Characterization of System Imaging Performance in Conventional Mammography and Digital Breast Tomosynthesis

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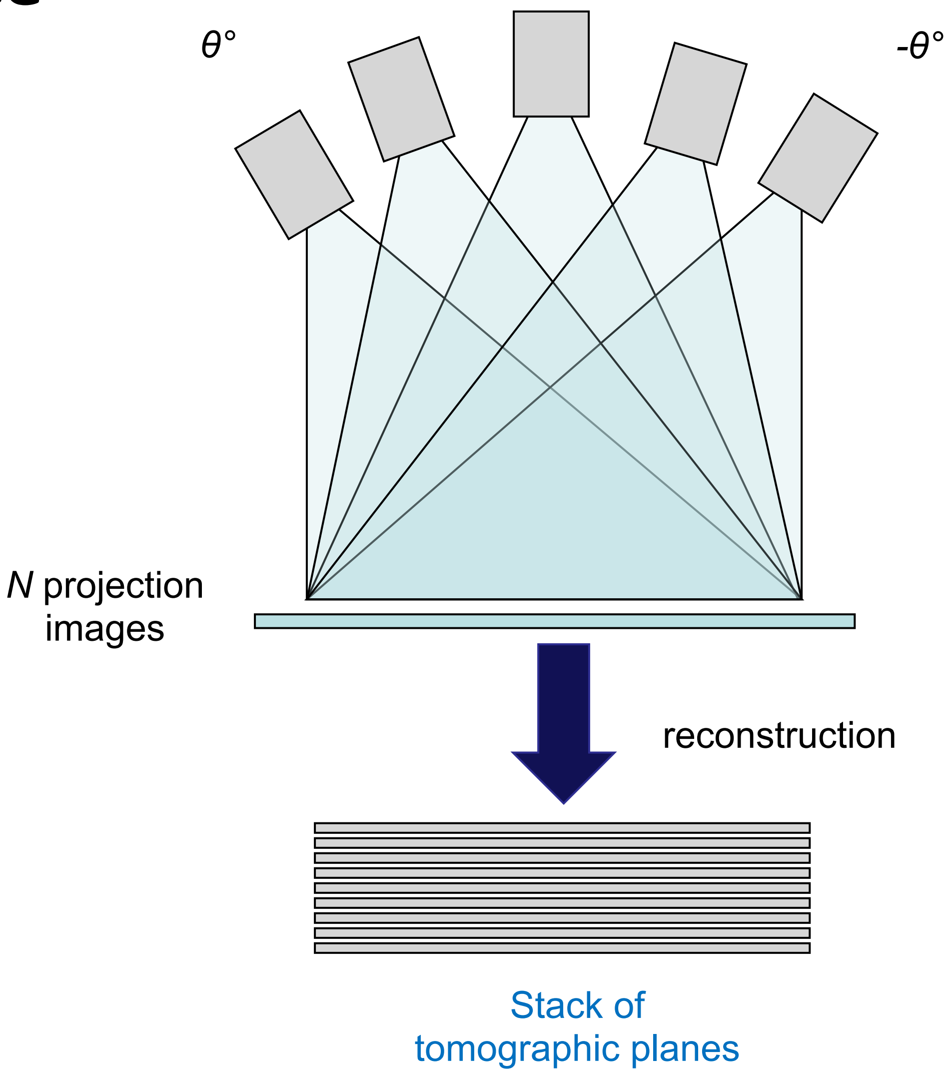
System Imaging Performance

- 2D digital mammography
- Digital breast tomosynthesis
- How are we to compare these imaging modalities?
- Breast screening:
  - Clinical task is to detect lesions in an background of varying gladularity (texture)



System Imaging Performance

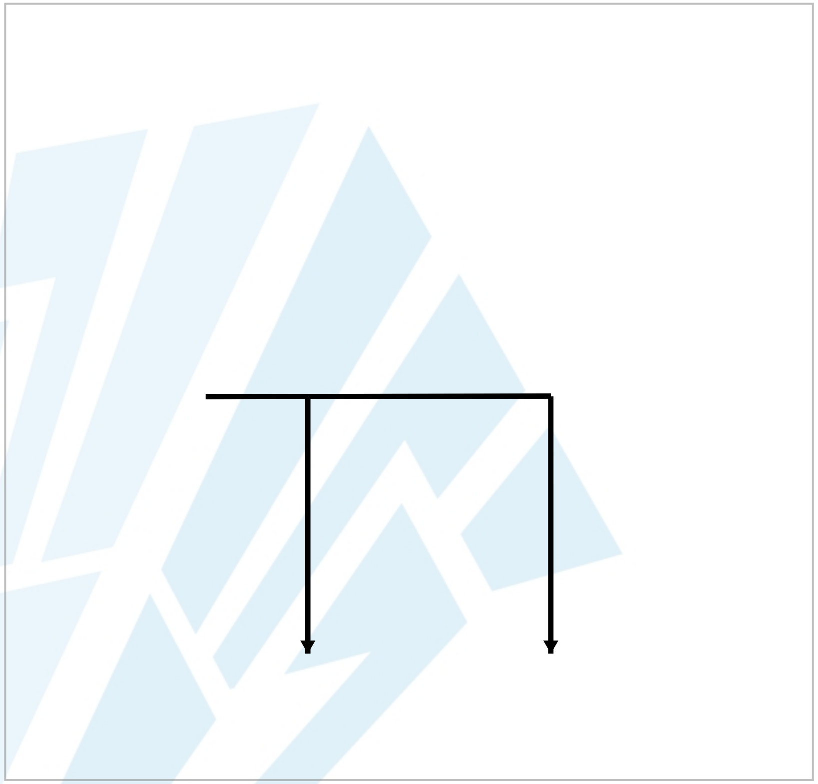
- Technical characterization of the detector
  - Modulation Transfer Function (MTF), Normalized Noise Power Spectrum (NNPS), Detective Quantum Efficiency (DQE)
- System efficiency
  - Generalized DQE, system DQE or effective DQE (eDQE)
  - Still uses the concepts of MTF and NPS
- Test objects
  - Adapted to cope with 3D nature of the generated image volume

Characterize imaging performance

- Response function
- Sharpness (Modulation Transfer Function)
- Noise (noise separation using variance, Noise Power Spectrum)
- Lag (image retention)
- Image quality
    - CDMAM to measure contrast-detail performance)

Detector performance – response function

- Detector gain is increased in DBT (tomo) mode
- Typical detector air kerma ~20 µGy (*cf* 80 µGy for 2D)

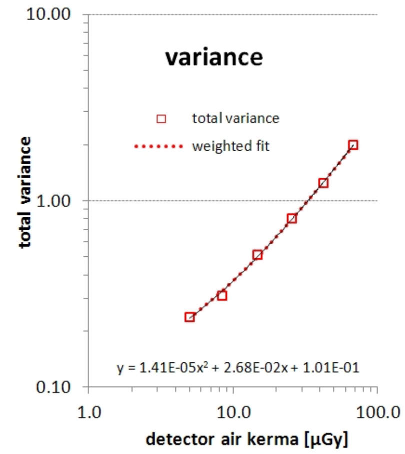


Siemens Inspiration

Hologic Selenia Dimensions

Detector performance

- Systems are still quantum limited, depsite the low detector exposure, due to the higher detector gain



2D mammo DBT

Siemens Inspiration

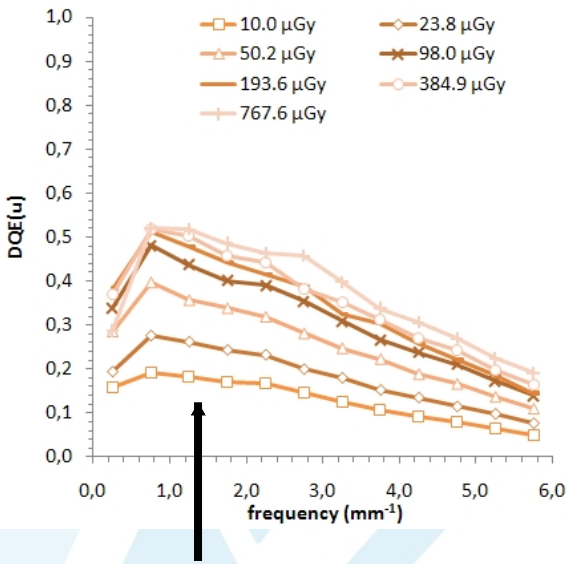
2D mammo DBT

Hologic Selenia Dimensions

Detector performance

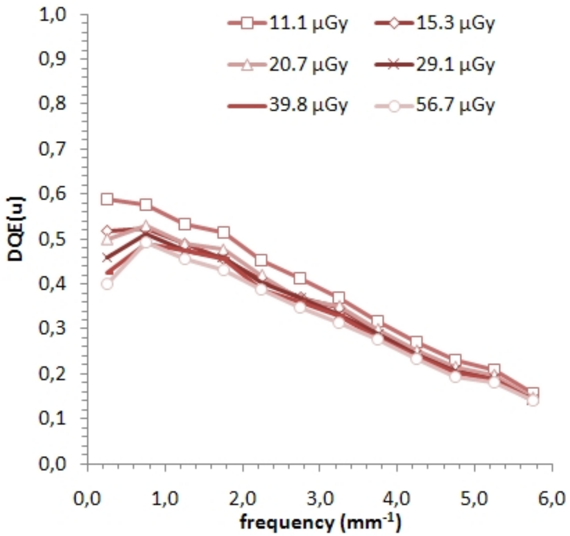
- Good DQE performance in DBT mode

2D mammo



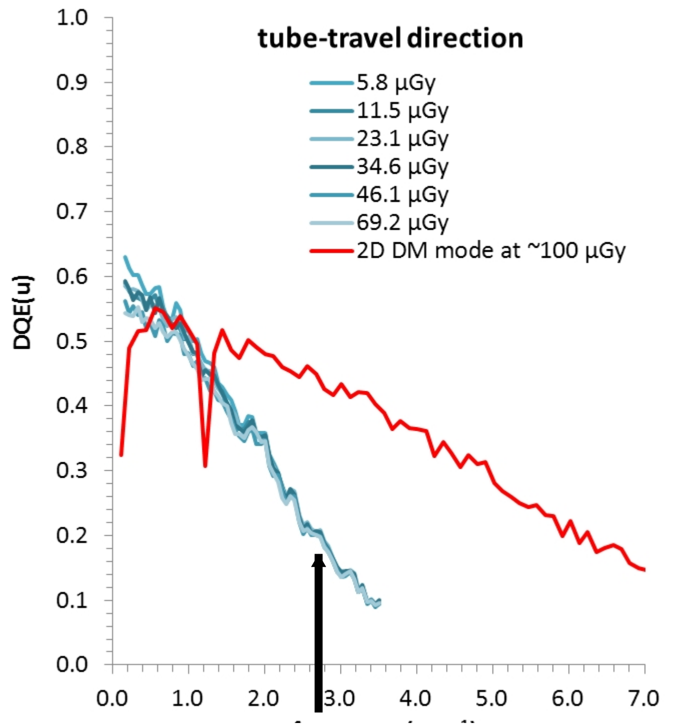
Electronic noise in 2D mode

DBT



Siemens Inspiration

DBT mode at 29 kV W/Al 2mm Al
DM at 28 kV W/Rh 2 mm Al

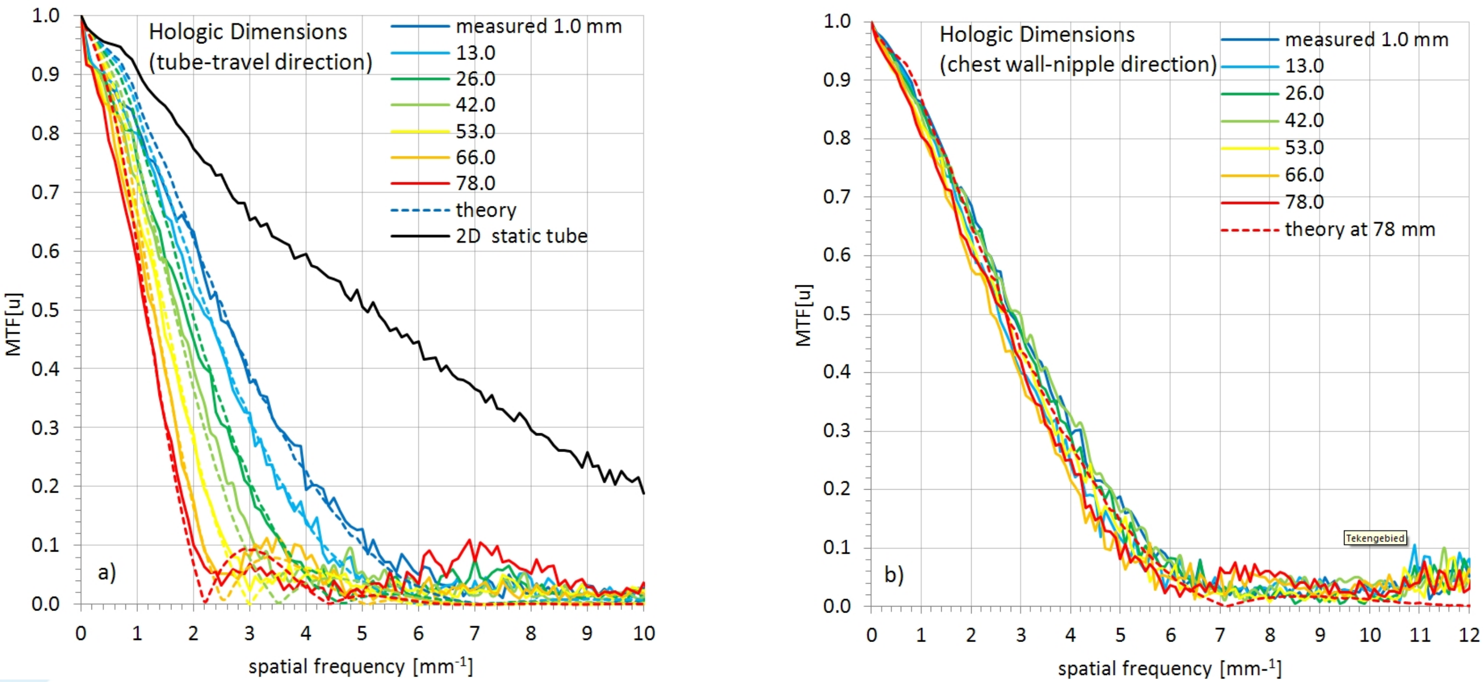


Binning in DBT mode

Hologic Selenia Dimensions

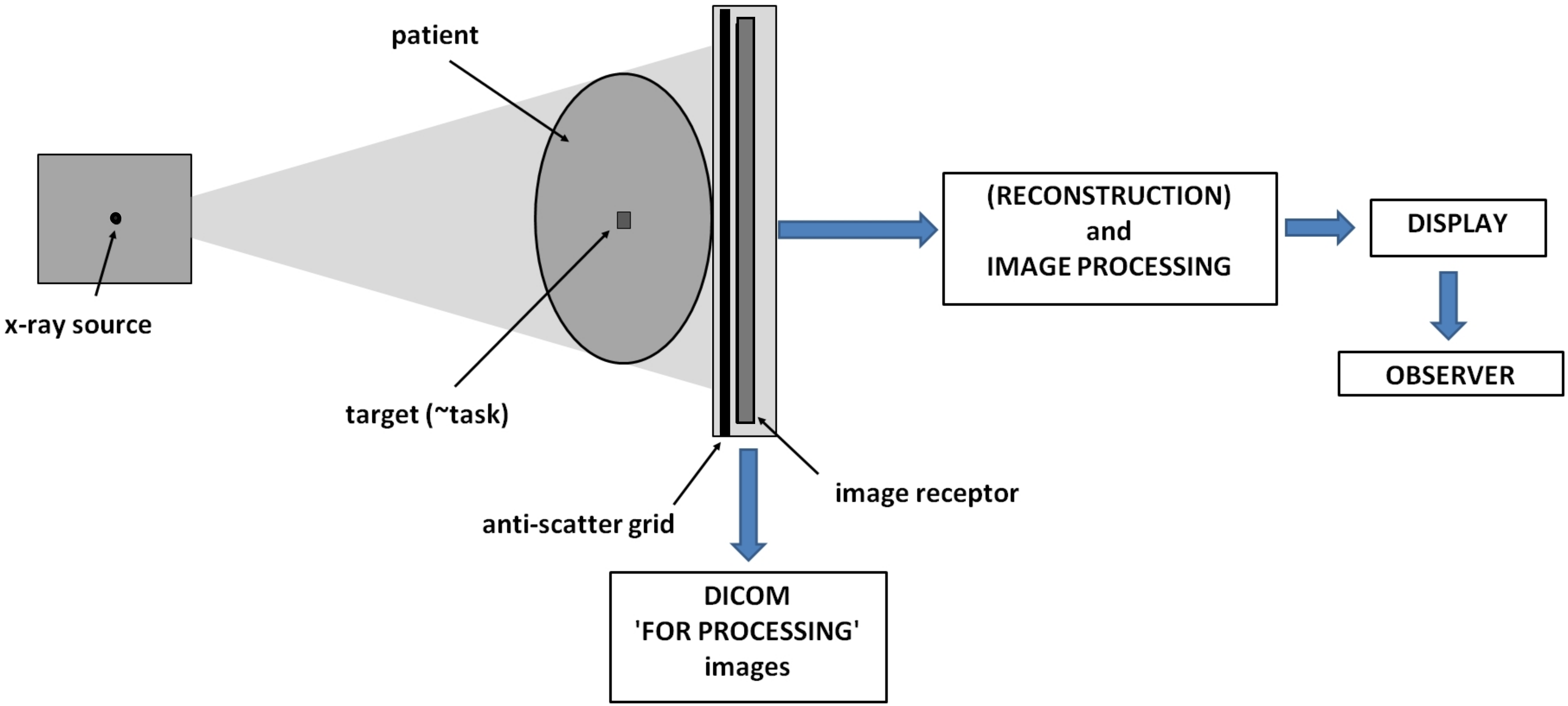
Switch from detector to system MTF…

- Focus motion during exposure leads to variable sharpness a function of height above the table
- Anisotropic blurring



