Detector DQE and Task-Based Observer Performance

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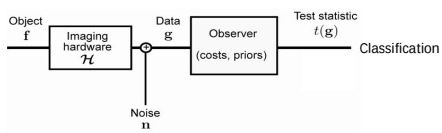
Outline

- **Framework for task-based assessment**
- Object models
  - SKE/BKE imaging tasks and beyond
- Descriptions of imaging performance (DQE)
- Connection of DQE/NEQ to task-based assessment
- Examples of quantitative assessment
- Conclusion

Quantitative assessment of image quality[1,2] must consider:



- Object models
- Imaging hardware (H)
  - *mapping to data space, CD*
- Noise (quantum noise, electronic noise, ...)

- Ideal Observer
  - computes test statistic, $t(\mathbf{g})$
  - given, $\mathbf{g}$, makes inference about object, f
  - determines FOM from statistics of $t(\mathbf{g})$
- Imaging task
  - detection, localization, characterization, estimation

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What are useful models of objects for quantitative system evaluation?[3]

Objects: $f = f_s + f_b$

Data: $g = H\ f + n$

$= H\ f_s + H\ f_b + n$

SKE/BKE Imaging Tasks

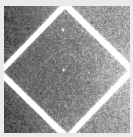
Objects: $f = f_s + f_b$

- Signal with known size, shape, amplitude and location

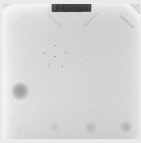
Data: $g = \Delta s + b + n$

- Uniform and statistically known background

Data: $g = b + n$



CDMAM

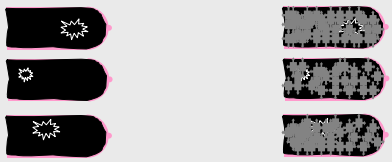


ACR/MAP

Imaging Phantoms

SKE and BKE and reality!

Objects: $f = f_s + f_b$



Signal location and amplitude uncertainty

Anatomical structures (lumpy backgrounds)

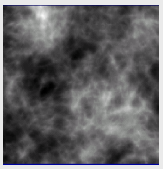
MIB Simulation

Background Known Statistically (BKS)

Lumpy background[4]

$$f(\mathbf{r}) = \sum_{n=1}^{N} l(\mathbf{r} - \mathbf{r}_n)$$

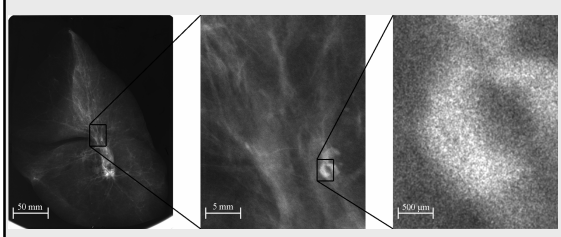
Clustered lumpy background[5]



$$f(\mathbf{r}) = \sum_{k=1}^{N_k} \sum_{n=1}^{N_k} l_k(\mathbf{r} - \mathbf{r}_{nk} - \mathbf{R}_k)$$

MIB

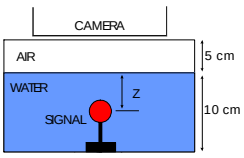
High-resolution images of actual objects[6]

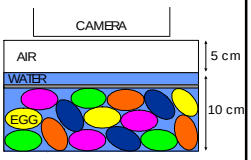


High-resolution images of the thorax and the frequency components in signals
Christoph.hoeschen@medizin.uni-magdeburg.de

MIB Imaging Phantoms

- Experimental set-up for collecting signal data
- Experimental setup for collecting non-uniform random background data[7]





Sain and Barrett, "Performance evaluation of a modular gamma camera using a detectability index," JNM 44: 58-66 2003

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What are meaningful metrics for the CD mapping model (very fine pixels)?

