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New Family of Generalized Metrics for Comparative Imaging System Evaluation

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Abstract

A family of imaging task-specific metrics designated Relative Object Detectability (ROD) metrics was developed to enable objective, quantitative comparisons of different x-ray systems. Previously, ROD was defined as the integral over spatial frequencies of the Fourier Transform of the object function, weighted by the detector DQE for one detector, divided by the comparable integral for another detector. When effects of scatter and focal spot unsharpness are included, the generalized metric, GDQE, is substituted for the DQE, resulting in the G-ROD metric. The G-ROD was calculated for two different detectors with two focal spot sizes using various-sized simulated objects to quantify the improved performance of new high-resolution CMOS detector systems. When a measured image is used as the object, a Generalized Measured Relative Object Detectability (GM-ROD) value can be generated. A neuro-vascular stent (Wingspan) was imaged with the high-resolution Micro-Angiographic Fluoroscope (MAF) and a standard flat panel detector (FPD) for comparison using the GM-ROD calculation. As the lower integration bound increased from 0 toward the detector Nyquist frequency, increasingly superior performance of the MAF was evidenced. Another new metric, the R-ROD, enables comparing detectors to a reference detector of given imaging ability. R-RODs for the MAF, a new CMOS detector and an FPD will be presented. The ROD family of metrics can provide quantitative more understandable comparisons for different systems where the detector, focal spot, scatter, object, techniques or dose are varied and can be used to optimize system selection for given imaging tasks.

INTRODUCTION

Evaluation of intrinsic x-ray detector performance is widely and successfully carried out using accepted metrics, such as the modulation transfer function (MTF), noise power spectrum (NPS), and detective quantum efficiency (DQE). These metrics fall short of giving a comprehensive performance assessment because they do not incorporate the degradation that occurs when a detector becomes part of an imaging chain, and they do not include specific object geometries. The generalized metrics GMTF and GDQE include the effects of focal spot blur and scatter associated with an imaging chain, but still neglect the object or task. A new family of generalized metrics has been created and characterized, and include these performance-degrading effects to give a more clinically relevant and task-specific description of detector performance once it becomes part of an imaging system. These metrics have been used to compare detectors including the Micro-Angiographic Fluoroscope (MAF), a Paxscan 2020 flat panel detector (FPD), (see Fig. 1), and Perkin-Elmer Dexela 1207 CMOS x-ray detector (Dex) (pixel size 75 μm , Nyquist frequency = 6.6 cycles/mm).

The previously presented ROD metric is defined as the integral over spatial frequencies of the Fourier transform of an object function weighted by the detector DQE for one detector divided by the comparable integral for another detector, as shown in Equation 1. The ROD is capable of giving a quantitative comparison of relative detector performances in imaging a specific object, the result of which depends primarily on the object geometry and detector DQE.

$$ROD = \frac{\int \int |OBJ(u, v)|^2 DQE_1(u, v) du dv}{\int \int |OBJ(u, v)|^2 DQE_2(u, v) du dv} \quad \text{EQN 1}$$

An object function can be defined as the position-dependent difference in signal relative to background for an object in air, and the task-specific frequency spectrum is generated by taking the Fourier Transform of the object function as can be seen in Equations 2 and 3

$$obj(x, y) = \frac{(background - signal)}{background} = \frac{(N_0 - N_0 e^{-\mu t(x, y)})}{N_0} = (1 - e^{-\mu t(x, y)}) \quad \text{EQN 2}$$

$$OBJ(u, v) = \int \int obj(x, y) e^{-2\pi i(ux + vy)} dx dy \quad \text{EQN 3}$$

where $obj(x, y)$ is the object function in real space, N_0 is the incident number of photons, μ is the attenuation coefficient, $t(x, y)$ is a function describing the thickness of the object, and $OBJ(u, v)$ is the Fourier transformed function of $obj(x, y)$. The ROD metric has been used to successfully compare the performance of detector pairs in imaging specific simulated tasks such as spheres, short lengths of wire, and contrast-filled blood vessels¹. The ROD has the potential to become a figure of merit in the evaluation of detector performance for a given object of interest. While having some relation to the d^2 ratio² used by perceptionists, the ROD family of metrics give a comprehensive, objective evaluation of the 'relative' performance of detector and imaging systems providing quantities that may be easier to appreciate because of their comparative nature. The intention of the ROD metrics at this time is to assess the abilities of the hardware alone, without an observer element, although addition of this may be done in future work.

