Optimizing Image Quality and Dose in Digital Mammography: X-ray Spectrum and Exposure Parameter Selection

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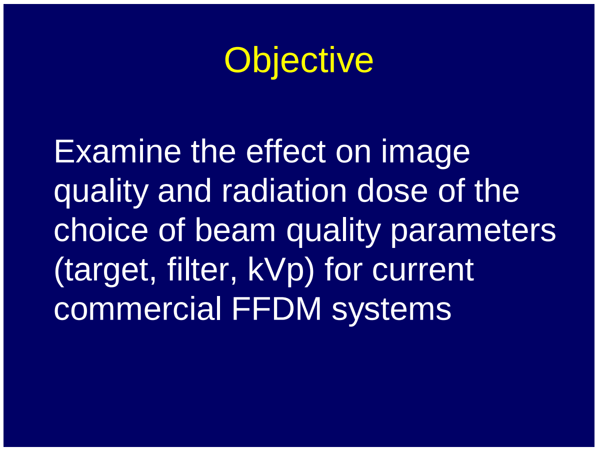
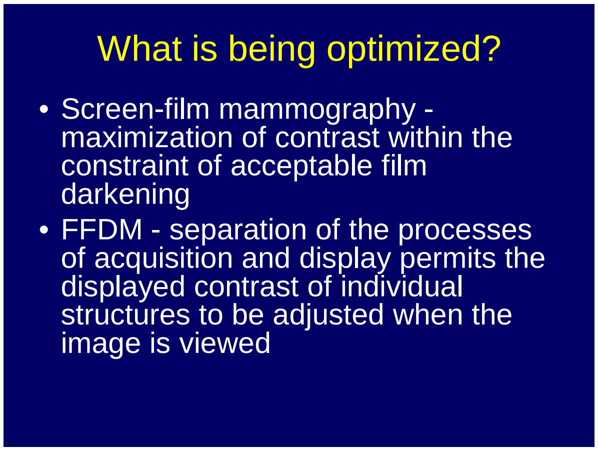


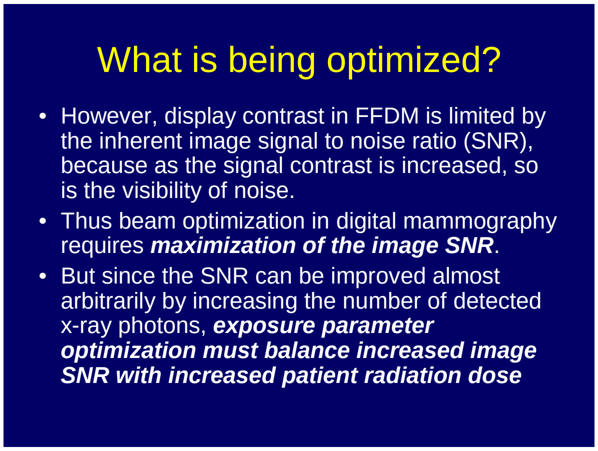
Objective

Examine the effect on image quality and radiation dose of the choice of beam quality parameters (target, filter, kVp) for current commercial FFDM systems



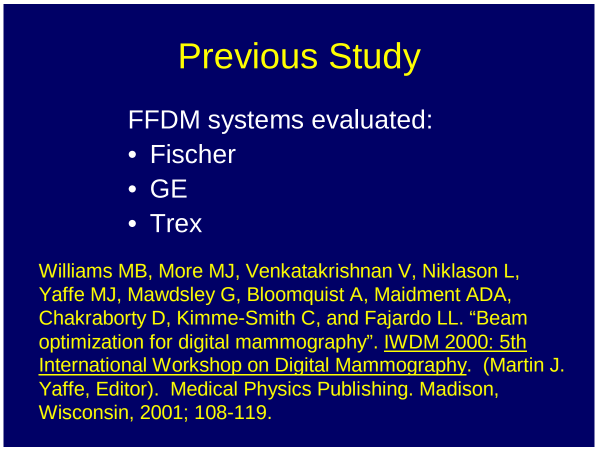
What is being optimized?

- Screen-film mammography - maximization of contrast within the constraint of acceptable film darkening
- FFDM - separation of the processes of acquisition and display permits the displayed contrast of individual structures to be adjusted when the image is viewed



What is being optimized?

- However, display contrast in FFDM is limited by the inherent image signal to noise ratio (SNR), because as the signal contrast is increased, so is the visibility of noise.
- Thus beam optimization in digital mammography requires ***maximization of the image SNR***.
- But since the SNR can be improved almost arbitrarily by increasing the number of detected x-ray photons, ***exposure parameter optimization must balance increased image SNR with increased patient radiation dose***

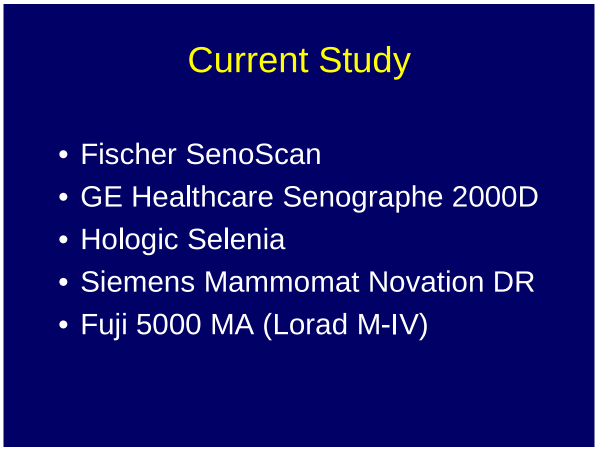


Previous Study

FFDM systems evaluated:

