A Robust Approach to Measuring the Detective Quantum Efficiency of Radiographic Detectors in a Clinical Setting

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ABSTRACT

The detective quantum efficiency (DQE) is widely accepted as a primary measure of x-ray detector performance in the scientific community. A standard method for measuring the DQE, based on IEC 62220-1, requires the system to have a linear response meaning that the detector output signals are proportional to the incident x-ray exposure. However, many systems have a non-linear response due to characteristics of the detector, or post processing of the detector signals, that cannot be disabled and may involve unknown algorithms considered proprietary by the manufacturer. For these reasons, the DQE has not been considered as a practical candidate for routine quality assurance testing in a clinical setting. In this article we described a method that can be used to measure the DQE of both linear and non-linear systems that employ only linear image processing algorithms. The method was validated on a Cesium Iodide based flat panel system that simultaneously stores a raw (linear) and processed (non-linear) image for each exposure. It was found that the resulting DQE was equivalent to a conventional standards-compliant DQE with measurement precision, and the gray-scale inversion and linear edge enhancement did not affect the DQE result. While not IEC 62220-1 compliant, it may be adequate for QA programs.

1. INTRODUCTION

While the medical benefits from x-ray imaging are enormous, the potential of biological risks associated with exposure to ionizing radiation makes it critical that diagnostic x-ray imaging systems be designed and maintained to produce the best possible images using the least acceptable levels of x-ray exposure. To achieve this, regulatory programs often establish acceptable levels of radiation exposure for common procedures and image-quality tests are designed to evaluate selected performance-based tasks. While scientific and professional communities have made these tests more quantitative than in the pre-digital era, it is widely recognized that x-ray systems produce the best possible image quality in terms of image signal-to-noise ratio (SNR) only when the detective quantum efficiency (DQE) is as close to unity as possible at all spatial frequencies of importance.

The DQE describes the equivalent quantum efficiency of an x-ray detector and is a surrogate measure of the detector “dose efficiency”. An expression for the DQE is given by:

\[ DQE(u) = \frac{XQ_o G^2 |T(u)|^2}{W(u)} = \frac{\bar{d}^2 |T(u)|^2}{XQ_o W(u)} \]  

where \( X \) [mR] is the exposure incident at the image plane, \( Q_o \) [quanta/mm\(^2\)/mR] is the number of x-ray quanta in the beam per unit exposure, \( G \) is the system gain relating \( \bar{q} \), the average number of incident quanta per unit area where \( \bar{q} = XQ_o \), to \( \bar{d} \), the corresponding average dark-subtracted pixel value, and \( W(u) \) is the associated image Wiener noise power spectrum (NPS). This expression is valid for linear and shift-invariant imaging systems,
and was adopted by the International Electrotechnical Commission (IEC) in a standard method for DQE testing with the substitution $XQ_o = q = W_q(u)$ as the Wiener NPS of the incident Poisson-distributed quanta in IEC 62220-1.9

While the importance of ensuring optimal DQE are clear, there are several reasons why it is part of clinical quality assurance programs in only a small number of leading-edge facilities.10–12 For example, DQE measurements generally require an environment where x-ray exposure conditions can be controlled and monitored, and clinical instruments cannot always be removed from use for the time it takes to perform DQE testing. An additional impediment for many systems is that while an assessment of the DQE requires access to linear (or linearized13–15) image data, manufacturers often implement non-linear image processing to give images a preferred look. In many cases, these algorithms are considered proprietary and not disclosed to the user, making it difficult or impossible to extract the required linear image data. In addition, they may incorporate adaptive noise-reduction algorithms and automatic exposure control features that depend on certain patient features or exposure conditions. This means both $G$ and $T(u)$ may be functions of unknown parameters and as a result the system response may be adaptive and vary from one exposure to another, and possibly from one region to another in a single image. These confounding conditions make it difficult or impossible in many cases to perform standards-compliant DQE testing in a clinical environment.

In this article, we describe a method of measuring the DQE that can be implemented on both linear and non-linear systems. It uses a “neutral-attenuator” method to linearize the system response and a slanted-edge method to determine the MTF, and is validated by comparing the DQE obtained using both processed (non-linear) and raw (linear) image data with a standards-compliant DQE on the same system.

