Introduction to Image Interpretation

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Goal of Medical Imaging

- Enable expert observers to detect the presence of abnormalities or to estimate properties of abnormalities
- Good physical description of image quality
- Do we, therefore, understand and can we predict and optimize expert observers' ability to detect the presence of abnormalities or to estimate properties of abnormalities?

In Another Word

- Does good understanding of image formation equate to good understanding of image interpretation?

Outline

- Six levels of efficacy of diagnostic imaging
- The ideal observer
- A few mathematical observer
- Human observers
- Model observers

The Efficacy of Diagnostic Imaging

The Efficacy of Diagnostic Imaging

DENNIS G. FRYBACK, PhD, JOHN R. THORNBURY, MD

The authors discuss the assessment of the contribution of diagnostic imaging to the patient management process. A hierarchical model of efficacy is presented as an organizing structure for appraisal of the literature on efficacy of imaging. Demonstration of efficacy at each lower level in this hierarchy is logically necessary, but not sufficient, to assure efficacy at higher levels. Level 1 concerns technical quality of the images; Level 2 addresses diagnostic accuracy, sensitivity, and specificity associated with interpretation of the images. Next, Level 3 focuses on whether the information produces change in the referring physician's diagnostic thinking. Such a change is a logical prerequisite for Level 4 efficacy, which concerns effect on the patient management plan. Level 5 efficacy studies measure (or compute) effect of the information on patient outcomes. Finally, at Level 6, analyses examine societal costs and benefits of a diagnostic imaging technology. The pioneering contributions of Dr. Lee B. Lusted in the study of diagnostic imaging efficacy are highlighted. *Key words:* diagnostic imaging; efficacy studies; cost–effectiveness; ROC analysis. **(Med Decis Making 1991;11:88–94)**

The model described in this paper was formulated in discussions of Scientific Committee Number 69 of the National Council on Radiation Protection and Measurements. Portions of the text draw on draft materials produced by that working group. The group was chaired by one of the authors (JRT) and the other (DGF) was a member. The authors gratefully acknowledge the contributions of the other members, Robert A. Goepp, DDS, Lee B. Lusted, MD, Keith I. Marton, MD, Barbara J. McNeil, MD, PhD, and Milton C. Weinstein, PhD, who were involved in the initial model development meeting. Others subsequently involved in helping to elaborate aspects of the model were Kunio Doi, PhD, Charles E. Metz, PhD, Harvey Rudolph, PhD, Alvin I. Mushlin, MD, and Charles E. Phelps, PhD.

Hierarchical Model of The Efficacy of Diagnostic Imaging

- Level 1: Technical efficacy
- Level 2: Diagnostic accuracy efficacy
- Level 3: Diagnostic thinking efficacy
- Level 4: Therapeutic efficacy
- Level 5: Patient outcome efficacy
- Level 6: Societal efficacy

Level 1: Technical efficacy

- Resolution of line pairs
- Modulation transfer function change
- Gray-scale range
- Amount of mottle
- Sharpness

Level 2: Diagnostic accuracy efficacy

- Yield of abnormal or normal diagnosis in a case series
- Diagnostic accuracy
- Positive and negative predictive values
- Sensitivity and specificity
- Measures of ROC curve height or area

Level 3: Diagnostic thinking efficacy

- Number (percentage) of cases in a series in which image judged “helpful” to making the diagnosis
- Entropy change in differential diagnosis probability distribution
- Difference in clinicians’ subjectively estimated diagnosis probability pre- and posttest information
- Empirical subjective log-likelihood ratio for test positive and negative in a case series

Level 4: Therapeutic efficacy

- Number (percentage) of times image judged helpful in planning management of the patient in a case series
- Percentage of times medical procedure avoided due to image information
- Number or percentage of times therapy planned pretest changed after the image information was obtained
- Number or percentage of times clinicians' prospectively stated therapeutic choices changed after test information

Level 5: Patient outcome efficacy

- Percentage of patients improved with test compared with without test
- Morbidity (or procedures) avoided after having image information
- Change in quality-adjusted life expectancy
- Expected value of test information in quality-adjusted life years (QALY)
- Cost per QALY saved with image information

Level 6: Societal efficacy

- Benefit-cost analysis from society viewpoint
- Cost-effectiveness analysis from society viewpoint

Key Points

- The six levels of efficacy
- "Demonstration of efficacy at each lower level in this hierarchy is logically necessary, but not sufficient, to assure efficacy at higher levels."