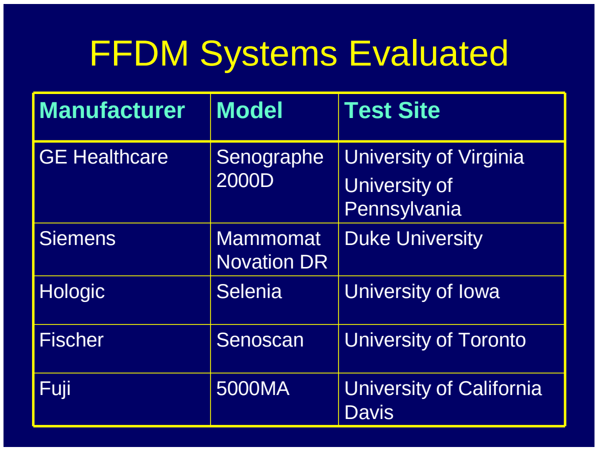
- Fischer
- GE
- Trex

Williams MB, More MJ, Venkatakrishnan V, Niklason L, Yaffe MJ, Mawdsley G, Bloomquist A, Maidment ADA, Chakraborty D, Kimme-Smith C, and Fajardo LL. “Beam optimization for digital mammography”. IWDM 2000: 5th International Workshop on Digital Mammography. (Martin J. Yaffe, Editor). Medical Physics Publishing. Madison, Wisconsin, 2001; 108-119.



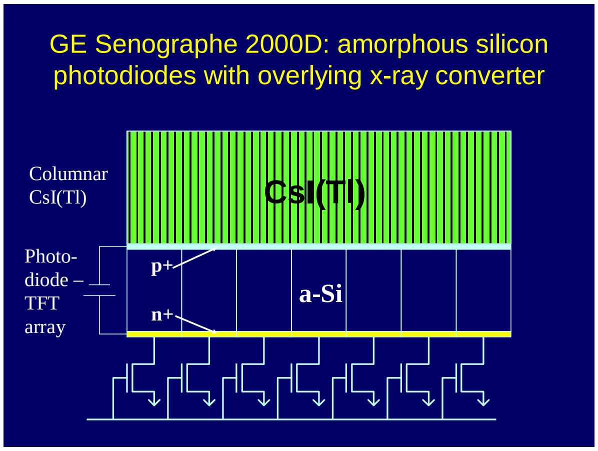
Current Study

- Fischer SenoScan
- GE Healthcare Senographe 2000D
- Hologic Selenia
- Siemens Mammomat Novation DR
- Fuji 5000 MA (Lorad M-IV)



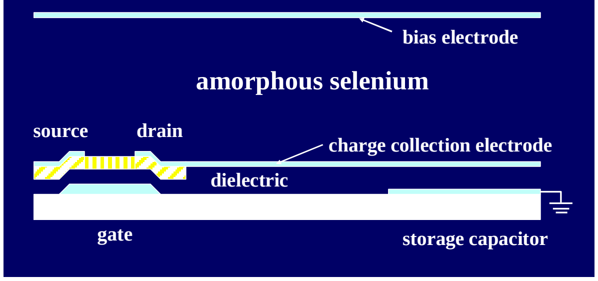
FFDM Systems Evaluated

Manufacturer	**Model**	**Test Site**
GE Healthcare	Senographe 2000D	University of Virginia University of Pennsylvania
Siemens	Mammomat Novation DR	Duke University
Hologic	Selenia	University of Iowa
Fischer	Senoscan	University of Toronto
Fuji	5000MA	University of California Davis

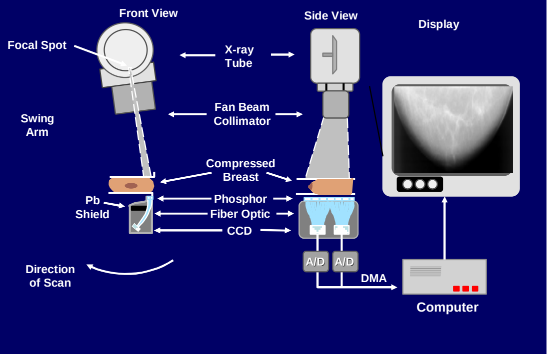


GE Senographe 2000D: amorphous silicon photodiodes with overlying x-ray converter

Hologic Selenia and Siemens Mammomat Novation DR: photoconducting amorphous selenium layer read out by a-Si thin film transistor array



Fischer Senoscan: CCD-based scanned slot system



Dual Sided Imaging Plate Readout

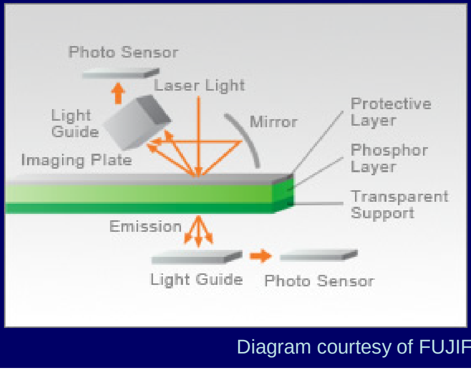


Diagram courtesy of FUJIFILM

Acquisition Parameters

FFDM system	Target	Filter	kVp range
Fischer	W	Al	28 – 37
GE	Mo, Rh	Mo, Rh	23 – 39
Hologic	Mo	Mo, Rh	23 – 39
Siemens	Mo, W	Mo, Rh	23 – 35
Fuji (Lorad M-IV)	Mo	Mo, Rh	22 – 34