Marshall NW and Bosmans H 2012Measurements of system sharpness for two digital breast tomosynthesis systems *Phys Med Biol* **57**, 7629-7650

Imaging system



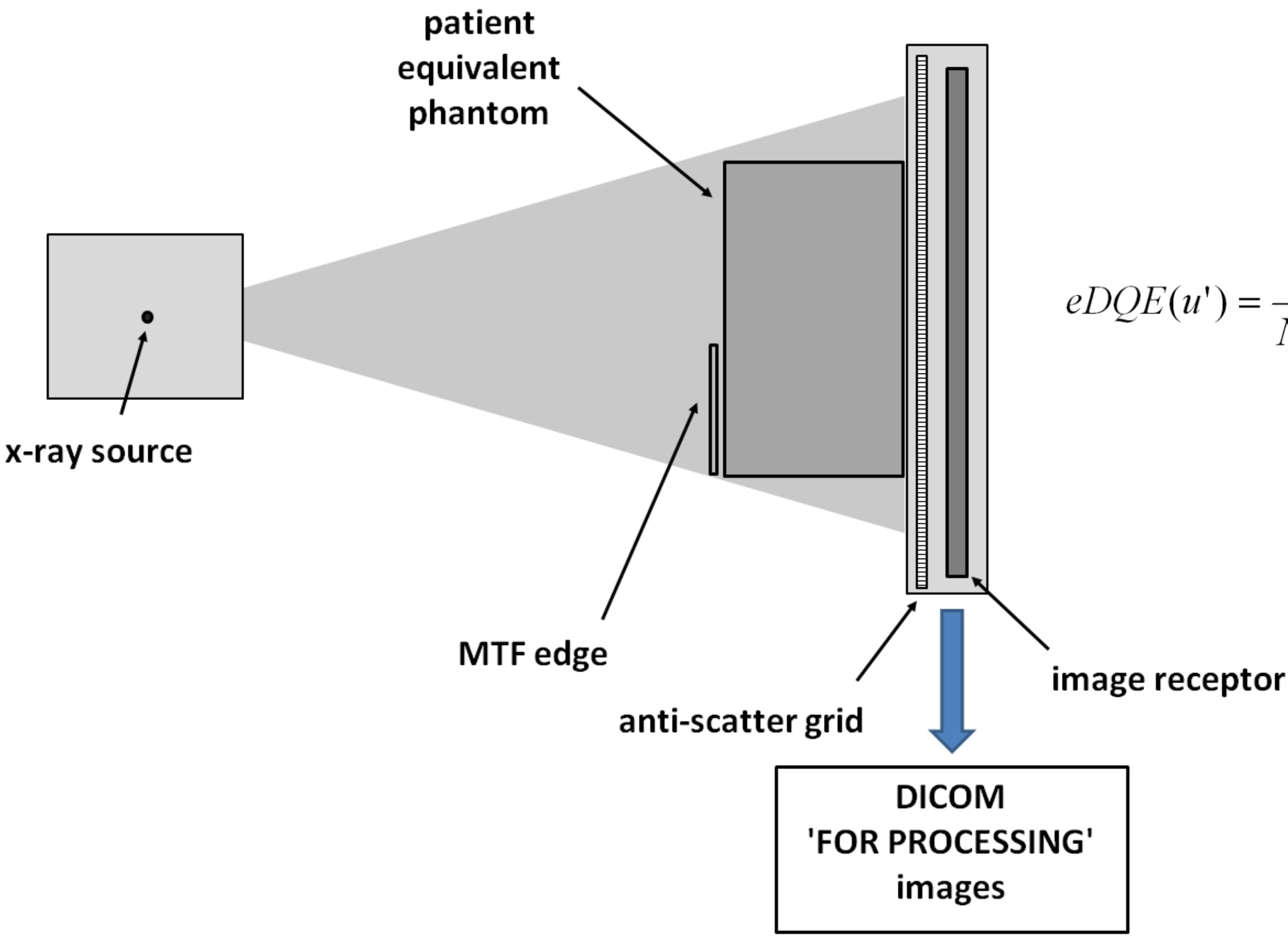
System efficiency

- eDQE introduced by Samei *et al* (2008), also work by Wagner *et al* (1980), Siewerdsen and Jaffray (2000), Kyprianou *et al* (2005) on system efficiency
- Why use eDQE?
  - A metric that includes the influence of source unsharpness and scattered radiation handling on system efficiency
  - Allows systems with different scatter rejection techniques, focus unsharpness and detector efficiencies to be compare
- Calculated from projection images, not the reconstructed planes
  - all important system parameters in the acquisition chain up to reconstruction…

E. Samei et al “Detector or System? Extending the Concept of Detective Quantum Efficiency to Characterize the Performance of Digital Radiographic Imaging Systems,” Radiology **249(3**), 926–937, (2008).

I. Kyprianou *et al* “Generalizing the MTF and DQE to include x-ray scatter and focal spot unsharpness….” Med. Phys. **32(2**), 613–626, (2005).

Generic effective DQE (eDQE) - geometry



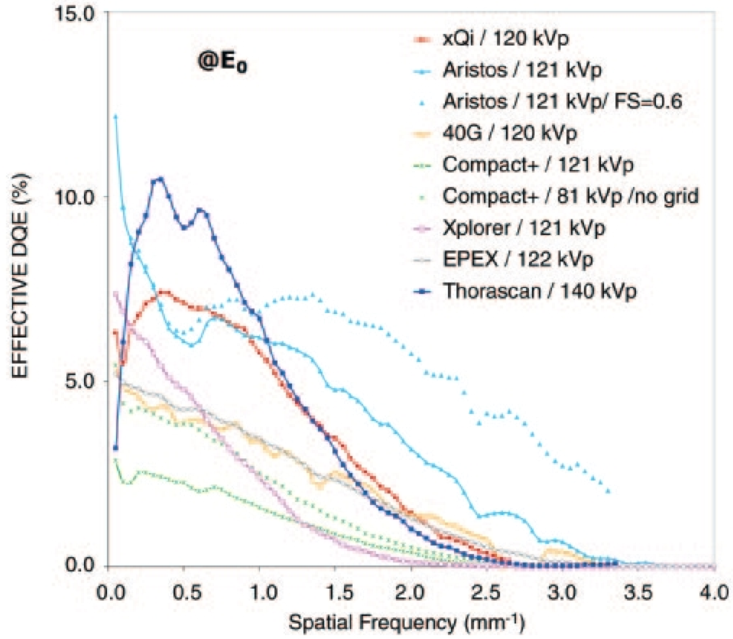
$$eDQE(u') = \frac{MTF(u')^2}{NNPS(u') \cdot E \cdot TF \cdot q}(1-SF)^2$$

Effective DQE

- For general detectors, eDQE ranges from 5% - 10%
  - Compare to DQE of 30% - 60%
- Detector performance alone does not determine system performance

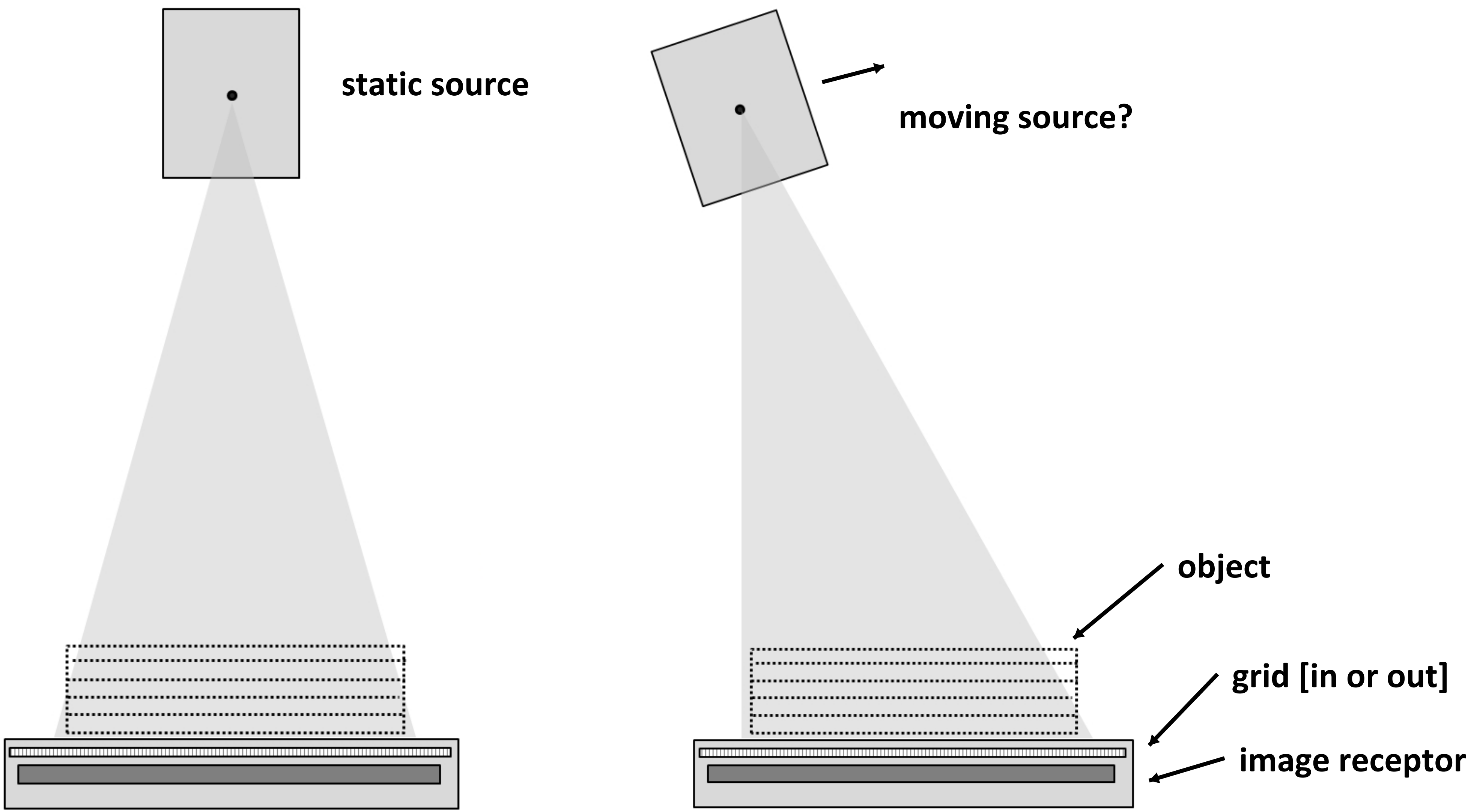
Slot scan chest system: DQE 15%, SF ~10%
eDQE ~10%

Grid system with CsI detector: DQE 45%, SF ~30%
eDQE ~8%



E. Samei et al "Detector or System? Extending the Concept of Detective Quantum Efficiency …." Radiology **249(3)**, 926–937, (2008).

2D mammography ⟷ Digital Breast Tomosynthesis (DBT)



Systems evaluated

- Siemens Inspiration
  - moving source
  - no antiscatter grid for DBT
- Hologic Selenia Dimensions
  - moving source
  - no antiscatter grid for DBT
- GE Essential with MTD
  - step-and-shoot
  - antiscatter grid for DBT

System	GE Essential	Hologic Selenia Dimensions	Siemens MAMMOMAT Inspiration
Detector type	Full field—indirect	Full field—direct (a-Se)	Full field—direct (a-Se)
Detector size (cm)	24 × 30	24 × 29	24 × 30
Detector pixel size (μm)	100	70 (binned 2 × 2)[a]	85
Detector motion	Static	Rotating	Static
X-ray tube target	Mo or Rh	W	W
X-ray tube filtration	0.03 mm Mo or 0.025 mm Rh	0.7 mm Al	0.05 mm Rh
X-ray tube motion	Step-and-shoot	Continuous	Continuous
Angular range (deg)	25	15[c]	50[d]
Number of projections	9	15	25
Scan time (s)	7	3.7	25[d]
Source to detector distance (cm)	66	70	65.5
Detector to center of rotation distance[f] (cm)	4	0	4.7
Air gap (cm)	2.2	2.5	1.7
Reconstruction method	Iterative	FBP	FBP

Sechopoulos I "A review of breast tomosynthesis. Part I. The image acquisition process" *Med Phys* **40**, 014301-1-12 (2013)

eDQE – measurement steps

- The eDQE is defined as: $$eDQE(u') = \frac{MTF(u')^2 (1 - SF)^2}{NNPS(u') \cdot TF \cdot E \cdot q}$$
- We need to measure:
  - Transmission Factor (TF) of the PMMA phantom
  - Scatter Fraction (SF) for PMMA
  - Modulation Transfer Function (MTF) at some height above the bucky
  - Normalized Noise Power Spectrum (NNPS)
  - Air kerma at the surface of the phantom corrected to the detector plane (E)
  - Number of x-ray photons μGy^{-1} mm^{-2} (***q***) – taken from Boone's data