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Ideal Observer (Bayesian Observer)

- Utilizes all statistical information available regarding the task to maximize task performance as measured by Bayes risk or some other related measure of performance.
  - Barrett & Myers, P802

Information Available to the Ideal Observer

- All information in image
- Prior information on the task
  - Kinds of signal(s)
  - Prevalence
  - Background statistics

Degradation of Ideal-Observer Performance

- Image noise and image artifacts
- Biological variation of signals
- Bayesian statistics

An Example Ideal Observer

- Signal: a fixed size, fixed contrast, flat block
- Noise: zero-mean, white, Gaussian

Likelihood Ratio

- **Signal likelihood:**

$$L\left(\tilde{\vec{r}} \mid \vec{s}\right) = \prod_j \frac{M_s}{\sqrt{2\pi\sigma}} \, e^{-\left(r_j - \mu_{s_j}\right)^2 / 2\sigma^2}$$

- **Noise likelihood:**

$$L\left(\tilde{\vec{r}} \mid \vec{n}\right) = \prod_j \frac{M_n}{\sqrt{2\pi\sigma}} \, e^{-\left(r_j - \mu_{n_j}\right)^2 / 2\sigma^2}$$

Likelihood Ratio

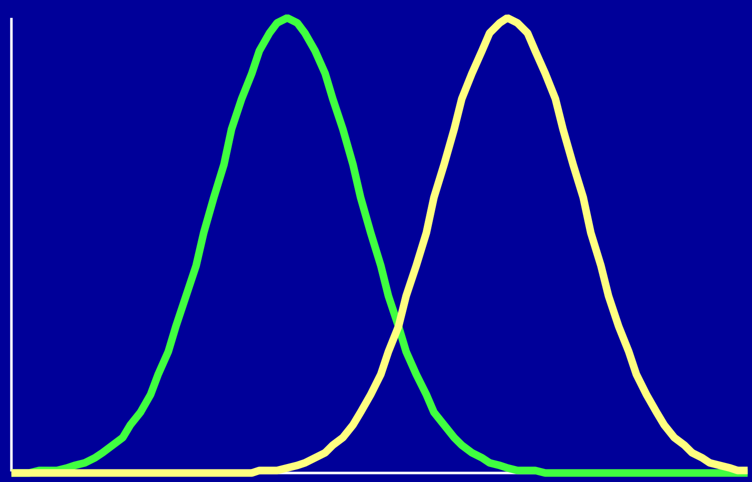
- **Prevalence and likelihood ratio:**

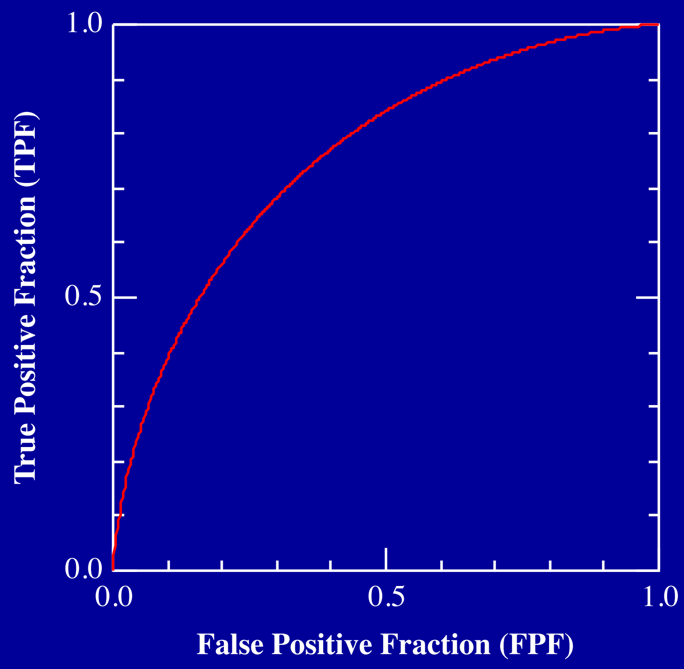
$$L\left(\tilde{\vec{r}} \mid \vec{s}\right)p\left(\vec{s}\right) \quad L\left(\tilde{\vec{r}} \mid \vec{n}\right)p\left(\vec{n}\right) \qquad LR\left(\tilde{\vec{r}}\right) = \frac{L\left(\tilde{\vec{r}} \mid \vec{s}\right)p\left(\vec{s}\right)}{L\left(\tilde{\vec{r}} \mid \vec{n}\right)p\left(\vec{n}\right)}$$

- **Log-likelihood ratio:**

$$LLR\left(\tilde{\vec{r}}\right) = \mathbf{ln}\left[L\left(\tilde{\vec{r}} \mid \vec{s}\right)\right] - \mathbf{ln}\left[L\left(\tilde{\vec{r}} \mid \vec{n}\right)\right] + \mathbf{ln}\left[p\left(\vec{s}\right)\right] - \mathbf{ln}\left[p\left(\vec{n}\right)\right]$$