METHODS AND MATERIALS

The concept of ROD is versatile and can be generalized to create a suite of more specialized metrics. When the effects of scatter and focal spot geometric unsharpness are included, the generalized metric, GDQE³, may be substituted for the DQE resulting in the G-ROD metric, or generalized relative object detectability. The definition of GDQE is shown below in Equation 4,

$$GDQE(f, \rho, X, m) = \frac{GMTF(f, \rho, m)^2}{m^2 \varphi_{in} GNNPS(f, X, m)} = \frac{\left[(1 - \rho) MTF_f\left(\frac{m-1}{m} f\right) + \rho MTF_s\left(\frac{f}{m}\right) \right]^2 MTF_D\left(\frac{f}{m}\right)^2}{m^2 \varphi_{in} GNNPS(f, X, m)} \quad \text{EQN 4}$$

where GMTF is generalized MTF, MTF_f is the focal spot blur MTF, MTF_s is scatter blur MTF, MTF_D is the detector MTF, ϕ_{in} is x-ray fluence reaching the detector face, ρ is the scatter fraction, X is exposure, and m is the magnification of the plane of the object. Scatter blur MTF_s is defined as the frequency content of the spatial distribution of scatter entering the detector, and focal spot MTF_f is defined as the modulus of the Fourier transform of a pinhole image of the focal spot, i.e. of the point spread function. Both parameters are weighted based on the amount of primary and scatter photons reaching the detector at the time of exposure. The definition of G-ROD is shown below in Equation 5 where ρ is the scatter fraction, X is exposure, and m is the magnification of the plane of the object.

$$G - ROD(\rho, X, m) = \frac{\iint |OBJ(u, v)|^2 GDQE_1(u, v, \rho, X, m) du dv}{\iint |OBJ(u, v)|^2 GDQE_2(u, v, \rho, X, m) du dv} \quad \text{EQN 5}$$

Of the two detectors being compared, the detector with the higher Nyquist frequency is placed in the numerator for this calculation. This convention ensures that for high frequency calculations, the calculated value will be greater than one. Although DQE and GDQE are experimentally measured, the object function is simulated for the G-ROD. To evaluate visualization of a radiograph of a real object, the Fourier transform of a measured object function (which is equivalent to the Fourier transform of the idealized object function convolved with the system MTF or GMTF), may be divided by the measured normalized noise power spectrum (NNPS), and integrated over spatial frequency for each detector system. The GNNPS can also be used if magnification is included. The ratio of these integrals for the two detectors can provide a metric that quantitatively compares two systems using all experimentally derived quantities. This metric is designated the generalized measured relative object detectability, or GM-ROD, and is defined below in Equation 6.

$$GM - ROD = \frac{\left[\int \int \frac{|OBJ(u, v)_{meas}|^2}{GNNPS(u, v)_1} du dv \right]_1}{\left[\int \int \frac{|OBJ(u, v)_{meas}|^2}{GNNPS(u, v)_2} du dv \right]_2} \quad \text{EQN 6}$$

The GM-ROD metric calculates the signal-to-noise ratio at each spatial frequency and is then integrated up to the Nyquist frequency of each detector. The bounds of integration can be varied to emphasize a comparison of either high or low frequency regimes of the detectors in question.

