g} A_s^{-1}(f) T_{SYS}^2(f) + \Delta x g_4] \Phi_4(X) + NPS_{ADD}(f) \quad (1)$$

where f is the spatial frequency, X is the detector entrance exposure, $NPS_{STRUCTURE}(f, X^2)$ is the structure noise, x is the pixel width, $\tilde{g}$ is the effective system gain in units of digital number (DN) per absorbed x-ray photon, $A_s(J)$ is the frequency-dependent Swank noise factor,¹⁵ T_{SYS} is the system MTF, g_4 is the electron-to-digital-number conversion factor,

$\Phi_4(X)$ is the digital output signal at zero-frequency and exposure X , and $NPS_{ADD}(f)$ is the additive electronic noise. The NPS consists of additive contributions from structure noise that scales with X^2 , which is negligible in images corrected for variations in detector sensitivity;¹³ quantum noise that scales with X , which includes the sum of primary quantum and Poisson excess noise (given by the first term in the brackets in Eq. 1) and secondary quantum noise (given by the second term in the brackets in Eq. 1); and additive electronic noise, which is independent of exposure. For simplicity, this work considers only the one-dimensional MTF. In previous work, we have demonstrated that the two-dimensional MTF can also be readily measured using the NR method and the two-dimensional NPS.¹² The NPS of other detector technologies (e.g., those used in CR) have been shown to have the same form as Eq. (1), suggesting this approach is not limited in scope.¹⁶

Measurements were done on an indirect flat panel detector (Varian, Palo Alto, CA) with a 600 μm CsI:Tl phosphor and 194 μm pixels and a custom built high-resolution, high-sensitivity solid state x-ray image intensifier (SSXII) with a 350 μm CsI:Tl phosphor and 32 μm pixels.^{14,17–19} An average of at least three measurements were taken in each instance and the standard deviation was used to represent the “accuracy” or variability of the measurement.

2.1 “Slope” approach

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 $f_N/128$, where f_N represents the Nyquist frequency of the detector. A linear regression fitted to a plot of $NPS(f)$ versus signal was used to separate the quantum and additive noise with the slope representing the quantum noise per unit signal [Eq. (1)] at each spatial frequency f . The system MTF [$T_{SYS}(f)$] was then determined, from the quantum noise component of the NPS. The functional form of $T_{SYS}(f)$ was assumed to be a single Gaussian, which has been derived based on considerations of physical systems²⁰

$$T_{SYS}(f) = h_2 \exp\left(-\frac{(f - h_3)^2}{h_4}\right) \quad (2)$$

This generally provided an excellent fit of the data. Use of different functional forms has been discussed elsewhere.¹³ The following fitting function [derived from Eq. (1) and Eq. (2)] was then used to fit the quantum noise component of the NPS

$$F_{\text{Gaussian Mixture}}(f) = \frac{h_1}{A_S(f)} \left[h_2 \exp\left(-\frac{(f - h_3)^2}{h_4}\right) \right]^2 + h_5 \quad (3)$$

where $A_S(f)$ is the calculated frequency-dependent Swank factor and h_i corresponds to the i th fitting parameter. Derivation and calculation of $A_S(f)$ has been described by Hadjok et al., demonstrating excellent agreement with Monte Carlo and measured results.¹⁵ The MTF was then determined directly from this fit; therefore, the only specifications of the detector

needed are the x-ray absorbing material (e.g., CsI) and its approximate thickness for the determination of $A_s(f)$. Uncertainties in the phosphor thickness have been shown to have minimal influence on the MTF results.¹³ Exceptional agreement between the NR MTF and the “true” MTF has been demonstrated using simulated detector systems (Fig. 1) and measurements have indicated accuracies are better than the standard edge response method (Fig. 2).^{12, 13} Given its high accuracy, this approach is considered to be the “gold standard” for this study.

2.2 “Simplified” approach

The “slope” approach described above simplifies the MTF measurement by eliminating the need for, alignment of, and subsequent image analysis of precision test objects and has demonstrated very high accuracy. For further simplification, we investigate the accuracy of using fewer images by determining the MTF from various subsets of images acquired for the “slope” approach, using as few as two images obtained at one exposure level. An average of the number of flat-field images selected was used to correct for gain variations. No offset correction was implemented.

3. RESULTS AND DISCUSSION

The dark-field NPS [$\Phi_4 = 0$; $NPS(f) = NPS_{ADD}(f)$] was measured and compared with the flat-field NPS [$NPS(f)$ given by Eq. (1)] obtained at ~75% maximum signal (roughly 3000 DN for the 12-bit detectors studied). The additive instrumentation noise was approximately constant as a function of spatial frequency and its magnitude was substantially less than the quantum NPS for both detectors, as shown in Figure 3. Similar results have been measured by others on other detector technologies.¹⁶ This indicates the NPS measured from a single set of flat-field images can be used to directly obtain the MTF, eliminating the necessity of isolating and separating the additive instrumentation noise term. Using a simple fitting technique [Eq. (3)], non-negligible “white” instrumentation noise would be absorbed in the h_5 fitting parameter and is therefore expected also to not alter the measured MTF. Alternatively, the additive instrumentation NPS can be directly measured and subtracted from the total NPS.

