Relationship of DQE to visual image quality

Robert M. Gagne, Ph.D.
Office of Science and Technology
Center for Devices and Radiological Health
Food and Drug Administration
Rockville, Maryland 20857

Outline

- Meaningful metrics
  – search for the “Holy Grail”
- Ideal observer formulation
  – detected versus display data
- Assumptions
  – SKE/BKE imaging task and beyond
- Connection to visual image quality

Meaningful Metrics
(“Holy Grail”)

“Holy Grail” of Imaging Physics

Connections between:

I – Meaningful metrics (lab and clinic)

II - Imaging phantom studies

III - Clinical imaging performance

ICRU Report 54[1]

- Represents state-of-the-art of image assessment (up to around 1995) including technical efficacy and diagnostic accuracy
- Technical efficacy approaches used by all manufacturers of digital radiography and mammography equipment[2,3]

What are meaningful metrics?

- Gray scale transfer, resolution, noise and cost (patient dose or imaging time)
- Grounded in statistical decision theory (SDT)[4,5]
  - task based
- Detective Quantum Efficiency (DQE) as summary measure[6]
  - **spatial frequency domain**
  - assumptions

Meaningful Metrics

Detective Quantum Efficiency

Transfer of information in terms of SNR

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

Noise Equivalent Quanta

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

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

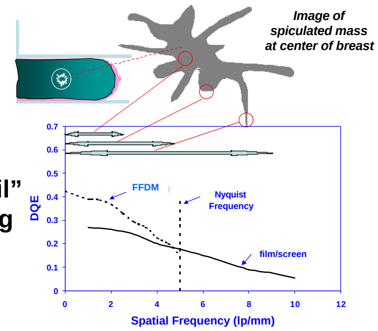
- G, gray-scale transfer
- MTF(n), resolution
- NPS(n), noise
- Q, input quanta (cost)

Meaningful Metrics

Exposure at detector close to optimum for film-screen (11 mR)

Image of spiculated mass at center of breast

"Holy Grail" of Imaging Physics



Ideal Observer

Ideal Observer

Ideal Observer

Image Formation

- Two stage process: data detection followed by data display[7]

Image Formation

Detection — **Display**

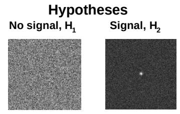
- Evaluation of the quality of **detected data**
  - ideal observer from Bayesian decision theory[4]
  - task-based performance

Ideal Observer

Ideal Observer[8,9]

- Given image data, **g**.
- Decide which hypothesis (H_1 or H_2).

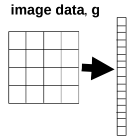
Hypotheses



3. Using Bayes theorem to form likelihood ratio, L, as decision scalar.

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

image data, g



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

Ideal Observer

$$L = (\Delta\overline{\mathbf{g}}^t \mathbf{C}_n^{-1})\,\mathbf{g}$$

- **Expected Difference Signal (Δg)**
- **System Noise (C_n, covariance matrix)**

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

Ideal Observer's FOM for SKE/BKE tasks

$$SNR_I^2 = \Delta\overline{\mathbf{g}}^t\, \mathbf{C}_n^{-1}\, \Delta\overline{\mathbf{g}}$$

Upper bound for human and machine performance!!![10]

Ideal Observer

Connection to NEQ/DQE

Spatial Domain:

$$\Delta\bar{g} = H\Delta\bar{f}$$

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

$$SNR_I^2 = \Delta\bar{f}^t (H^t C_n^{-1} H)\Delta\bar{f}$$

- $(H^t C_n^{-1} H)$, Image noise referred to object domain == NEQ(ν) ![1]

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

$$SNR_I^2 = G^2 \int \frac{|\Delta f(\nu)|^2 \, MTF^2(\nu)}{W_n(\nu)} d\nu$$

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

Meaningful Metrics

"Holy Grail" of Imaging Physics

Connections between:

I – Meaningful metrics (lab and clinic)

II - Imaging phantom studies

III - Clinical imaging performance

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

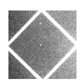
Imaging Phantoms:
. ACR/MAP
. CDMAM
. etc