2. THEORY

For an ideal linear detector, the average dark-subtracted pixel value $\bar{d}$ is proportional to the average x-ray energy deposited in the pixel, $E_d$ [keV]:

$$\bar{d} = kE_d = ka\bar{E},$$  \hspace{1cm} (2)

where $k$ [keV$^{-1}$] is a constant of proportionality, $a$ [mm$^2$] is the pixel area, $\bar{E}$ [keV mm$^{-2}$] is the area density of deposited energy given by

$$\bar{E} = \bar{q}E_q = \bar{q} \int_0^{kV} s(E)\alpha(E)E_a(E)dE,$$  \hspace{1cm} (3)

$\bar{q}$ [mm$^{-2}$] describes a uniform Poisson distribution of x-ray quanta incident on the detector, $E_q$ [keV] is the average energy deposited per incident x-ray photon, $s(E)$ is the normalized x-ray spectrum where $\int_0^{kV} s(E)dE = 1$, $\alpha(E)$ is the detector quantum efficiency, and $E_a(E)$ [keV] is the average x-ray energy deposited in the detector by a photon having energy $E$.

The fundamental measurement of all x-ray detectors is directly related to deposited energy $E_d$ where $E_d = a\bar{q}E_q$, and digital post-processing algorithms act on this quantity. It therefore seems reasonable to express the average pixel value of both linear and non-linear systems more generally in the form $\bar{d} = f(E_d)$. A key benefit of this representation is that the function $f$ will normally be well behaved over the useful range of exposures, such as a constant of proportionality or a log transformation. A robust inverse transformation can therefore be defined such that $E_q = \frac{1}{a\bar{q}}f^{-1}(\bar{d}) \equiv f_q^{-1}(\bar{d})$ which can be determined by mapping $E_q$ values as a function of $\bar{d}$, giving a linearized pixel value $\tilde{d}_L = k_L a\bar{q}f_q^{-1}(\bar{d})$ where $k_L$ is a new constant of proportionality.

The form of $f_q^{-1}$ could be obtained by attenuating a beam with a specified material if not for beam-hardening effects, although it may be possible to construct an attenuator that would attenuate all energies by the same fraction by combining two or more materials that do not have K-edge energies in the useful energy range.16 As an alternative, we use a material having linear attenuation coefficient $\mu(E)$ [cm$^{-1}$] and thickness $t$ [cm] combined with a theoretical correction for beam hardening. With this approach, $E_q$ becomes a function of attenuator thickness $t$:

$$E_q(t) = \int_0^{kV} s(E)\alpha(E)E_a(E)e^{-\mu(E)t}dE.$$  \hspace{1cm} (4)
The shape of $f_q^{-1}(\bar{d})$ is then determined by plotting measured pixel values $\bar{d}$ as a function of $E_q(t)$ determined theoretically from Eq. (4). This linearization transformation is used to convert the series of images with average pixel value $\bar{d}$ into images with average linearized pixel value $\bar{d}_L$.

The MTF is determined using a slanted-edge method\textsuperscript{17–20} after linearizing images of the edge, normalized to open images, according to the above method. The NPS is determined from a series of linearized open images, and the DQE determined according to Eq. 1.

### 3. METHODS

The linearized DQE method was implemented using images from a General Electric Revolution QX/i digital radiography flat panel detector. This system provides both “processed” and “raw” images for each exposure. Processed images have an inverted gray scale and some edge enhancement that is based on user settings with an unknown algorithm and cannot be completely disabled. Raw images have a linear response and no edge enhancement. These differences are illustrated in Fig. 1 which shows profiles through images of a copper step-wedge attenuator. The small-signal MTF and DQE were determined using both raw and processed images, and validated by comparing with separate MTF and DQE measurements made following the IEC standard\textsuperscript{9} using raw images.

The linearization transformation $f_q^{-1}$ was determined using measured pixel values $\bar{d}$ and theoretical $E_q(t)$ values from Eq. (4) for known thicknesses $t$ of copper shim stock (nominal thicknesses 0.025, 0.051, 0.152, 0.254 and 0.457 mm with a nominal accuracy of 10% stated by the supplier\textsuperscript{21}) for an RQA-5 spectrum (70 kV, 21 mm added Al and a verified HVL of 7.1 mm Al). Copper linear attenuation coefficients $\mu$ were obtained from the NIST database\textsuperscript{22} using a copper density of 8.96 g/cm$^3$.

The detector quantum efficiency $\alpha$ was estimated as the probability of interaction assuming 0.471 g/cm$^2$ of CsI and a 1 mm thickness. The form of $f_q^{-1}$ was determined from a second-order polynomial fit of $\bar{d}$ as a function of $E_q$.

The accuracy of this method is dependent on having an x-ray spectrum with a half-value layer (HVL) that accurately conforms to the RQA-5 standard, and copper steps of known thickness. The HVL was measured and confirmed to be within 1% of the nominal 7.10-mm Al value. Copper thicknesses were measured with a micrometer and verified to agree with nominal values ±0.003 mm (the accuracy of the measurement).
neutral-attenuator method was validated by verifying that \( f_q^{-1} \) is a linear transformation when determined using raw image data.

