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Practical expressions describing detective quantum efficiency in flat-panel detectors

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ABSTRACT: In radiology, image quality excellence is a balance between system performance and patient dose, hence x-ray systems must be designed to ensure the maximum image quality is obtained for the lowest consistent dose. The concept of detective quantum efficiency (DQE) is widely used to quantify, understand, measure, and predict the performance of x-ray detectors and imaging systems. Cascaded linear-systems theory can be used to estimate DQE based on the system design parameters and this theoretical DQE can be utilized for determining the impact of various physical processes, such as secondary quantum sinks, noise aliasing, reabsorption noise, and others. However, the prediction of DQE usually requires tremendous efforts to determine each parameter consisting of the cascaded linear-systems model. In this paper, practical DQE formalisms assessing both the photoconductor- and scintillator-based flat-panel detectors under quantum-noise-limited operation are described. The developed formalisms are experimentally validated and discussed for their limits. The formalisms described in this paper would be helpful for the rapid prediction of the DQE performances of developing systems as well as the optimal design of systems.

KEYWORDS: Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc); X-ray detectors; Detector design and construction technologies and materials
1 Introduction

In diagnostic radiology, excellence in image quality is a balance between system performance and patient radiation dose, hence x-ray systems must be designed to ensure the maximum image quality is obtained for the patient dose as low as possible [1]. The concept of detective quantum efficiency (DQE) is universally used to quantify, understand, measure, and predict the performance of x-ray detectors and imaging systems [2]. Both the empirical and theoretical estimation of the DQE are based on linear-systems theory and Fourier concepts [3]. As such, the DQE analysis assumes a linear and shift-invariant system and wide-sense stationary random noise processes. A practical expression for use when measuring the DQE is given by [1, 3]

\[
DQE(k) = \frac{qG^2 MTF^2(k)}{NPS(k)} = \frac{MTF^2(k)}{\overline{q}[NPS(k)/\overline{d}^2]},
\]

where \(k\) is the Fourier conjugate of the two-dimensional (2D) spatial variable and \(G = \overline{d}/\overline{q}\) is the system large-area gain factor. This equation shows that the DQE of any detector can be determined if the system modulation-transfer function (MTF) and the image noise-power spectrum (NPS) with the associated mean image pixel value \(\overline{d}\) and the incident number of quanta per unit area \(\overline{q}\) can be determined. It is noted that while the NPS in the DQE calculation includes the effect of noise aliasing, the MTF should not because the signal aliasing is non-linear process.

The theoretical DQE based on the cascaded linear-systems theory is powerful because it can be used to determine all quantities related to system design parameters such as secondary quantum sinks, noise aliasing, reabsorption noise, and others [1, 3]. In this paper, simple, practical DQE formalisms assessing photoconductor- and scintillator-based flat-panel detectors are described under typical operation conditions, such as quantum-limited operation. The developed formalisms are validated by comparing with the measured DQE values and discussed for their limits.
2 Background and theory

Signal and noise propagation in a flat-panel detector can be understood using a simple serial cascade of simple elemental transfer relationships as illustrated in figure 1 consisting of the following steps [4]: 1) absorption of x-ray quanta in the x-ray converter (e.g., photoconductor or scintillator) with a probability $\alpha$ equal to the quantum efficiency; 2) random relocation of the interaction locations, described as a scatter operation with the probability density function $p(r)$ in the image plane or $T_1(k)$ in the Fourier domain, to determine where x-ray energy is deposited; 3) production of secondary quanta (e.g., charge carriers or optical quanta) with an average gain of $\beta$ secondary quanta per x-ray interaction; 4) random relocation of secondary quanta (due to charge-carrier diffusion or optical scattering) as described as $T_2(k)$ in the Fourier domain; 5) random escape of secondary quanta from the x-ray converter; 6) random collection of secondary quanta (e.g., charge carriers by the pixel electrode or conversion of optical quanta into charge carriers in the photodiode) with probability $\eta$; 7) realization of a measurable signal by aperture integration of secondary quanta and scaling to detector units; 8) spatial sampling represented by multiplying the presampled detector signal with a train of delta functions to determine discrete detector-element values; and 9) addition of detector readout noise caused by peripheral addressing/signal-processing circuitries during signal readout. The average image signal and NPS for the model can be determined by cascading expressions of signal and noise propagation through each process [3]. Assuming square pixel geometry with width $p$ and active aperture width $a$, the theoretical DQE in this paper, consistent with others [5, 6], is given by

$$DQE(k) = \frac{\bar{q}a^2\gamma T_1^2(k)T_2^2(k)\text{sinc}^2(\pi ak)}{\frac{\bar{q}a^2\bar{q}}{\gamma} + \bar{q}a^2 \sum_{j=0}^{\infty} \left\{ \frac{\bar{q}}{\gamma} \left( \frac{\beta}{\gamma} - 1 \right) T_2^2(k \pm \frac{j}{p}) \text{sinc}^2 \left( \pi a(k \pm \frac{j}{p}) \right) \right\}} + p^2\sigma_{\text{read}}^2,$$  

(2.1)

where $\bar{m} = \alpha \beta$, $\bar{\gamma} = \alpha \beta \kappa \eta$, and $\gamma = a^2 / p^2$. Although more detailed models have recently been introduced for an improved assessment of the NPS [7]–[9], eq. (2.1) is reasonable for the DQE estimation of conventional flat-panel detectors.

