Practical Expressions Describing Detective Quantum Efficiency in Flat-Panel Detectors

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Motivation and Objectives

- Due to the health risks associated with exposure to radiation, technical excellence in medical imaging is critical to high-quality medical care. In radiology, image quality excellence 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 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 study, simple, practical DQE formalisms assessing photoconductor- and scintillator-based flat-panel detectors under typical operation conditions, such as quantum-limited operation, are described. The developed formalisms are validated by comparing the measured DQE values and discussed for their limits. This study will be very useful for the rapid prediction of the DQE performances of developing systems as well as the optimal design of systems.

Materials and Methods

Cascaded model

- Assumptions
  - Linear, shift invariant response and wide-sense stationary Gaussian noise in detector systems
  - Square pixel geometry with pitch p and active aperture width a
  - Statistically uncorrelated detector readout noise in space
- The following cascaded model does not consider any parallel branch describing fluorescence x-ray generation and interactions. However, quantum absorption reflects the average energy deposition considering the escape of fluorescence and Compton scattered rays because the Monte Carlo simulation accounts for all the x-ray interaction processes

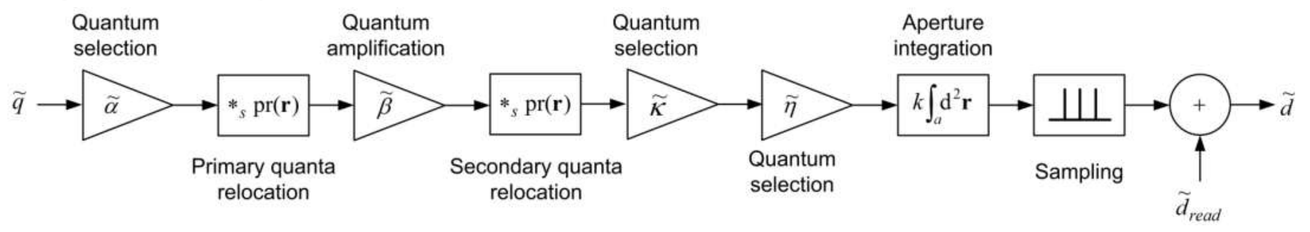


Figure 1. Simple cascaded model to describe signal and noise propagation in a flat-panel detector. The overhead tilde designates a random variable. The symbol "$*_s$" is the quantum-scatter operator.

Symbol	Property	Value [a)] D1 (direct) [b)]	D2 (indirect) [c)]
a	Pixel aperture [mm]	$p\sqrt{\gamma_2}$	
p	Pixel pitch [mm]	0.139	0.143
γ_2	Fill factor	0.79	0.68
	Incident photon fluence [mm^{-2} mR^{-1}]	2.6×10^5 ($\bar{q}\,[\mathrm{mm^{-2}}]=\bar{q}_0\times X\,[\mathrm{mR}]$) [d)]	
α	Average quantum absorption efficiency	0.53	0.81
I	Swank factor	0.96	0.76
T_1	MTF due to primary quantum scattering	1	
β	Secondary quantum gain per interacting quantum	1070	2600
T_2	MTF due to secondary quantum scattering	Measured	1
κ	Average coupling efficiency	0.32	1
η	Average collection efficiency	0.65	1
T_3	MTF due to aperture integration	$\lvert\mathrm{sinc}(\pi au)\,\mathrm{sinc}(\pi av)\rvert$	
σ_{read}	Additive readout electronic noise [e^-]	3000 [e)]	4600 [f)]

[a)] Numerical values were estimated using Monte Carlo codes, MCNP™ (Version 2.5.0., ORNL, USA) and DETECT2000 (Laval University, Quebec, Canada) for x rays and optical photons, respectively.
[b)] a-Se based direct-conversion flat-panel detector
[c)] CsI(Tl)-based indirect-conversion flat-panel detector
[d)] 8.82 mR and 0.37 mR for D1 and D2, respectively
[e), f)] Provided by companies