Another new metric, the referenced ROD, or R-ROD, can be used to characterize the task-specific function of detector 1 relative to a reference detector, R. The definition of R-ROD is shown in Equation 7:

$$R - ROD = \frac{\iint |OBJ(u, v)|^2 DQE_1(u, v) du dv}{\iint |OBJ(u, v)|^2 DQE_R(u, v) du dv} \quad \text{EQN 7}$$

where $OBJ(u, v)$ is the object's spatial frequency distribution. A reference detector could be an idealized or even perfect detector with DQE of 1 in which case the R-ROD might be

expected to be fractional. The R-ROD is dependent on the specific object so that a comparison of the R-ROD for different objects could give a quantitative and comparative assessment for a given detector design. The R-ROD has also been generalized to include effects of focal spot and scatter geometric unsharpness. The generalized referenced relative object detectability, GR-ROD, is defined below in Equation 8.

$$GR - ROD = \frac{\iint |OBJ(u, v)|^2 GDQE_1(u, v) du dv}{\iint |OBJ(u, v)|^2 GDQE_R(u, v) du dv} \quad \text{EQN 8}$$

RESULTS

A study was performed to compare the performance of the MAF and FPD (see Figure 1) in the task of imaging simulated spheres using the G-ROD metric. The spheres were solid aluminum spheres, and had diameters ranging from 50-600 μm . The G-ROD calculation comparing the MAF and the FPD was calculated for three measured x-ray tube focal spot sizes, small (0.3mm), medium (0.5mm), and large (0.8mm), at both low (1.05) and high (1.2) magnifications. The scatter fraction was held constant at 0.28¹. The G-ROD results are shown in Figures 2, 3, and 4, and plotted with the ROD calculation. The ROD curve for MAF/FPD shows that the MAF performs almost eight times better than the FPD in imaging a sphere of 50 μm diameter, and the ROD value decreases monotonically with increasing diameter up to a point, then trends towards the ratio of the DQEs for 0 frequency. The G-ROD calculation shows a trend similar to the ROD with lower maximal values, which indicates that the MAF performance degrades more rapidly than the FPD when the imaging system parameters are included in the calculation. When the two simulated magnifications are compared, the case with higher magnification clearly degrades more than the case with lower magnification in accordance with the $1/m^2$ relationship of the GDQE (EQN 4). As focal spot size increases, geometric unsharpness increases and greatly contributes to the relative performance degradation of both magnification cases.

A separate study was conducted to compare the performance of the MAF and FPD imaging systems via the GM-ROD metric using experimentally obtained object functions, in this case an image of a neuro-vascular Boston Scientific Wingspan stent. An image of the stent was taken with both detectors with a modified ANSI head phantom in place to create the same amount of x-ray attenuation as would be seen in a neuro-endovascular intervention. All parameters, including SOD, SID, magnification, focal spot size, exposure, and x-ray beam collimation were held constant for both detector acquisitions. The SID for both detectors was fixed at 90cm and the SOD was fixed at 80cm, creating a magnification of 1.1x for the stent. A small x-ray focal spot (0.3mm) was used and tube parameters selected were 80 kV, 160 mA, and 25.0 ms pulse width. This resulted in an exposure per frame of 99 μR . To obtain an object function with minimized quantum mottle, 100 frames of the image were averaged together, flat field and dark field corrected, and then cropped to the region of interest, as shown in Figure 5. A two-dimensional Fourier transform of object functions generated from these images is used in Equation 5 for GM-ROD. The GNNPS is calculated for each image from sections of corrected background, as seen in Figure 5. The quotient of the object function and the GNNPS gives a signal to noise ratio for all frequencies, and is integrated

over each detector's respective range of frequencies to give the GM-ROD value. For this measurement, the GM-ROD value was determined to be 4.8, indicating the superior performance of the MAF in this comparison. The lower bound of the integration was shifted upward to change the emphasis of the comparison to better examine the higher frequency abilities of the detectors (Table 1). For the calculation in which the lower bound is 0.56 cycles/mm, the GM-ROD value decreases before increasing for an increasing bound of integration apparently due to the detailed frequency distribution of the stent image.

Another study was performed to compare the performance of three detectors to an idealized reference detector for the task of imaging an aluminum sphere of varying diameter (50-600 μm). The detectors included in the study were the Micro-Angiographic Fluoroscope (MAF), a standard FPD, and the Perkin-Elmer Dexela. The DQE for the reference detector was defined to be 1 for all spatial frequencies up to its Nyquist frequency to simulate an ideal detector.