Methods

- Common set of breast equivalent phantoms circulated among all test sites
- Phantoms simulated nine breast types (3 compressed thicknesses x 3 fibroglandular/adipose compositions)
- For each phantom, for each possible target/filter combination, images were obtained over a range of kVps, manual mode, average pixel value approximately constant
- SNR and mean glandular dose (MGD) were calculated for each

Number of Images Processed Example: Senographe 2000D at UVa

- 9 phantom types
- 3 target/filter combinations
- 8 kVps per target/filter combination
- 2 images per target/filter/kVp/phantom combination
- **Total of 432 images**

Phantom

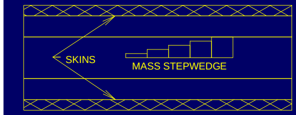
Thickness

3 cm, 5 cm, 7 cm

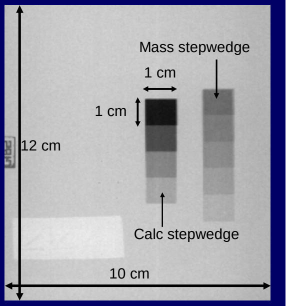
Glandular/adipose mass fraction

30/70, 50/50, 70/30

Skins are 100% adipose



CIRS, Inc., Norfolk, VA



SNR Analysis

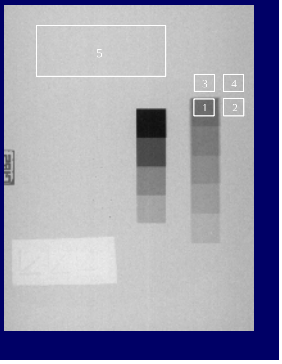
Two images obtained for each phantom/target/filter/kVp combination.

Raw (For Processing) images used.

$$Signal \equiv \overline{P_2} - \overline{P_1} - \left(\overline{P_4} - \overline{P_3}\right)$$

$$Noise \equiv \frac{\sigma_{5,difference}}{\sqrt{2}}$$

$$FOM \equiv \frac{SNR^2}{MGD}$$



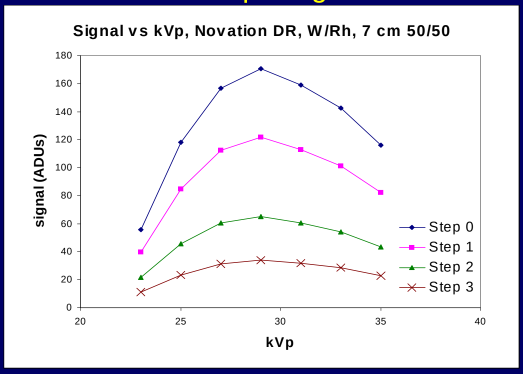
Dose Calculation

- Boone, J. (1999). Glandular breast dose for monoenergetic and high-energy x-ray beams: Monte Carlo assessment. Radiology 213, 23-37.
- Sobol, WT and Wu, X. (1997) Parameterization of mammography normalized average glandular dose tables. Medical Physics 24(4), 547-555.
- Stanton, L., Villafana, T., Day, J., and Lightfoot, D. (1984). Dosage evaluation in mammography. Radiology 150, 577-584.

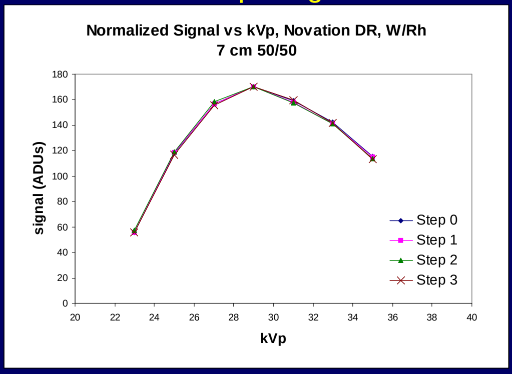
Limitations of the FOM

- SNR did not include spatial frequency dependence
  - Systems with higher MTFs and thus less smoothing of Poisson x-ray noise may be penalized
  - Inter-system comparisons can be misleading
- Exposure time was not taken into account
- The primary sources of uncertainty in the data were:
  - Noise in the measured HVL data
  - Fluctuating system noise; this varied greatly among manufacturers

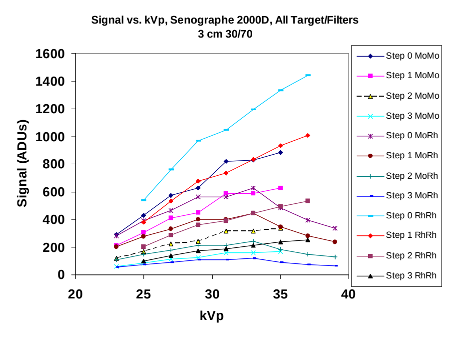
Independence of Shape of Signal vs. kVp on Step Height