Likelihood Ratio as Decision Variable





Likelihood Ratio as the Optimal Decision Variable

- Based on Bayesian probability theory
- Any monotonic transformations thereof are equivalent

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Mathematical Filters

- Pre-whitening filter
- Matched filter
- Wiener filter

Pre-Whitening Filter

- Poisson noise is white (delta autocorrelation function)
- Imaging system PSF (MTF) colors (correlates) white noise
- Possible to recover white noise (whitening)

Pre-Whitening Filter

- **Noise power spectrum** $W(\vec{\rho})$
- **Pre-whitening filter** $K(\vec{\rho}) = \left(\sqrt{W(\vec{\rho})}\right)^{-1}$
- **Whitened noise power spectrum**

$$\hat{W}(\vec{\rho}) = W(\vec{\rho})\left[K(\vec{\rho})\right]^2 = 1$$

Matched Filter

- Optimal filter for the detection of a fixed signal

Matched Filter

- **Additive signal and noise**
- **Fixed signal (not a random variable)**

$$\tilde{y}(\vec{r}) = \begin{cases} s(\vec{r}) + \tilde{n}(\vec{r}), & \text{signal present} \\ \tilde{n}(\vec{r}), & \text{signal absent} \end{cases}$$

- **Maximizes SNR**

$$\left[SNR(\vec{r})\right]^2 = \frac{\left[s(\vec{r}) \otimes p(\vec{r})\right]^2}{\left\langle \left[\tilde{n}(\vec{r}) \otimes p(\vec{r})\right]^2 \right\rangle} \qquad \tilde{y}'(\vec{r}) = \tilde{y}(\vec{r}) \otimes p(\vec{r})$$

Matched Filter

$$\left[SNR\left(\vec{r}\right)\right]^2 = \frac{\left|\int_{-\infty}^{\infty} e^{2\pi i\vec{\rho}\cdot\vec{r}} S\left(\vec{\rho}\right) P\left(\vec{\rho}\right) d\vec{\rho}\right|^2}{\int_{-\infty}^{\infty} S_n\left(\vec{\rho}\right) \left|P\left(\vec{\rho}\right)\right|^2 d\vec{\rho}}$$

$$\left[SNR\left(\vec{r}\right)\right]^2 = \frac{\left|\int_{-\infty}^{\infty} e^{2\pi i\vec{\rho}\cdot\vec{r}} S\left(\vec{\rho}\right) P\left(\vec{\rho}\right) d\vec{\rho}\right|^2}{S_n \int_{-\infty}^{\infty} \left|P\left(\vec{\rho}\right)\right|^2 d\vec{\rho}}$$

$$\left[SNR\left(\vec{r}\right)\right]^2 \propto \frac{\left|\int_{-\infty}^{\infty} e^{2\pi i\vec{\rho}\cdot\vec{r}} S\left(\vec{\rho}\right) P\left(\vec{\rho}\right) d\vec{\rho}\right|^2}{\left[\int_{-\infty}^{\infty} \left|S\left(\vec{\rho}\right)\right|^2 d\vec{\rho}\right]\left[\int_{-\infty}^{\infty} \left|P\left(\vec{\rho}\right)\right|^2 d\vec{\rho}\right]}$$

Matched Filter

$$\left[SNR\left(\vec{r}\right)\right]^2 \propto \frac{\left|\int_{-\infty}^{\infty} e^{2\pi i\vec{\rho}\cdot\vec{r}} S\left(\vec{\rho}\right) P\left(\vec{\rho}\right) d\vec{\rho}\right|^2}{\left[\int_{-\infty}^{\infty}\left|S\left(\vec{\rho}\right)\right|^2 d\vec{\rho}\right]\left[\int_{-\infty}^{\infty}\left|P\left(\vec{\rho}\right)\right|^2 d\vec{\rho}\right]} \leq 1$$

$$P\left(\vec{\rho}\right) \propto \left[S\left(\vec{\rho}\right)\right] e^{2\pi i\vec{\rho}\cdot\vec{r}}$$

$$P\left(\vec{r}'\right) \propto s\left(\vec{r} - \vec{r}'\right)$$

Wiener Filter

- Optimal filter for estimation of a signal

Wiener Filter

- **Additive signal and noise**

$$\tilde{y}(\vec{r}) = \tilde{s}(\vec{r}) + \tilde{n}(\vec{r})$$

- **Signal not correlated with noise**

$$\left\langle \tilde{s}(\vec{r})\tilde{n}(\vec{r}\,') \right\rangle = 0$$

- **Minimizes mean-squared error**

$$\left\langle \left| \hat{\tilde{s}}(\vec{r}) - \tilde{s}(\vec{r}) \right|^2 \right\rangle \qquad \hat{\tilde{s}}(\vec{r}) = \tilde{y}(\vec{r}) \otimes p(\vec{r})$$