The FPD presampled MTF measured using the noise and edge response methods is shown in Figure 4. The MTF obtained using five flat-field images was in agreement with the most rigorous “slope” approach with an increase in the experimental variability, as demonstrated by the increase in the size of the error bars from less than the thickness of the curve to comparable with the ER variability. The NR and ER methods agree within experimental uncertainty, with systematic differences following the demonstrated error in the ER method (Figure 2).

Similar agreement was observed with the SSXII, as shown in Figure 5. The averaged absolute percent difference between measurements is shown in Figure 6. Using as few as two images acquired at a single exposure resulted in no systematic error (as shown by the NR MTF curves overlapping in Figure 5) and less than 30% maximum variability (corresponding to variability in the MTF of less than 0.01) at 10 cycles/mm. Increasing the number of images analyzed resulted in an increase in accuracy. Fifteen images acquired at

one exposure level provided comparable accuracy to the most rigorous slope approach, with less than 5% variability at the highest spatial-frequencies. This suggests that additional data acquisition is unnecessary, unless additional precision is required.

4. SUMMARY AND CONCLUSION

A new method for determination of the two-dimensional presampled MTF, the “noise response” (NR) method, has been described. 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. Isolation of the quantum NPS by plotting the total NPS versus exposure was shown to provide highly accurate MTFs for image simulations in which the “true” MTF was known exactly. A subset of these images was used to investigate the accuracy of measuring the MTF using fewer flat-field images obtained at a single exposure level. Measurements on indirect digital detectors suggest as few as two images acquired at a single exposure level can be used with no observable systematic error and less than 30% maximum variability at the very highest spatial frequencies where the standard edge method can deviate by as much as 80%. Increasing the number of images analyzed resulted in an increase in accuracy. Fifteen images provided comparable accuracy with the most rigorous NR slope approach, with less than 5% variability. This suggests additional image acquisitions may be unnecessary, unless very high accuracy is desired. Reducing the number of images acquired for the noise response method further simplifies and facilitates routine MTF measurements that are workable in routine quality assurance.

ACKNOWLEDGEMENTS

This work was supported by NIH R01 Grants EB002873 and EB008425 and an equipment grant from Toshiba Medical Systems Corporation.

REFERENCES

1. Fujita H, Tsai DY, Itoh T, Doi K, Morishita J, Ueda K, Ohtsuka A. A simple method for determining the modulation transfer function in digital radiography. *IEEE Trans Med Imaging*. 1992; 11:34–39. [PubMed: 18218354]
2. Samei E, Flynn MJ, Reimann DA. A method for measuring the presampled MTF of digital radiographic systems using an edge test device. *Med Phys*. 1998; 25:102–113. [PubMed: 9472832]
3. 62220-1, I. E. C.. Medical electrical equipment: Characteristics of digital x-ray imaging devices - Part 1: Determination of the detective quantum efficiency. Geneva, Switzerland: International Electrotechnical Commission; 2003.
4. Greer PB, van Doorn T. Evaluation of an algorithm for the assessment of the MTF using an edge method. *Med Phys*. 2000; 27:2048–2059. [PubMed: 11011732]
5. Buhr E, Gunther-Kohfahl S, Neitzel U. Accuracy of a simple method for deriving the presampled modulation transfer function of a digital radiographic system from an edge image. *Med Phys*. 2003; 30:2323–2331. [PubMed: 14528954]
6. Carton AK, Vandenbroucke D, Struye L, Maidment AD, Kao YH, Albert M, Bosmans H, Marchal G. Validation of MTF measurement for digital mammography quality control. *Med Phys*. 2005; 32:1684–1695. [PubMed: 16013727]
7. Neitzel U, Buhr E, Hilgers G, Granfors PR. Determination of the modulation transfer function using the edge method: influence of scattered radiation. *Med Phys*. 2004; 31:3485–3491. [PubMed: 15651631]

