Review of the Physics of Mammography

Charles R Wilson, Ph.D., FACR, FAAPM
Medical College of Wisconsin

Milestones in Mammography

- 1913
  - A. Solomon, a Berlin pathologist, images 3,000 gross mastectomy specimens.
  - Observed micro-calcifications in breast carcinomas.
- 1930
  - S. Warren described a stereoscopic system using double emulsion film with screens, 70 kVp.
- 1938
  - J. Gershon-Cohen published on radiographic appearance of the normal breast with age.
  - Concluded that improvement in technique was needed for clinical use.
- 1960
  - R. Egan develops low kVp mammography technique

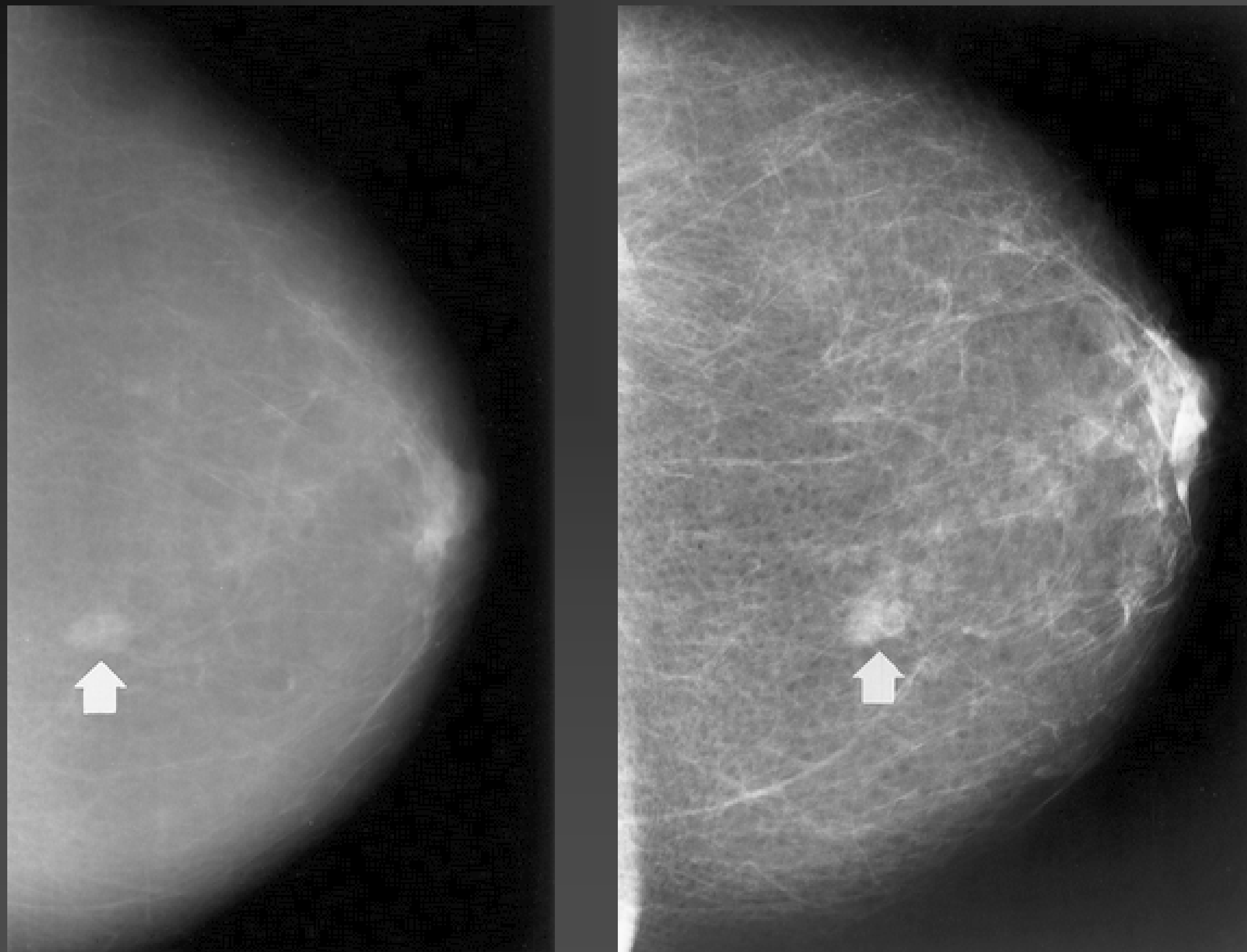
Robert Egan's Technique – 1960's

- Low kVp technique
  - verified kVp using a 15 mm Al wedge
- Beryllium window x-ray tube with minimum filtration
- Space charge limitations resulted in long exposure times, ~6 seconds
- Long SID: reduce focal spot blurring and provide adequate field coverage
- Metal extension cones: no field light
- Fine-grain industrial film
- No grid