Wiener Filter

$$\left\langle \left[\hat{\tilde{s}}\left(\vec{r}\right) - \tilde{s}\left(\vec{r}\right) \right] \tilde{y}\left(\vec{r}'\right) \right\rangle = 0$$

$$\left\langle \left[\tilde{s}\left(\vec{r}\right) \otimes p\left(\vec{r}\right) + \tilde{n}\left(\vec{r}\right) \otimes p\left(\vec{r}\right) - \tilde{s}\left(\vec{r}\right) \right] \left[\tilde{s}\left(\vec{r}'\right) + \tilde{n}\left(\vec{r}'\right) \right] \right\rangle = 0$$

$$W_s\left(\vec{\rho}\right) P\left(\vec{\rho}\right) + W_n\left(\vec{\rho}\right) P\left(\vec{\rho}\right) - W_s\left(\vec{\rho}\right) = 0$$

$$P\left(\vec{\rho}\right) = \frac{W_s\left(\vec{\rho}\right)}{W_s\left(\vec{\rho}\right) + W_n\left(\vec{\rho}\right)}$$

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Ideal Observer vs. Human Observer

	Ideal Observer	Human Observer
Noise	degrade	degrade
Biological variability	degrade	degrade
Reader variability	—	degrade
Prior information	yes	estimate

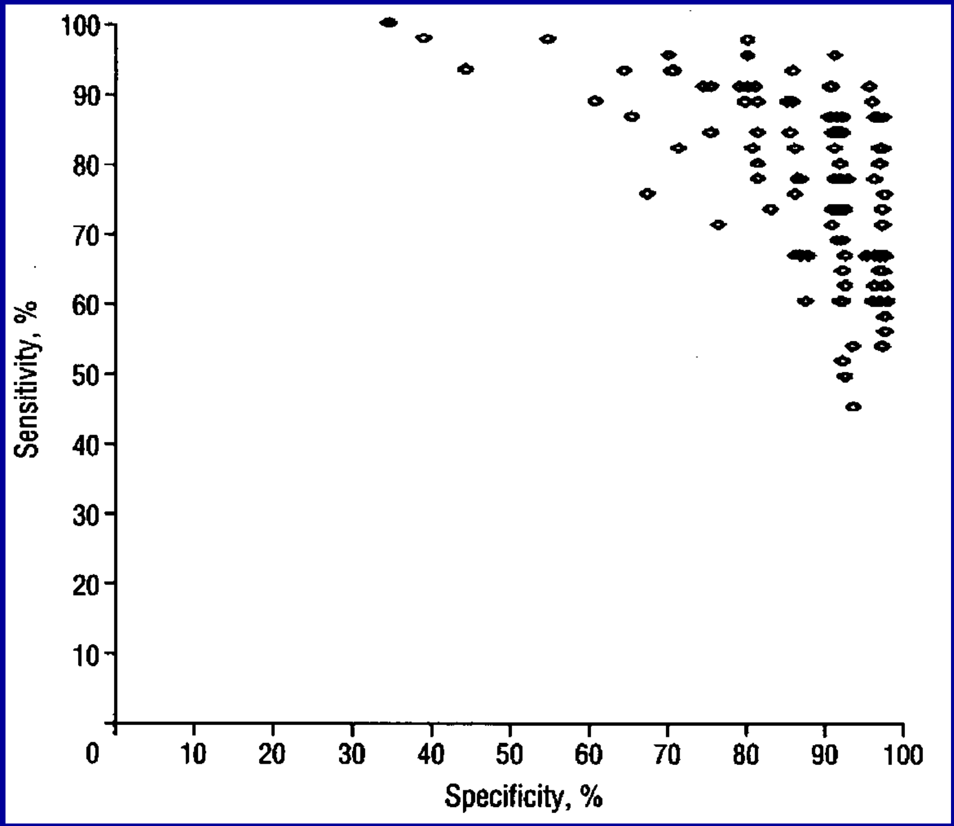
Inefficiency of Human Observers

- Can estimate the likelihood approximately
- Can estimate prevalence
- Not always a rational (Bayesian) decision-maker
- Efficiency typically 30-50% or even as low as 15%