- Detective Quantum Efficiency (DQE) as summary measure[8-10]
  - **spatial frequency domain**
  - **assumptions (LSIV and stationarity)**
- Gray scale transfer, resolution, noise and cost (patient dose or imaging time)
- Grounded in statistical decision theory (SDT)[11,12]
  - task based

Detective Quantum Efficiency

Transfer of information in terms of SNR

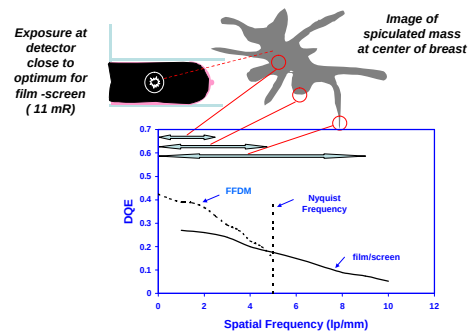
$$DQE(n) = \frac{SNR^2_{out}(n)}{SNR^2_{in}(n)}$$

Noise Equivalent Quanta

$$NEQ(n) = G^2\, MTF^2(n) / NPS(n)$$

$$DQE(n) = \frac{NEQ(n)}{\overline{Q}}$$

- G, gray-scale transfer
- MTF(n) , resolution
- NPS(n) , noise
- Q, input quanta (cost)



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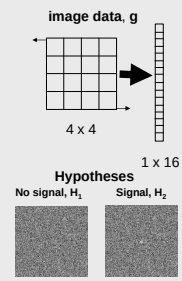
Ideal Observer[13,14,2]

1. Given image data, **g**.
2. Decide which hypothesis (H_1 or H_2).
3. Use Bayes theorem to form likelihood ratio, L, as optimal decision scalar.

$$L = t(\mathbf{g}) = p(\mathbf{g} \mid H_2) / p(\mathbf{g} \mid H_1)$$

4. Make assumptions.
   - linear, shift invariant imaging system
   - signal and background known exactly (SKE/BKE)
   - additive, zero-mean, Gaussian distributed noise
   - low-contrast signal



$$t(g) = (D\mathbf{s}^t \mathbf{K}_n^{-1})\mathbf{g}$$

- Expected Difference Signal (Ds)
- System Noise (K_n, covariance matrix)

"Our old friend the prewhitening matched filter"

5. Calculate figure-of-merit (SNR^2) from mean and variance of decision scalar for set of many images.
6. Estimate quality of detected data in terms of SNR^2 of ideal observer.

Ideal Observer's FOM for SKE/BKE tasks in Gaussian noise

$$SNR_I^2 = D\mathbf{s}^t \mathbf{K}_n^{-1} D\mathbf{s}$$

Upper bound for human and machine performance!!!

Origin of NEQ/DQE approach!!!

Connection to DQE/NEQ

Spatial Domain:

$$D\mathbf{s} = \mathbf{H}\ \mathbf{f}_s$$

- f_s , Expected Input Signal
- H , System Transfer Function

$$SNR_I^2 = \mathbf{f}_s^t (\mathbf{H}^t \mathbf{K}_n^{-1} \mathbf{H})\, \mathbf{f}_s$$

- $(\mathbf{H}^t \mathbf{K}_n^{-1} \mathbf{H})$, Image noise referred to object domain[1] == NEQ(n)

Spatial Frequency Domain (previous assumptions, stationary noise and continuous mathematics!!)

$$SNR_I^2 = \mathbf{G}^2 \int \frac{|\mathbf{F}_s(n)|^2\, \mathbf{MTF}^2(n)}{\mathbf{W}_n(n)}\, dn$$

- G^2MTF^2/W_n, Image noise referred to object domain[1] == NEQ(n)!