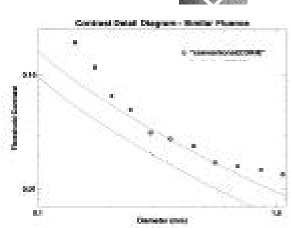
Ideal Observer

Connection to imaging phantom studies[11,12]

- Fuji 9000 Reader
- Fuji HR-V imaging plates
  - 18 cm x 24 cm
  - 0.1 mm pixel
- Prediction from lab (solid lines)
  - SNR = 3 and 5
- Human performance

CDMAM contrast detail imaging phantom – 4 AFC





Ideal Observer

Connection to imaging phantoms – ACR/MAP

- Data on G, MTF and W_n from literature[13]
- Mammo system
  - Mo/Mo
  - Ortho M/Min R
  - OD = 1.26
- Speck constituents
- Calculate SNR_I

RMI 156

Group	d (mm)	Contrast	SNR_I
1	0.54	0.32	36 (34)*
2	0.4	0.23	19 (20)*
3	0.32	0.18	12 (10)*
4	0.24	0.13	6
5	0.16	0.09	2

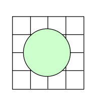
* reference 14

Assumptions

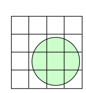
Assumptions?

Assumptions

What is the impact of violating the assumption on shift-invariance?



micro-calcification vertex alignment



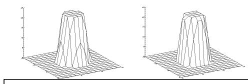
micro-calcification center alignment

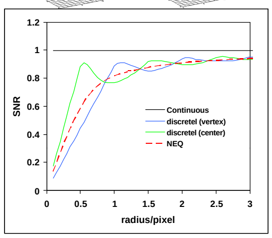
- Digital imaging systems are not shift invariant (Giger and Doi)[15]
- Current FOMs (SNR^2 using NEQ, DQE) not cognizant of signal position
  - spatial vs. spatial frequency domain (aliasing)
- Current research topic[16-19]

Assumptions

Discrete Pixels in a-Se Detector[20]

- shift-variant but linear imaging system
- "perfect resolution"
- noise is "white"
  - "well behaved" flat field correction
- imaging tasks
  - detection of pillbox

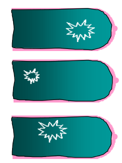




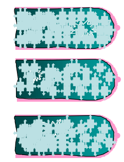
FDA/CDRH/OST AAPM03

Assumptions

SKE and BKE and reality!



Signal location and amplitude uncertainty



Anatomical structures (lumpy backgrounds)

FDA/CDRH/OST AAPM03

Assumptions

What is the impact of violating the SKE and BKE assumptions?

- Signal and background only known statistically (not exactly)
- Ideal observer SNR
  - difficult or impossible to calculate and **nonlinear** on the data[21-23]
- Human observers have difficulty performing nonlinear operations on the data[24]
- Best linear observer (Hotelling)[25-27]
  - Upper bound on human performance for imaging systems with humans as end users!!!

FDA/CDRH/OST AAPM03

Assumptions

Connection to NEQ/DQE

Spatial Domain:

$$SNR_I^2 = \Delta\overline{\mathbf{g}}^t(\mathbf{H}^t\mathbf{C}_f\mathbf{H}+\mathbf{C}_n)^{-1}\Delta\overline{\mathbf{g}}$$

- **C_f, Background structure noise**

Spatial Frequency Domain (additive noise, stationary overall noise and continuous mathematics!![1]**)**

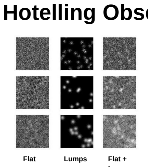
$$SNR_I^2 = \mathbf{G}^2\int\frac{|\Delta f(\nu)|^2\,\mathbf{MTF}^2(\nu)}{(\mathbf{MTF}^2(\nu)\mathbf{W}_f(\nu)+\mathbf{W}_n(\nu))}d\nu$$

- **$W_f(\nu)$, Background Structure**

FDA/CDRH/OST AAPM03

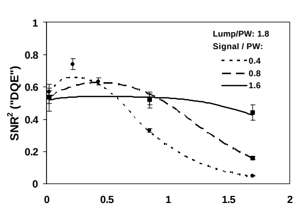
Assumptions

Hotelling Observer and Lumpy Backgrounds



- **Monte Carlo simulation[17]**
- **BKE and lumpy backgrounds**
- **Hotelling observer FOM (analytically and from data)**
- **Spatial domain (vectors and matrices)**