To compare the ability of the real detectors to image the low frequency range relative to an ideal detector, an idealized FPD (Nyquist frequency 2.5cycles/mm) was created. The results of this evaluation are shown in Figure 6. The MAF and Dexela detectors both outperform the ideal FPD in imaging high frequencies, due to their small pixel size. It is clear that for imaging lower frequencies (large diameters), none of the three real detectors show superiority, and the R-ROD value levels off at 0.5 for all detectors.

A similar comparison was performed to evaluate the ability of the detectors to image in the high spatial frequencies relative to an ideal detector designed by Jain⁴ with Nyquist frequency defined as 10 cycles/mm. The results of this calculation are shown in Figure 7.

In contrast to the previous case where MAF and Dexela detectors outperformed the ideal FPD, the high resolution reference detector performs substantially better than all three detectors over all object diameters. As expected, the relative ability of the FPD is substantially weaker than the MAF and Dexela. Dexela appears to perform slightly better than the MAF for all object sizes except the smallest diameter spheres. Once again, all three detectors trail off to a value of 0.5 as the diameter of the sphere increases. The value of the R-ROD calculation for large objects are approximately matched across all detectors because the value trends towards the ratio of the DQEs at zero spatial frequency, or the QDE of the cesium iodide phosphor layer.

A study to compare the relative performances of the well-characterized MAF, FPD, and Dexela detector to an ideal detector in the context of an imaging chain was performed using the new GR-ROD metric. The same two ideal detectors that were reported in the R-ROD study were used as the ideal detectors in this case (Nyquist frequencies of 2.5 cycles/mm and 10 cycles/mm). The calculations were performed for three focal spot sizes (small (0.3mm), medium (0.5mm), and large (0.8mm)), for two magnifications (1.05 and 1.2), and for a 0 scatter fraction. Focal spot MTF was taken into consideration for each of the three detectors, and the ideal detectors were appropriately defined to be in ideal detection systems (no focal spot blurring). The results of the GR-ROD calculations are shown in Figures 8a,

8b, 8c, 8d, 8e, 8f, 8g, 8h, 8i, 8j, 8k, 8l for each focal spot size, magnification, and ideal detector Nyquist frequency.

The trends exemplified in the results of this study are consistent with those seen in the R-ROD and G-ROD results, specifically the degradation of detector performance with increasing focal spot and magnification. Regardless of focal spot size and magnification, the MAF and Dexela detectors both outperform the ideal FPD in the high frequency range. For the calculations involving the ideal detector with Nyquist of 10 cycles/mm, the real detectors perform worse at high frequencies, and as seen in all cases, trend to a value of 0.5 for low frequencies.

The relative performance of the real detectors depends heavily on the Nyquist frequency chosen for the simulated ideal detector. To compare the effects of selected Nyquist frequency, several simulations were performed comparing MAF performance to different ideal detectors with a range of Nyquist frequencies. The results are shown below in Figure 9.

It can be seen here that the chosen Nyquist frequency of the ideal detector has a substantial impact on the results of the R-ROD calculation. At the minimum Nyquist frequency, the MAF clearly out-performs the ideal detector up until the largest spheres, or the lowest spatial frequencies, where the values trend to 0.5 once more. As the Nyquist frequency selected for the ideal reference detector increases, the relative performance of the MAF degrades, as expected, until the calculated R-ROD values reach a minimum value for all sphere sizes, indicating a maximum performance level for the simulated detectors for the range of object sizes selected for this study.

The outcome of the R-ROD and GR-ROD calculations depend heavily on the chosen Nyquist frequency value of the simulated detector. Providing a series of such reference curves that compare a new detector being developed with ideal detectors of various Nyquist frequencies could be helpful in optimizing the design of the new real detector or detector system.