Mammography Positioning – circa 1960

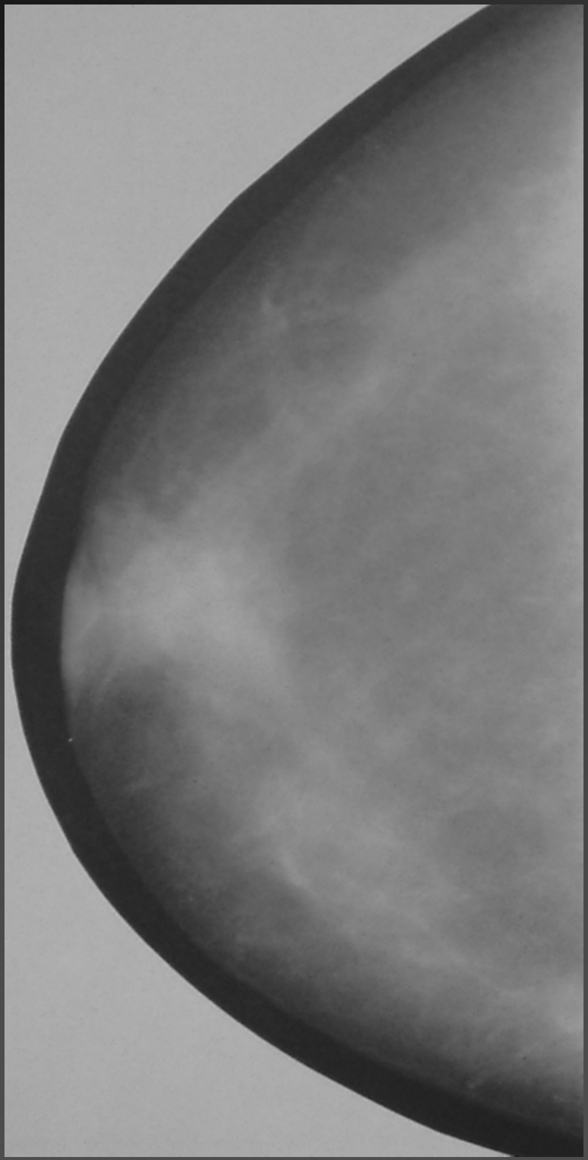
Mammography Positioning – Current

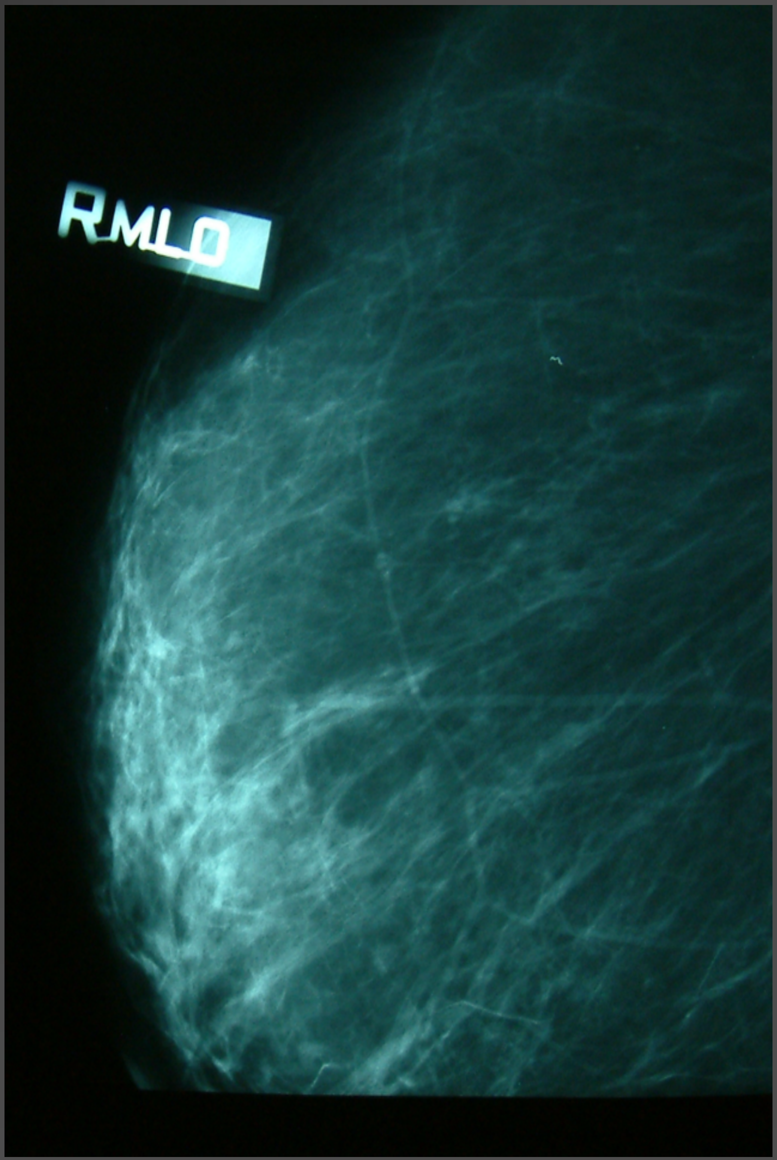
Mammograms: 1975 and Current



With permission: Breast Imaging: From 1965 to the Present E.Sickles, Radiology 215:1 2000.

Mammograms: 1960's vs Current



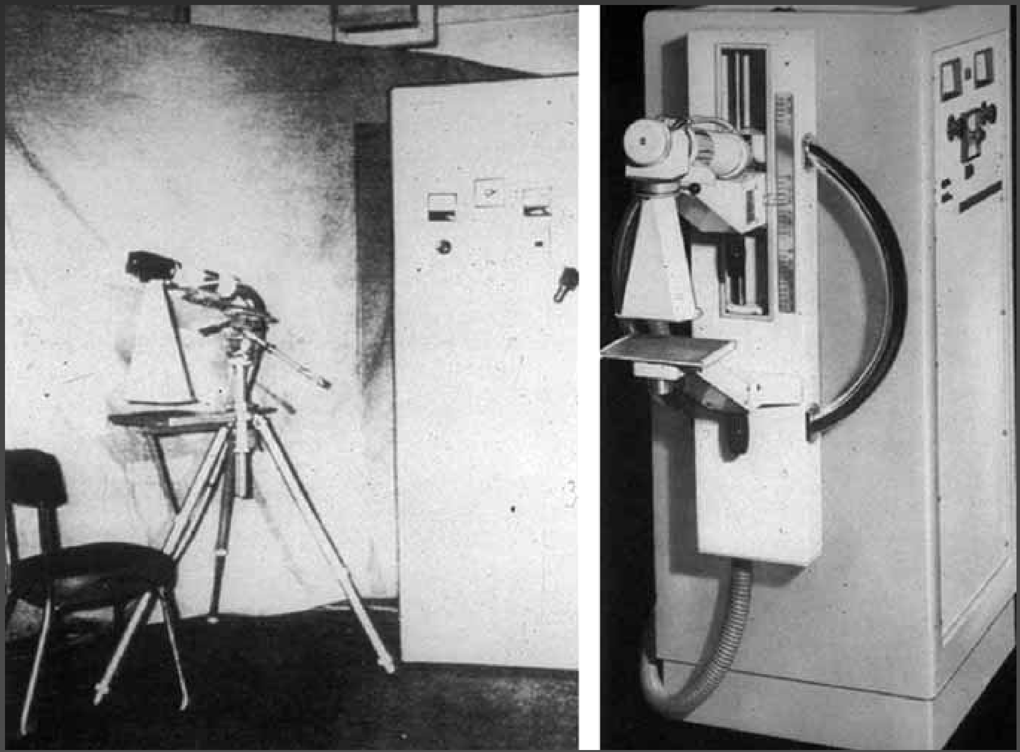


Milestones in Mammography

- 1963
  - First randomized trial of screening, HIP of NY
  - ~30% reduction in mortality in screened cohort
- 1966
  - J Wolf explores use of xeroradiography
- 1970's
  - Breast Cancer Detection Demonstration Project
    - Xerography, radiography, thermography, physical exam
- 1986
  - ACR Voluntary Mammography Accreditation Program
- 1992
  - Mammography Quality Standards Act