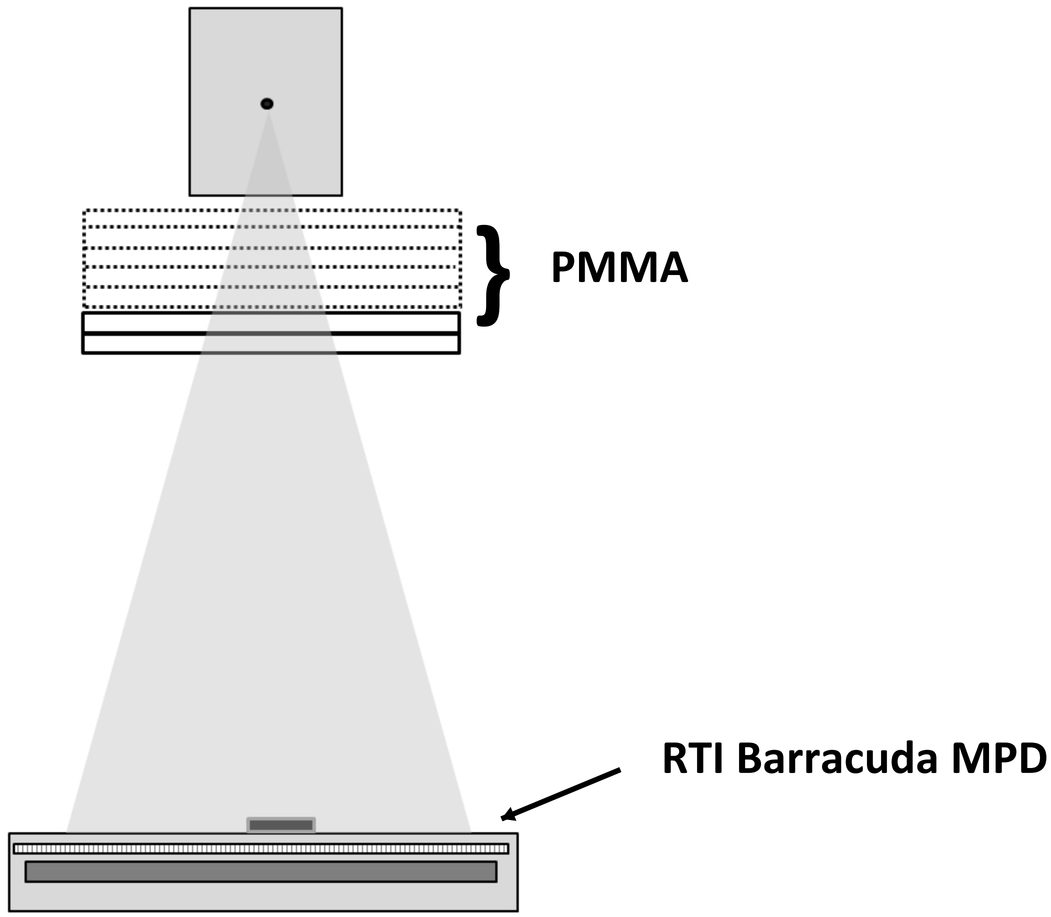
Samei *et al* "Detector or system? Extending the concept of detective quantum efficiency…" Radiology **249**(3) (2008)

Boone et al "Molybdenum, rhodium, and tungsten anode spectral models …. with application to mammography," Med. Phys. 24 (12) (1997)

Transmission Fraction (TF)

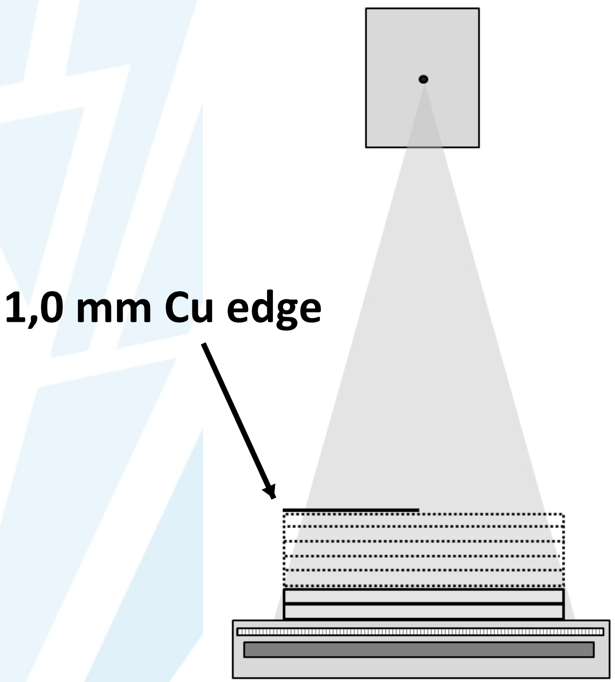
- eDQE measured for 20, 40, 60 and 70 mm PMMA phantoms
  - Measure TF for these thicknesses
  - Pseudo narrow beam conditions

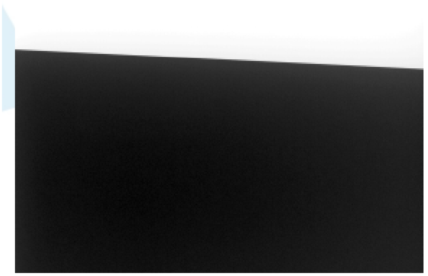
  given the small angle of acceptance of the MPD

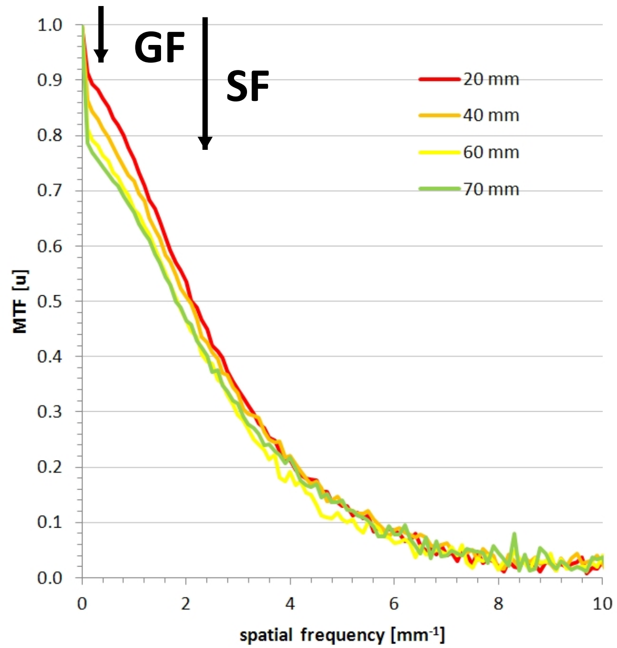


Scatter Fraction (SF)

- SF for Hologic and Siemens 2D (grid in) and Siemens DBT (grid out) taken from Salvagnini *et al* (2012)
- SF for Hologic DBT (grid out) and GE Essential measured using MTF scatter edge method
- Glare Fraction (GF) measured using Pb beam stops



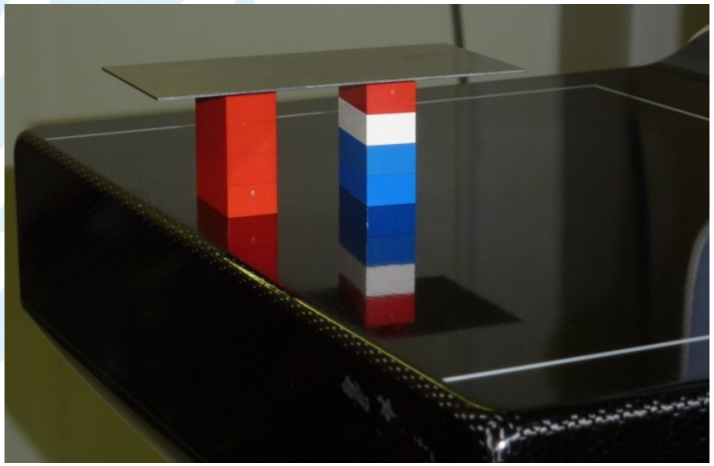


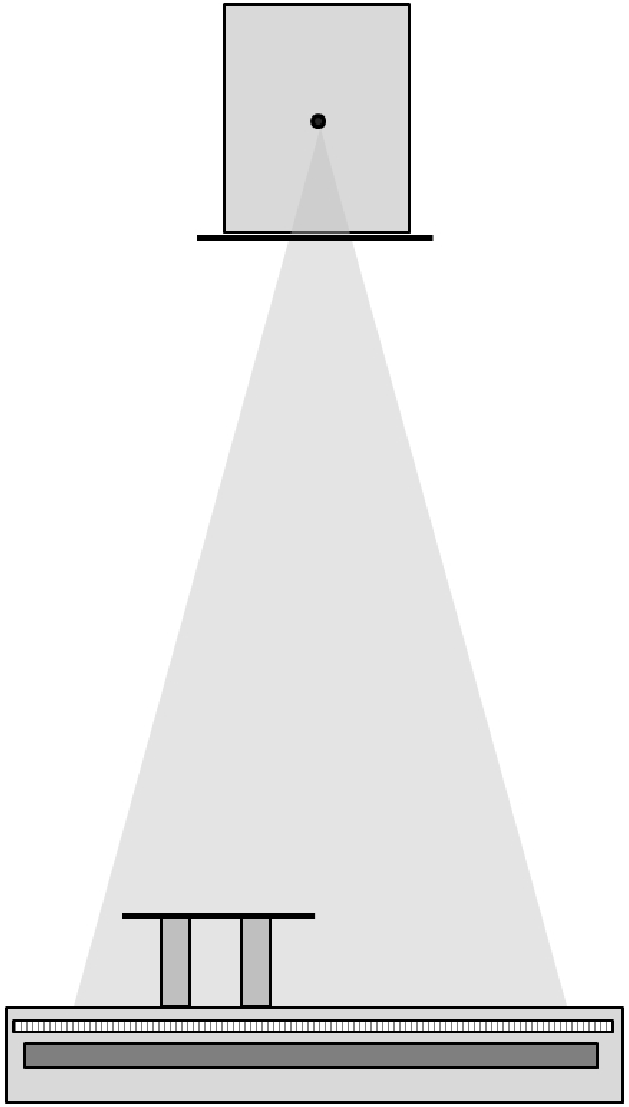


Salvagnini *et al* "Quantification of scattered radiation in projection mammography…" Med Phys **39**(6) (2012)

Modulation Transfer Function (MTF)

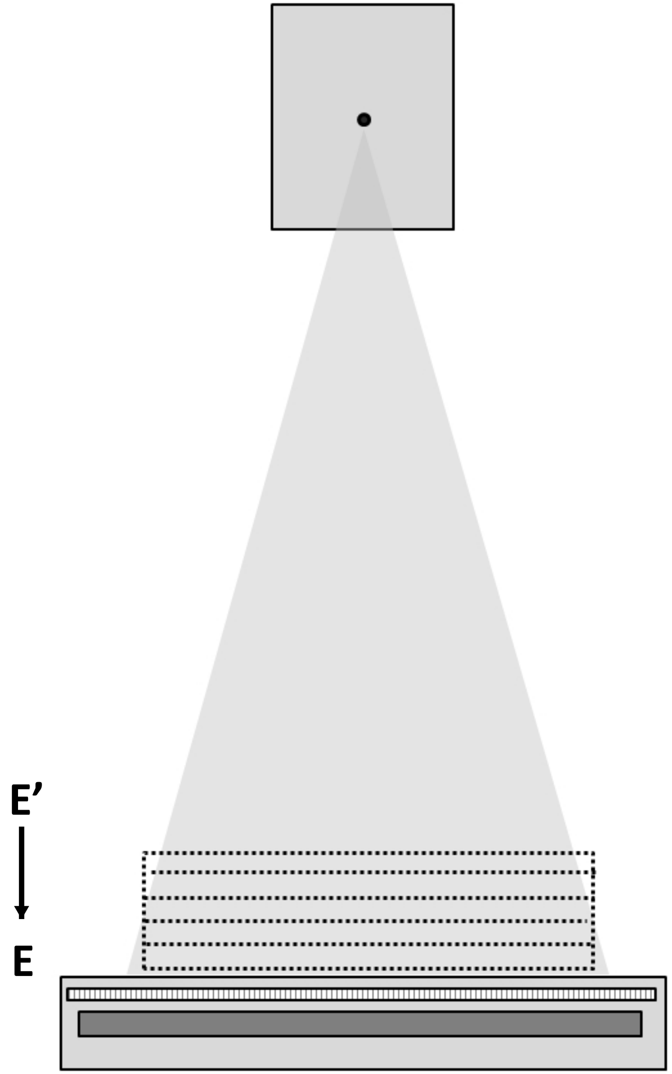
- MTF measured with 0,8 mm thick steel edge at 20, 40, 60 and 70 mm above the breast table
- Includes influence on MTF of…
  - Physical source dimension
  - Effective source dimension due to motion during exposure
- Practically, edge supported using plastic blocks





Normalized Noise Power Spectrum (NNPS)

- Acquire images of PMMA under Automatic Exposure Control (AEC)
  - 20, 40, 60 and 70 mm PMMA
  - Note the tube current-time product (mAs)
- Calculate NNPS using IEC method (256x256 half overlapping ROIs etc)
  - Linearize using response function measured with 2 mm Al
- Use mAs and output measurement to calculate pre-phantom exposure, corrected to detector plane



Results – transmission fraction and AEC setting

Hologic Selenia

PMMA (mm)	2D mammography q photons ($mm^{-2}\mu Gy^{-1}$)	kV	TF	target/ filter	mAs	DBT q photons ($mm^{-2}\mu Gy^{-1}$)	kV	TF	target/ filter	mAs
20	5323	25	0.197	W/Rh	55	5534	26	0.144	W/Al	43
40	6161	28	0.067	W/Rh	100	7535	30	0.061	W/Al	61
60	6954	30	0.025	W/Rh	260	10425	36	0.037	W/Al	94
70	7621	31	0.018	W/Ag	360	12701	42	0.045	W/Al	87

Siemens Inspiration

PMMA (mm)	2D mammography q photons ($mm^{-2}\mu Gy^{-1}$)	kV	TF	target/ filter	mAs	DBT q photons ($mm^{-2}\mu Gy^{-1}$)	kV	TF	target/ filter	mAs
20	5461	26	0.222	W/Rh	30.4	5461	26	0.222	W/Rh	61.8
40	6161	28	0.068	W/Rh	65.5	6161	28	0.068	W/Rh	127
60	6776	30	0.026	W/Rh	142	6954	31	0.024	W/Rh	220
70	7158	31	0.016	W/Rh	197	7440	32	0.015	W/Rh	284

GE Essential MTD

PMMA (mm)	2D mammography q photons ($mm^{-2}\mu Gy^{-1}$)	kV	TF	target/ filter	mAs	DBT q photons ($mm^{-2}\mu Gy^{-1}$)	kV	TF	target/ filter	mAs
20	4357	25	0.116	Mo/Mo	28	4443	26	0.136	Mo/Mo	29
40	5366	28	0.044	Mo/Rh	50	6356	29	0.066	Rh/Rh	49
60	7129	31	0.024	Rh/Rh	71	7129	31	0.024	Rh/Rh	71
70	7371	31	0.015	Rh/Rh	110	7371	31	0.015	Rh/Rh	110

Results – Scatter Fraction

- High scatter fractions for grid-out DBT
- Linear grids for Siemens and GE 2D mammo have similar scatter fractions
- Rotated linear grid (grid lines run parallel to tube motion) for GE tomo is slightly less efficient than 2D GE grid

Hologic Selenia Dimensions

	2D mammography			DBT		
PMMA (mm)	kV	target/ filter	SF	kV	target/ filter	SF
20	25	W/Rh	0.03	26	W/Al	0.24
40	28	W/Rh	0.06	30	W/Al	0.36
60	30	W/Rh	0.10	36	W/Al	0.44
70	31	W/Ag	0.11	42	W/Al	0.49

