AAPM 55th: Virtual Tools for Validation of X-ray Breast Imaging Systems

Task-based Assessment of X-ray Breast Imaging Systems Using In-silico Modeling Tools

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FDA

Outline

- Introduction
- Framework of task-based image quality assessment
  - Object and imaging system
  - Task
  - Model observer
  - Figures of merit
- State-of-the-art virtual clinical trials
- Conclusions

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Introduction

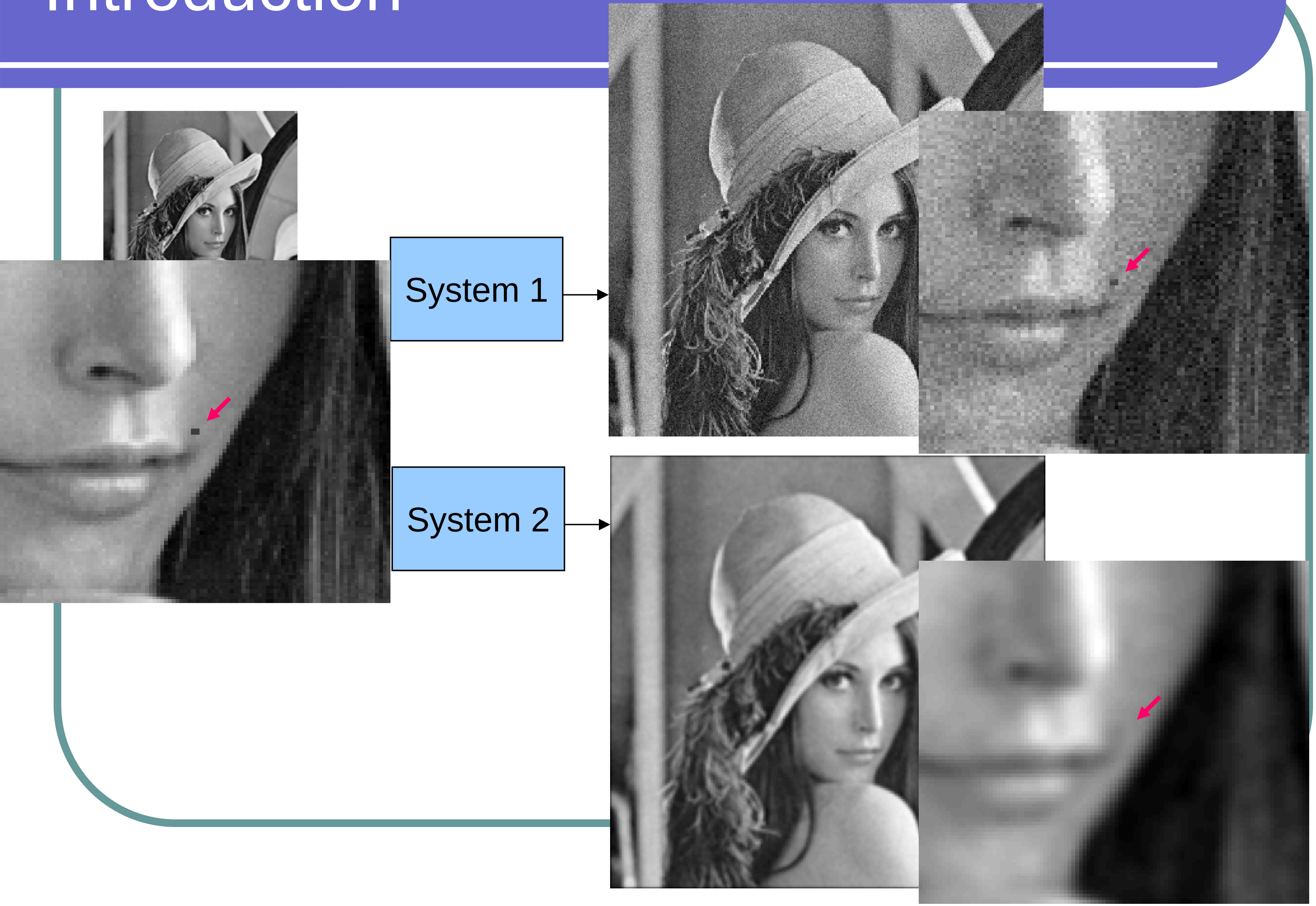
- Medical Imaging systems are developed to help detect or diagnose abnormalities
  - Digital mammography
  - Digital breast tomosynthesis
  - Breast CT
- Image quality assessment should be able to test whether and how well the system can fulfill its purpose