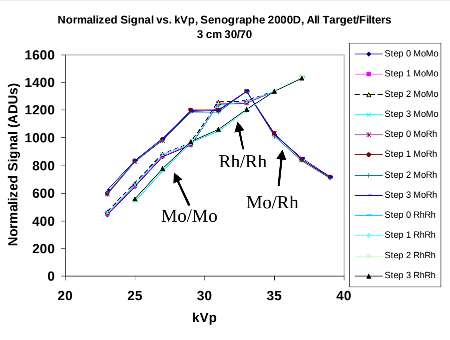
Independence of Shape of Signal vs. kVp on Step Height



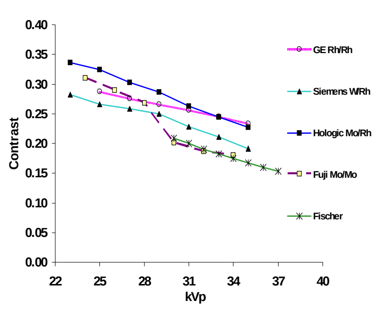
Independence of Optimum Target/Filter on Step Height



Independence of Optimum Target/Filter on Step Height

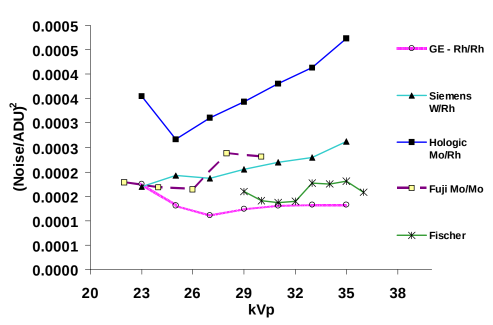


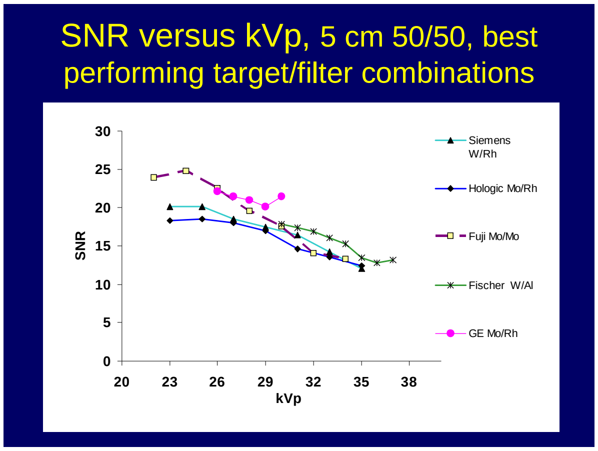
Contrast vs kVp, 5 cm 70/30, best performing target/filter combinations



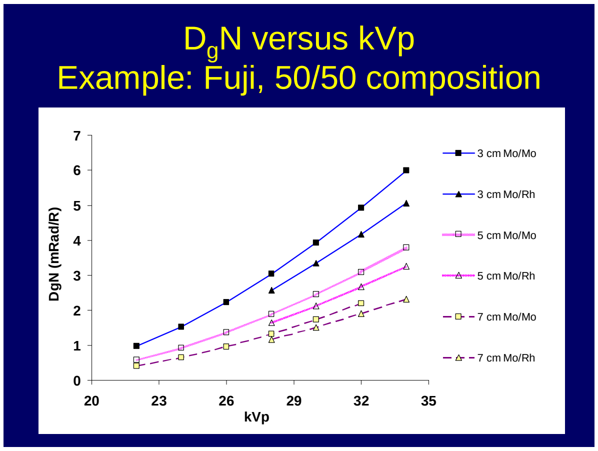
$$contrast = \frac{signal}{avg.bkgnd.\ pixel\ value}$$

$(\text{Noise/ADU})^2$ vs. kVp, 5 cm 30/70, best performing target/filter combinations

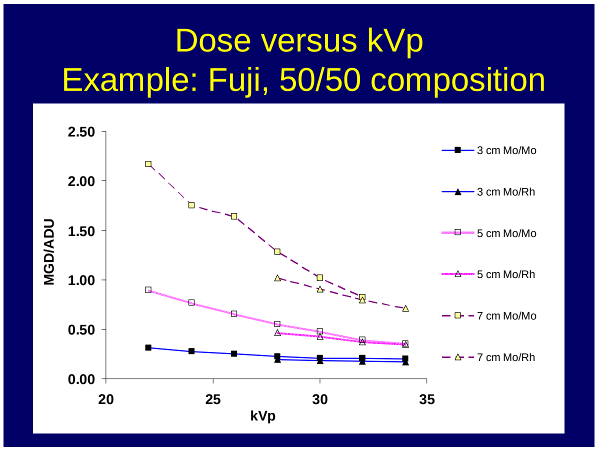




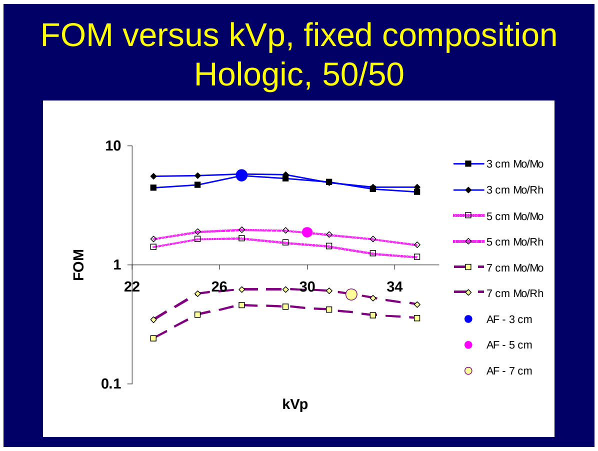
SNR versus kVp, 5 cm 50/50, best performing target/filter combinations