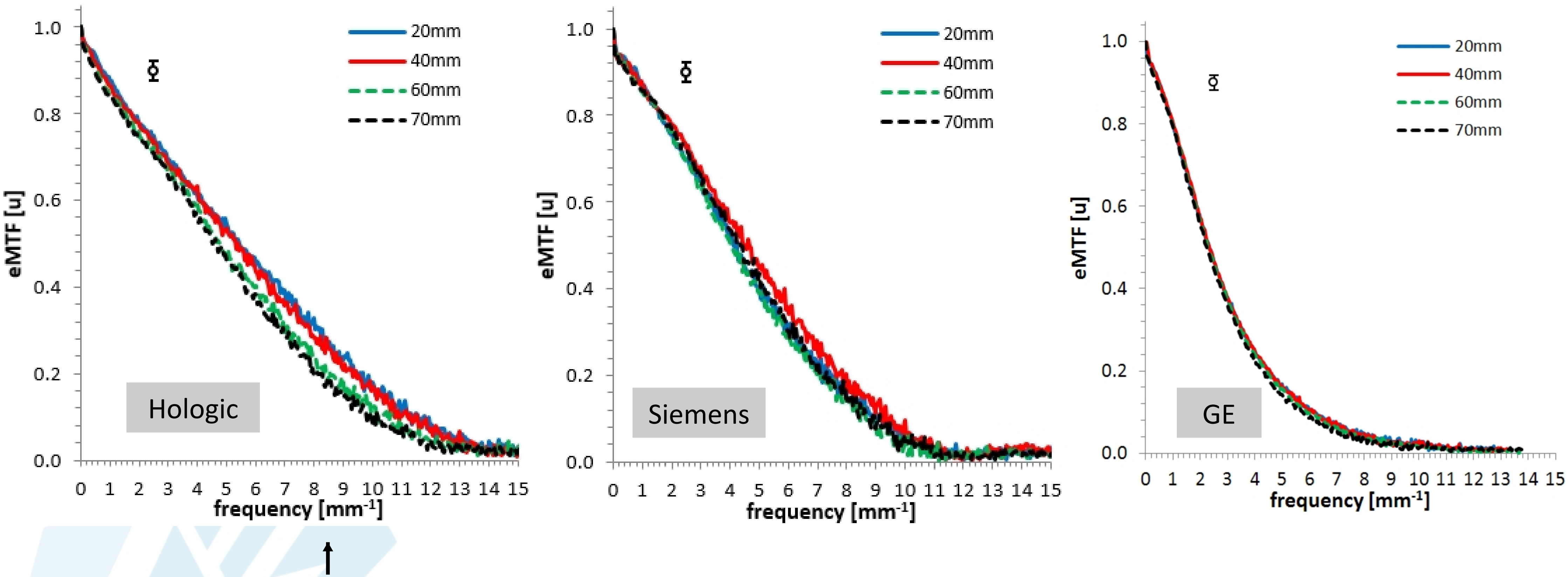
Siemens Inspiration

PMMA (mm)	kV	target/ filter	SF	kV	target/ filter	SF
20	26	W/Rh	0.05	26	W/Rh	0.21
40	28	W/Rh	0.08	28	W/Rh	0.35
60	30	W/Rh	0.13	31	W/Rh	0.46
70	31	W/Rh	0.15	32	W/Rh	0.53

GE Essential MTD

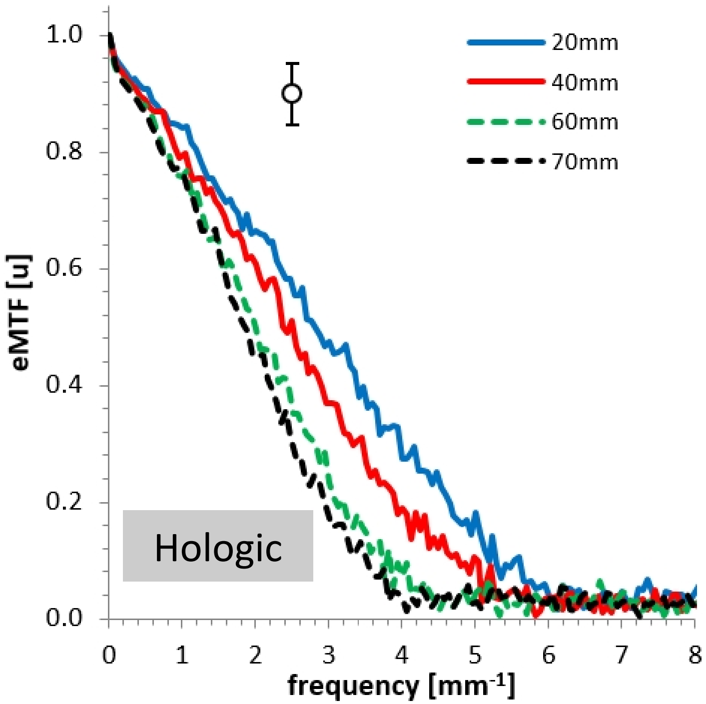
PMMA (mm)	kV	target/ filter	SF	kV	target/ filter	SF
20	25	Mo/Mo	0.09	26	Mo/Mo	0.12
40	28	Mo/Rh	0.13	29	Rh/Rh	0.18
60	31	Rh/Rh	0.18	31	Rh/Rh	0.24
70	31	Rh/Rh	0.20	31	Rh/Rh	0.27

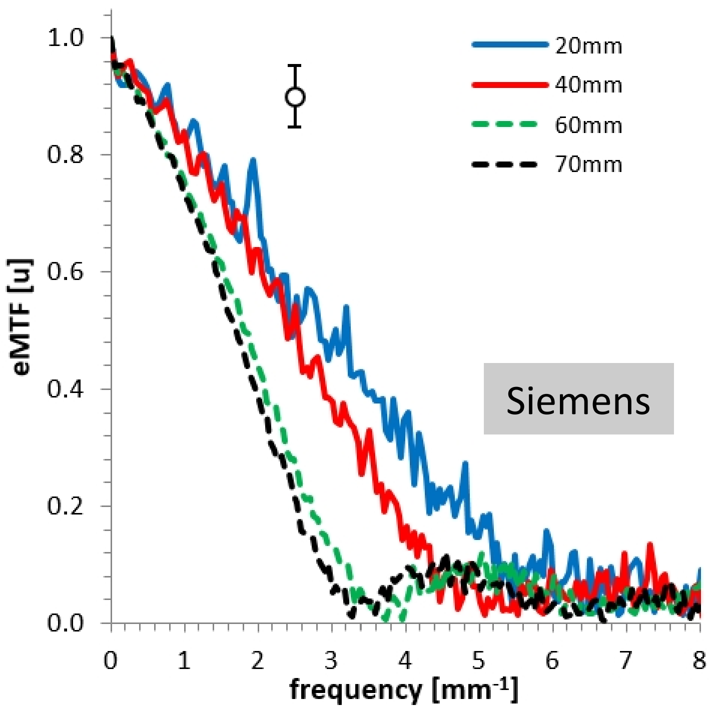
Results – MTF for 2D mode

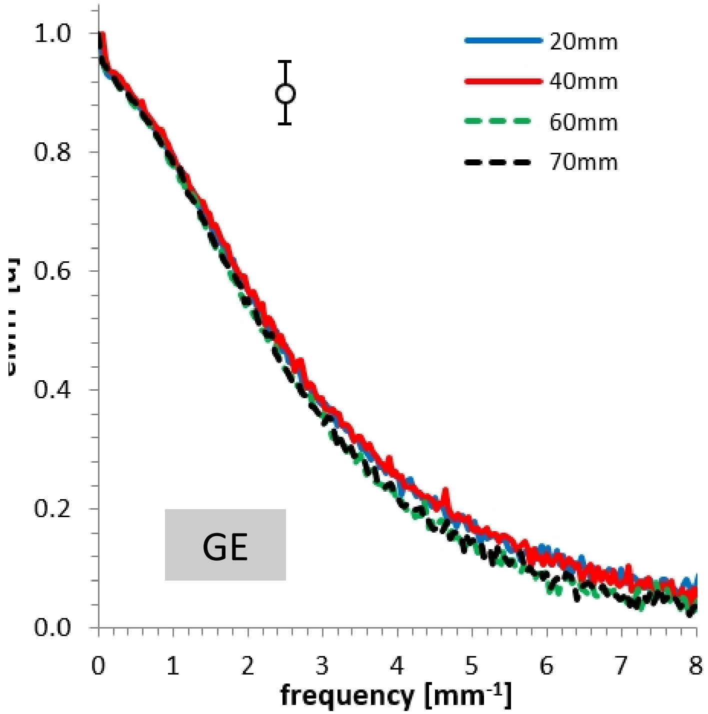


- Small effect on MTF due to focus size as edge moved closer to source
- a-Se systems are sharper than the CsI system

Results – MTF for DBT mode – tube-travel direction





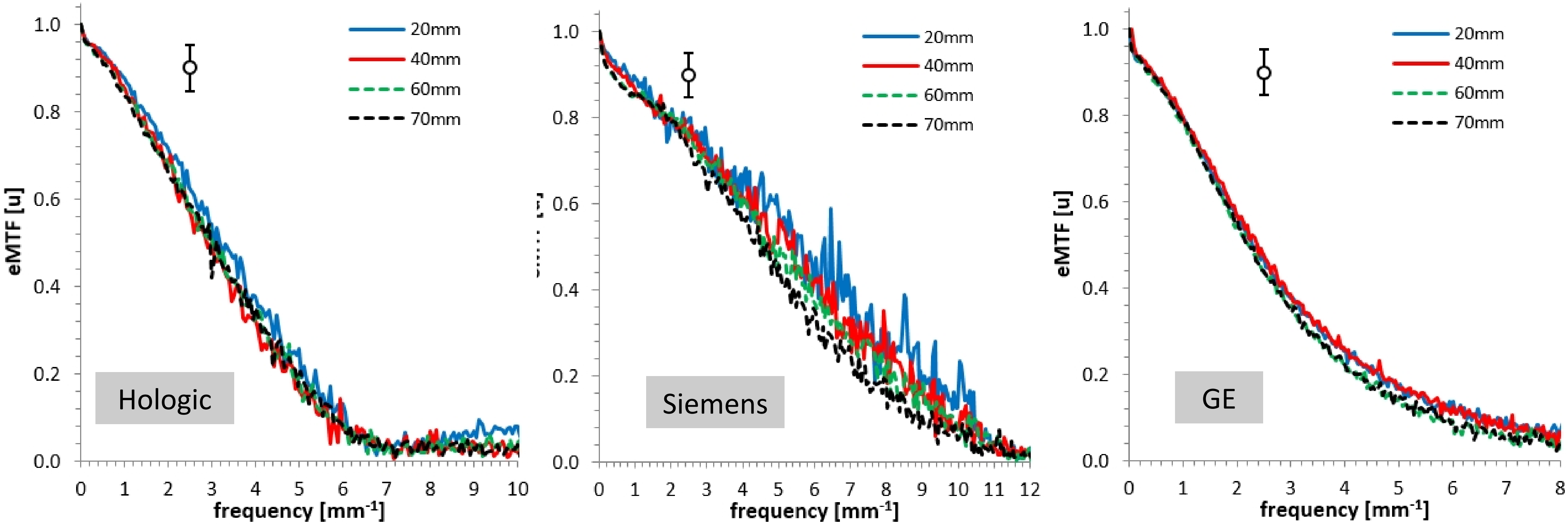


2x2 binning (0,14 mm pixel)
~30 ms pulse/projection
~1,49 mm effective focus length

~89 ms pulse/projection
~2,2 mm effective focus length

variable ms pulse/projection
but step-and-shoot
i.e. no tube motion during
exposure

Results – MTF for DBT mode – front-back direction

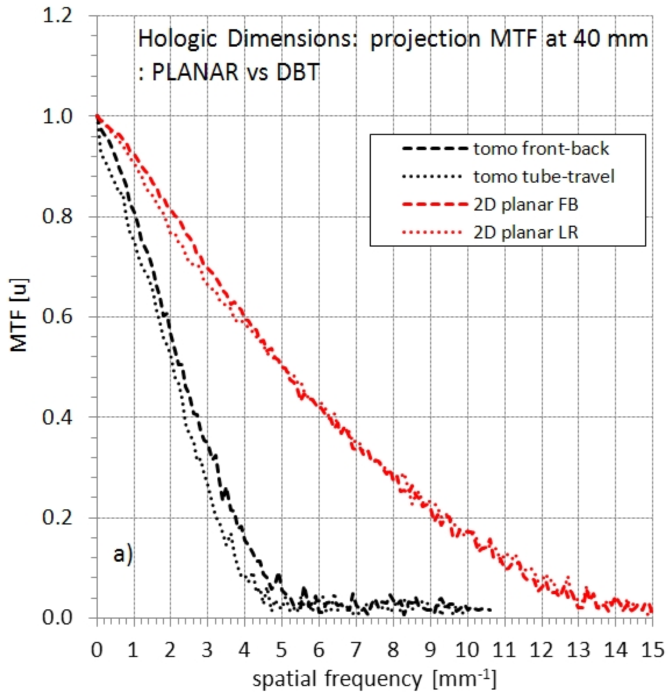


2x2 binning (0,14 mm pixel)

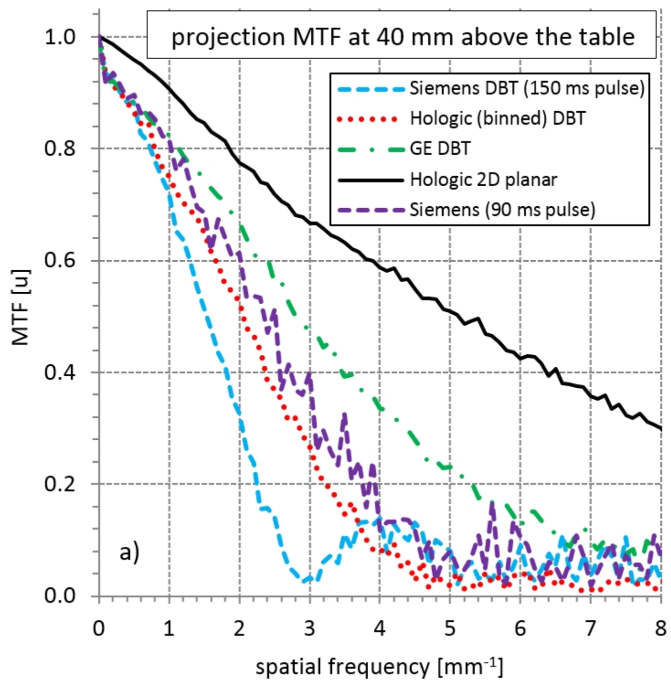
- No source motion in the front-back direction for flying focus systems
- Flying focus systems have anisotropic sharpness vs height above table
- Isotropic system presampling MTF for step and shoot system

System sharpness – projections

- Hologic stores binned (2x2) projections – binning unsharpness dominates over tube motion at positions closer to the detector
- Strong differences in sharpness between the systems