Introduction

- Image quality assessment
  - Beauty contest
  - Fidelity measures (e.g., MSE)
  - Task-based measures

Lena

Introduction



Introduction to Task-based assessment

- Image quality assessment
  - Beauty contest
  - Fidelity measures (e.g., MSE)
  - Task-based measures ✓

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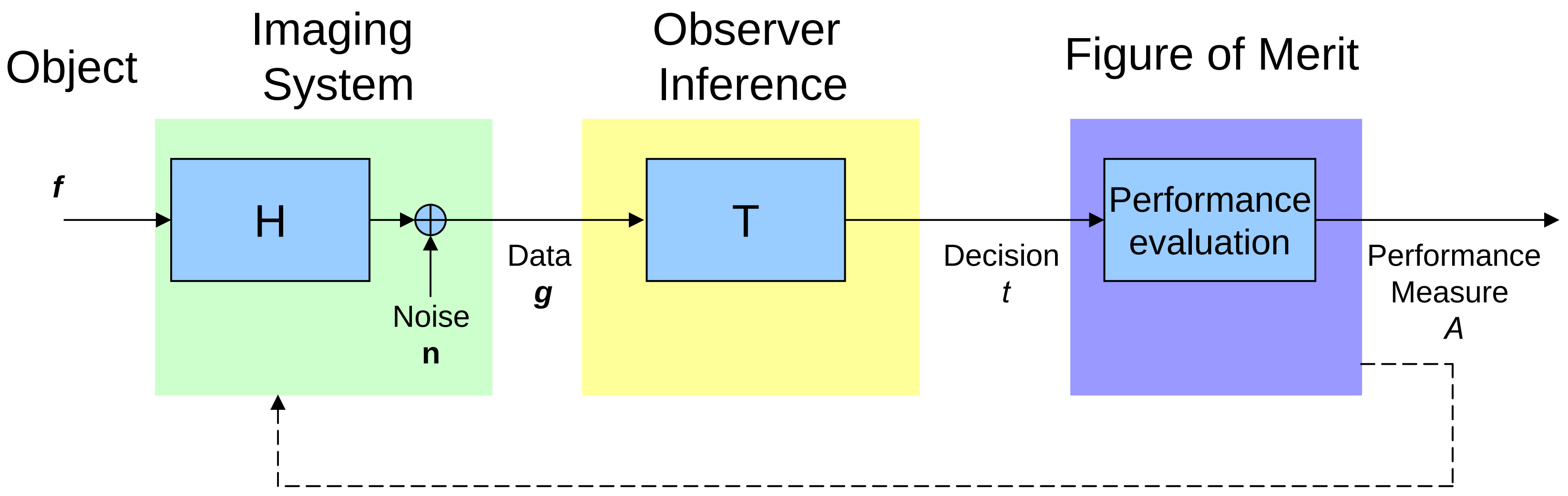
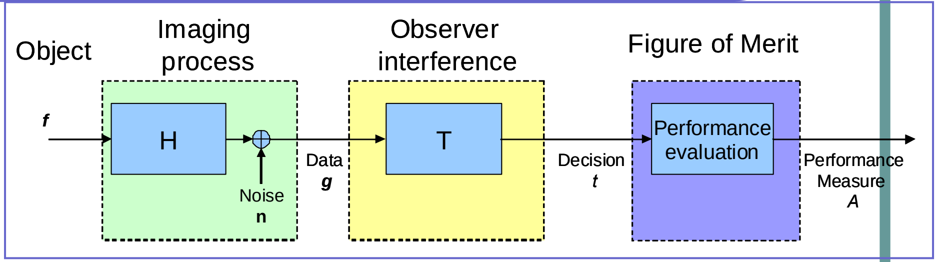
Framework of task-based Image Quality assessment