First Dedicated Mammography Unit

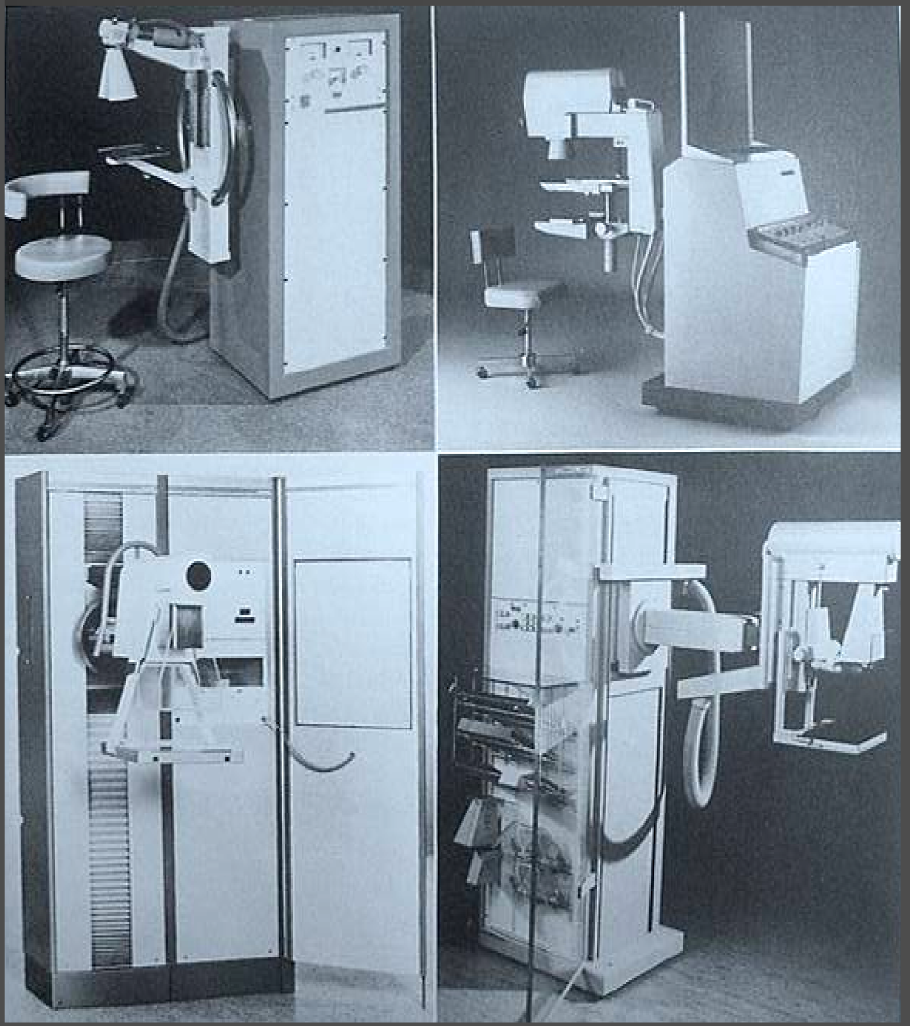
- 1965
  - Charles Gros, MD, Strasbourg, FR
  - CGR Senographe (Breast in French is Sein)
  - Very popular unit by 1970, 2000 were installed world-wide



With permission: Short History of Mammography: A Belgian Perspective, A. Van Steen, R. Van Triggelen, JBR-BTR, 2007.

Dedicated Mammography Units

- 1973
  - Picker (Mammorex),
  - Siemens (Mammomat)
  - Philips (Diagnost)
- 1974
  - GE (MMX)



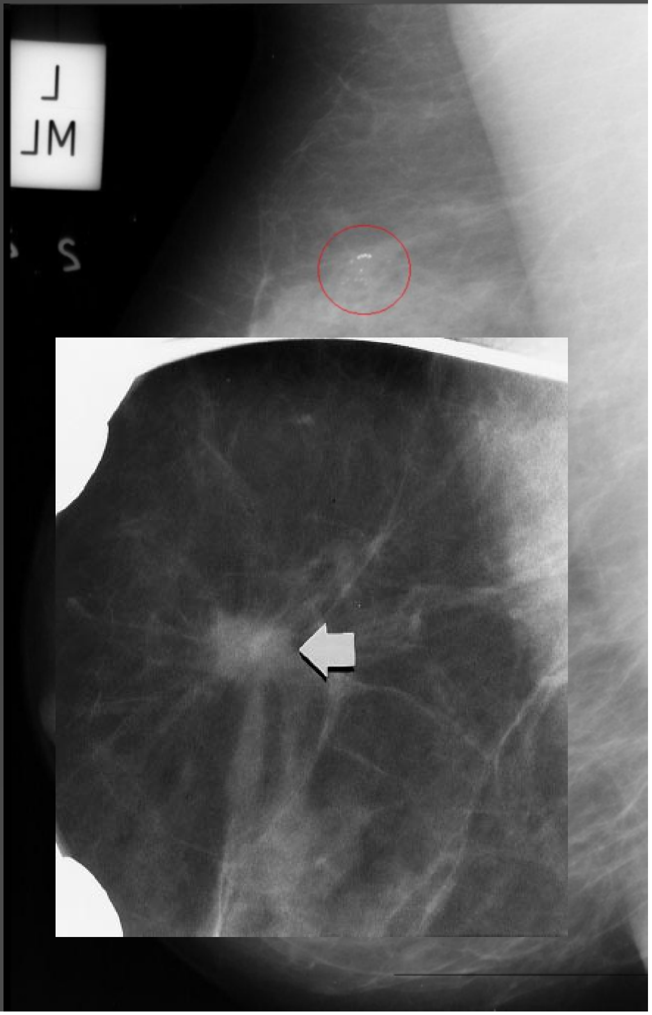
Current Dedicated Mammography Unit

- Gantry mounted x-ray and detector assemblies
- X-ray tube target/filtration and focal spot appropriate for mammography
- Compression device
- AEC
- Film/screen and grid designed for mammography
- Dedicated film processor

Pathognomonic Signs of Breast Cancer

Small Details With Inherent Low Subject Contrast

- Masses
  - spiculated
  - shape and margins are important
- Micro-calcifications
  - 100 to 300 microns
  - shape and distribution important
- Others
  - Asymmetric densities
  - Architectural distortions