The linearized MTF was determined using both raw and processed image data. Both were compared to an IEC-type MTF measurement using linear (raw) image data for validation.

The frequency-dependent NPS was computed using three open-field images. The IEC value of \( Q_o \) for the RQA-5 spectrum was used. The linearized DQE computed using both raw (linear) and processed (non-linear) image data was compared with an IEC 62220-1\(^9\) compliant DQE measurement.

4. RESULTS

4.1 System Gain

A comparison of theoretical \( \hat{E}_q(t) \) values from Eq. (4) with measured pixel values \( \bar{d} \) from raw images is shown as a function of copper thickness in Fig. 2. Although there is very good agreement, pixel values become slightly inflated with increasing copper thickness. It was confirmed this was due to a 5% additive term, consistent with the 5% low-frequency drop observed in the IEC MTF measurement. It is important to note, therefore, that the small disagreement in Fig. 2 is not an error. Rather, it shows that for linear image data, pixel values are proportional to theoretical \( \hat{E}_q \) values plus a component due to glare in the detector.

The transformation to linearized pixel value, \( f_q^{-1} \) is shown in Fig. 3 for both raw and processed images. As expected, the transformation is a straight line for the raw image data. The fact that it does not pass through the origin is due to the 5% glare offset. The processed image data shows an inverted gray scale. In both cases, the transformation is well behaved as expected.

4.2 MTF

Figure 4 compares the linearized MTF using linear image data with an IEC MTF for each distance tested. Excellent agreement is seen for the 50, 100 and 200 mm data. Good agreement is seen in the 1 mm data except at low frequencies where there is a small but non-trivial increase in the small-signal MTF. A distance of 50 mm was selected to be used for the measurement of DQE.
Figure 3: The form of $f_{q}^{-1}$ is given by this plot of deposited energy $\hat{E}_{q}$ (proportional to linearized pixel value) vs. measured pixel value $\bar{d}$. For processed image data, it can be trusted only between the first and last data point.

Figure 5 shows a comparison of the linearized small-signal MTF, obtained using both raw and processed image data, with an IEC-compliant MTF that has been normalized to a 15-mm window to reduce the impact of the low-frequency drop. With linear image data, the linearized and IEC MTFs appear equivalent within the precision of the measurement. The linearized MTF obtained with processed image data shows evidence of edge enhancement.

4.3 NPS and DQE

Figure 6 shows a comparison of the linearized Wiener NPS (normalized by squared pixel value) obtained using both raw and processed image data, with an IEC NPS. Each curve is the result of averaging five realizations of the measurement. The measurement from raw data has undergone linearization with $f_{q}^{-1}$, and appears to be a few percent greater than the IEC measurement, although considered equivalent within experimental accuracy. The NPS from processed data is substantially greater which indicates that image processing has increased noise.

Figure ?? compares the results of the IEC DQE measurement with the linearized method, (both are based on five realizations of the measurement). In this test, the semi-transparent edge was 50 mm from the detector cover. The IEC method requires the edge to be as close to the image plane as physically possible, and therefore a distance of 0 mm was used from the edge to detector cover.

5. CONCLUSIONS

A method of computing the DQE that can be implemented on both linear and non-linear image data is described. The method uses a copper step wedge to linearize image data. It is validated on a CsI-based flat-panel detector from which both linear (raw) and non-linear (processed) image data is available for the same exposures. In all cases, the DQE results are within a few percent of a traditional IEC-compliant DQE analysis.

Two important observations are that:

1. Gray-scale inversion of the system response, applied by the manufacturer when computing the processed images, did not affect the results; and
Figure 4: Comparison of the linearized MTF with an IEC MTF with the edge placed 0, 50, 100 and 200 mm from the detector cover. Linear images were used throughout.

Figure 5: Comparison of the linearized MTF measured from both raw and processed image data with a conventional (IEC) MTF. The linearized MTF shows the effect of edge enhancement with processed images.
Figure 6: Comparison of linearized Wiener NPS (normalized by squared pixel value) and DQE, and determined from raw and processed images, with the IEC method. The NPS shows the effect of edge-enhancement processing, but the DQE does not.

2. Edge enhancement, applied by the manufacturer to the processed images, affected the MTF and NPS showing an increase in both at mid frequencies, but did not affect the DQE, consistent with expectations for linear processing of image data.

While the method is not IEC compliant, it may be adequate for QA testing in a clinical environment.

REFERENCES