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Examples of quantitative assessment

- Basis for observer SNR
  - wholly on empirically determined parameters[15]
  - simulated image formation with validation of end results[16-18]
- Spatial or spatial frequency domains
  - assumptions
- Connection to DQE/NEQ

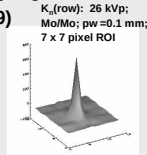
SKE/BKE Imaging Tasks – Digital Mammography

Approach (15 images, total mAs = 1569)

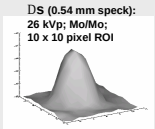
- Estimate a row of covariance matrix from the image data (K_n)
  - **several hundred samples per image**
- Estimate expected difference signal (Δs) from the image data
  - **one sample per image**
- Calculate SNR using "bootstrapping" techniques

$$SNR_I^2 = \Delta \mathbf{s}^t \mathbf{K}_n^{-1} \Delta \mathbf{s}$$

K_n(row): 26 kVp; Mo/Mo; pw =0.1 mm; 7 x 7 pixel ROI

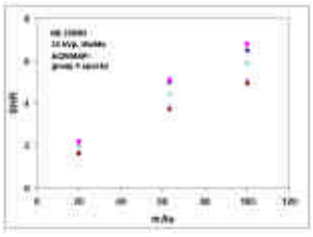


Δs (0.54 mm speck): 26 kVp; Mo/Mo; 10 x 10 pixel ROI

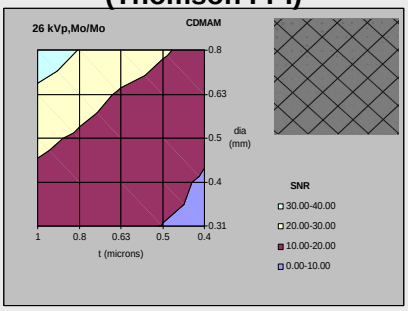


SKE/BKE Imaging Tasks (GE 2000D)

- SNR_I as a function of mAs for all specks in group 4 (0.24 mm) of ACR/MAP
  - range of about 7 to 2
- Difference of 30 % between specks within a group
  - overlap between groups (not shown)



SKE/BKE Imaging Tasks (Thomson FPI)



SKE/BKE Imaging Tasks – Digital Fluoroscopy

Approach

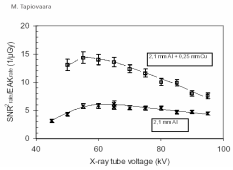
- Estimate observer SNRs using spatial-temporal noise power spectrum (NPS)[19]
  - noise stationarity assumption
- Calculate unbiased SNR

$$SNR_I^2 = G^2 \int \frac{|F_s(n)|^2 MTF^2(n)}{W_n(n)} dn$$

STUK STUK-A196 / Mar 2003

OBJECTIVE MEASUREMENT OF IMAGE QUALITY IN FLUOROSCOPIC X-RAY EQUIPMENT: FLUOROQUALITY

M. Tapiovaara

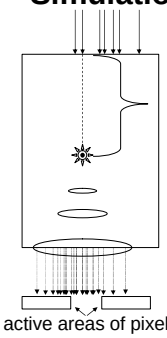


http://www.stuk.fi/julkaisut/stuk-a/stuk-a196.pdf

Impact of signal size, location, and pixel fill-factor on detectability?[18]

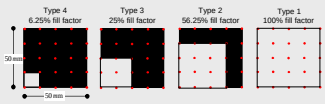
- Simulation of image formation
  - depth dependent PSFs (GdOS) using Monte Carlo for light transport within phosphor[20]
- Set of noise and signal plus noise images
  - signals: spherical calcifications (50µm - 400 µm dia)
- Fill-factor: $\frac{\text{photo-sensitive area}}{\text{pixel area}}$

Simulation of Image Formation

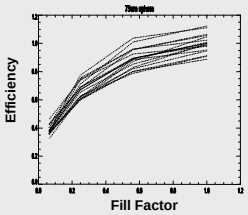


Fill factor efficiency

Pixel Design
(50 µm x 50 µm)

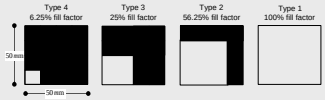


- 75 µm spherical calcification
  - 25 positions (red)
- Efficiency as SNR² / <SNR²(100% fill) > versus fill factor (DQE?)