Framework of task-based Image Quality assessment

- The key elements*



  - Object and the Imaging System
    - Describe the data generation process
  - Task
    - Define the type of decision that an observer needs to make after examining the images
  - Observer
    - Can be human/model/human with model that reads the images and makes the decision
  - Figures of merit
    - Numbers that summarize the image quality of a system based on how well an observer performs a specific task

**Barrett HH, Myers KJ, "Foundations of Image Science", P920*

Object and the imaging system

$$g = \mathcal{H} f + n$$

g: data measurement
$\mathcal{H}$: system transformation
f: object
n: measurement noise

- Object f :
  Encourage numerical object model to have good realism
  - Resemble the anatomical structure
  - Internal structure can be randomized
- Imaging system $\mathcal{H}$:
  model the imaging physics (x-ray transportation, detector response, noise model etc.)
  - Analytical methods
  - Monte-Carlo methods*

*Monte Carlo Simulation of x-ray transport in a GPU with CUDA: http://code.google.com/p/mcgpu/

Task

- A binary detection task

Given data g, to determine whether the object contains a certain signal or not:

$$H0 : \boldsymbol{f} = \boldsymbol{f}_b \qquad \text{(Signal-absent)}$$

$$H1 : \boldsymbol{f} = \boldsymbol{f}_s + \boldsymbol{f}_b \qquad \text{(Signal-present)}$$

$\boldsymbol{f}_b$: *background*

$\boldsymbol{f}_{s:}$ *signal*

Model Observer

- Mechanism of a Model observer (MO)

  MO computes a scalar decision variable t from $\boldsymbol{g}$

  $$t = T(\boldsymbol{g})$$

  T: the MO's discriminant function

  If $t >= \lambda$, a decision in favor of signal present

  If $t < \lambda$, a decision in favor of signal absent

  λ: a threshold value

Model Observer

- Types of MO
  - Ideal MO
    - Makes optimal use of all available information to perform the task
    - *Bayesian MO, Hotelling MO (Ideal linear MO, Pre-whitened matched filter MO)*
  - Anthropomorphic MO (human MO)
    - is designed to mimic the limited abilities of human observer
    - *Non-prewhitening with Eye filter, PW with Internal noise*
  - Channelized MO
    - Uses channel functions to first extract features from data
    - Efficient channels
      - Approach the performances of ideal MOs
      - *Fourier, Laguerre-Gauss, singular vectors of a linear imaging system, partial least square, etc.*
    - Anthropomorphic channels
      - Approximate the performances of human observers
      - *Gabor, Difference of Gaussian, square channels, etc.*

Figures of Merit (FOM)

- MO Performance is reflected in the probability distribution of the decision variable t
  - AUC:[0,1], Area under the receiver operating curve (ROC)

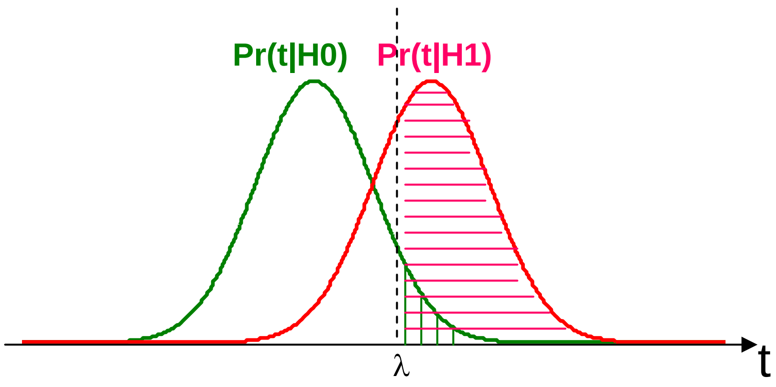
$$\mathrm{AUC} = \int \mathrm{TPF}(\lambda)\, d\mathrm{FPF}(\lambda)$$