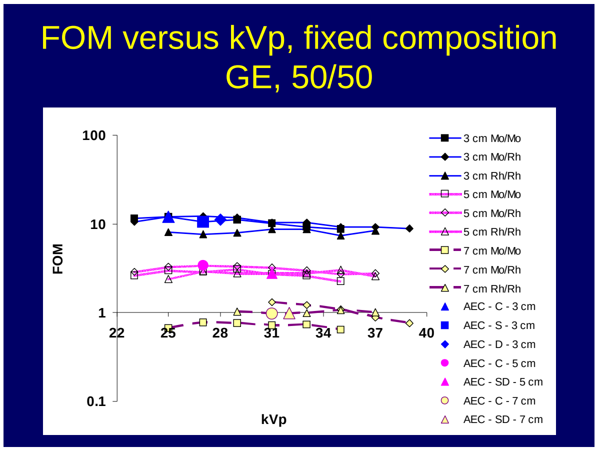
D_gN versus kVp
Example: Fuji, 50/50 composition



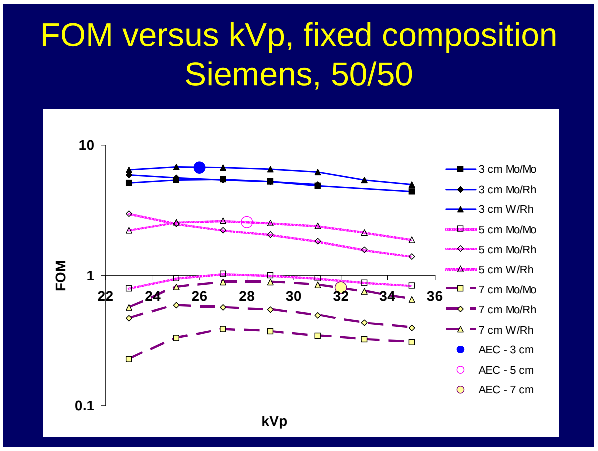
Dose versus kVp
Example: Fuji, 50/50 composition



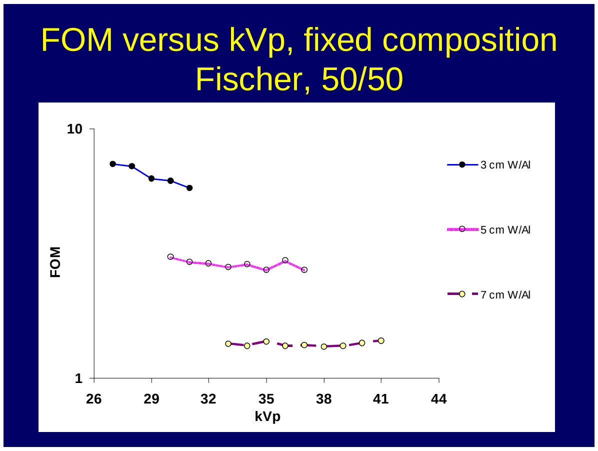
FOM versus kVp, fixed composition Hologic, 50/50



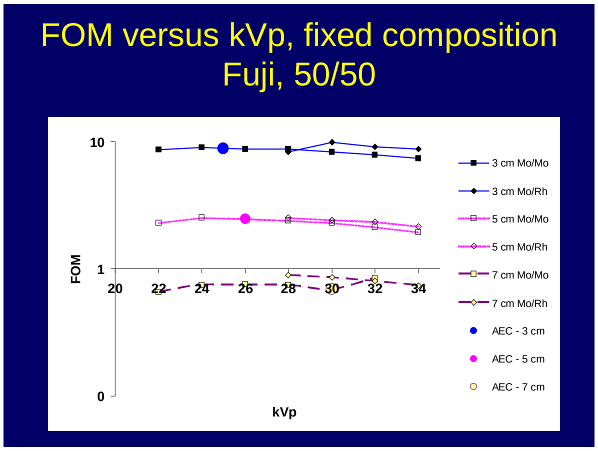
FOM versus kVp, fixed composition GE, 50/50