Equation (2.1) is impractical for repeated estimations of the DQE for new technological developments and detector designs because of expensive 2D NPS computations which are required even for the one-dimensional (1D) analysis of a 2D detector. Since both the signal blur and noise correlation occur over 2D space, the 1D DQE is obtained by evaluating eq. (2.1) along the appropriate axis, for example $DQE(u) = DQE(u, v)|_{v=0} = DQE(u, 0)$ where $u$ and $v$ are Fourier variables in Cartesian coordinates.
In a direct-conversion flat-panel detector based on photoconductor, we may neglect the signal spreading due to negligible charge diffusion [10], and then we have

$$ DQE_{\text{direct}}(k) \approx \frac{DQE_{\text{conv}}(0) \gamma T^2(k) \text{sinc}^2(\pi a k)}{1 + \frac{DQE_{\text{conv}}(0)}{\text{m}} \left( \frac{\pi}{\text{m}} - 1 \right) + \frac{DQE_{\text{conv}}(0) \sigma_{\text{read}}^2}{\eta a^2 T^2(k)}}. $$

(2.2)

where $DQE_{\text{conv}}(0)$ is the large-area DQE of the x-ray converter and is given by the quantum efficiency times the Swank factor ($= \alpha I$). When the detector is operated in quantum-noise-limited exposure region i.e. $\sigma_{\text{read}} < a g T^2(k) \sqrt{q / DQE_{\text{conv}}(0)}$, eq. (2.2) can be reduced to

$$ DQE_{\text{direct}}(k) \approx DQE_{\text{conv}}(0) \gamma T^2(k) \text{sinc}^2(\pi a k) \left[ 1 - \frac{DQE_{\text{conv}}(0) \sigma_{\text{read}}^2}{\eta a^2 T^2(k)} \right]. $$

(2.3)

Similarly, with an assumption that optical scattering is most dominant in signal spreading processes in an indirect-conversion flat-panel detector based on scintillator, eq. (2.1) can be simplified to

$$ DQE_{\text{indirect}}(k) \approx \frac{DQE_{\text{conv}}(0)}{1 + \frac{DQE_{\text{conv}}(0)}{\text{m}} \left( \frac{1}{\gamma T^2(k)} - \frac{1}{\text{m}} \right) + \frac{DQE_{\text{conv}}(0) \sigma_{\text{read}}^2}{\eta a^2 T^2(k)}}. $$

(2.4)

For $\sigma_{\text{read}} < a g T^2(k) \sqrt{q / DQE_{\text{conv}}(0)}$, eq. (2.4) is reduced to

$$ DQE_{\text{indirect}}(k) \approx DQE_{\text{conv}}(0) - \frac{DQE_{\text{conv}}^2(0)}{\gamma a^2 T^2(k)} \left[ 1 - \frac{\sigma_{\text{read}}^2}{\eta a^2} \right]. $$

(2.5)

3 Model validation

The developed DQE formalisms were validated by comparisons with the measured DQEs from two different-type flat-panel detectors; amorphous selenium (a-Se) based detector with a pixel pitch of 139 µm and cesium iodide (CsI) based detector with a pixel pitch of 143 µm. The thicknesses of both converters are the same as 500 µm. Two detectors are, respectively, denoted by D1 and D2 hereinafter. The DQE analyses were compliant with IEC 62220-1 (IEC, Geneva, Switzerland, 2004) using a 70 kV RQA-5 spectrum. Detailed measurement procedures can be found in ref. [11].

The physical parameters involved in the cascaded models were estimated based on the absorbed energy distributions and the optical pulse-height distributions obtained from the Monte Carlo simulations. We employed two Monte Carlo codes, MCNPX (Version 2.5.0., ORNL, USA) and DETECT2000 (Laval University, Quebec, Canada) for x-ray and optical quanta transports, respectively. Extraction methods of physical parameters from the Monte Carlo simulation results are based on ref. [12] and the extracted values are summarized in table 1.