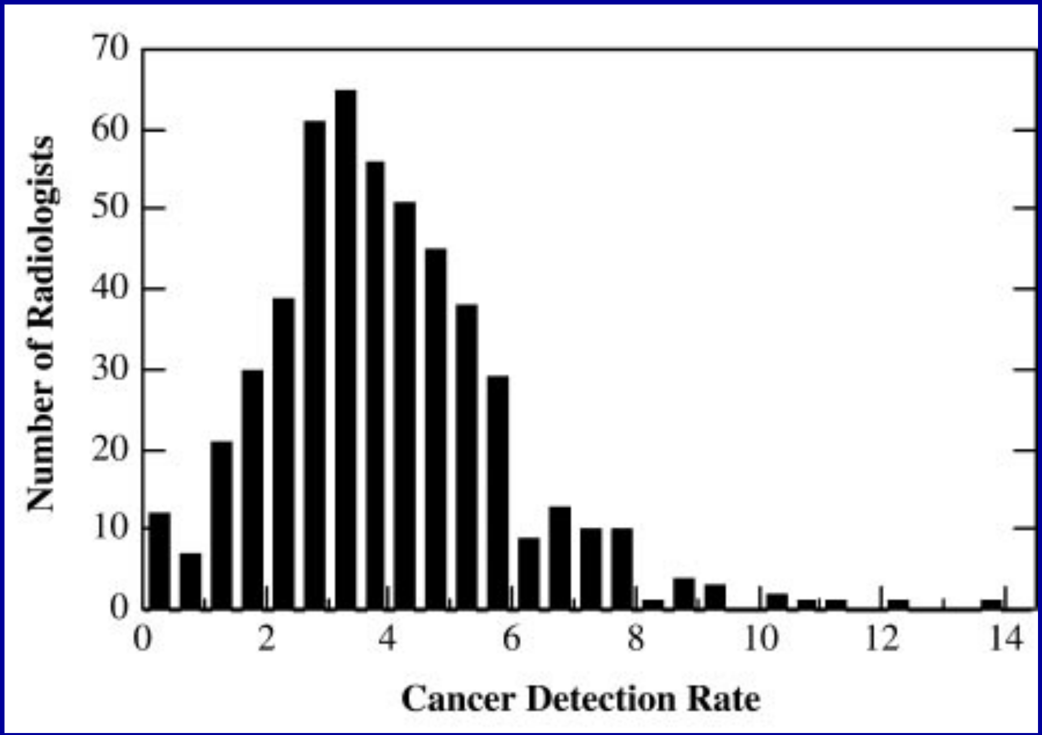
Reader Variability

- A range of skill levels (ROC curve heights)
- A range of operating points (cost-benefit assumptions)
- Drift over time
- Time-of-day effect (distractions)

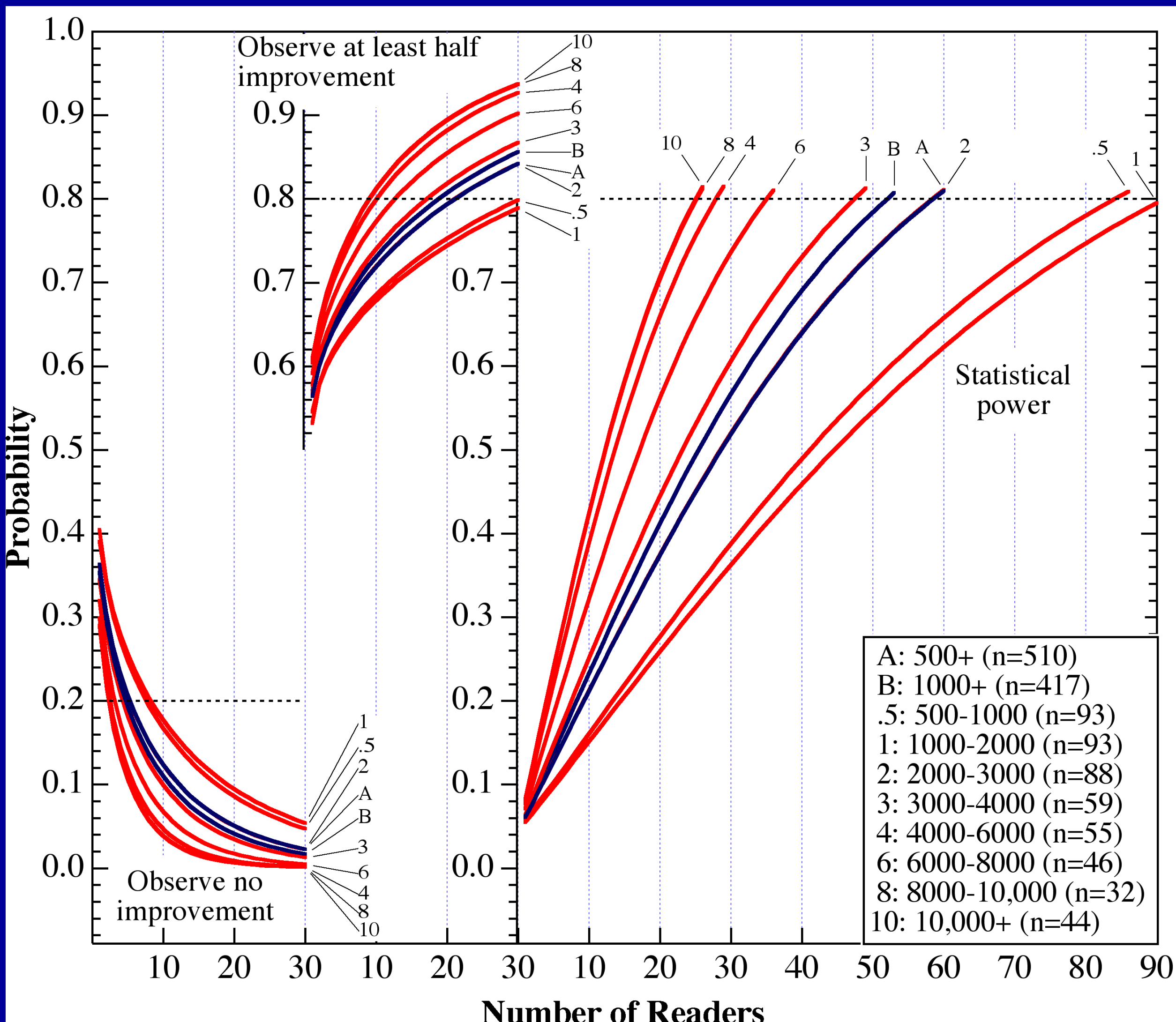
Reader Variability: Mammogram Interpretation