Interplay between:
- **pixel width (PW)**
- **lumpy background**
- **Gaussian signal**
- **system blur**



FDA/CDRH/OST AAPM03

Connection

Connection to visual image quality

FDA/CDRH/OST AAPM03

Connection

"Holy Grail" of Imaging Physics

Connections between:

I – Meaningful metrics (lab and clinic)

II - Imaging phantom studies

Observer Performance (SNR^2)

III - Clinical imaging performance

FDA/CDRH/OST AAPM03

Connection

How do we make connection to visual image quality?

- Lots of literature on model observers capable of handling non SKE/BKE imaging tasks such as lumpy backgrounds
  - Hotelling (upper bound), non-prewhitening (lower bound)
  - observers bracket human performance
- System design and optimization advantages
- Comparison to human performance
  - ROC analysis

FDA/CDRH/OST AAPM03

Conclusions

- Meaningful metrics are available and important to measure
  – search for the "Holy Grail" continues
- Observer FOM provides means for system performance assessment and optimization (detected data)
  – bounds on human performance
- Connection to visual image quality

FDA/CDRH/OST AAPM03

References

References:

1 – ICRU Report 54, "Medical Imaging – The Assessment of Image Quality," Bethesda, MD: International Commission on Radiation Units and Measurements, 1996.

2 – "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.

3 – "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.

4 – H.L. Van Trees, *Detection, Estimation, and Modulation Theory*, Vol. I, Wiley, New York, 1968.

5 – J.L. Melsa, D.L. Cohn, *Decision and Estimation Theory,* McGraw-Hill, New York, 1978.

6 – R. Shaw, "The equivalent quantum efficiency of the photographic process," *J. Photog. Sci.* **11**, 199-204, 1963.

7 – R.F. Wagner, D.G. Brown, "Unified SNR analysis of medical imaging systems," *Phys. Med. Biol*. **30**, 489-518, 1985.

FDA/CDRH/OST AAPM03

References

8 – 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.

9 – 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.

10 – R.F. Wagner, D.G. Brown, M.S. Pastel, "Application of Information Theory to the Assessment of Computed Tomography," *Med. Phys*. **6,** 83-94, 1979.

11 - 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.

12 - 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.

FDA/CDRH/OST AAPM03

References

13 - R.M. Nishikawa, M.J. Yaffee, "Signal-to-noise properties of mammographic film-screen systems, " *Med. Phys*. **12(1)**, 32-39, 1985.

14 - D. Charkraborty, private communication.

15 - 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.

16 - A.R. Pineda, H.H. Barrett, "What does DQE say about lesion detectability in digital radiography?" *Proc. SPIE* **4320**, 2001.

17 – M. Albert, A.D.A. Maidment, "Linear response theory for detectors consisting of discrete arrays," *Med. Phys*. **27(10)**, 2417-2434, 2000.

18 - E. Clarkson, A.R. Pineda, H.H. Barrett, "An analytical approximation to the Hotelling trace for digital –ray detectors," *Proc. SPIE* **4320**, 2001.

19 - R. M. Gagne, J.S. Boswell, K.J. Myers, "Signal detectability in digital radiography: Spatial domain figures of merit," to be published in *Med. Phys*. August 2003.

FDA/CDRH/OST AAPM03

References

20 – Private communication, R.M. Gagne.
21 – K.J. Myers, R.F. Wagner, "Detection and Estimation: Human vs. Ideal as a Function of Information," Proc. SPIE 914, 291-297, 1988.
22 – L.W. Nolte, D. Jaarsma, "More on the Detection of one of M Orthogonal Signals," J. Acous. Soc. Am. 41, 497-505, 1967.
23 – 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.
24 – R.F. Wagner, K.J. Myers, D.G. Brown, M.J. Tapiovaara, "Higher order tasks: Human vs. machine performance," *Proc. Soc. Photo-Opt. Instr. Eng.* **1090**, 183-194, 1989.
25 - 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.
26 - 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.

References

27 - H.H. 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.