FOM versus kVp, fixed composition Siemens, 50/50



FOM versus kVp, fixed composition Fischer, 50/50

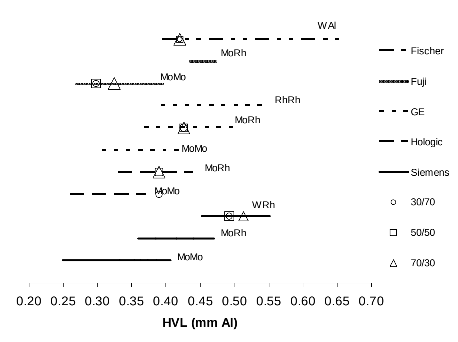


FOM versus kVp, fixed composition Fuji, 50/50

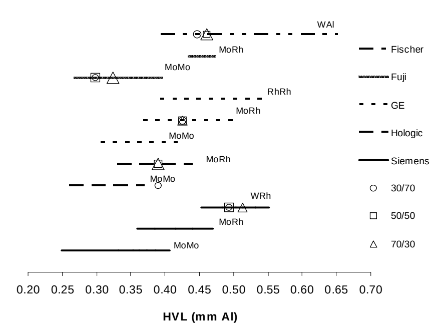
Techniques producing maximum FOM

		30/70	50/50	70/30
GE	**3 cm** **5 cm** **7 cm**	Mo / Rh / 27 Mo / Rh / 27 Mo / Rh / 27	Mo / Rh / 27 Mo / Rh / 27 Rh / Rh / 31	Mo / Rh / 27 Mo / Rh / 27 Rh / Rh / 33
Siemens	**3 cm** **5 cm** **7 cm**	W / Rh / 27 W / Rh / 27 W / Rh / 27	W / Rh / 27 W / Rh / 27 W / Rh / 29	W / Rh / 29 W / Rh / 29 W / Rh / 29
Hologic	**3 cm** **5 cm** **7 cm**	Mo / Rh / 27 Mo / Rh / 27 Mo / Rh / 27	Mo / Rh / 27 Mo / Rh / 27 Mo / Rh / 28	Mo / Rh / 27 Mo / Rh / 27 Mo / Rh / 28
Fischer	**3 cm** **5 cm** **7 cm**	W / Al / 27 W / Al / 29 W / Al / 35	W / Al / 27 W / Al / 30 W / Al / 35	W / Al / 27 W / Al / 30 W / Al / 35
Fuji	**3 cm** **5 cm** **7 cm**	Mo / Mo / 24 Mo / Mo / 24 Mo / Rh / 28	Mo / Mo / 24 Mo / Mo / 24 Mo / Rh / 28	Mo / Mo / 26 Mo / Mo / 26 Mo / Rh / 28