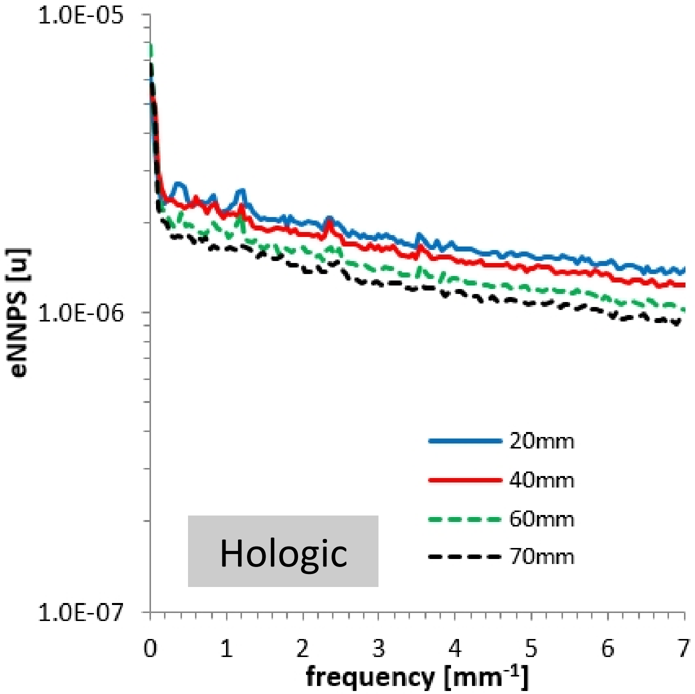


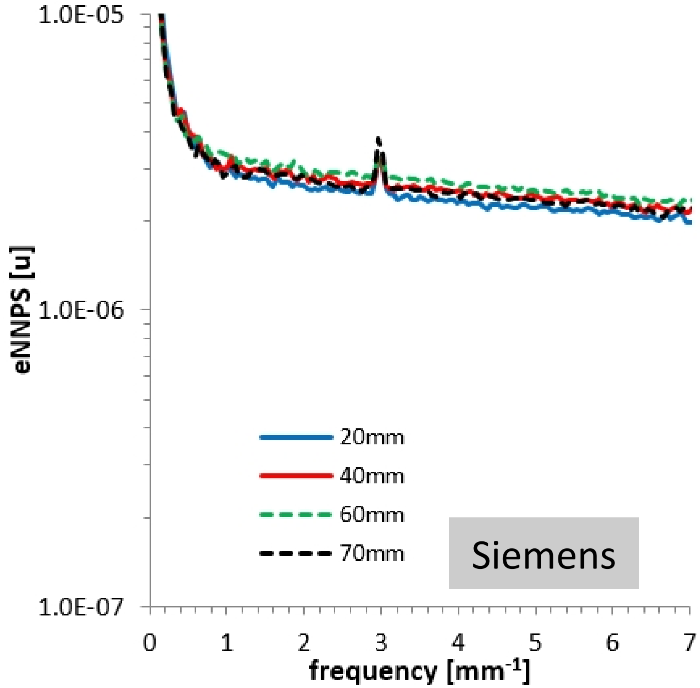
Hologic Dimensions

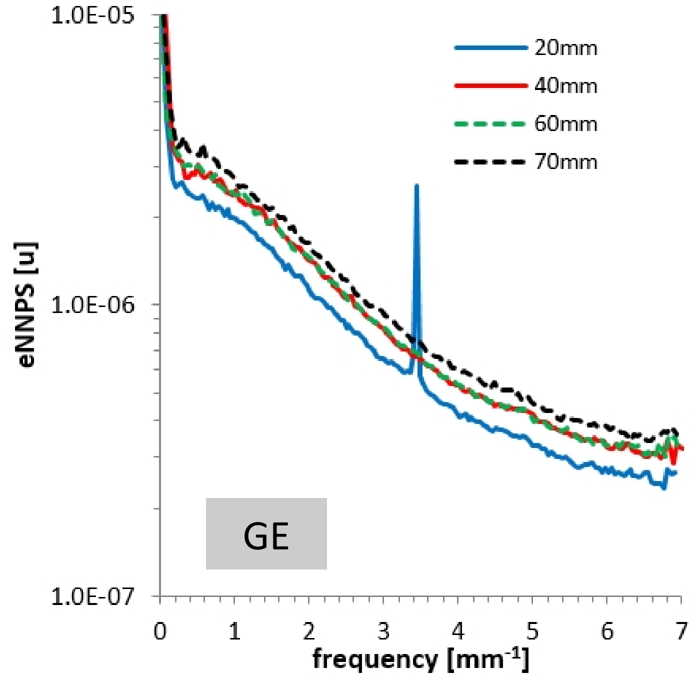


System comparison

Results – NNPS for 2D mode

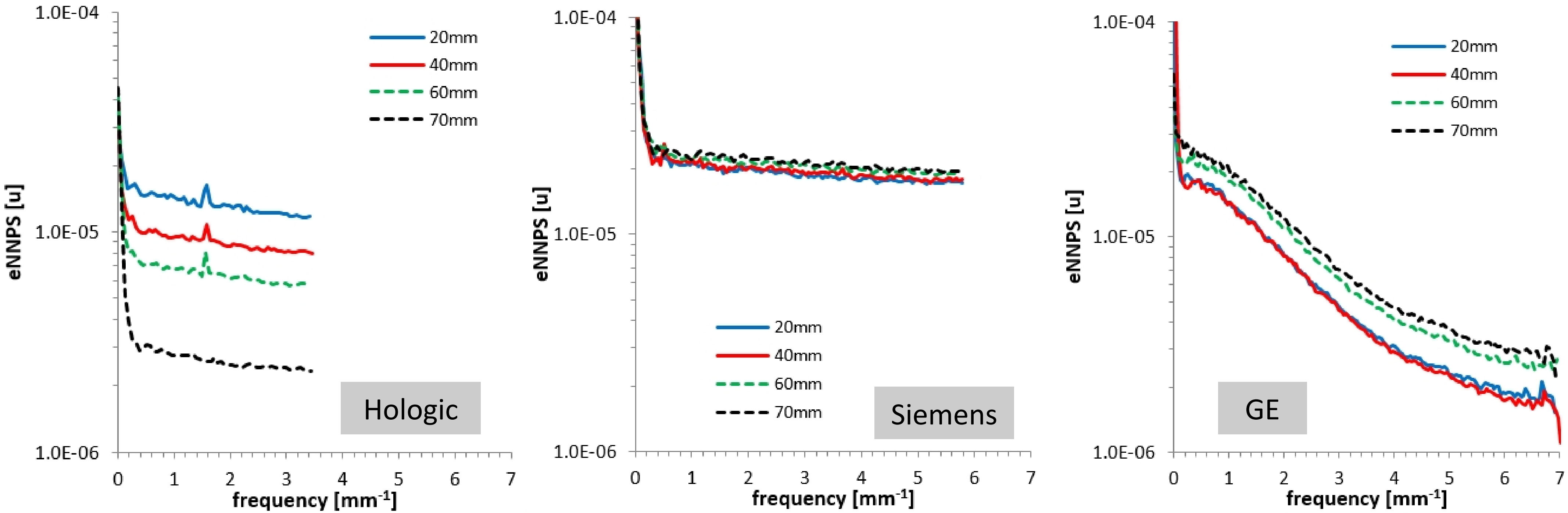






- NNPS isotropic for the three systems
- Spikes in the NNPS at grid line frequencies
- Approx 90 µGy per projection for the Siemens and GE
- Approx 90 to 180 µGy per projection for Hologic

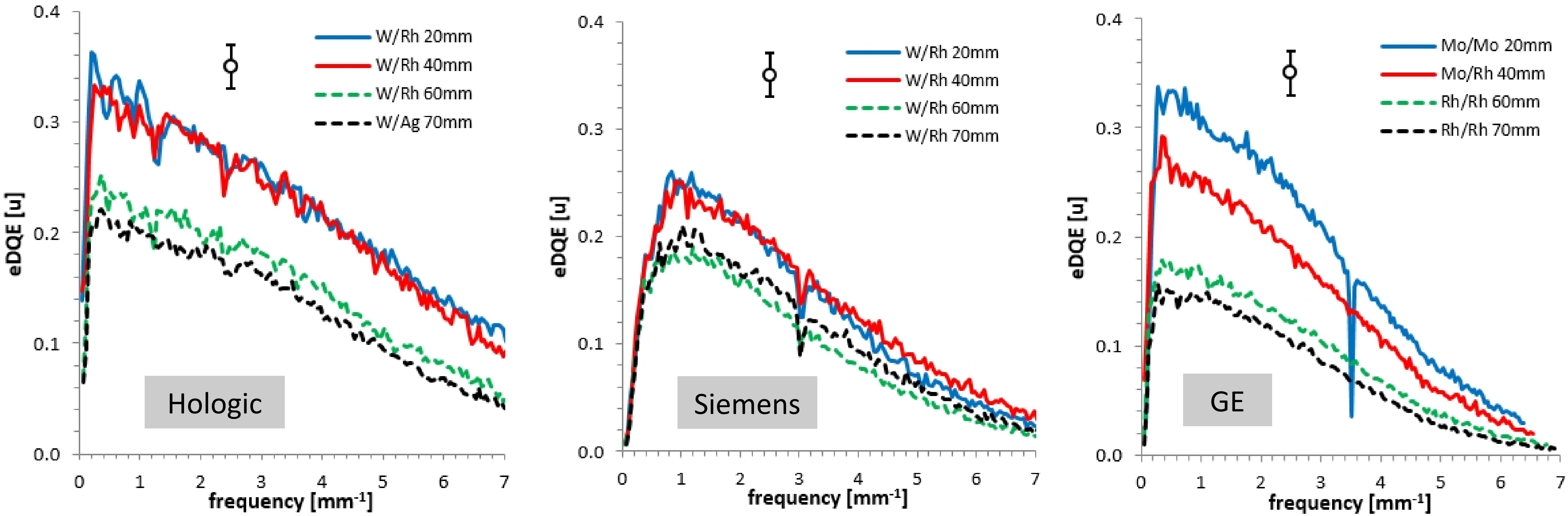
Results – NNPS for DBT mode



2x2 binning (0,14 mm pixel)

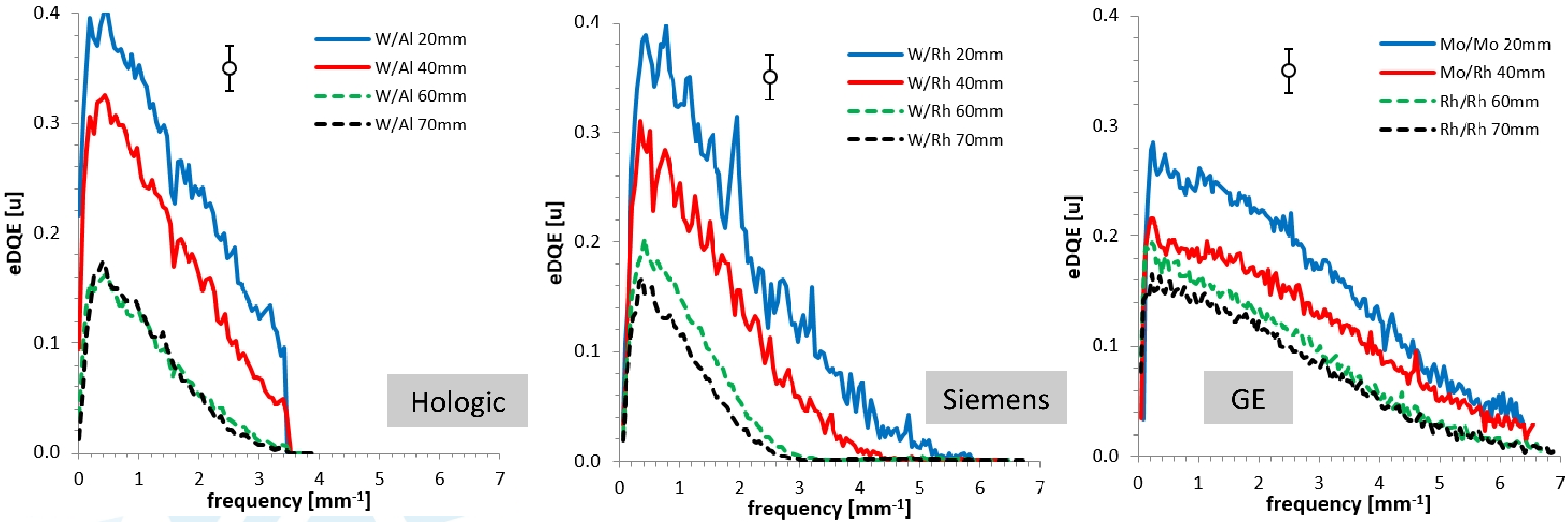
- NNPS isotropic for the three systems
- Only the detector blurs the noise…
- Phosphor blurring of quantum noise for GE

Results – eDQE for 2D mode



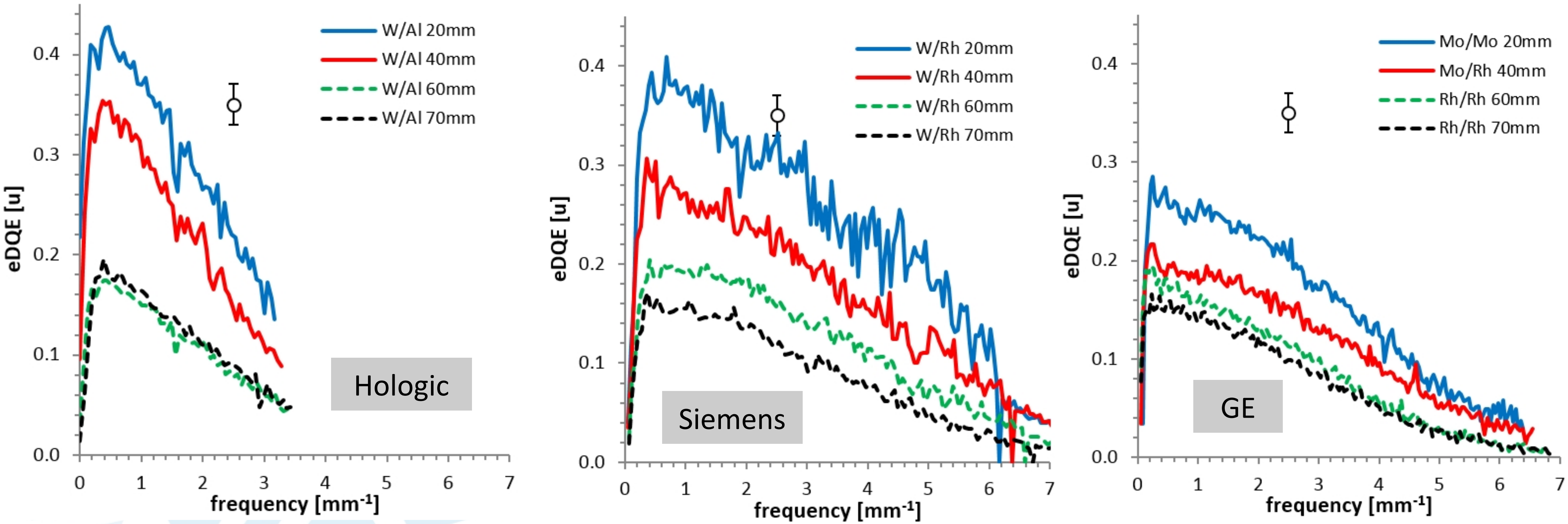
- Reduction in eDQE with increasing thickness
  - influence of scatter, even though grid is used
- Peak eDQE in the range 0,2 to 0,3 cf ~0,5 to 0,6 for detector DQE

Results – eDQE for DBT mode – tube travel direction



- Strong reduction in eDQE for Hologic and Siemens, especially for larger PMMA thicknesses
    - Influence of motion MTF
    - Scattered radiation
- For GE system, eDQE similar to that for 2D mode

Results – eDQE for DBT mode – front back direction



- The eDQE measure shows that system SNR transfer efficiency is anisotropic for flying focus systems
- For step and shoot system, eDQE is isotropic

eDQE summary

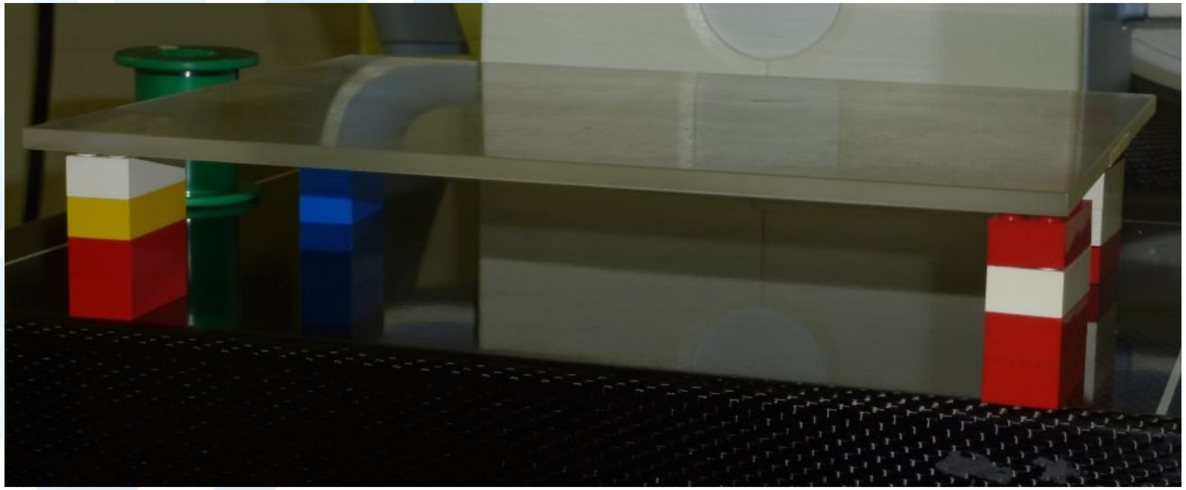
- In fact, is there such as thing as system efficiency?
  - DQE is well defined for radiation detectors
  - Some people refute the idea of system DQE
- What is eDQE for system with no source unsharpness and perfect scatter rejection?
  - In the limit, eDQE should tend towards the image receptor DQE
  - Performance becomes limited by the x-ray detector [...and the task]