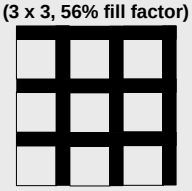


Shift Variant Imaging[21-25]

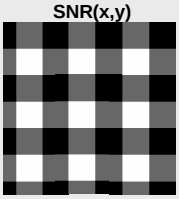
Pixel Design
(50 µm x 50 µm)



Detector Section
(3 x 3, 56% fill factor)



Detectability Map
SNR(x,y)



Beyond SKE/BKE imaging tasks!

- Observer SNR
  - ideal, if possible, or ideal linear (Hotelling),[26-28] as next best thing
- Signal and/or background only known statistically (not exactly)[29-31]
  - clustered lumpy background
  - Hotelling observer

Spatial Domain

$$\Delta \mathbf{s}^t (\mathbf{H}^t \mathbf{K}_b \mathbf{H} + \mathbf{K}_n)^{-1} \Delta \mathbf{s}$$

- $\mathbf{K}_b$, **Background structure noise**

Spatial Frequency Domain

$$\mathbf{G}^2 \int \frac{|\mathbf{F}_s(n)|^2 \, \mathbf{MTF}^2(n)}{(\mathbf{G}^2 \, \mathbf{MTF}^2(n) \mathbf{W}_b(n) + \mathbf{W}_n(n))} \, dn$$

- $\mathbf{W}_b(n)$ **Background Structure**

Conclusions

- Quantitative approaches available particularly for DR/DF/CT and SKE/BKE imaging tasks
- Observer FOM provides means for system performance assessment and optimization
  - bounds on human performance
- Connection to DQE/NEQ
- Lots to be done to move away from SKE/BKE imaging tasks

References:

1 – ICRU Report 54, "Medical Imaging – The Assessment of Image Quality," Bethesda, MD: International Commission on Radiation Units and Measurements, 1996.
2 – H.H Barrett and K.J. Myers, "Foundations of Image Science," John Wiley & Sons, Inc., New York, 2004.
3 – Myers, K.J. "State of the Art in Task-based Assessment of Image Quality," Keynote presentation, Conference on Medical Imaging Physics, SPIE International Symposium on Medical Imaging, San Diego, CA (Feb. 2004).
4 – J. P. Rolland, "Synthesizing anatomical images for image understanding," *Handbook of Medical Imaging Physics and Psychophysics*, J. Beutel, H.L. Kundel, R.L. Van Metter, eds., 1, 683-720, SPIE Press, Bellingham, WA, 2000.
5 – F.O. Bochud, C.K. Abbey, M.P. Eckstein, "Statistical texture synthesis of mammographic images with clustered lumpy backgrounds," Optics Express Vol. 4, No. 1, 33-43 (1999).
6 – Christoph.hoeschen@medizin.uni-magdeburg.de

References

7 – Sain and Barrett, "Performance evaluation of a modular gamma camera using a detectability index," JNM 44: 58-66 2003
8 – "Premarket Applications for Digital Mammography Systems; Final Guidance for Industry and FDAT," Food and Drug Administration, Center for Devices and Radiological Health, February 16, 2001.
9 – "Guidance for the Submission of 510(k)'s for Solid State X-ray Imaging Devices," Food and Drug Administration, Center for Devices and Radiological Health, August 6, 1999**.**
10 – R. Shaw, "The equivalent quantum efficiency of the photographic process," *J. Photog. Sci.* **11**, 199-204, 1963.
11 – H.L. Van Trees, *Detection, Estimation, and Modulation Theory*, Vol. I, Wiley, New York, 1968.
12 – J.L. Melsa, D.L. Cohn, *Decision and Estimation Theory,* McGraw-Hill, New York, 1978.
13 – H.H. Barrett, C.K. Abbey, E. Clarkson, "Objective Assessment of Image Quality. III. ROC Metrics, Ideal Observers, and Likelihood-Generating Functions." *J. Opt. Soc. Am.* **A15**, 1520-1535, 1998.