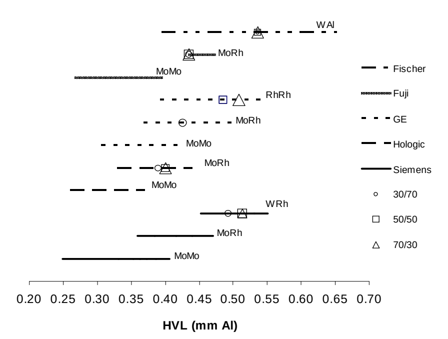
HVL at peak FOM, 3 cm

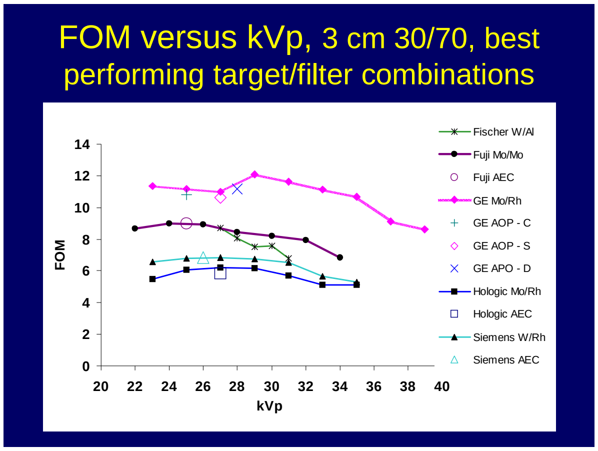


HVL at peak FOM, 5 cm

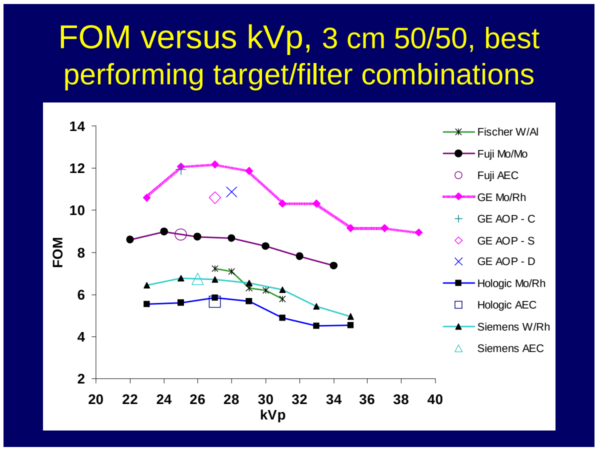


HVL at peak FOM, 7 cm

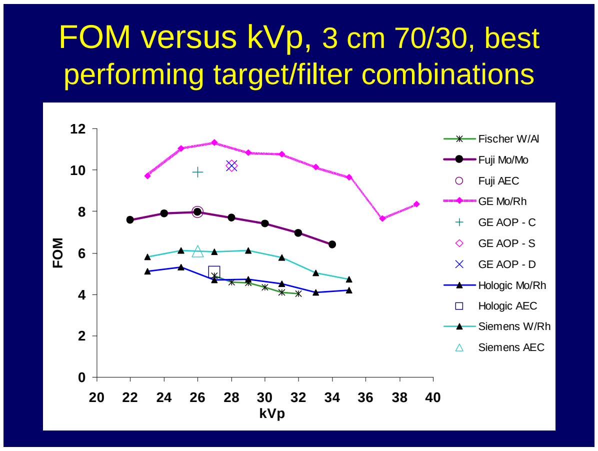




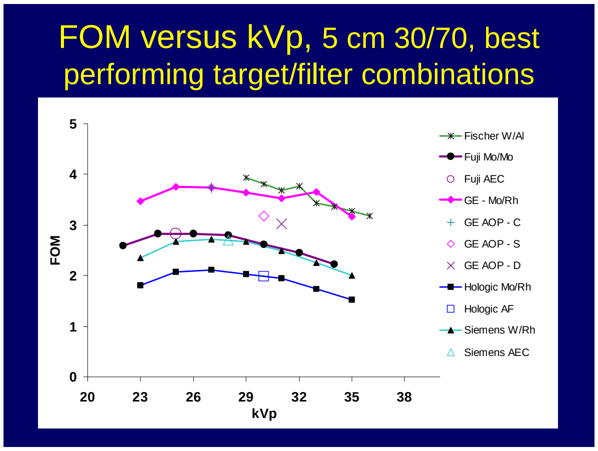
FOM versus kVp, 3 cm 30/70, best performing target/filter combinations



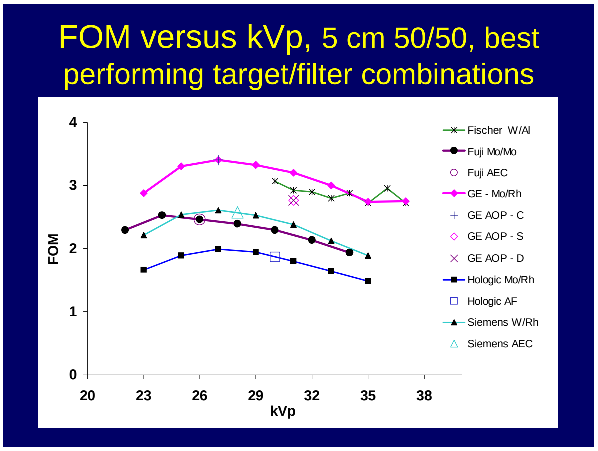
FOM versus kVp, 3 cm 50/50, best performing target/filter combinations



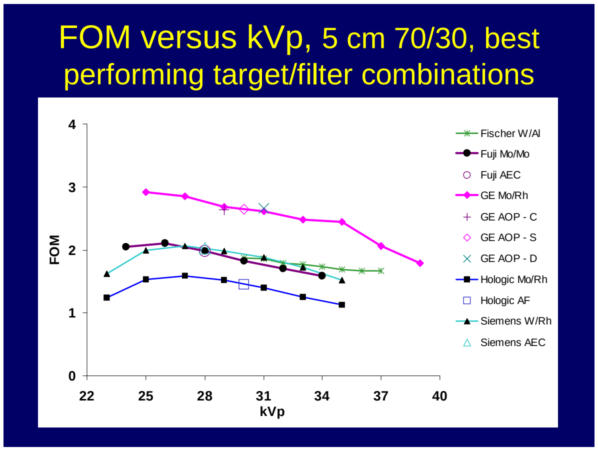
FOM versus kVp, 3 cm 70/30, best performing target/filter combinations



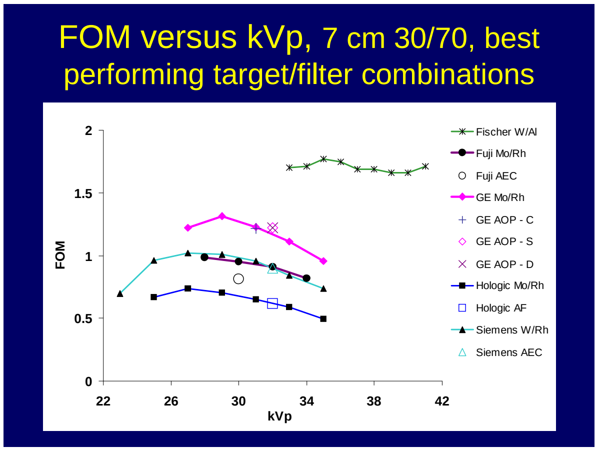
FOM versus kVp, 5 cm 30/70, best performing target/filter combinations



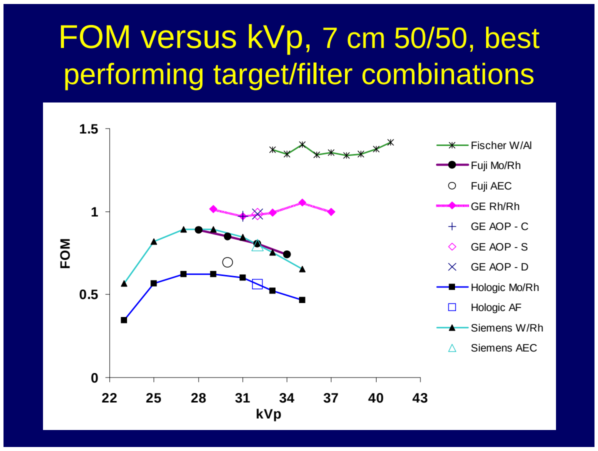
FOM versus kVp, 5 cm 50/50, best performing target/filter combinations