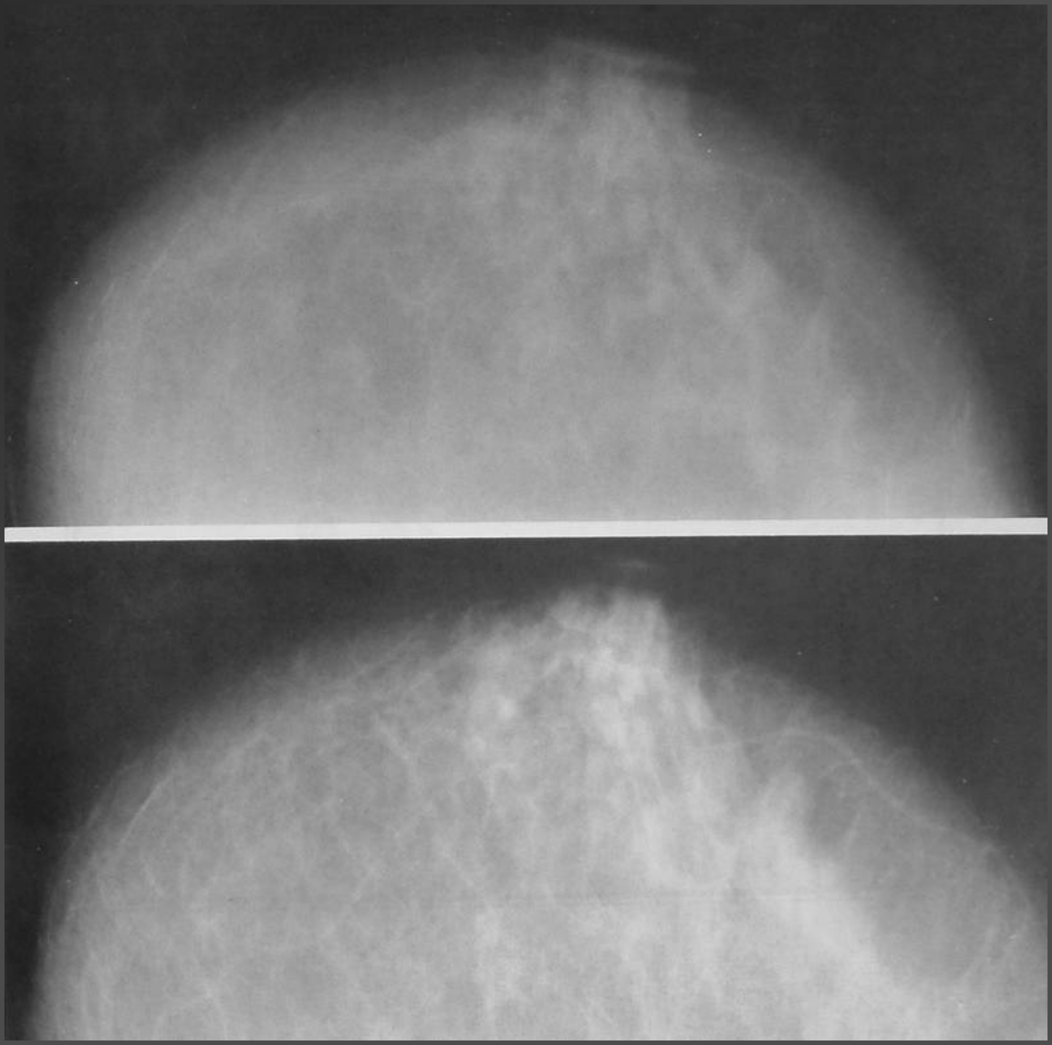
X-Ray Spectrum Shaping

- X-ray spectral shaping is needed to enhance visibility of the inherently low contrast pathognomonic signs
- Egan
  - tungsten tube, low kVp, beryllium window tube with minimal aluminum filtration
- Gros (CGR)
  - molybdenum target and molybdenum filter

Effect of Spectrum on Subject Contrast

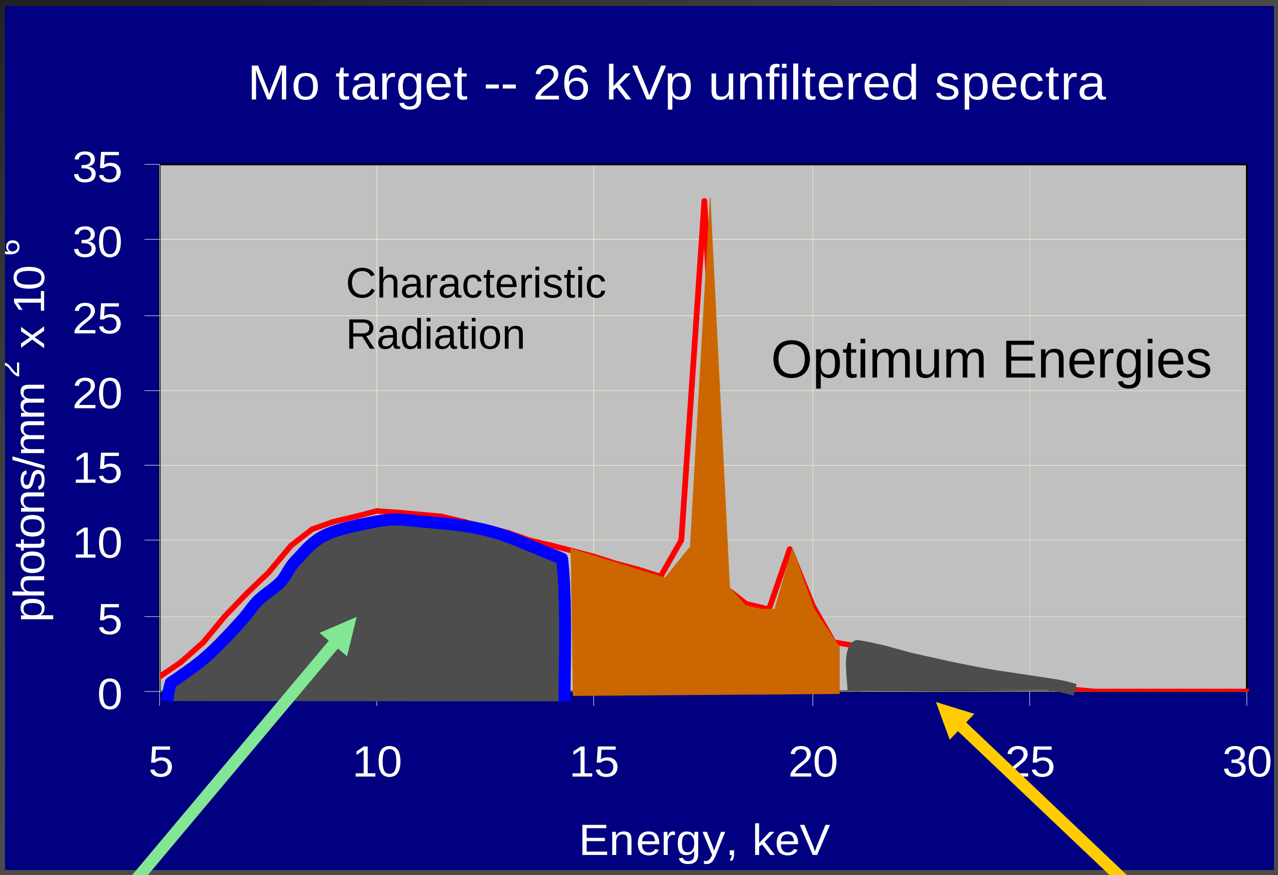
Tungsten and Al filter

Molybdenum target and filter



With permission: A Categorical Course in Physics Technical Aspects of Breast Imaging, M Yaffe, et al.,RSNA 1993