  - Detectability: $[0,\propto]$

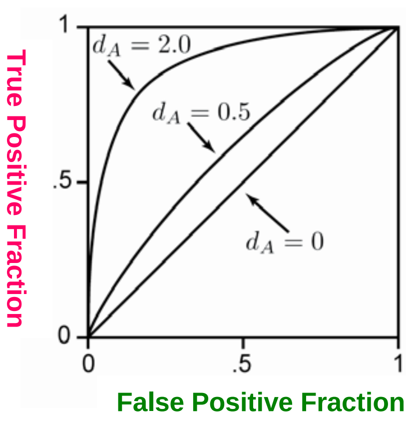
$$d_A = 2\mathrm{erf}^{-1}(2(\mathrm{AUC})-1)$$

  - SNR_t: $[0,\propto]$, when t being Gaussian

$$d' = SNR_t = \frac{|<t_1> - <t_0>|}{\sqrt{\frac{1}{2}(\sigma_1^2 + \sigma_0^2)}}$$



ROC



Figures of Merit (FOM)

- Implementation considerations
  - Training on MO

    The process to estimate information about the data statistics from a set of training images for use in the MO operator.
    - Signal template
    - Data covariance
      - Can be a challenging problem due to the large data size
      - Ensure the sample size is sufficient
      - Channelization can really help
    - Channel parameters for channelized MOs

Figures of Merit (FOM)

- Implementation considerations
  - Testing of the MO
    - Apply the MO to a new set of testing images to compute the FOM (no re-substitution, negative bias)
    - Analytically calculate the FOM for linear MOs under certain conditions. * (re-substitution, positive bias)

$$d'^2 = \Delta \boldsymbol{s}^t \boldsymbol{K}_{\boldsymbol{g}}^{-1} \Delta \boldsymbol{s}, \text{ for Hotelling MO}$$

$$d'^2 = \int \frac{|\boldsymbol{S}(f)|^2}{\text{NPS}(f)} df, \text{ for Hotelling MO under the stationarity condition}$$

    - Provide error bars on the estimated FOM to be statistically meaningful

** FO Bochud, CK Abbey, and MP Eckstein. 2000,JOSA A 17 (2): 193–205.*

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Study 1*

- Objective

  Is the outcome of optimizing the system acquisition geometry sensitive to the choice of reconstruction algorithm in Digital Breast Tomosynthesis (DBT)?

* *R Zeng, S Park, P Bakic, KJ Myers., IWDM 2012, " Is the outcome of optimizing the system acquisition parameters sensitive to the reconstruction algorithm in digital breast tomosynthesis?"*

Study 1

- Data generation: the simulated DBT image chain

Object

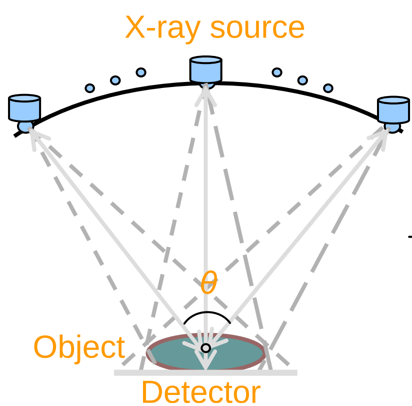
Lesion-absent (40)

Lesion-present (40)

Anatomical breast phantom*:
500 μm, cupsize B, 25% glandular density,
6 mm lesions (6 in each LP phantom)

*BakicEtAl-MedPhys2011-v38(6)

DBT data acquisition



Point and mono-energetic x-ray source; ideal photon counting detector; Separable footprints forward projector**; Poisson noise model; fixed total exposure.