FOM versus kVp, 5 cm 70/30, best performing target/filter combinations

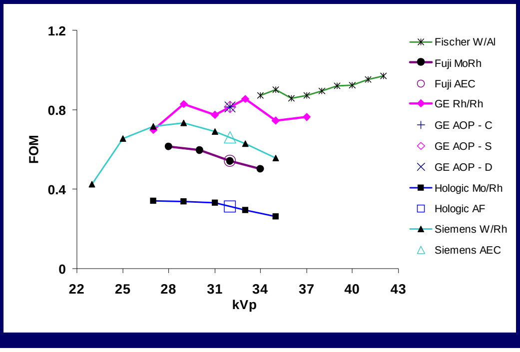


FOM versus kVp, 7 cm 30/70, best performing target/filter combinations

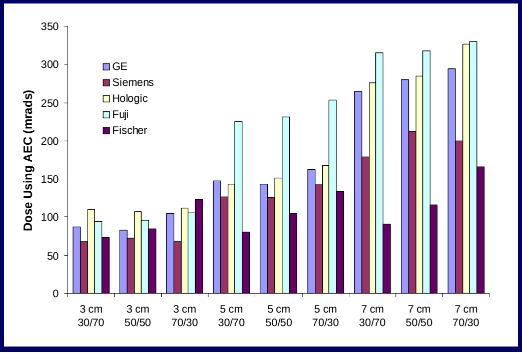


FOM versus kVp, 7 cm 50/50, best performing target/filter combinations

FOM versus kVp, 7 cm 70/30, best performing target/filter combinations



Mean Glandular Dose Using AEC Selections (max FOM settings for Fischer)



Conclusions – Detector Dependence

- Optimum exposure parameters for a specific breast type are system (detector) specific – there are no universal values
- The kVp dependence of the FOM and the relative performances of different target/filter combinations are independent of signal (step) size and step composition

Conclusions – kVp Dependence

- Peaks in FOM versus kVp curves are broad, when they exist
- The choice of target/filter is much more crucial than the choice of kVp

Conclusions – kVp Dependence

- In all cases the FOM is a decreasing function of kVp at the upper end of the kVp range tested here
- Thus at least for the target/filter combinations currently included in these FFDM systems, there is no advantage in expanding the available voltage range to even higher kVp.

Conclusions – Target/Filter Dependence

- For the Senographe 2000D, the maximum FOM was always obtained with either Mo/Rh or Rh/Rh target filter combinations, but never with Mo/Mo, even for the thinnest and most fatty breasts
- The Selenia produced maximum FOM values for nearly all breast types at an exposure parameter setting of Mo/Rh, 27 kVp, with only a slightly higher kVp (Mo/Rh, 28 kVp) for the two densest 7 cm breasts
- Contrary to the Senographe 2000D and the Selenia, the maximum FOM was obtained for the 5000MA with a Mo/Mo combination for most (6 of 9) breast types, with only the 7 cm phantoms benefiting more from Mo/Rh.

Conclusions – Noise Dependence

- There is a general inverse correlation between the normalized noise and the FOM, with higher noise systems tending to have lower FOM values
- This suggests that the system noise is an important determinant of FFDM system performance, irrespective of signal and dose performance.

Conclusions – HVL for Optimum Settings

- The HVL of the technique producing the highest FOM tended to fall at a location within the range of available HVL values that is quite system-specific.
- For the Senoscan and 5000MA systems, the optimum techniques had HVL values that increased with increasing breast thickness, but were always in the lower half of the available HVL ranges.
- For the Mammomat Novation DR, the optimum technique factors were nearly identical for all breast types, always utilized the W/Rh combination, and corresponded to a HVL that was near the top of the available range

Conclusions – AEC Dose

- There is a substantial difference among FFDM systems in the radiation dose delivered under AEC operation.
- In general, the Fuji system delivers the highest dose under its AEC settings of all systems tested, while the Novation DR delivers the least of all systems with AECs.
- The Senoscan, operated with kVp settings close to those maximizing the FOM for that system, delivers the lowest radiation dose of all systems tested for 5 cm and 7 cm breasts .

Conclusions – AEC Performance

- The AEC systems of current commercial systems generally select technique factors close to those producing the maximum FOM value, but selection could be improved in several cases
- Preset minimum kVp values may be too high in some systems

Conclusions – AEC Performance

- For the Senographe 2000D, the best FOM values for all 3 cm phantoms were obtained with the Mo/Rh target/filter combination.
- However, the AEC selected Mo/Mo for all 3 cm phantoms in all three modes, resulting in lower FOM values

Conclusions – AEC Performance

- For the Selenia, the FOM for the Mo/Rh combination is superior to that for the Mo/Mo combination at virtually any voltage for all breast types.
- Since the AEC (autofilter mode) selected Mo/Mo for 3 cm breasts of all compositions, dose performance could be improved without loss of image quality by programming the AEC for selection of the rhodium filter for smaller breast thickness

Conclusions – AEC Performance

- The W/Rh target filter combination on the Mammomat Novation DR outperformed Mo/Mo and Mo/Rh for all breast types imaged.
- Novation DR kVp selection is based on compressed thickness only, thus AEC selection is insensitive to changing breast composition, and the same target/filter/kVp is chosen for all breast compositions of a given thickness.
- The FOM curves suggest that compared to the current AEC selections, some performance improvement may be possible through the utilization of somewhat lower kVp settings for thicker (i.e. 7 cm or thicker) breasts with only minimal increase in MGD.

Acknowledgements

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