8. Friedman SN, Cunningham IA. Normalization of the modulation transfer function: the open-field approach. *Med Phys.* 2008; 35:4443–4449. [PubMed: 18975691]
9. Samei E, Ranger NT, Dobbins JT, Chen Y. Intercomparison of methods for image quality characterization. I. Modulation transfer function. *Med Phys.* 2006; 33:1454–1465. [PubMed: 16752580]
10. Carton AK, Bosmans H, Marchal G, Vandenbroucke D, Struye L, Maidment ADA, Kao YH, Albert M. Validation of MTF measurement for digital mammography quality control. *Med Phys.* 2005; 32:1684–1695. [PubMed: 16013727]
11. Neitzel U, Gunther-Kohfahl S, Borasi G, Samei E. Determination of the detective quantum efficiency of a digital x-ray detector: comparison of three evaluations using a common image data set. *Med Phys.* 2004; 31:2205–2211. [PubMed: 15377085]
12. Kuhls-Gilcris A, Bednarek DR, Rudin S. A method for the determination of the two-dimensional MTF of digital radiography systems using only the noise response. *Proc of SPIE.* 2010; 7622:76224W.
13. Kuhls-Gilcris A, Jain A, Bednarek D, Hoffmann K, Rudin S. Accurate MTF measurement in digital radiography using noise response. *Med Phys.* 2010; 37:724–735. [PubMed: 20229882]
14. Kuhls AT, Yadava G, Patel V, Bednarek DR, Rudin S. Progress in electron-multiplying CCD (EMCCD) based, high-resolution, high-sensitivity x-ray detector for fluoroscopy and radiography. *Proc SPIE.* 2007; 6510:65101C.
15. Hajdok G, Battista JJ, Cunningham IA. Fundamental x-ray interaction limits in diagnostic imaging detectors: frequency-dependent Swank noise. *Med Phys.* 2008; 35:3194–3204. [PubMed: 18697544]
16. Mackenzie A, Honey ID. Characterization of noise sources for two generations of computed radiography systems using powder and crystalline photostimulable phosphors. *Med Phys.* 2007; 34:3345–3357. [PubMed: 17879798]
17. Kuhls-Gilcris A, Yadava G, Patel V, Jain A, Bednarek DR, Rudin S. The solid state x-ray image intensifier (SSXII): An EMCCD-based x-ray detector. *Proc of SPIE.* 2008; 6913:69130K.
18. Kuhls-Gilcris A, Bednarek DR, Rudin S. Component analysis of a new solid state x-ray image intensifier (SSXII) using photon transfer and instrumentation noise equivalent exposure (INEE) measurements. *Proc SPIE.* 2009; 7258:725817.
19. Kuhls-Gilcris A, Jain A, Bednarek DR, Rudin S. The solid state x-ray image intensifier (SSXII) in single photon counting (SPC) mode. *Proc SPIE.* 2010; 7622:76221P.
20. Kyprianou IS, Badano A, Gallas BD, Myers KJ. Singular value description of a digital radiographic detector: Theory and measurements. *Med Phys.* 2008; 35:4744–4756. [PubMed: 18975719]
21. Cunningham IA. Use of the Detective Quantum Efficiency in a Quality Assurance Program. *Proc of SPIE.* 2008; 6913:69131–69134. 69133I.

Figure 1.

The presampled MTF for a simulated high-resolution detector system determined using the NR and ER methods, shown on a semi-logarithmic plot. The “true” MTF of the detector was known exactly and is also shown in the plot. The simulated detector characteristics are also listed.^{12,13}

Figure 2.

Percent difference of the MTF determined using the NR method and the ER method for a simulated detector system, relative to the true MTF. Also shown is the percent difference of the MTF measured using the ER method relative to the NR method for two indirect digital radiography detectors: a flat panel detector (FPD) and solid state x-ray image intensifier (SSXII). Differences between the NR and ER methods largely follow the inherent error of the ER method (indicated by the solid black curve).

Figure 3.

Additive instrumentation NPS measured directly from dark-field images compared with the total NPS measured from flat-field images that also includes quantum noise. For both detector technologies, additive noise was substantially less than quantum noise and was largely constant as a function of spatial frequency.

Figure 4.

The FPD presampled MTF measured using the noise and edge response methods plotted up to the Nyquist frequency of 2.5 cycles/mm. The NR MTF was obtained using the “Slope” method to isolate additive instrumentation noise and a subset of five images acquired at a single exposure level. The two NR MTF curves overlap. Error bars represent the standard deviation of at least three separate measurements.

Figure 5.

The SSXII presampled MTF measured using the noise and edge response methods plotted up to 10 cycles/mm, shown on a semi-logarithmic plot. The NR MTF was obtained using the “slope” method to isolate additive instrumentation noise and a subset of 2, 5, 10, 15, and 30 images acquired at a single exposure level. For clarity, variability in the measurements is indicated in Figure 6.

Figure 6.

The average absolute percent difference for the MTF measurements shown in Figure 5 relative to the “gold standard” slope noise response (NR) method, illustrating that the NR method can be used with as few as two images acquired at a single exposure level. Use of more images provides increased accuracy, with 5 images providing accuracy comparable to that of the standard edge response (ER) method. The “NR – Slope” curve represents the percent standard deviation of 3 measurements.