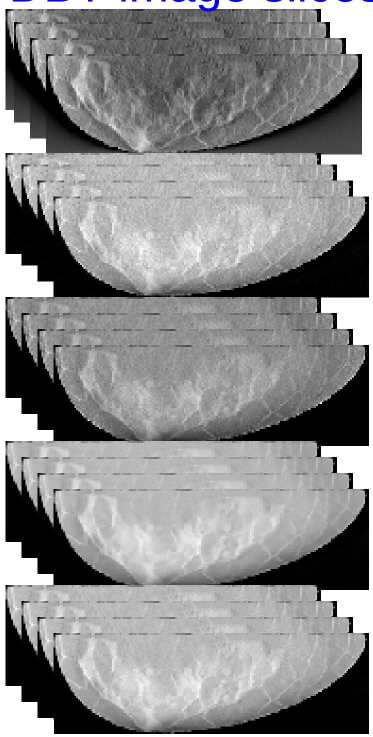
**Long&FesslerEtAl-IEEE-TMI2010-v29p1839

Reconstruction

- FBP
- SART
- ML
- TV-LS-mild
- TV-LS-strong

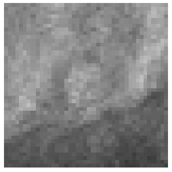
Step size was tuned to obtain relatively fast convergence;
Number of iterations was decided to have optimal lesion detectability in a small set of pilot data.

DBT image slices



Study 1

- Task
  - Location-known lesion detection task



Study 1

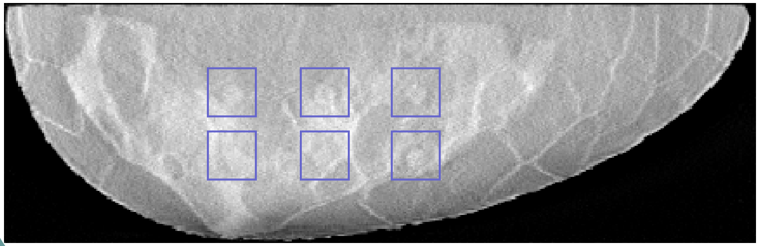
- Model-observer
  - 2D Laguerre-Gauss Channelized Hotelling MO: Efficient in detecting rotationally symmetric signals in stationary background *
  - Parameters: Channel width and number of channels
    - 3 mm channel width and 5 channels
    - Values were determined using a small set of pilot images such that the MO can reach its best detectability using the least number of channels

**Gallas and Barrett, JOSA2003-v20p1725: "Validating the use of channels to estimate the ideal linear observer".*

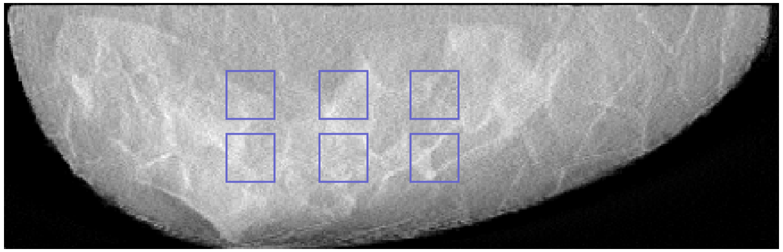
Study 1

- Training and testing of MOs
  - Image samples
    - Extracting 6 ROIs (31x31 pixels) from each LP DBT volume around the lesion centers from the lesion focal slice (240 LP ROIs)
    - Extracting 6 ROIs from each LA DBT volume centered at the same locations (240 LA ROIs)