Unfiltered Bremsstrahlung Spectrum

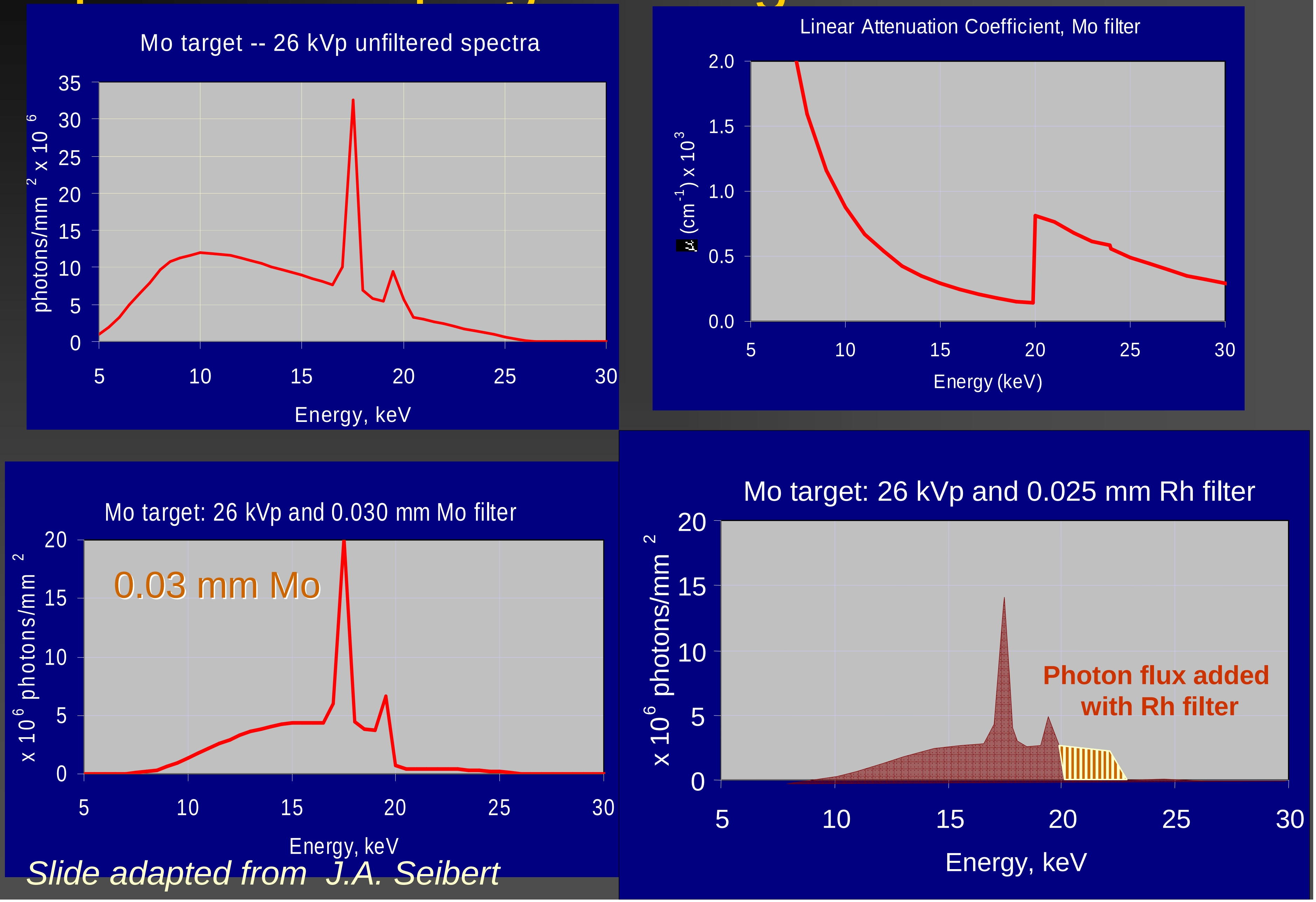


Low energy: high dose

High energy: low contrast

Slide courtesy J.A. Seibert

Spectral Shaping – K edge filtration

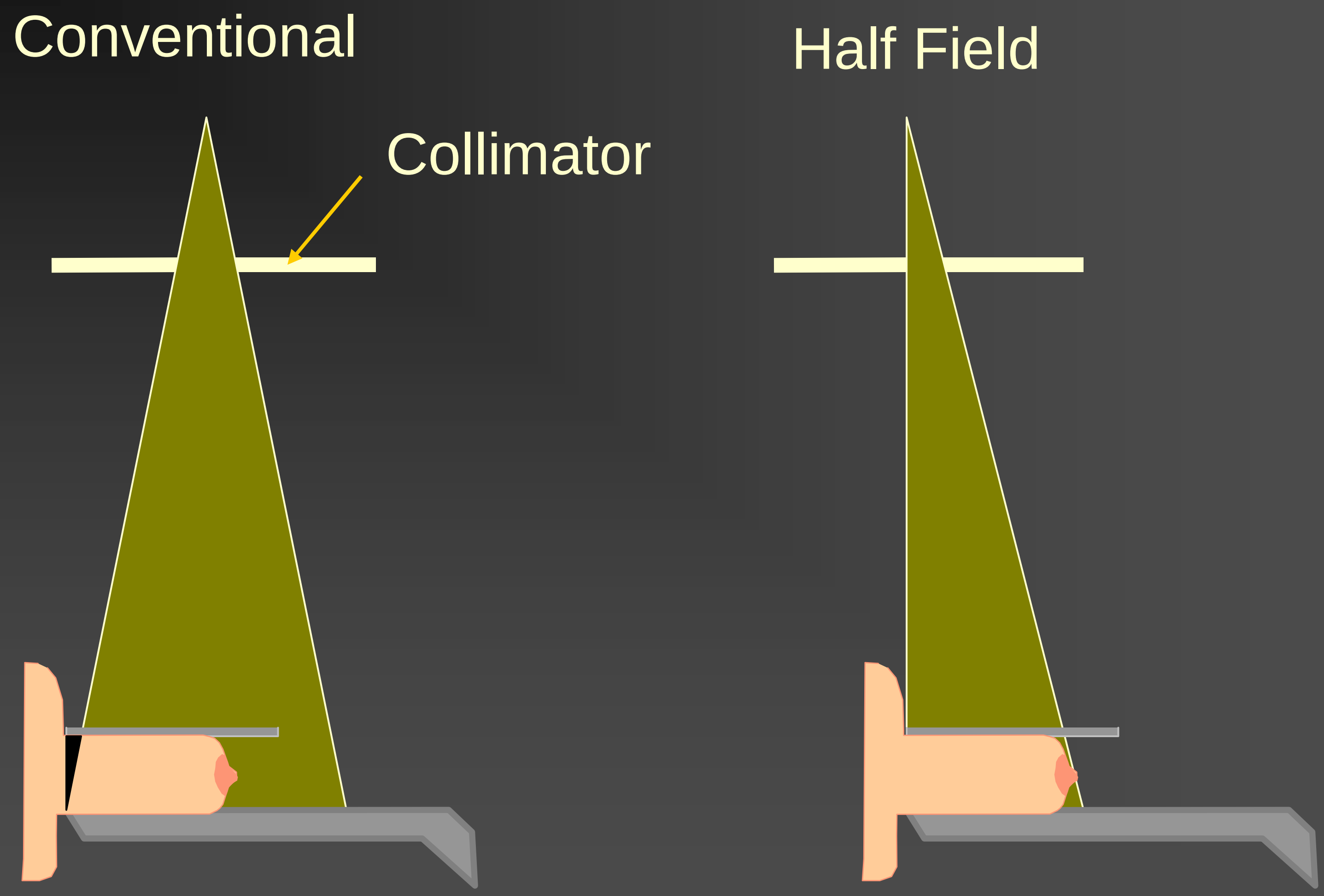


Slide adapted from J.A. Seibert

Target-Filter Recommendations

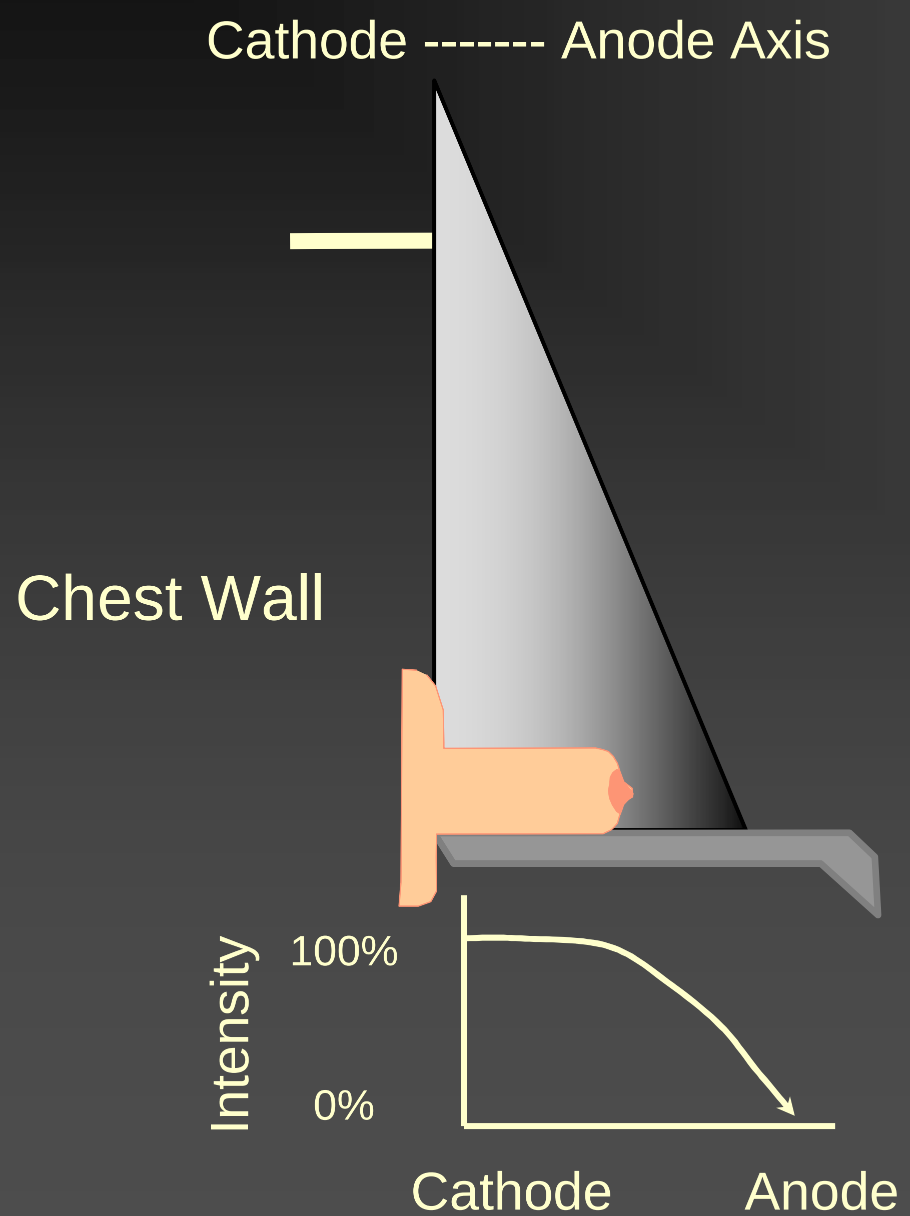
- Fatty breast up to ~ 4 cm thick
  - Mo target and 30 micron Mo filter
  - 24 – 26 kVp