CONCLUSIONS

The ROD is a useful new metric that allows for quantitative analysis of relative performance of two given detectors in imaging a specific task based on the object geometry and intrinsic detector qualities. The versatility of the concept of the ROD allows for the creation of more generalized metrics like the G-ROD, the GM-ROD, and the R-ROD, all displayed in Table 2. The R-ROD is a natural extension of the ROD metric to evaluate the task-specific performance of a real detector compared to a reference detector of any range of abilities, including idealized. The R-ROD has the potential to incorporate the performance degradation that occurs when a detector becomes part of an imaging chain by becoming the GR-ROD, or the generalized referenced ROD, which would make use of the metric GDQE rather than the currently used DQE. The generalized ROD, or G-ROD includes clinically relevant parameters (scatter fraction, exposure, magnification, focal spot size) and gives an assessment of the relative abilities of total imaging systems rather than the detector alone. The GM-ROD also takes clinical factors into account and uses experimentally obtained

images as the object function. The GM-ROD may be the most clinically relevant metric due to the fact that certain items that have complex geometries (i.e. stents, coils, tortuous blood vessels) are difficult to simulate for use as a task for the ROD or G-ROD, but can easily be imaged and put to use as an object function for GM-ROD. All of these metrics have the potential to become ‘figures of merit’ in the continuing advancement in x-ray detector and system performance analysis regarding task-specific detectability. Future work may include adding computer observer models to the family of ROD metrics, and the inclusion of temporal MTF and DQE for fluoroscopic systems⁵.

Acknowledgments

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REFERENCES

1. Singh V, Jain A, Bednarek DR, Rudin S. Relative object detectability (ROD): a new metric for comparing x-ray image detector performance for a specified object of interest. *Proc SPIE Int Soc Opt Eng.* Mar 19.2014 :90335L.
2. Ikejima, Lynda C.; Kiarashi, Nooshin; Ghate, Sujata V.; Samei, Ehsan; Lo, Joseph Y. Task-based strategy for optimized contrast enhanced breast imaging: Analysis of six imaging techniques for mammography and tomosynthesis. *Medical Physics.* 2014; 41:061908. [PubMed: 24877819]
3. Kyprianou IS, Rudin S, Bednarek D, Hoffmann KR. Generalizing the MTF and DQE to include x-ray scatter and focal spot unsharpness: application to a new microangiographic system. *Med Phys.* 2005; 32(2):613–26. [PubMed: 15789608]
4. Jain A, Bednarek DR, Rudin S. Theoretical performance analysis for CMOS based high resolution detectors. *Proc SPIE Int Soc Opt Eng.* Mar 6.2013 8668 [PubMed: 24353390]
5. Friedman SN, Cunningham IA. A Method to Measure the Temporal MTF to Determine the DQE of Fluoroscopy Systems. *Medical Imaging 2006: Physics of Medical Imaging, Proc. of SPIE Vol.* 6142:61421X–1.

Figure 1.

The MAF (Nyquist = 14.2 cycles/mm, pixel size 35 micron) deployed on the c-arm gantry. The FPD (Nyquist = 2.5 cycles/mm, pixel size = 194 micron) is above.

Figure 2.
The G-ROD for small focal spot.

Figure 3.
The G-ROD for medium focal spot.

Figure 4.
The G-ROD for large focal spot.

Figure 5.

The corrected and cropped images used for calculation of GM-ROD. In the MAF image (left) an ROI is drawn for calculation of the GNNPS.

Figure 6. Results of R-ROD calculation for idealized detector with Nyquist frequency = 2.5 cycles/mm.

Figure 7. Results of the R-ROD calculation for idealized detector with Nyquist frequency = 10 cycles/mm.

Figure 8a-d.
GR-ROD results for small focal spot.

Figure 8e-h.
GR-ROD results for medium focal spot.

Figure 8i-l.
GR-ROD results for large focal spot.

Figure 9.
Comparison of the real MAF to idealized detectors of various Nyquist frequencies ranging from 1-15 cycles/mm

Table 1

Calculated GM-ROD values for varying bounds of integration

Integration Bounds (cycles/mm) (in two dimensions)	GM-ROD (for MAF/FPD)
Full range (0 to Nyquist)	4.80
0.56 to Nyquist	3.43
1.0 to Nyquist	5.45
1.5 to Nyquist	10.06
2.0 to Nyquist	24.42

Table 2

Review of ROD family of metrics

Metric Name	Object Function	Detector Pair	Generalized Paramters
ROD	Simulated	Real	No
G-ROD	Simulated	Real	Yes
GM-ROD	Experimentally derived	Real	Yes
R-ROD	Simulated	One real, one simulated	No
GR-ROD	Simulated	One real, one simulated	Yes