Formalism on DQE

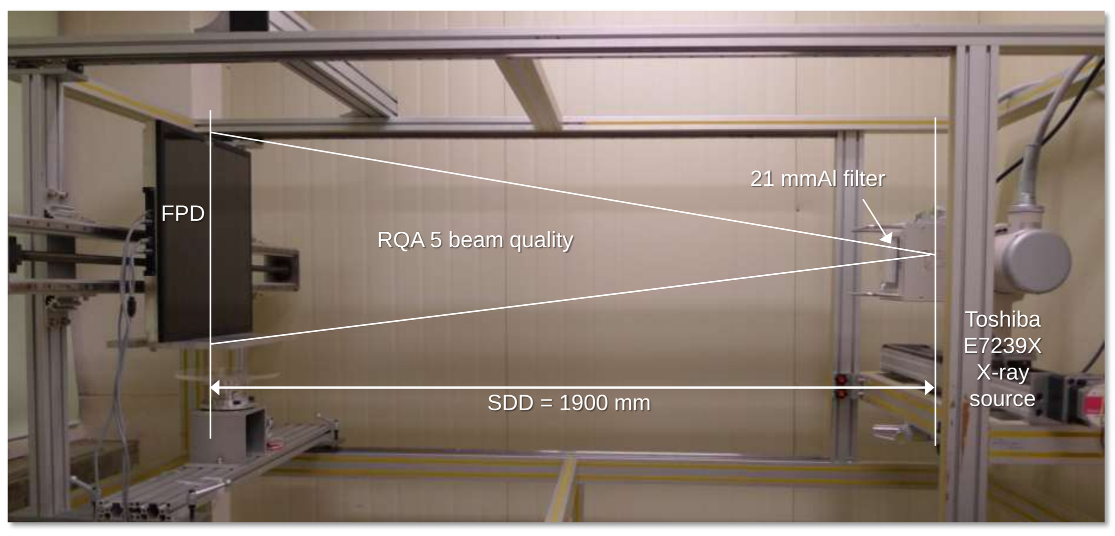
DQE — Eq. (1)

$$\mathrm{DQE}(\mathbf{k})=\frac{\bar{q}a^4\bar{g}^2T_1^2(\mathbf{k})T_2^2(\mathbf{k})T_3^2(\mathbf{k})}{\bar{q}a^4\bar{g}\sum_{j=0}^{\infty}\left\{\left[1+\frac{\bar{g}}{\bar{m}}\left(\frac{\beta}{I}-1\right)T_2^2(\mathbf{k}\pm\frac{j}{p})\right]T_3^2(\mathbf{k}\pm\frac{j}{p})\right\}+p^2\sigma_{read}^2}$$

$$\bar{m}=\alpha\beta,\quad \bar{g}=\alpha\beta\kappa\eta,\quad \mathrm{DQE}_{conv}(\mathbf{0})=\alpha I$$

Conditions	Approximate DQE for direct detectors	Conditions	Approximate DQE for indirect detectors
$T_2(\mathbf{k})\approx1$	Eq. (2) $\mathrm{DQE}_{direct}(\mathbf{k})\approx\dfrac{\mathrm{DQE}_{conv}(\mathbf{0})\gamma_2T_1^2(\mathbf{k})\mathrm{sinc}^2(\pi a\mathbf{k})}{1+\frac{\mathrm{DQE}_{conv}(\mathbf{0})}{\bar{m}}\left(\frac{\bar{m}}{\bar{g}}-1\right)+\frac{\mathrm{DQE}_{conv}(\mathbf{0})\sigma_{read}^2}{\bar{q}a^2\bar{g}^2}}$	$\mathrm{MTF}(\mathbf{k})\approx T_2(\mathbf{k})$	Eq. (5) $\mathrm{DQE}_{indirect}(\mathbf{k})\approx\dfrac{\mathrm{DQE}_{conv}(\mathbf{0})}{1+\mathrm{DQE}_{conv}(\mathbf{0})\left(\frac{1}{\gamma_2\bar{g}^2T_2^2(\mathbf{k})}-\frac{1}{\bar{m}}\right)+\frac{\mathrm{DQE}_{conv}(\mathbf{0})\sigma_{read}^2}{\gamma_2\bar{q}a^2\bar{g}^2T_2^2(\mathbf{k})}}$
$\bar{m}\approx\bar{g}$, $\sigma_{read}<a\bar{g}\sqrt{\frac{\bar{q}}{\mathrm{DQE}_{conv}(\mathbf{0})}}$	Eq. (3) $\mathrm{DQE}_{direct}(\mathbf{k})\approx\mathrm{DQE}_{conv}(\mathbf{0})\gamma_2T_1^2(\mathbf{k})\mathrm{sinc}^2(\pi a\mathbf{k})\left[1-\frac{\mathrm{DQE}_{conv}(\mathbf{0})\sigma_{read}^2}{\bar{q}a^2\bar{g}^2}\right]$	$\sigma_{read}<a\bar{g}T_2(\mathbf{k})\sqrt{\frac{\gamma_2\bar{q}}{\mathrm{DQE}_{conv}(\mathbf{0})}}$	Eq. (6) $\mathrm{DQE}_{indirect}(\mathbf{k})\approx\mathrm{DQE}_{conv}(\mathbf{0})-\frac{\mathrm{DQE}_{conv}^2(\mathbf{0})}{\gamma_2\bar{g}^2T_2^2(\mathbf{k})}\left[1-\frac{\sigma_{read}^2}{\bar{q}a^2}\right]$
$\sigma_{read}<<a\bar{g}\sqrt{\frac{\bar{q}}{\mathrm{DQE}_{conv}(\mathbf{0})}}$	Eq. (4) $\mathrm{DQE}_{direct}(\mathbf{k})\approx\mathrm{DQE}_{conv}(\mathbf{0})\gamma_2T_1^2(\mathbf{k})\mathrm{sinc}^2(\pi a\mathbf{k})$	$\sigma_{read}<<a\bar{g}T_2(\mathbf{k})\sqrt{\frac{\gamma_2\bar{q}}{\mathrm{DQE}_{conv}(\mathbf{0})}}$	Eq. (7) $\mathrm{DQE}_{indirect}(\mathbf{k})\approx\mathrm{DQE}_{conv}(\mathbf{0})-\frac{\mathrm{DQE}_{conv}^2(\mathbf{0})}{\gamma_2\bar{g}^2T_2^2(\mathbf{k})}$