- Glandular breast ~ 5 to 7 cm
  - Mo target and 25 micron Rh filter
  - 27 – 31 kVp
- Breast thickness > 7 cm
  - Rh target and 25 micron Rh filter

X-ray Beam Geometry



Slide courtesy of J.A. Seibert

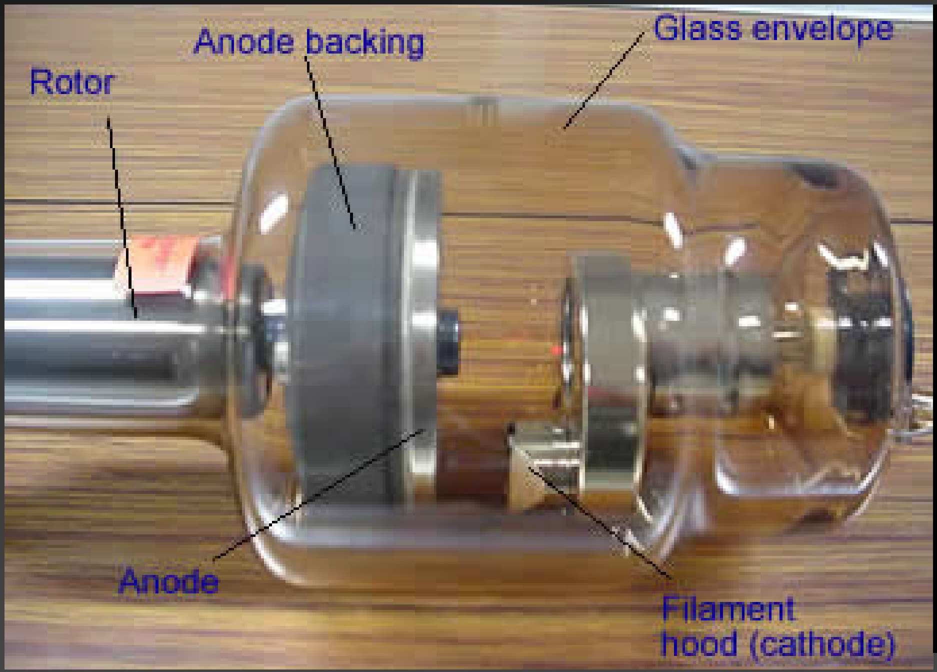
Heel Effect



- Target self-absorption reduces the intensity in the cathode to anode direction
- Large target angle is needed, > 20^0, for full field coverage
- Projected focal spot size improves as well