Reader Variability:
Breast Cancer Detection Rate



Reader Variability: Unexpected Consequence



Human Observer

- Strategies not well understood
- Experience plays important role
- Model observers

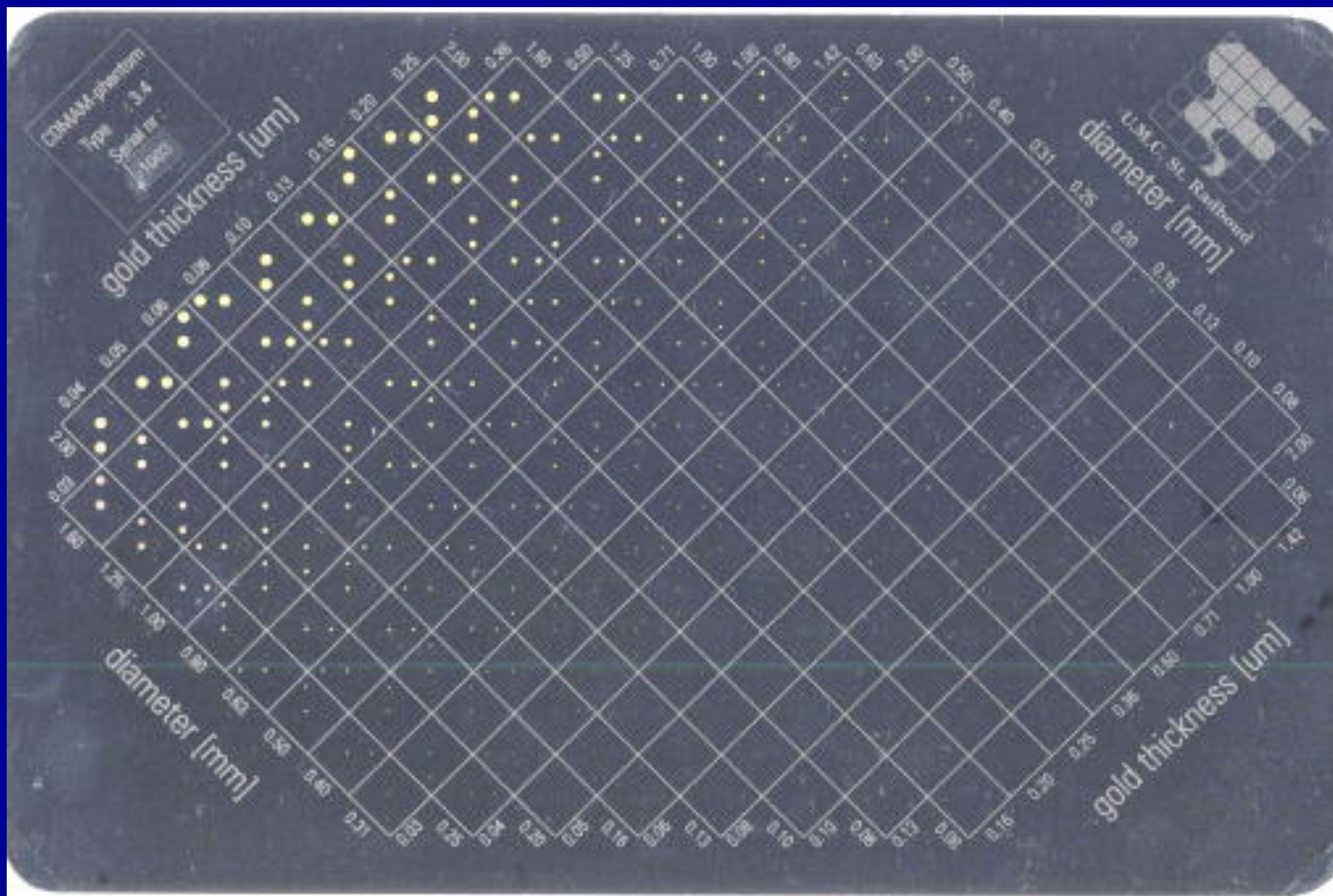
Observer Performance Studies

- Sample of expert observers read sample of cases with known diagnostic “truth”
- ROC analysis
- Necessary to estimate human observer performance
- For detection and classification tasks
- Can be resource-intensive