4 Results and discussion

Figure 2 summarizes comparisons of the measured and theoretical image quality for two detectors. For the direct-conversion D1 detector, the measured MTF is slightly less than the aperture transfer function which can be described by the sine cardinal function $\text{sinc}(\pi a u)$. This observation may imply that the quantum-relocation processes due to primary and/or secondary quanta slightly degrade...
Table 1. Numerical values used in the theoretical DQE calculations for a-Se (D1) and CsI (D2) based flat-panel detectors.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Pixel aperture [mm]</td>
<td>$p\sqrt{\gamma}$</td>
</tr>
<tr>
<td>$p$</td>
<td>Pixel pitch [mm]</td>
<td>0.139</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Fill factor</td>
<td>0.79</td>
</tr>
<tr>
<td>$\bar{\eta}_0$</td>
<td>Incident photon fluence [mm$^{-2}$mR$^{-1}$]</td>
<td>$2.6 \times 10^5$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Average quantum absorption efficiency</td>
<td>0.53</td>
</tr>
<tr>
<td>$I$</td>
<td>Swank factor</td>
<td>0.96</td>
</tr>
<tr>
<td>$T_1$</td>
<td>MTF due to primary quanta scattering</td>
<td>1</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Secondary quantum gain per interacting quanta</td>
<td>1070</td>
</tr>
<tr>
<td>$T_2$</td>
<td>MTF due to secondary quanta scattering</td>
<td>1</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Average coupling efficiency</td>
<td>1</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Average collection efficiency</td>
<td>1</td>
</tr>
<tr>
<td>$T_3$</td>
<td>MTF due to aperture integration</td>
<td>$</td>
</tr>
<tr>
<td>$\sigma_{\text{read}}$</td>
<td>Additive readout electronic noise [e$^-$]</td>
<td>3000</td>
</tr>
</tbody>
</table>

Figure 2. Comparisons between empirical and theoretical MTF, NPS and DQE for a-Se (D1) and CsI (D2) based flat-panel detectors. NNPS designates the normalized NPS [see the bracketed term in the denominator of eq. (1.1)].

the total system transfer function. The agreement between empirical and approximate theoretical NPSs is excellent. Theoretical white-spectral characteristic due to noise aliasing [5] is well proved by the measured NPS. Although there are some discrepancies at the spatial frequencies greater than about 1 mm$^{-1}$, the approximate DQE model reasonably describes the measured data.

For indirect-conversion D2 detector, there is a large discrepancy between the aperture transfer function and the measured MTF, and which is mainly due to the secondary quanta scattering within the CsI layer. The agreement between the calculated and measured NPSs is excellent. Approximate
Figure 3. Calculated DQEs for hypothetical 1D direct and indirect-conversion detectors with respect to various additive electronic noise levels. $u_N$ denotes the Nyquist frequency.

DQE formalism underestimates the measured DQE values for the spatial frequency greater than 1.5 mm$^{-1}$.

Figure 3 shows the DQE simulation results with respect to various additive electronic noise levels. The simulation assumes 1D line detector configurations for simplicity in the calculations. All the simulations were performed for exposure of 1 mR at the detector entrance surface. The MTF of the hypothetical indirect-conversion 1D detector is based on the Gaussian point-spread function with the standard deviation $\sigma = p$. Other simulation parameters were taken from table 1. As shown in figure 3 where the spatial frequency $u$ was normalized by the Nyquist frequency $u_N$, the electronic readout noise affects the approximate DQE model for direct-conversion detectors over the entire spatial frequency band, while the approximate DQE model for indirect-conversion detector is relatively insensitive to the additive noise at lower frequencies. For the direct-conversion detector, it is expected that the approximate DQE model [eq. (2.3)] well follows the complete DQE model [eq. (2.1)] when the detector is operated in quantum-noise-limited region or $\sigma_{\text{read}} = 0\ e^-$. Equation (2.3) well describes eq. (2.1) up to the electronic noise level of $10^4\ e^-$ in this simulation. For $\sigma_{\text{read}} > 10^4\ e^-$, however, eq. (2.3) gradually underestimates eq. (2.1) as $\sigma_{\text{read}}$ further increases. For the indirect-conversion detector, the approximate DQE model [eq. (2.5)] underestimates eq. (2.1) in the high frequency band even for $\sigma_{\text{read}} = 0\ e^-$. This frequency band widens as $\sigma_{\text{read}}$ increases.

In the quantum-noise-limited operation, the DQE(0) of indirect-conversion detectors can be simply determined by the DQE(0) of scintillator or $\alpha l$, while that of direct-conversion detectors is determined by the DQE(0) of photoconductor scaled by the pixel fill factor $\gamma$. To preserve the photoconductor DQE(0) performance in direct-conversion detectors, therefore, it is required that the pixel should be designed to have a fill factor as high as possible. Electrical design in which all field lines terminate on the pixel electrode is essential.

5 Conclusion

Practical DQE formalisms have been described in this paper and it has been demonstrated that the developed DQE formalisms reasonably agree to the measured DQE values for the conventional
flat-panel detectors. Especially the approximate DQE model of direct-conversion detectors well describes the complete DQE model when the detectors are operated in the quantum-noise-limited region. On the contrary, the approximate DQE model of indirect-conversion detectors describes the complete DQE model up to \(\sim 75\%\) of the Nyquist-frequency limit at the quantum-noise-limited operation. The approximate DQE formalisms would be very useful for the rapid evaluation of the measured DQE and the extraction of detector performance parameters such as quantum absorption efficiency, Swank noise factor, and secondary quantum gain.

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References