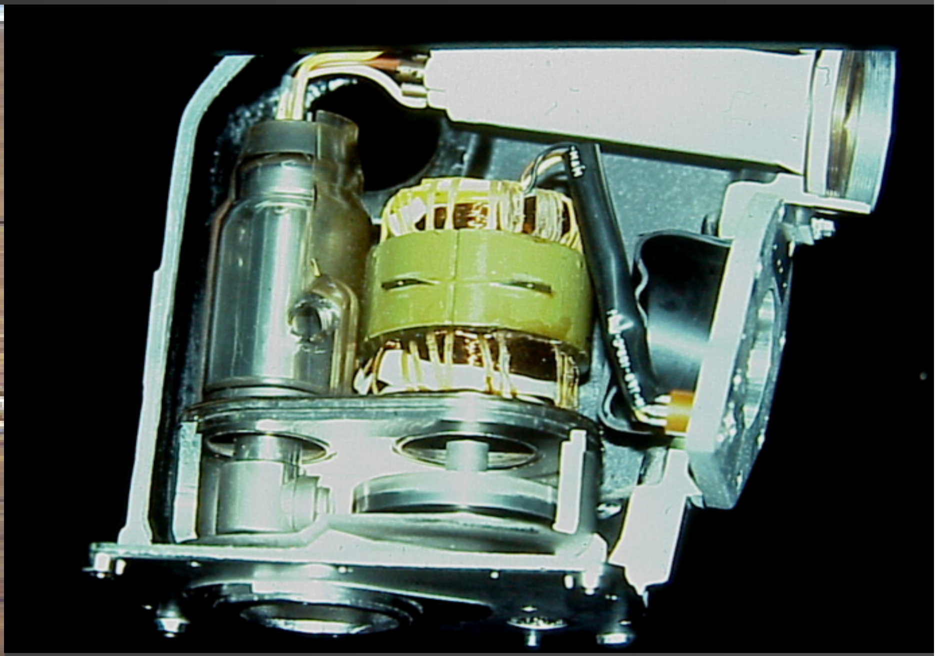
X-Ray Tubes

Conventional



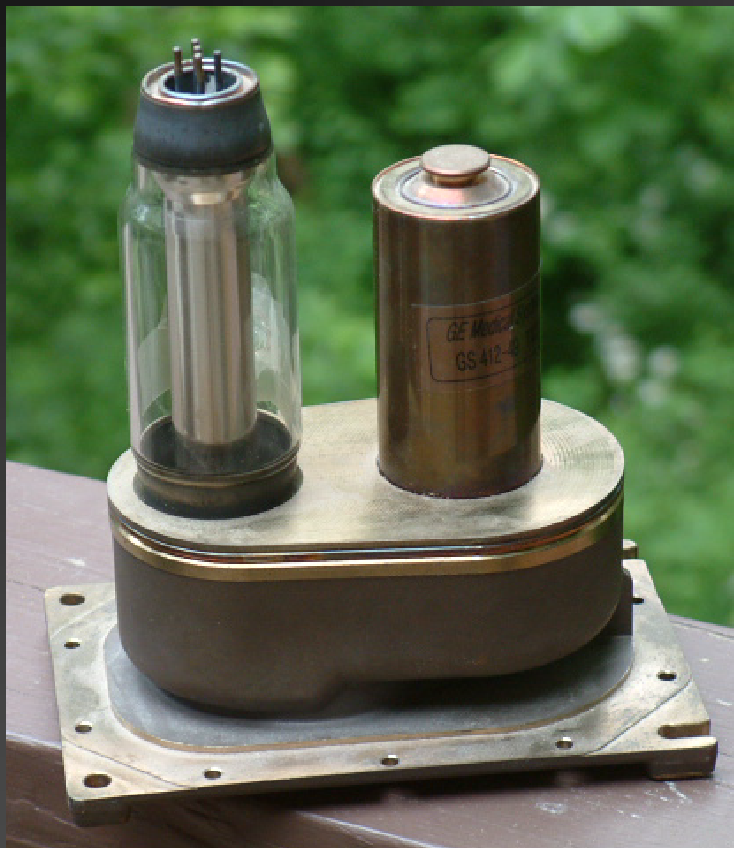
- glass envelope
- tungsten anode
- anode angle ~7^0 to 16^0
- axis of rotation – horizontal
- Al filter for dose reduction

Mammography

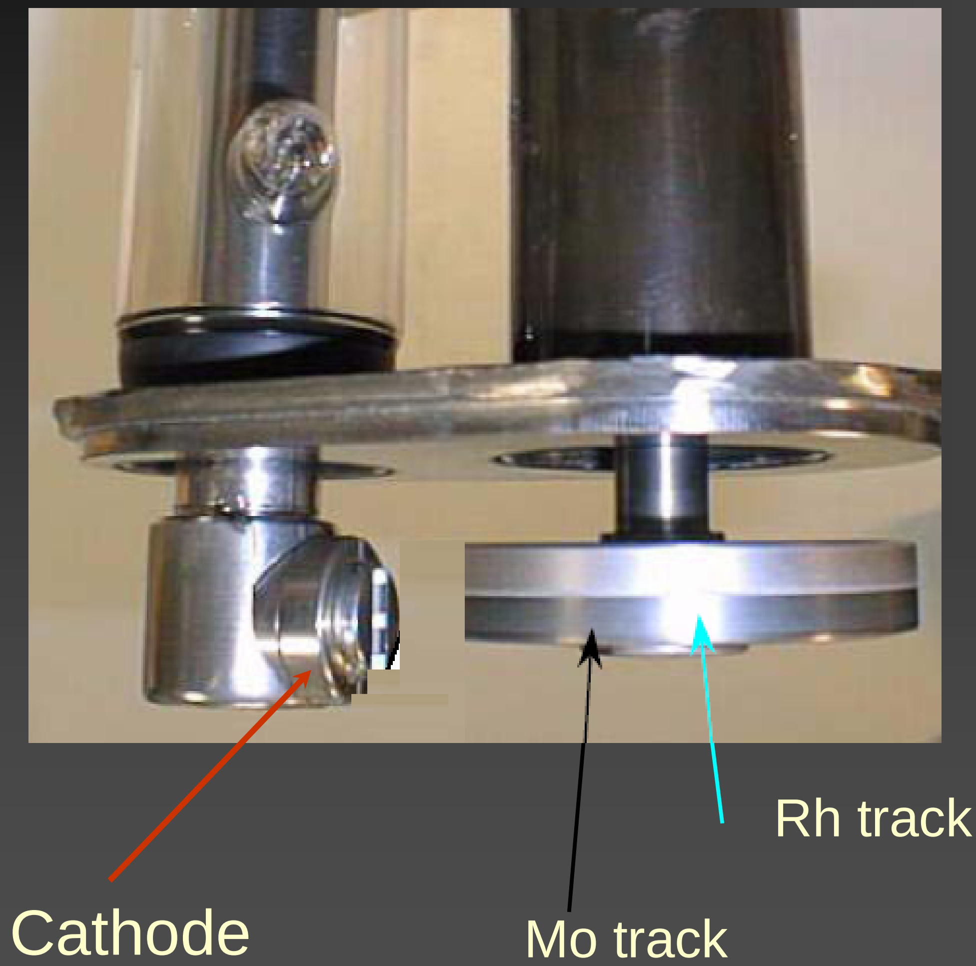


- metal tube housing
- grounded Mo, Rh anode
- anode angle 0^0 - tube tilt of 26^0
- axis of rotation ~ vertical
- Mo or Rh filters for spectral shaping