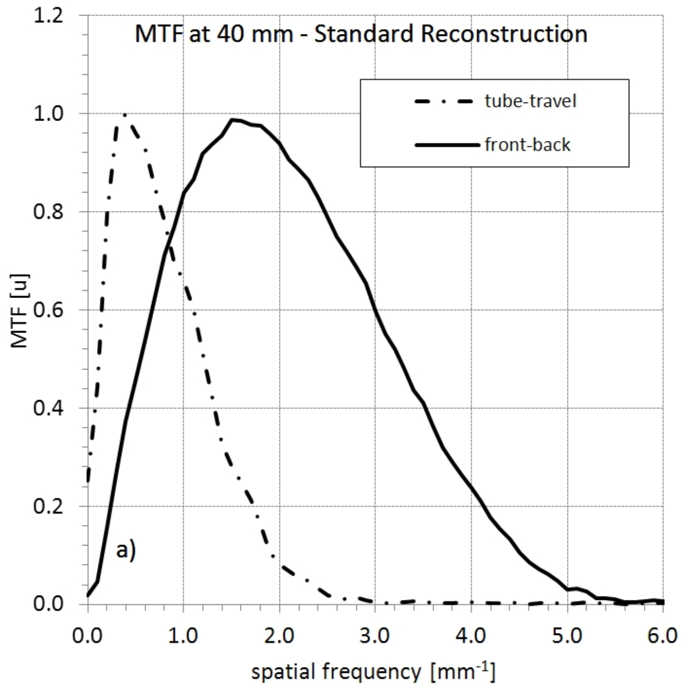
eDQE summary

- eDQE is a measure of system efficiency, not image quality *per se*
- Only uses projection data, therefore no account taken of tomographic reconstruction and associated parameters
  - Will not evaluate reduction in anatomical noise compared to 2D due to reconstruction, nor angular range
  - These factors will influence task performance (object detectability) and are not assessed by eDQE method
- These are major aspects of DBT system performance and are not evaluated by system efficiency as defined by the eDQE method
- Detectability index calculated in the DBT tomo planes is a better approach? - work ongoing

Image quality of the reconstructed image

- In-plane sharpness
  - MTF measured using 25 µm Φ W wire
  - Wire supported using a 10 mm PMMA plate
- Sharpness an-isotropy seen in the projections follows through to planes

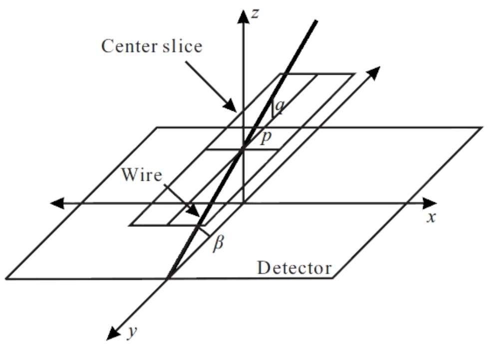


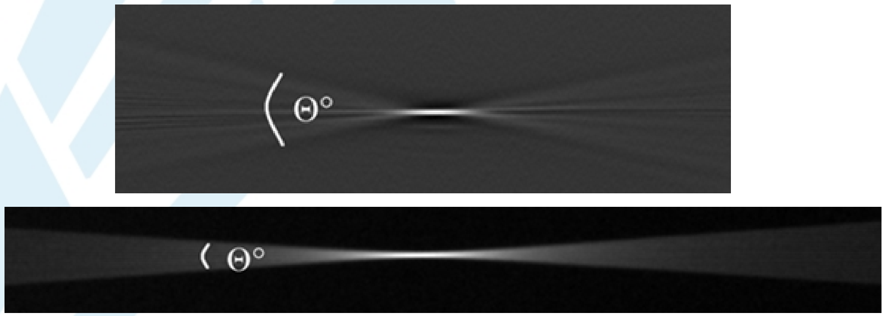


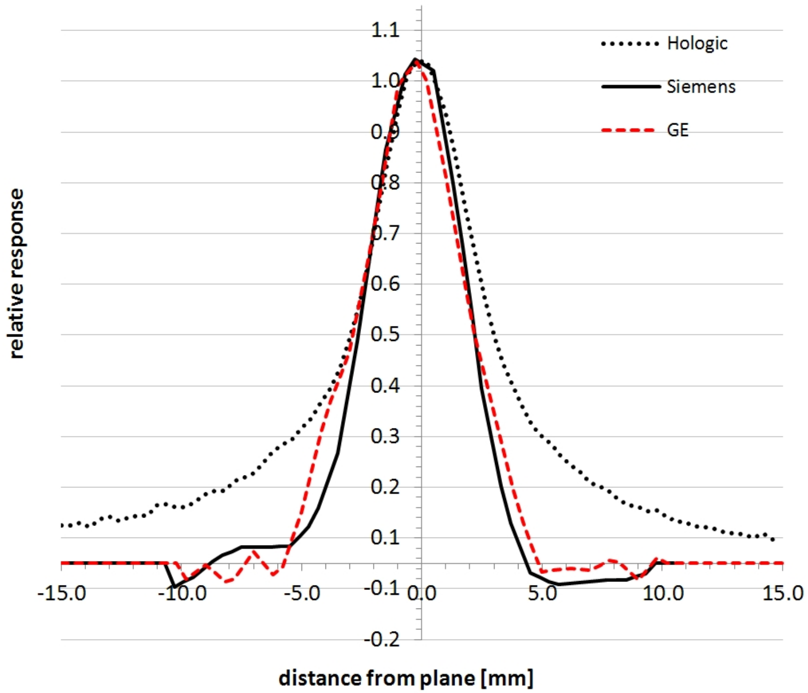
Siemens Inspiration
(150 ms pulse)

Image quality of the reconstructed image

- System characterization – z resolution
- Measured with a 1,0 mm Φ Al sphere or thin angled wire





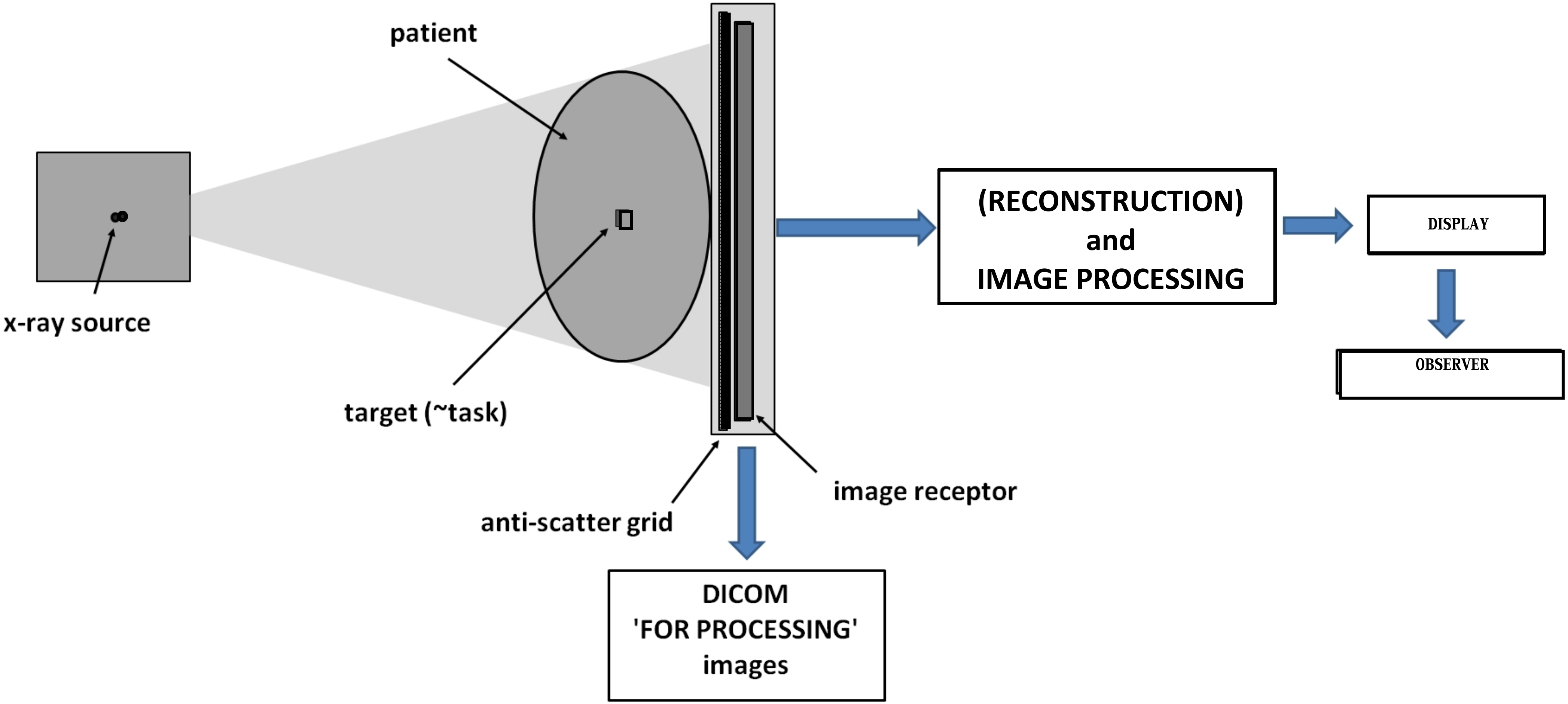


DBT system	FWHM (mm)
Siemens	4.6
Hologic	5.4
GE	4.8

Back to task based evaluations….

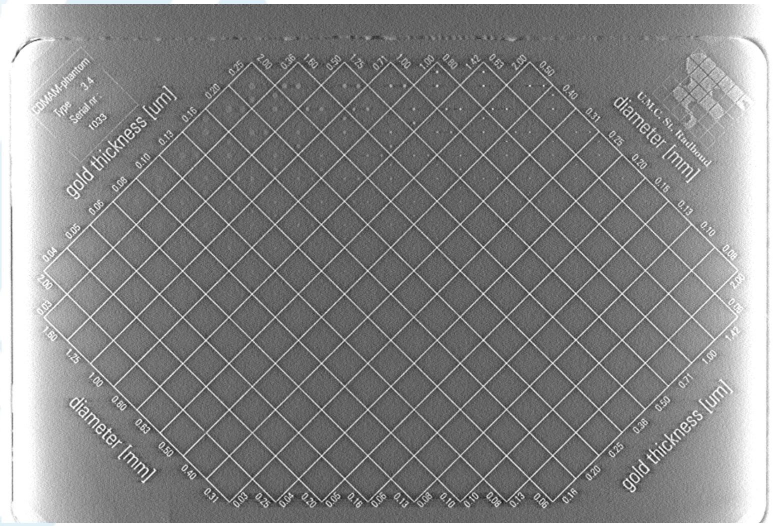
- A lot of abstract curves - how do we interpret these results?
- It seems as though there is anisotropy in system sharpness and therefore in the system signal-to-noise (SNR) efficiency
    - What is the impact on object detection?
- A structured phantom is required if we are to assess the impact of these findings on task performance…

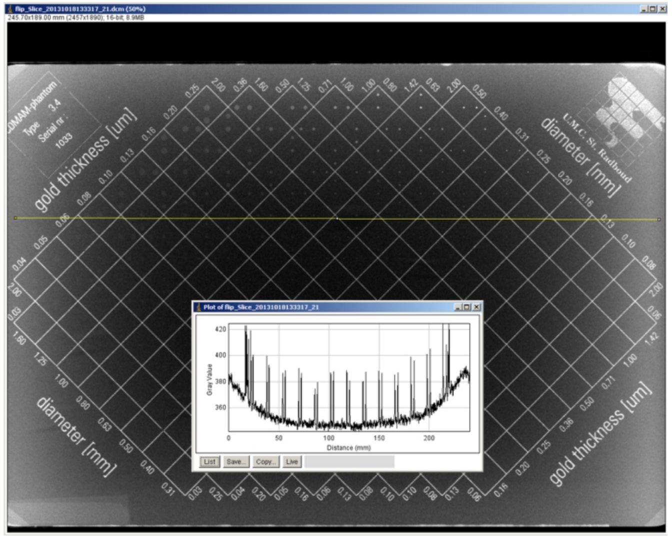
Imaging system



Task based evaluation of 2D mammo and DBT

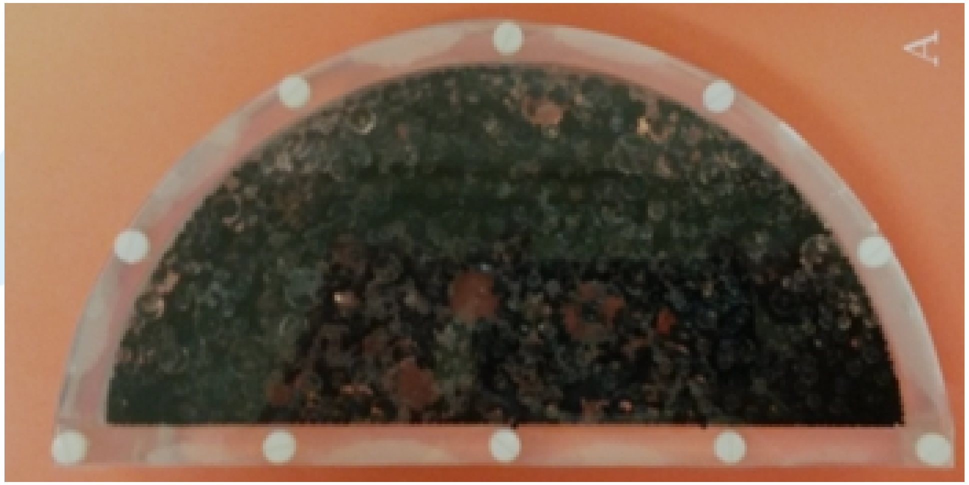
- For 2D mammo we have CDMAM – suitable for DBT?
- Flat test object (difficult to position in-plane?), gold cylinders (wide angle systems?), CDCOM ok?
- **No overlying anatomy -> does not test ability of system to suppress overlying anatomical noise**





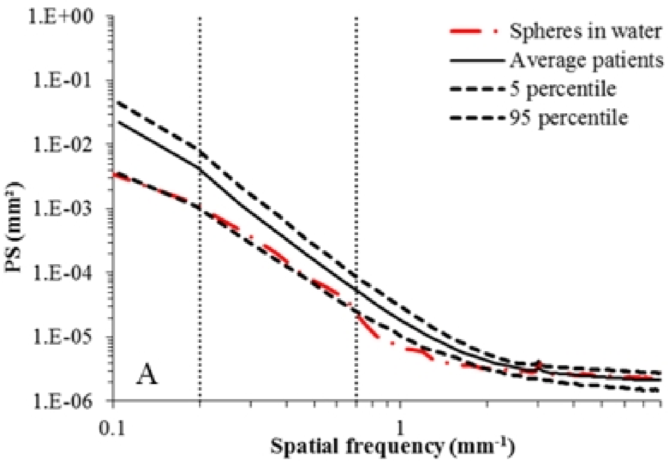
Task based evaluation of 2D mammo and DBT

- How to make a fair comparison between DBT and 2D mammo using a test object?
- 'Task based' evaluation:
  - Design a phantom with ~realistic structure and lesions
  - Background is formed from spheres with different diameters

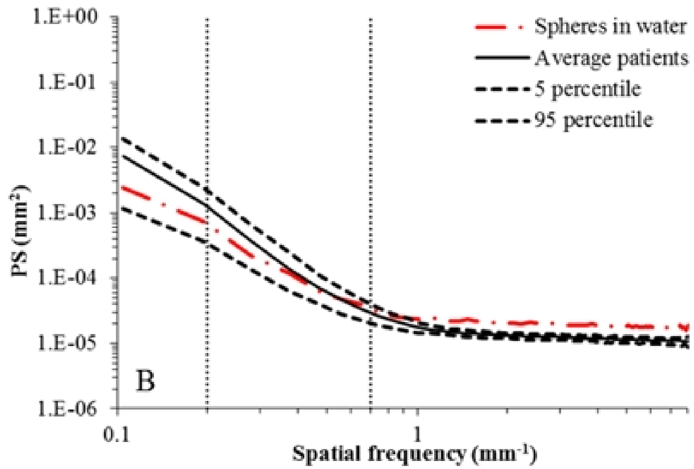


G.J. Gang et al , "Anatomical background and generalized detectability …." Med. Phys. 37(5), 1948–1965 (2010).