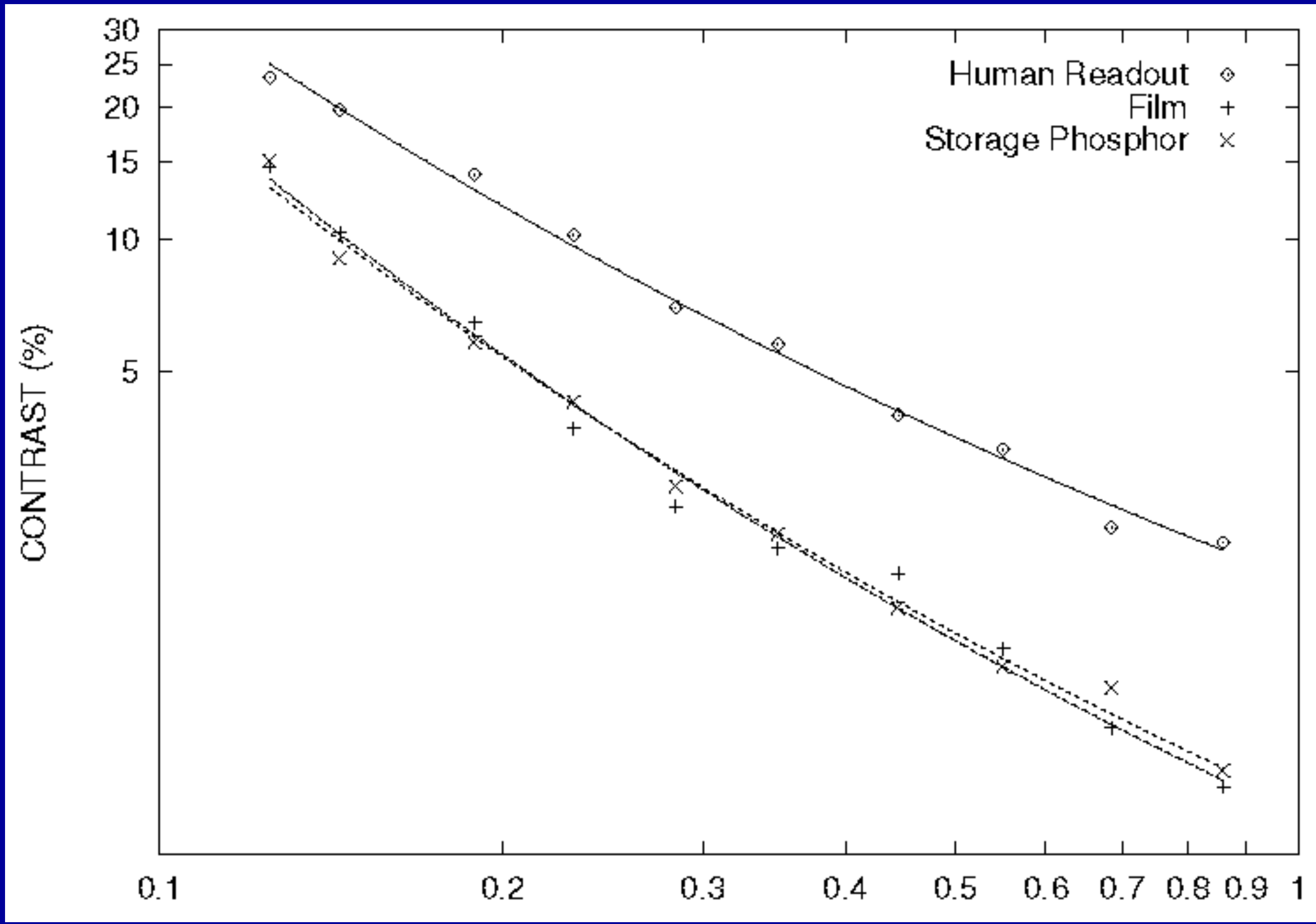
Contrast Detail Experiment

- Phantom experiment
- Visibility of flat object as a function of object contrast and size
- Human observers or computer
- Useful for understanding imaging system characteristics

Contrast Detail Experiment



Contrast Detail Experiment



Two-Alternative Forced Choice

- Percent correct = area under ROC curve
- Suitable with computer generated images

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Model Observers

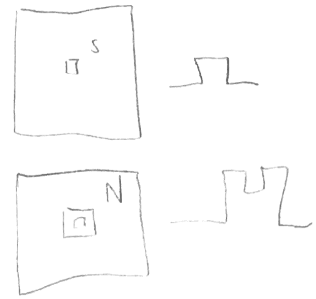
- Predict human performance
- Optimization of new imaging systems
- Understand strategies of human expertize in image interpretation
- Develop computer (mathematical) observers

Summary

- Diagnostic efficacy is an complex and multi-facet issue
- Human observers and model observers are both important in gaining insight

$$L'(\vec{v}|\vec{\mu}) \quad \frac{M_n}{\sqrt{2\pi}\,\sigma} e^{-\frac{(\tilde{v}_j - \mu_{nj})^2}{2\sigma^2}}$$

$$L'(\vec{\underset{\sim}{v}}|\vec{s}) = \prod_j \frac{M_n}{\sqrt{2\pi}\,\sigma} e^{-\frac{(\hat{v}_j - \mu_{sj})^2}{2\sigma^2}}$$



$$L(\vec{\underset{\sim}{v}}|\vec{s}) = L'(\vec{\underset{\sim}{v}}|\vec{s}) \cdot p(\vec{s})$$