ROI: region of interest
LP: lesion present
LA: lesion absent



LP ROIs



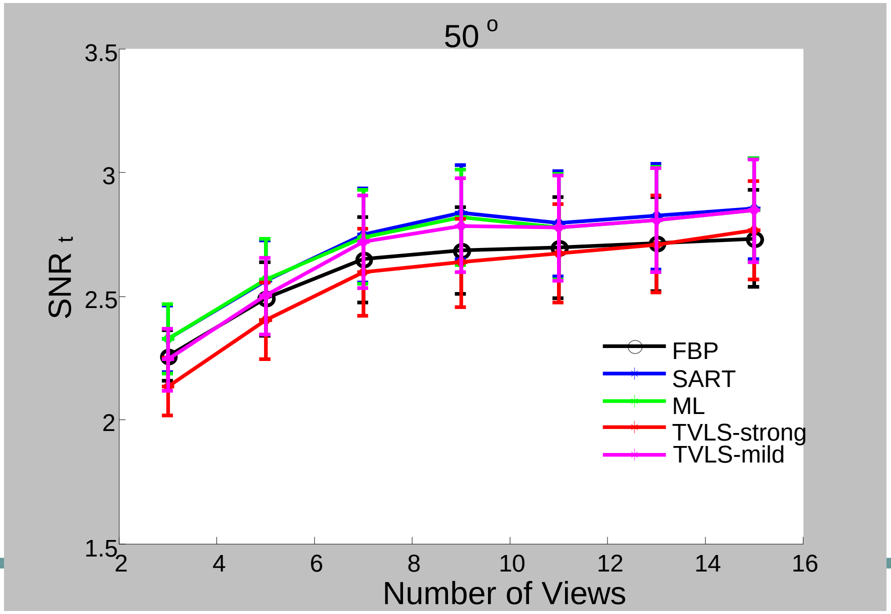
LA ROIs

Study 1

- Training and testing of MOs
  - Training: use the120 pairs of LA and LP image samples to estimate
    - Signal template: $\Delta \boldsymbol{s} = \text{mean}_{\text{LP-ROIs}} - \text{mean}_{\text{LA-ROIs}}$
    - Covariance matrix: $\boldsymbol{K}_{5\times5} = \frac{1}{2}(\boldsymbol{K}_{\text{LP-ROIs}} + \boldsymbol{K}_{\text{LA-ROIs}})$
  - Testing: use the other independent 120 pairs to
    - Calculate the decision variable t for each image ROI
    - Compute the SNR_t
  - Error bar
    - Shuffle the image samples 15 times and repeat the calculation of SNR_t to estimate the its variance

Study 1

- Optimization scenarios
  - Optimizing the angular span with the number of views fixed at 5;
  - Optimizing the angular span with the number of views fixed at 9;
  - Optimizing the number of views with the angular span fixed at 20o;
  - Optimizing the number of views with the angular span fixed at 50o