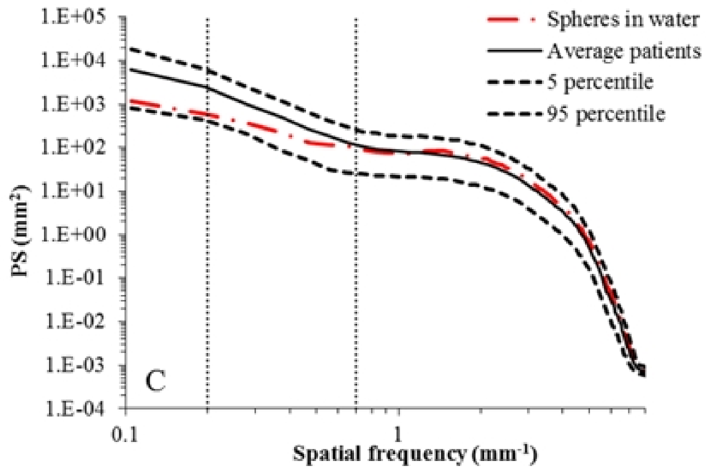
Task based evaluation of 2D mammo and DBT



2D mammo



DBT projections



DBT planes

- Power law analysis shows reasonable match for patient anatomical noise

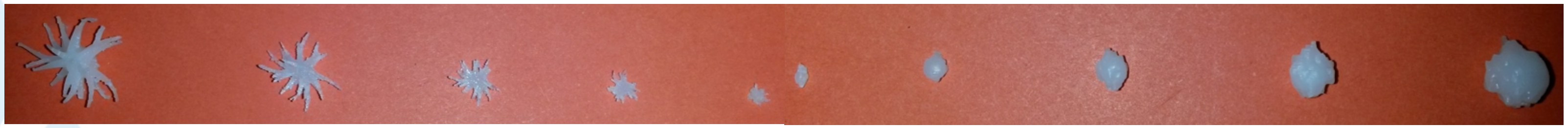
Comparative power law analysis of structured breast phantom and patient images in digital mammography and breast tomosynthesis

L. Cockmartin,[a] H. Bosmans, and N. W. Marshall
Department of Radiology, UZ Gasthuisberg, Herestraat 49, B-3000 Leuven, Belgium

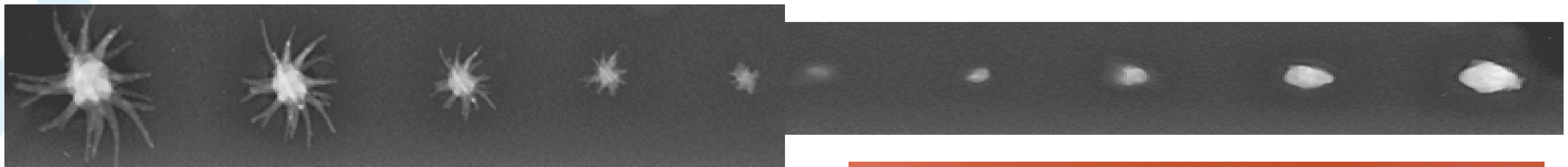
Task based evaluation of 2D mammo and DBT

- Lesions: calcification or 3D printed spiculated and non-spiculated ~masses using Leuven developed mass models
- There are currently difficulties in printing accurate linear attenuation coefficients – we have a reasonable match

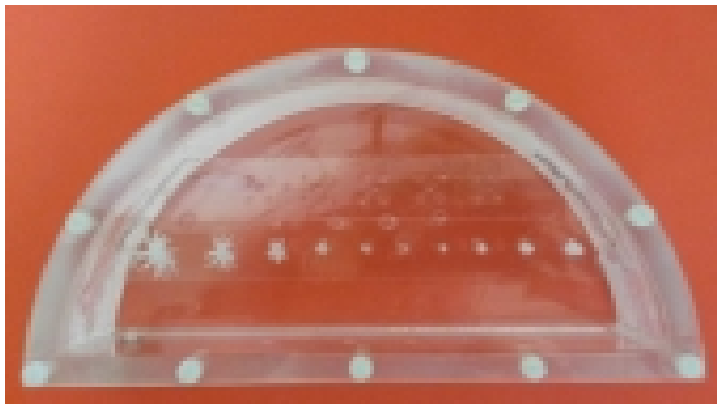
photograph



X-ray image

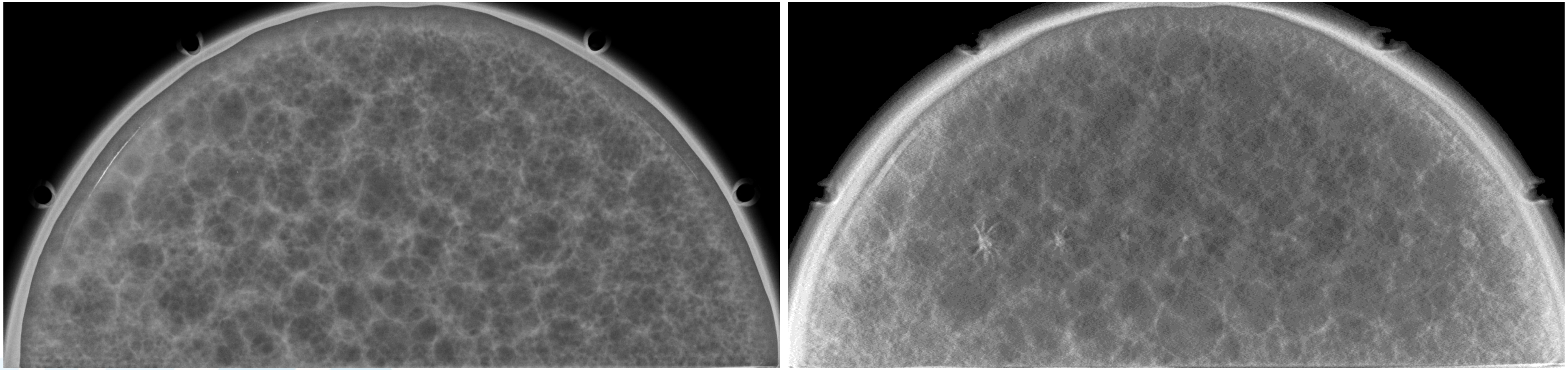


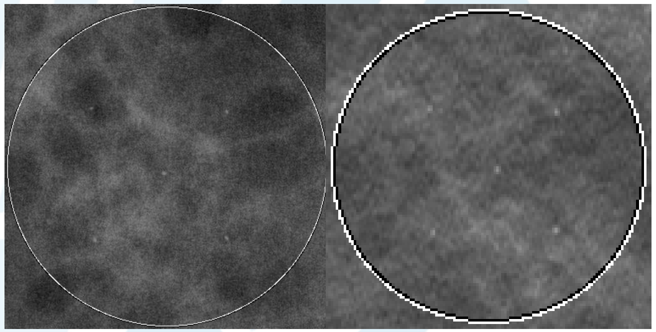
Targets in the phantom before spheres added:



E. Shaheen et al "The simulation of 3D mass models …" Med. Phys. (2014)

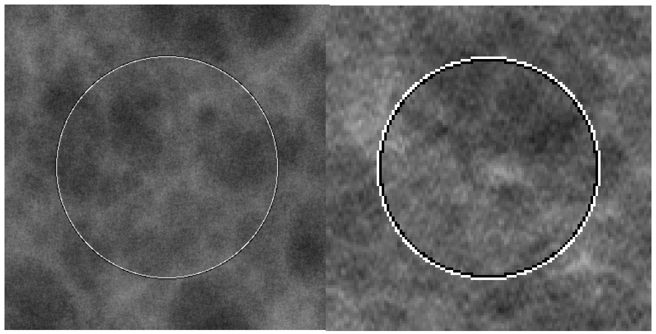
Task based evaluation of 2D mammo and DBT





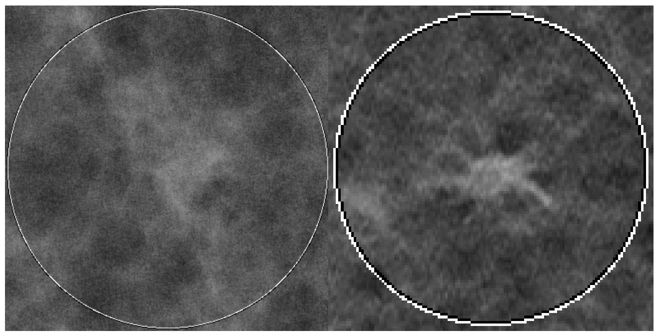
2D DBT

microcalcifications



2D DBT

non-spiculated mass

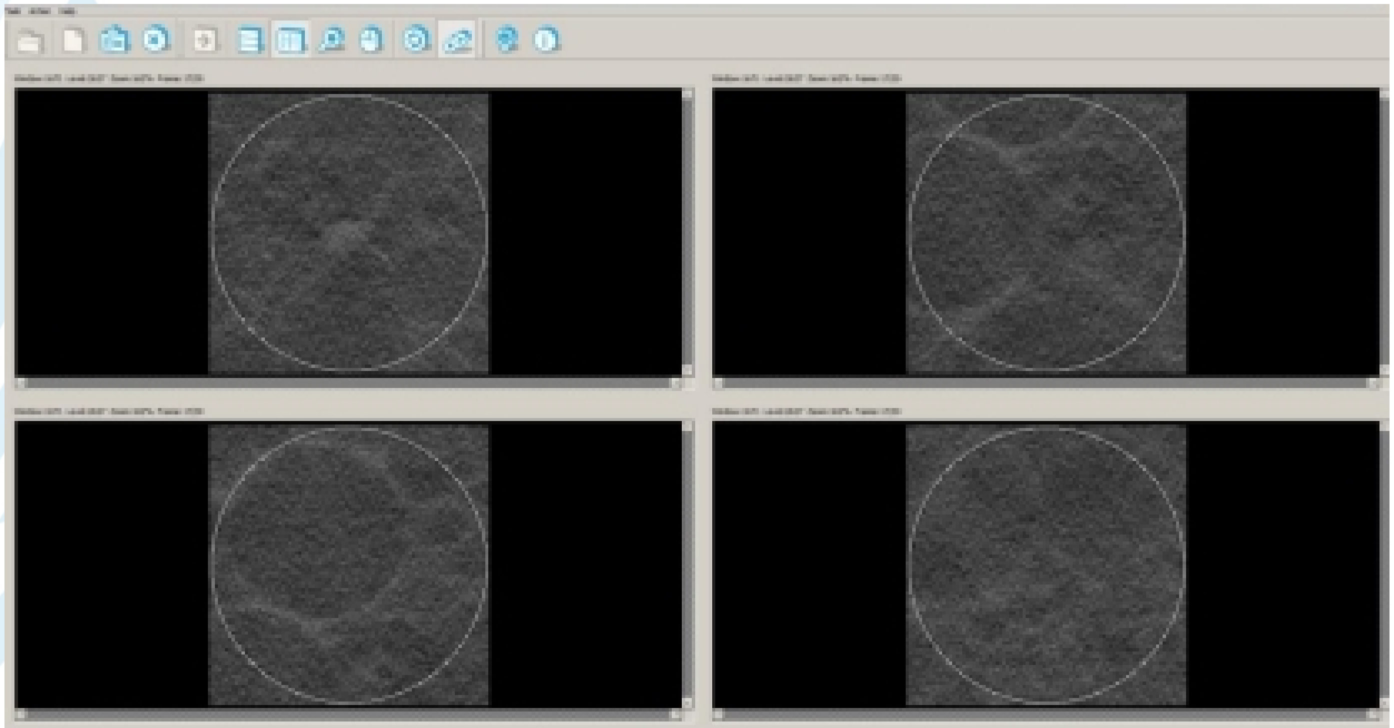


2D DBT

spiculated mass

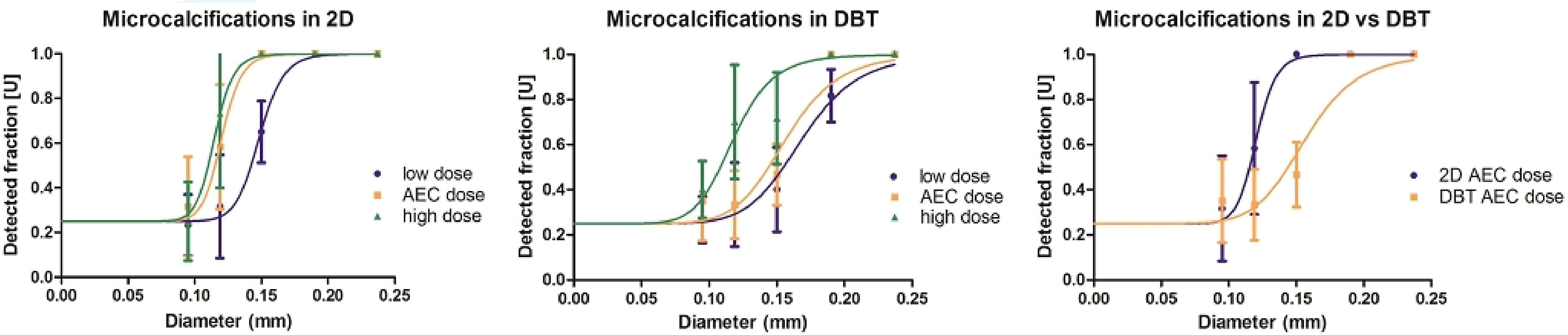
Task based evaluation of 2D mammo and DBT

- 4-AFC study to compare 2D and DBT lesion detection for four DBT systems compared: Siemens, Hologic, Fuji and GE



Task based evaluation of 2D mammo and DBT

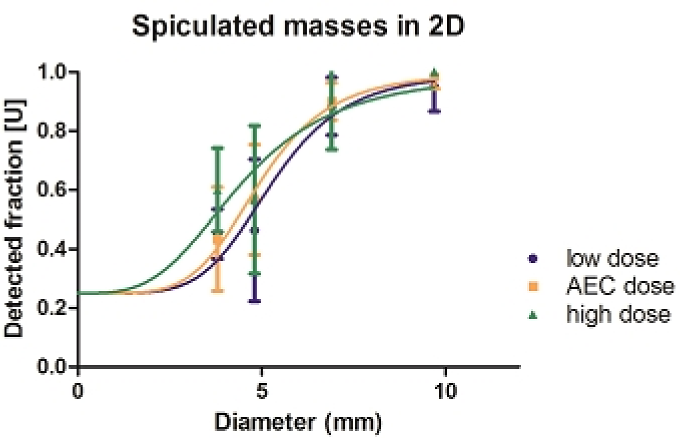
- Compare microcalcification detection for one DBT system at three dose levels
- 2D mode vs DBT

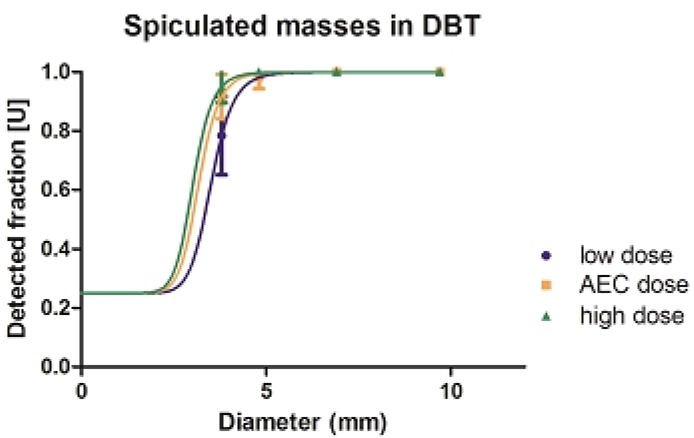


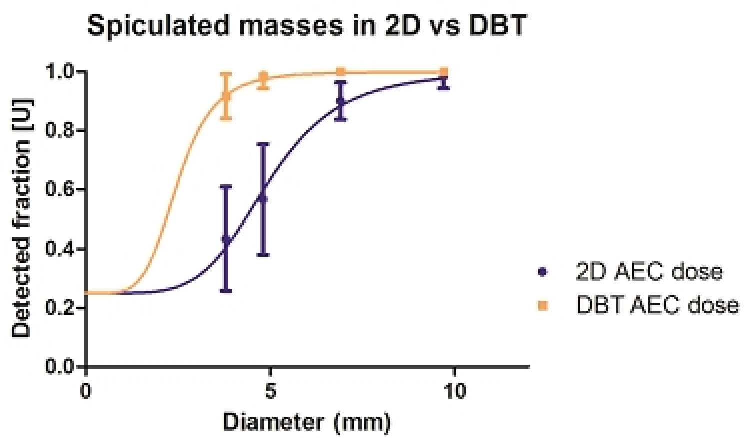
- Appears that 2D has slightly superior microcalcification performance (could be expected from the eDQE results?)