Validation of cascaded model



RQA5 [a)] tube voltage	70 kVp
Half-value layer	7.1 mmAl
Mandatory SNR$_{in}^2$	30174 #/mm^2/μGy
Added filter	21 mmAl
Adjusted Tube voltage	68 kVp
Measured HVL	7.114 mmAl
Calculated SNR$_{in}^2$	30187 #/mm^2/μGy
Percent difference (SNR$_{in}^2$)	0.04 %

[a)] Recommended beam quality by the IEC (International Electrotechnical Commission, Report 1267)

1 Dimensional DQE

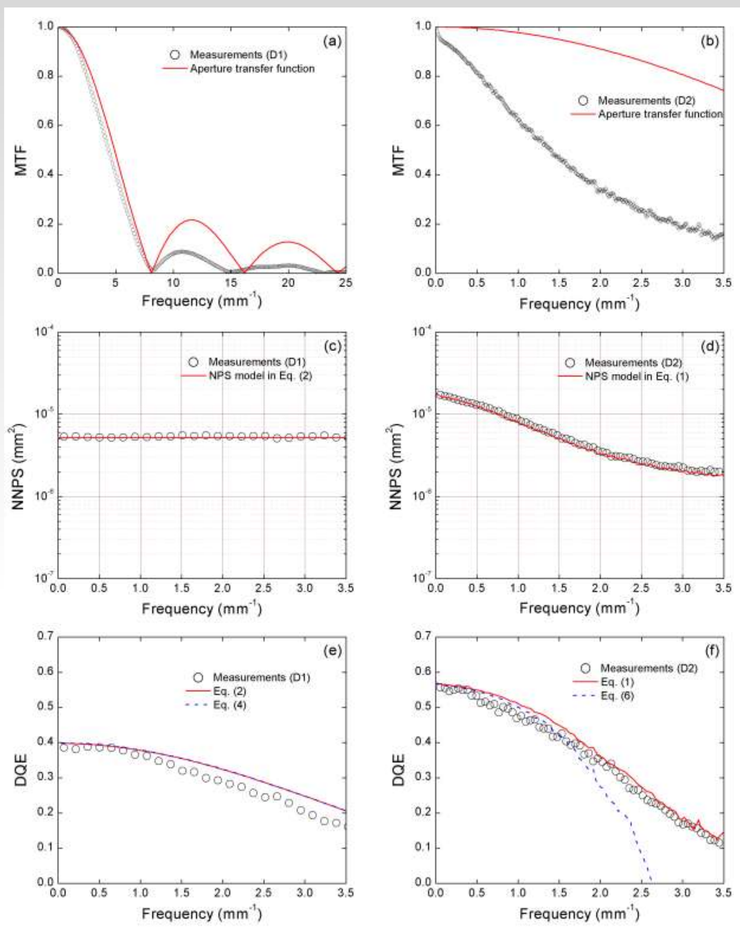
- In Cartesian coordinates; $\mathrm{DQE}(\mathbf{k})=\mathrm{DQE}(u,v)$
- The one-dimensional DQE of two-dimensional detector can be obtained by evaluating the two-dimensional DQE along the appropriate axis.