$$L(\vec{\underset{\sim}{v}}|\vec{n}) = L'(\vec{\underset{\sim}{v}}|\vec{n}) \cdot p(\vec{n})$$

$$LR(\vec{\underset{\sim}{v}}) = \frac{L(\vec{\underset{\sim}{v}}|\vec{s}) \cdot p(\vec{s})}{L(\vec{\underset{\sim}{v}}|\vec{n}) \cdot p(\vec{n})}$$

$$LLR(\vec{\underset{\sim}{v}}) = \ln\left[L(\vec{\underset{\sim}{v}}|\vec{s})\right] - \ln\left[L(\vec{\underset{\sim}{v}}|\vec{n})\right] + \ln\left[p(\vec{s})\right] - \ln\left[p(\vec{n})\right]$$

<u>Pre-whitening</u>

$W(\vec{p})$

$$K(\vec{p}) = \frac{1}{\sqrt{W(\vec{p})}}$$

$$\hat{w}(\vec{p}) = w(\vec{p})\left[K(\vec{p})\right]^2$$

<u>Matched</u>

$$y(\vec{r}) = \begin{cases} s(\vec{r}) + n(\vec{r}) \\ n(\vec{r}) \end{cases}$$

$$y'(\vec{r}) = y(\vec{r}) \otimes p(\vec{r})$$

$$\left[SNR(\vec{r})\right]^2 = \frac{\left[s(\vec{r}) \otimes p(\vec{r})\right]^2}{\langle \left[n(\vec{r}) \otimes p(\vec{r})\right]^2 \rangle}$$

$$\left[SNR(\vec{p})\right]^2$$

$\vdots$

$p(\vec{r}) \propto s(\vec{r} - \vec{r}'$

<u>Weiner</u>

$$\hat{y}(\vec{r}) = \check{s}(\vec{r}) + \tilde{n}(\vec{r})$$

$$\hat{\tilde{s}} = \hat{s} \otimes p(\vec{r})$$

$$\langle |\hat{\tilde{s}}(\vec{r}) - \tilde{s}(\vec{r})| \rangle$$ minimize

$\vdots$

$$P(\vec{p}) = \frac{W_s(\vec{p})}{W_s(\vec{p}) + W_n(\vec{p})}$$