Task based evaluation of 2D mammo and DBT

- Compare spiculated mass detection for one DBT system at three dose levels
- 2D mode vs DBT







- DBT has superior mass detection performance
- Difficult to infer this from eDQE results – eDQE is 'task neutral', no anatomical background, not calcualted from the planes

Summary points

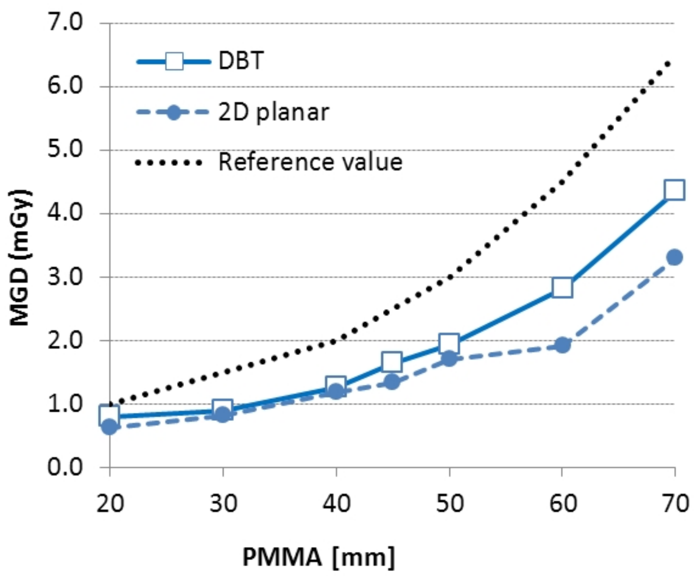
- Detector evaluations are starting point in system evaluation
  - Check how detector is operated
- System efficiency measurements show scatter is not limiting factor on SNR for thinner breast, but large influence for thicker breasts
- Flying focus systems are anisotropic in terms of eDQE
  - What does this mean?
- eDQE difficult to interpret and limited to projections – ignores reconstruction
- We need a task based evaluation performed in a realistic background, using the reconstructed data

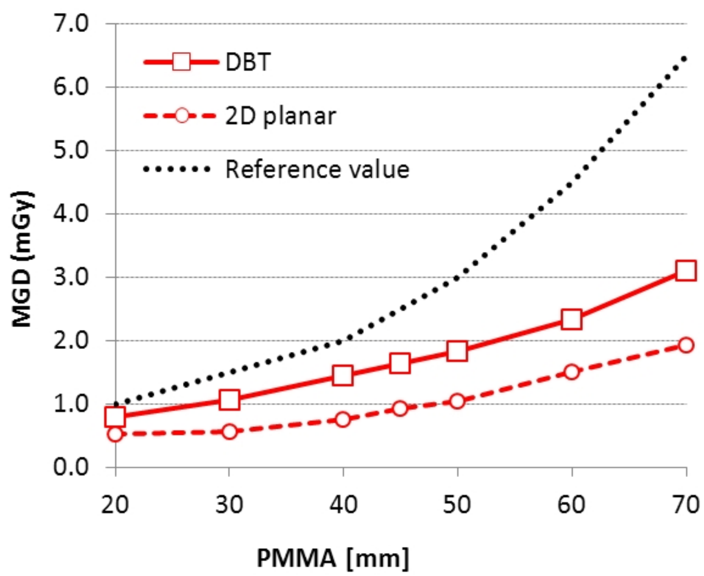
Thanks to UZ Leuven Medical Physics ….

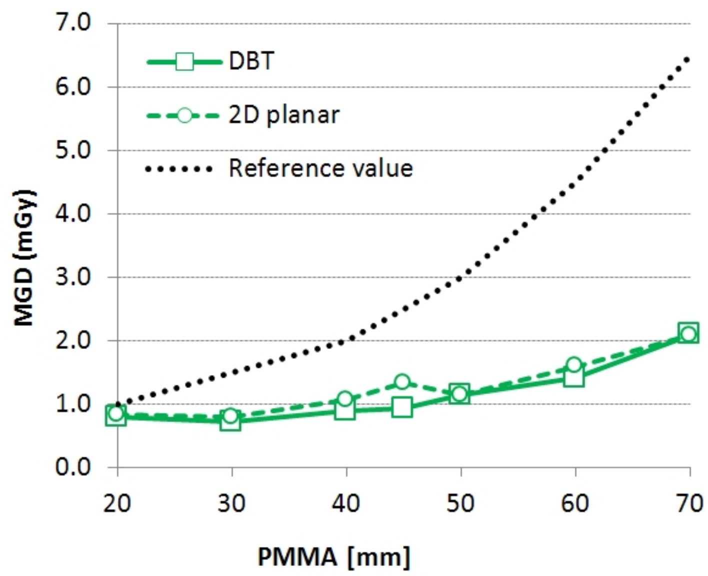
…now where did I leave my bike?

What about dose?

- eDQE is an effiency – dose (MGD) is removed from the evaluation
- There are certainly differences in dose levels between the systems
- Dose <u>should </u>influence image quality
- Dose levels within the achievable level of 2D mammography

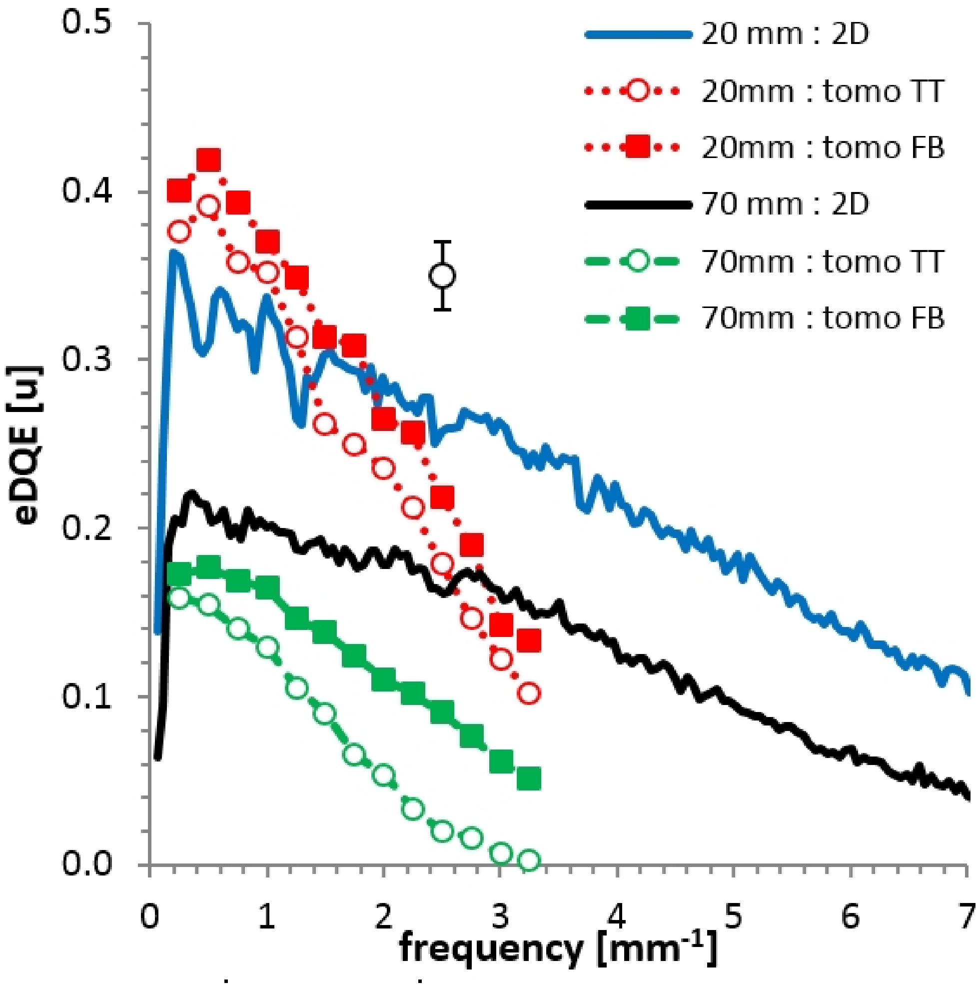






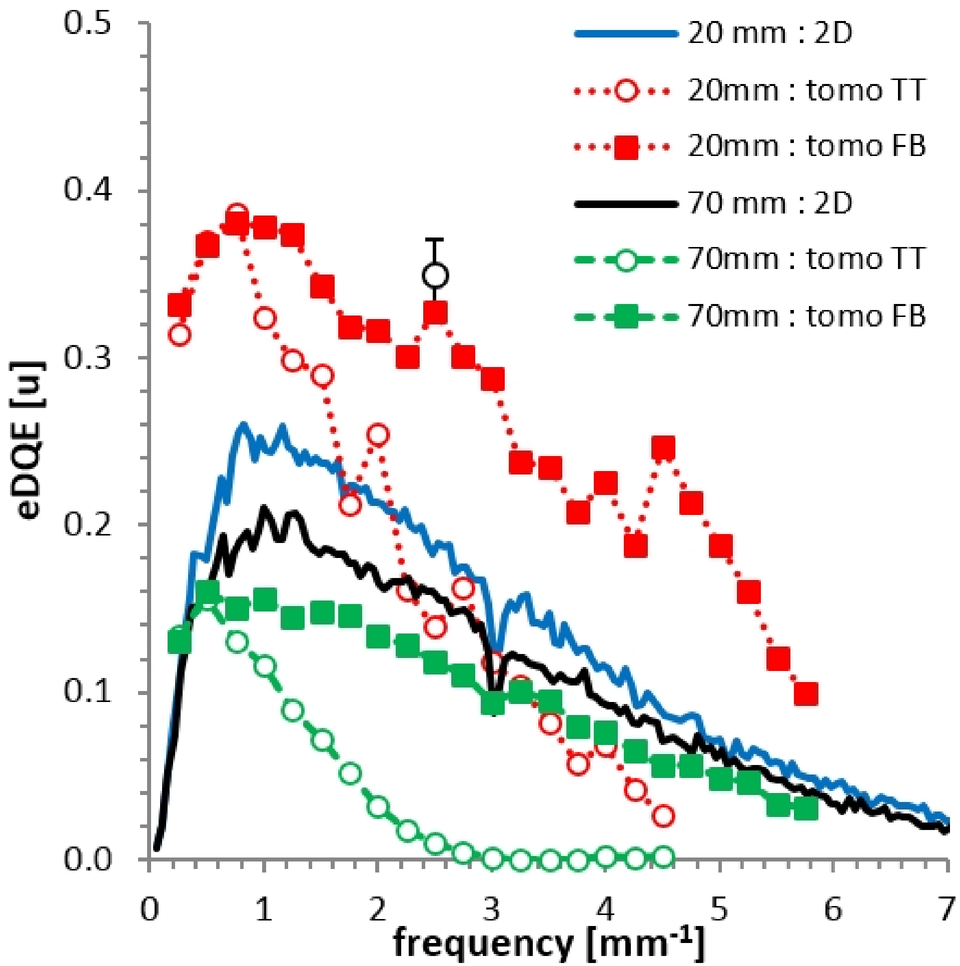
Results – Hologic eDQE: 2D vs DBT

- 20 mm DBT, peak eDQE higher/of same order as 20 mm 2D
  - Binning is reducing eDQE
  - Focus motion not too influential (25 ms pulse length)
- 70 mm DBT, strong reduction (~75%) for FB direction
- Still some influence of focus motion in eDQE, especially at 70 mm



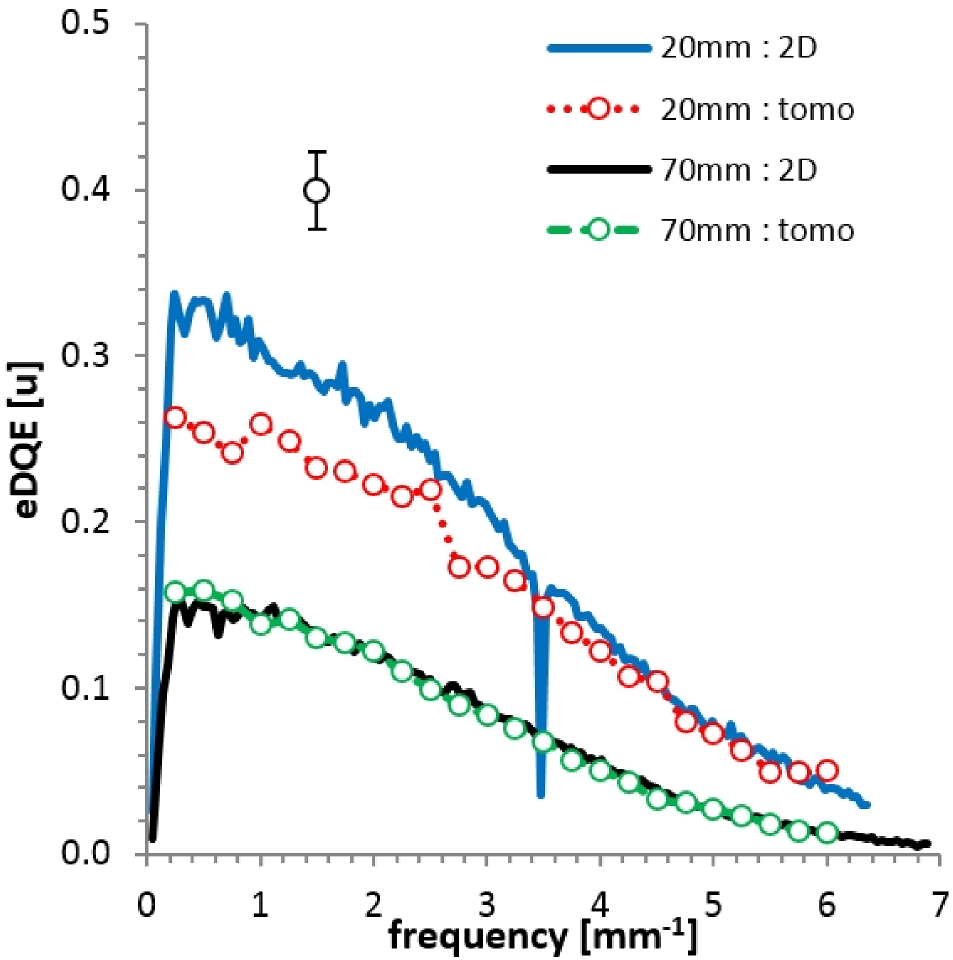
Results – Siemens eDQE: 2D vs DBT

- 20 mm DBT, peak eDQE ~60% higher than for 20 mm 2D
  - Strong influence of focus motion even for 20 mm position
- 70 mm DBT, large reduction in eDQE in tube travel direction
  - 90 ms length, leading to focus motion blurring
- Strong an-isotropy in terms of system efficiency



Results – GE Essential eDQE: 2D vs DBT

- 20 mm DBT, slightly lower *cf* 2D
  - 26 kV vs 25 kV Mo/Mo
  - SF higher (0.12 vs 0.09)
- 70 mm, eDQE for DBT and 2D ~identical
  - Same spectrum (31 kV Rh/Rh)
  - Step and shoot -> no focus motion blurring
- No an-isotropy in terms of system efficiency



Some points about the DBT acquisitions

- Hologic Dimensions
  - 0° DBT mode for the x-ray output, TF and SF data (W/Al only in DBT)
  - Standard (moving tube) DBT for MTF and AEC acquisitions
- Siemens Inspiration
  - 2D mode for x-ray output, TF and SF (same T/F can be used for 2D and DBT)
  - Standard (moving tube) DBT for MTF and AEC acquisitions
- GE Essential
  - 2D mode for x-ray output, TF and SF (same T/F can be used for 2D and DBT)
  - 2D grid and DBT grid used
  - Standard (step and shoot) DBT for MTF and AEC acquisitions
- Calculations performed on central (~0°) projection images