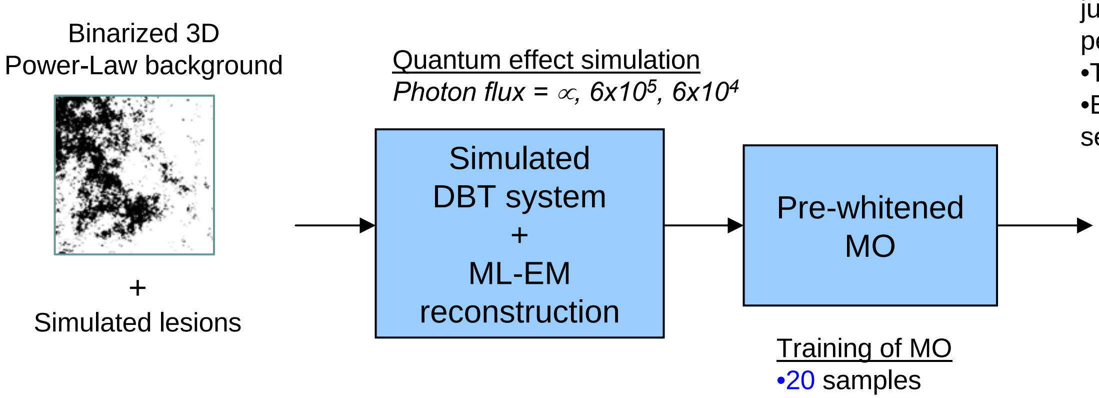


Study 1

- Major findings
  - The results provided evidence that
    - The information in the reconstructed volume was mainly determined by the acquisition process;
    - The choice of reconstruction algorithm may not be critical for evaluation of the DBT system geometry parameters.

Study 2*

- Reiser & Nishikawa 2010-MedPhys-37(4) : "Task-based assessment of breast tomosynthesis: Effect of acquisition parameters and quantum noise"



Stationarity assumption: stationarity was justified by comparing the NPW MO performance evaluated using
•The frequency domain analytical formula;
•Empirical estimation by applying the MO to a set of trainging set

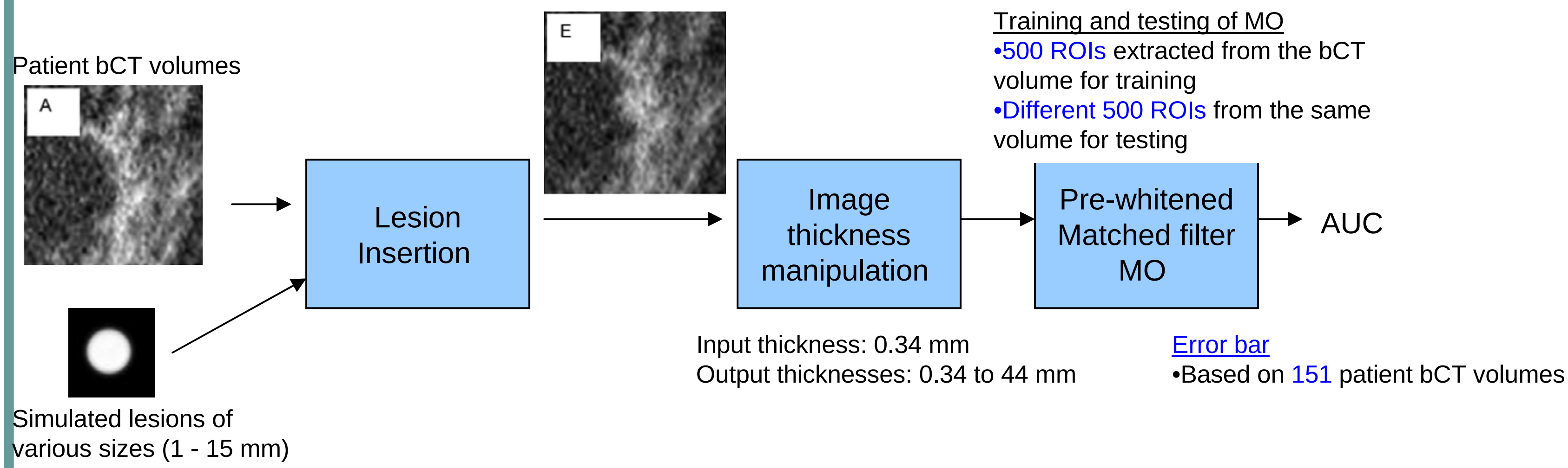
$$d'^2 = \int \frac{|S(f)|^2}{\mathrm{NPS}(f)} df$$

- Major findings:
  - In the absence of quantum noise, increasing the angular span increased the detectability;
  - Quantum noise generally degraded detectability for smaller signal if the angular sampling was already sufficient

** I Reiser, R Nishikawa, 2012, MedPhy, v37(4)*

Study 3*

- Packard & Abbey et al 2012-MedPhys 39(4): Effect of slice thickness on detectability in breast CT using a prewhitened matched filter and simulated mass lesions



- Major finding
  - While the optimal section thickness is tuned to the size of the lesion being detected, overall performance is more robust for thin section images compared to thicker images for the tested lesion size range.

