Optimization of the detection thresholds of single-photon counting sensors for breast cancer screening procedures

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Photocounting detection threshold

• **High enough** to discriminate signal from noise
• **Low enough** to detect every incident primary X-ray

**Problem:** False counts due to charge-sharing in Pixel Detectors (worst when decreasing pixel size)

**Solution:** Higher detection threshold

**Problem:** Image noise due to scattered radiation

**Solution ?:** Higher detection threshold ?

**Effect of detection threshold on system performance in mammography??**
Detector performance in X-ray imaging

Fourier-based linear system analysis
Statistical decision theory

Detective quantum efficiency (DQE):

\[
DQE(f) = \frac{|GqMTF(f)|^2}{NPS(f) \times q}
\]

\[
DQE \approx \frac{SNR^2}{SNR^2_{\text{max}}}
\]
Detector performance in broad-spectrum X-ray imaging

Fourier-based linear system analysis
Statistical decision theory

Detector contrast modulation in the domain of X-ray energy

Broad-spectrum DQE

\[ DQE(0) = \frac{\left| \int G(E) \Delta \mu(E) q_b(E) dE \right|^2}{NPS(0) \times \int \Delta \mu(E)^2 q_b(E) dE} \]

Difference in attenuation coefficients between breast and lesion to detect

Large-area detector gain

Noise Power Spectrum
X-ray fluence

X-ray focal spot

\( \Delta \mu(E) \)

cf task-dependent DQE
System performance in X-ray imaging

Fourier-based linear system analysis
Statistical decision theory
Scatter-reduction technique

System DQE

Primary radiation transmission factor of grid

\[ DQE(f) = \frac{t \cdot |GqMTF(f)|^2}{1 + SPR \cdot NPS(f) \times q} \]

Scatter-to-primary ratio

X-ray focal spot

Antiscatter grid (t)

SPR, G, MTF, NPS @ q

X-ray detector
System performance in broad-spectrum X-ray imaging

Fourier-based linear system analysis
Statistical decision theory
Detector contrast modulation in the domain of X-ray energy
Scatter-reduction technique

\[
DQE(0) = \frac{t^2 \left| \int G(E) \Delta \mu(E) q_b(E) dE \right|^2}{NPS_p(0) + NPS_s(0) + NPS_{add}} \times \frac{1}{\int \Delta \mu(E)^2 q_b(E) dE}
\]

\text{primary radiation} \quad \text{scattered radiation} \quad \text{additive noise}

DQE = 1 for an ideal X-ray image detector:
• with optimal \textbf{energy weighting} function ( \( G(E) \propto \Delta \mu(E) \))
• and combined to an ideal \textbf{scatter-reduction} system (t=1 and SPR=0)

\textit{Ideal photocounting detector: Quantum-Noise-Limited,}
\textit{Quantum efficiency =1 (and Swank factor = 1)}

\textit{Scatter fluence approximated by:} \( q_s(E) \approx \text{SPR}.q_p(E) \)
Lesion detection tasks in breast cancer screening

• **Mass densities:** (border, density, capsule, halo and silhouette sign)

• **Calcifications:** (shape, density, distribution, definition, unilateral or bilateral, surrounding tissue or associated mass, increase in number, size):
  
  • **Type I:** calcium oxalate dihydrate  
    (almost always benign)

  • **Type II:** calcium phosphate  
    (related to cellular degradation and breast carcinoma)
Effect of photocounting energy threshold on DQE

Mo/Mo spectrum @ 30 kVp, *microcalcification* detection in a 4 cm thick, 50% glandular breast
Effect of photocounting energy threshold on DQE
Mo/Mo @ various kVps, microcalcification detection in a 2, 4, 6, 8 cm thick, 50% glandular breast

Thickness = 2 cm

Thickness = 4 cm

Thickness = 6 cm

Thickness = 8 cm
Effect of photocounting energy threshold on DQE

W/Al @ various kVps, microcalcification detection in a 2,4,6,8 cm thick, 50% glandular breast

Thickness = 2 cm

Thickness = 4 cm

Thickness = 6 cm

Thickness = 8 cm
Figure of Merit (FOM) for breast cancer screening

Signal-to-noise ratio for lesion detection

$$\text{FOM} = \frac{\text{SNR}^2}{\text{Dg}} \propto \frac{\text{Benefit}}{\text{Risk}}$$

Mean glandular dose

$$\text{DQE} \approx \frac{\text{SNR}^2}{\text{SNR}_{\text{max}}^2}$$

allows a figure of merit describing system performance to be defined as:

$$\text{FOM} = \frac{\text{DQE}(0) \times \text{SNR}_{\text{max}}^2}{\text{Dg}}$$
Effect of photocounting energy threshold on FOM
W/Al @ various kVps, microcalcification detection in a 2, 4, 6, 8 cm thick, 50% glandular breast
Effect of photocounting energy threshold on FOM

W/Al @ various kVps, in a 4 cm thick, 50% glandular breast
Microcalcification & tumor detection

Microcalcification detection
Tumour detection

Breast thickness = 4 cm
Conclusion & future work:

• Effect of the detection energy threshold on the mammographic performance of photocounting sensors can be quantified by examining:
  
  - DQE @ 0 lp/mm : modified to include effects related to energy weighting and scattered radiation
  
  - FOM: considering the influence of X-ray spectral shape (tube voltage, anode/filter combination) on system performance

• Higher photocounting thresholds can be implemented when imaging thick breasts without compromising system performance. This might allow charge-sharing-related image noise to be reduced in some situations.

• An accurate optimization of detection thresholds requires the precise knowledge of the spectral distribution of scattered radiation (measurements or Monte-Carlo simulations)
Conclusion & future work:

• A task-dependent aspect is reintroduced in the description of system performance in mammography. This evolution is driven by technological developments in the field of semiconductor-based X-ray imagers.

• A DQE analysis at 0 lp/mm is sufficient for detection threshold optimization, but the frequency dependence is needed to compare the performance of various X-ray imaging technologies.

• This extension of linear system analysis is of a more general interest in X-ray imaging than threshold optimisation:

The performance of X-ray imaging systems must be described in comparison to ideal energy-sensitive sensors operating in scatter-free conditions.
Conclusion & future work:

Development of a **Low-Dose Digital Mammography** system at UCT/MRC Medical Imaging Research Unit, based on existing **slot-scanning technology**

→ Platform for testing:

- extended imaging theories,
- new detector technologies,
- new scanning methods.
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