References

14 – K.J. Myers, "Ideal observer models of visual signal detection," *Handbook of Medical Imaging Physics and Psychophysics*, J. Beutel, H.L. Kundel, R.L. Van Metter, eds., **1**, 559-592, SPIE Press, Bellingham, WA, 2000.
15 – R.M. Gagne, K. Chakrabarti, J. Thomas, B. Gallas, K. Myers, "Toward objective evaluation of imaging phantom scores – ACR/MAP," presentation at AAPM Annual Meeting (July 2004).
16 – R.J. Jennings, H. Jafroudi, R.M. Gagne, T.R. Fewell, P.W. Quinn, D.E. Steller-Artz, J.J. Vucich, M.T. Freedman, S.K. Mun, "Storage-phosphor-based digital mammography using a low-dose x-ray system optimized for screen-film mammography," *Proc. SPIE* **2708**, 220-232, 1996.
17 – R.M. Gagne, H. Jafroudi, R.J. Jennings, T.R. Fewell, P.W. Quinn, D.E. Steller-Artz, J.J. Vucich, M.T. Freedman, S.K. Mun, "Digital mammography using storage phosphor plates and a computer-designed x-ray system," DIGITAL MAMMOGRAPHY '96, Elsevier Science B.V., 133-138, 1996.

References

18 – B.D. Gallas, J.S. Boswell, A.G. Badano, R.M. Gagne, K.J. Myers, "EZ model and simulation: x rays interacting in a phosphor," to be published *Medical Physics* (2004).
19 – http://www.stuk.fi/julkaisut/stuk-a/stuk-a196.pdf
20 – A. Badano, R. M. Gagne, B. D. Gallas, R. J. Jennings, J. S. Boswell, and K. J. Myers, "Lubberts effects in columnar phosphors," to be published *Medical Physics* (2004).
21 – M.L. Giger and K. Doi, "Effect of pixel size on detectability of low-contrast signals in digital radiography," J. Opt. Soc. Am. A 4(5), 966-975, 1987.
22 - A.R. Pineda, H.H. Barrett, "What does DQE say about lesion detectability in digital radiography?" *Proc. SPIE* **4320**, 2001.
23 - M. Albert, A.D.A. Maidment, "Linear response theory for detectors consisting of discrete arrays," *Med. Phys*. **27(10)**, 2417-2434, 2000.
24 - E. Clarkson, A.R. Pineda, H.H. Barrett, "An analytical approximation to the Hotelling trace for digital –ray detectors," *Proc. SPIE* **4320**, 2001.
25 - R. M. Gagne, J.S. Boswell, K.J. Myers, "Signal detectability in digital radiography: Spatial domain figures of merit," *Med. Phys*. 30(8), 2180-2193(2003).

References

26 - R.D. Fiete, H.H. Barrett, W.E. Smith, and K.J. Myers, "The Hotelling trace criterion and its correlation with human observer performance," J. Opt. Soc. Am. A 4, 945-953, 1987.
27 - H.H. Barrett, J. Yao, J.P. Rolland, and K.J. Myers, "Model observers for assessment of image quality," Proc. Natl. Acad. Sci. USA 90, 9758-9765, 1993.
28 - C.K. Abbey, F.O. Bochud, "Modeling visual detection tasks in correlated image noise with linear model observers," *Handbook of Medical Imaging Physics and Psychophysics*, J. Beutel, H.L. Kundel, R.L. Van Metter, eds., **1**, 629-654, SPIE Press, Bellingham, WA, 2000.
29 – K.J. Myers, R.F. Wagner, "Detection and Estimation: Human vs. Ideal as a Function of Information," Proc. SPIE 914, 291-297, 1988.
30 – L.W. Nolte, D. Jaarsma, "More on the Detection of one of M Orthogonal Signals," J. Acous. Soc. Am. 41, 497-505, 1967.
31 – D.G. Brown, M.F. Insana, M. Tapiovaara, "Detection Performance of the Ideal Decision function and Its McLaurin Expansion: Signal Position Unknown," *J. Acous. Soc. Am.* **97**, 379-398, 1995.