** NJ Packard, C Abbey, K Yang, J Boone, 2012, MedPhy, v39(4)*

Many other virtual clinical trials

- AR Pineda, S Yoon, DS Paik, R Fahrig, “Optimization of a tomosynthesis system for the detection of lung nodules,” Medical Physics. 2006; 33(5):1372-9.
- H C Gifford, C S Didier, M Das and SJ Glick, ``Optimizing breast-tomosynthesis acquisition parameters with scanning model observers." Proc SPIE, vol. 6917, 2008.
- A Chawla A, J Lo, J Bake, E Samei, “Optimized image acquisition for breast tomosynthesis in projection and reconstruction space,” Medical Physics. 2009; 36(11): 4859.
- Y Lu, HP Chan et al, “Image quality of microcalcifications in digital breast tomosynthesis: Effects of projection-view distributions,” Medical Physics, 2011; 38(10):5703.
- D Van de Sompel, SM Brady, J Boone, "Task-based performance analysis of FBP, SART and ML for digital breast tomosynthesis using signal CNR and Channelised Hotelling Observers," Med Image Anal. 2011; 15(1):53-70.
- S. Young, P. Bakic, K. J. Myers, R. J. Jennings and S. Park, "A virtual trial framework for quantifying the detectability of masses in breast tomosynthesis projection data," Medical Physics, 2013; **40(5):** 051914-1
- …

Work toward developing MOs

- Related to ideal MOs
  - J. Witten, S. Park, and K. J. Myers,“Singular vectors of a linear imaging system as efficient channels for the Bayesian ideal observers,” IEEE Transactions on Medical Imaging, 28 (5), p. 657 – 667 (2009).
  - L. Platisa, B. Goossens, E. Vansteenkiste, S. Park, B. D. Gallas, A. Badano, and W. Philips, “Channelized Hotelling observers for the assessment of volumetric imaging data sets,” J. Opt. Soc. Am. A, 28 (6), p. 1145 - 1161 (2011).
  - G. Zhang, K. Myers, S. Park, "Investigating the feasibility of using partial least squares as a method of extracting salient information for the evaluation of digital breast tomosynthesis", 2013 SPIE Medical Imaging
- Related to human MOs
  - Castella Cyril, Abbey Craig K., Eckstein Miguel P., Verdun Francis R., Kinkel Karen, Bochud François O.; 'Human linear template with mammographic backgrounds estimated with a genetic algorithm'; Journal of the Optical Society of America A 24; pp. B1-B12 (2007).
  - Ivan Diaz, Pontus Timberg, Sheng Zhang, Craig Abbey, Francis Verdun and François O. Bochud, "Development of model observers applied to 3D breast tomosynthesis microcalcifications and masses", Proc. SPIE 7966, 79660F (2011);
  - A. Avanaki, K. Espig, C. Marchessoux, E. Krupinski, and T. Kimpe, “Integration of spatiotemporal contrast sensitivity with a multi-slice channelized Hotelling observer,” 2013 SPIE Medical Imaging
  - M Das, H Gifford, “Comparison of model-observer and human-observer performance for breast tomosynthesis: Effect of reconstruction and acquisition parameters”, 2011 SPIE Medical Imaging.

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Conclusion

- The 4 key elements
  - Object and imaging system, Task, Model Observer, Figures of Merit
- Virtual clinical trials can be essential to the research and development of medical imaging systems, complementary to clinical studies
  - Spare patient from x-ray exposure
  - Avoid lengthy reader studies
  - Flexible to explore many possibilities of system configurations
  - Can achieve sufficient statistical power for the many system configurations to be evaluated

- Acknowledgements
  - AAPM Task group 234
  - Kyle J Myers

THANK YOU!