$$\mathrm{DQE}(u)=\mathrm{DQE}(u,v)\big|_{v=0}=\mathrm{DQE}(u,0)$$

- In similar, the one-dimensional theoretical DQE is calculated considering two-dimensional noise aliasing [see Eq. (1)] because noise is aliased over two dimension.
- If a detector has one dimension, for example, linear array, the DQE on a single axis could be considered. In this case, to describe the one-dimensional DQE, the dimensions of incident photon fluence and pixel fill factor should be reduced;
  - $\bar{q}_1=\bar{q}\times a$
  - $\gamma_1=a/p$

Results

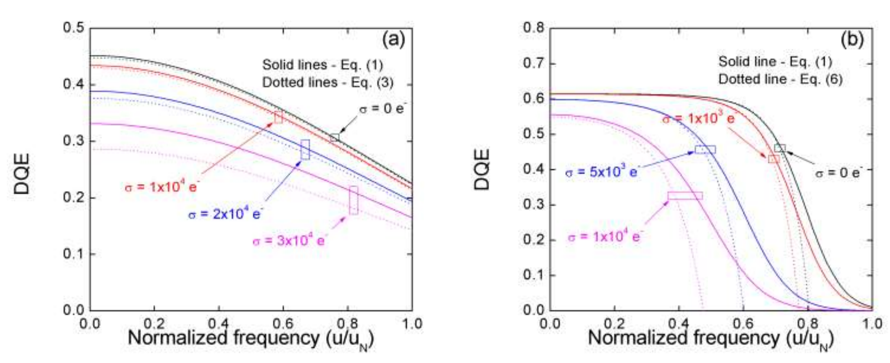
Model validation



- For direct-conversion detectors:
  - The measured MTF is less than the aperture transfer function (or sine cardinal function), which implies that the signal spreading exists in primary and/or secondary quantum relocation stages.
  - Theoretical white-spectrum characteristics due to noise aliasing is well supported by the measured noise-power spectrum.
  - Approximate DQE greatly describes the measured data.
- For indirect-conversion detectors:
  - There is a large discrepancy between the aperture transfer function and the measured MTF, which is mainly due to the secondary quantum scattering in the CsI(Tl) layer.
  - The agreement between the calculated and measured NPS is excellent.
  - Approximate DQE underestimates for the spatial frequency greater than 1.5 mm^{-1}.
- Although the developed DQE formalism slightly overestimates the measured data obtained from both direct and indirect-conversion detectors, the agreements between them are excellent.

Effect of additive noise on the approximate DQE

- Additive electronic readout noise affects the DQE of direct-conversion detectors in the entire spatial frequencies, while the DQE of indirect-conversion detector at higher frequencies is relatively more sensitive to the additive noise.
- For direct-conversion detectors:
  - Approximate DQE well describes the real DQE [Eq. (1)] when the detector is operated at quantum-noise-limited region or $\sigma_{read}=0$.
  - Approximate DQE reasonably follows the real DQE up to $\sigma_{read}=10^4$ e^- in this simulation.
  - For $\sigma_{read}>10^4$ e^-, the approximate DQE over the entire frequencies levels off as σ_{read} increases, which could be explained by Eq. (3).
- For indirect-conversion detectors:
  - The approximate DQE in the high frequency band underestimates the real DQE even for $\sigma_{read}=0$.
  - This frequency band widens as σ_{read} increases.



- The simulation assumes one-dimensional detector configuration for simplicity.
- All the simulations have been performed for the entrance surface exposure of 1 mR.
- MTF of the hypothetical indirect detector is based on the Gaussian point-spread function with $\sigma=p$.
- Refer to the above Table for the other simulation parameters.

Discussion and Conclusions

- When a detector is operated in quantum-noise-limited region, the DQE(0) of indirect-conversion detectors is determined by the DQE(0) of scintillator, while that of direct-conversion detector is the same as DQE(0) of photoconductor scaled by the pixel fill factor.
  - To preserve the photoconductor DQE performance in direct-conversion detectors, it is required that the pixel could be designed to have a fill factor as high as possible.
  - Electrical design in which all field lines terminate on pixel electrodes is essential.
- To maintain DQE(0) under out of quantum-noise-limited operation, it is required a reduced noise level;
  - $\sigma_{reduced}=\sigma_{read}\times\sqrt{\bar{q}/\bar{q}_0}$
  - $\bar{q}_0$ = the incident photon fluence required for the quantum-limited-noise operation

- The developed DQE formalism greatly agrees to the measured DQE values.
- Approximate DQE of direct-conversion detectors correctly describes the real DQE in the quantum-noise-limited operation.
- Approximate DQE of indirect-conversion detectors reasonably describes the real DQE up to ~75% of the Nyquist-frequency limit in the quantum-noise-limited operation.
- The approximate DQE formulas 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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