Mammography X-Ray Tube

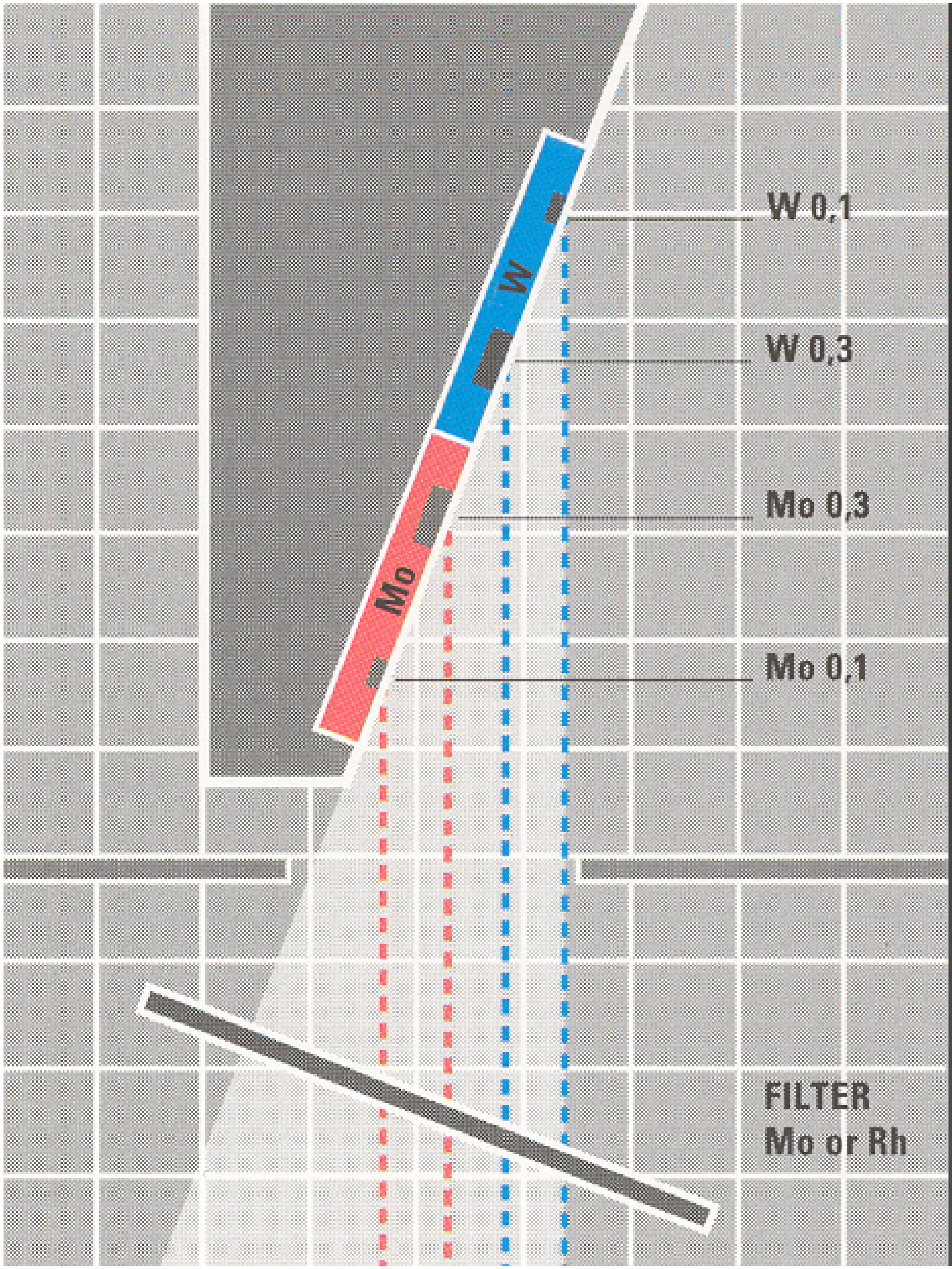


Dual Target X-ray Tube



Anode angle 0^0
Tube angled at 26^0
Large and small
filaments for each track.
Four focal spots.

Pin hole image of focal spots.



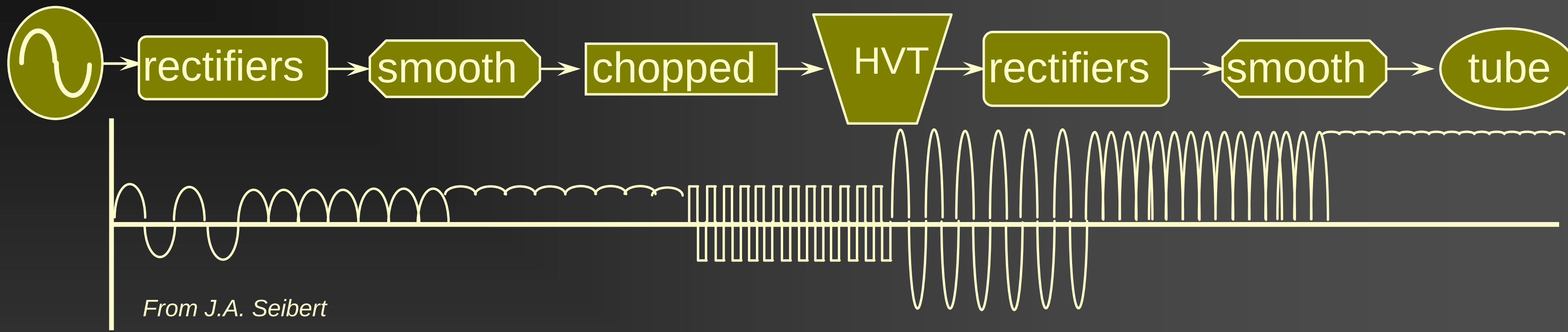
Siemens Opdose

26^0 anode angle

W or Mo target

Mo or Rh
(tilted) filter

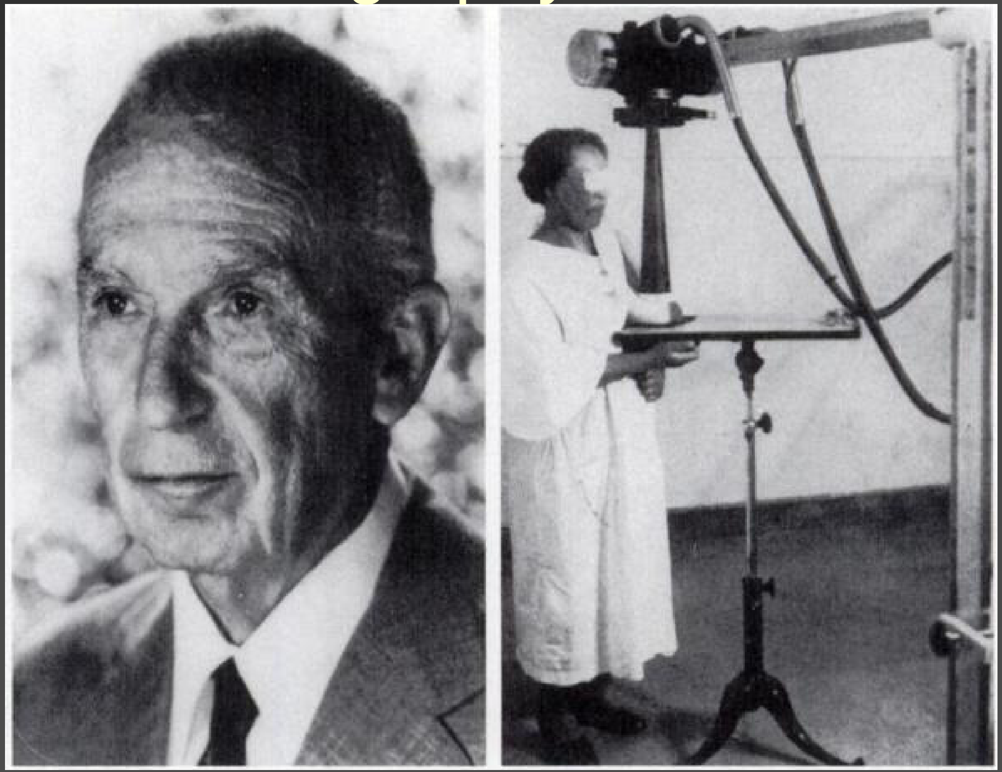
Medium/High Frequency Generators



- 1984 Lorad introduced a high frequency generator mammography unit
- 60 Hz is rectified, smoothed, chopped to a frequency 6 kHz or higher
- transformer efficiency is greater at higher frequencies – thus smaller in size
- less ripple - better beam quality and increased output

Breast Compression

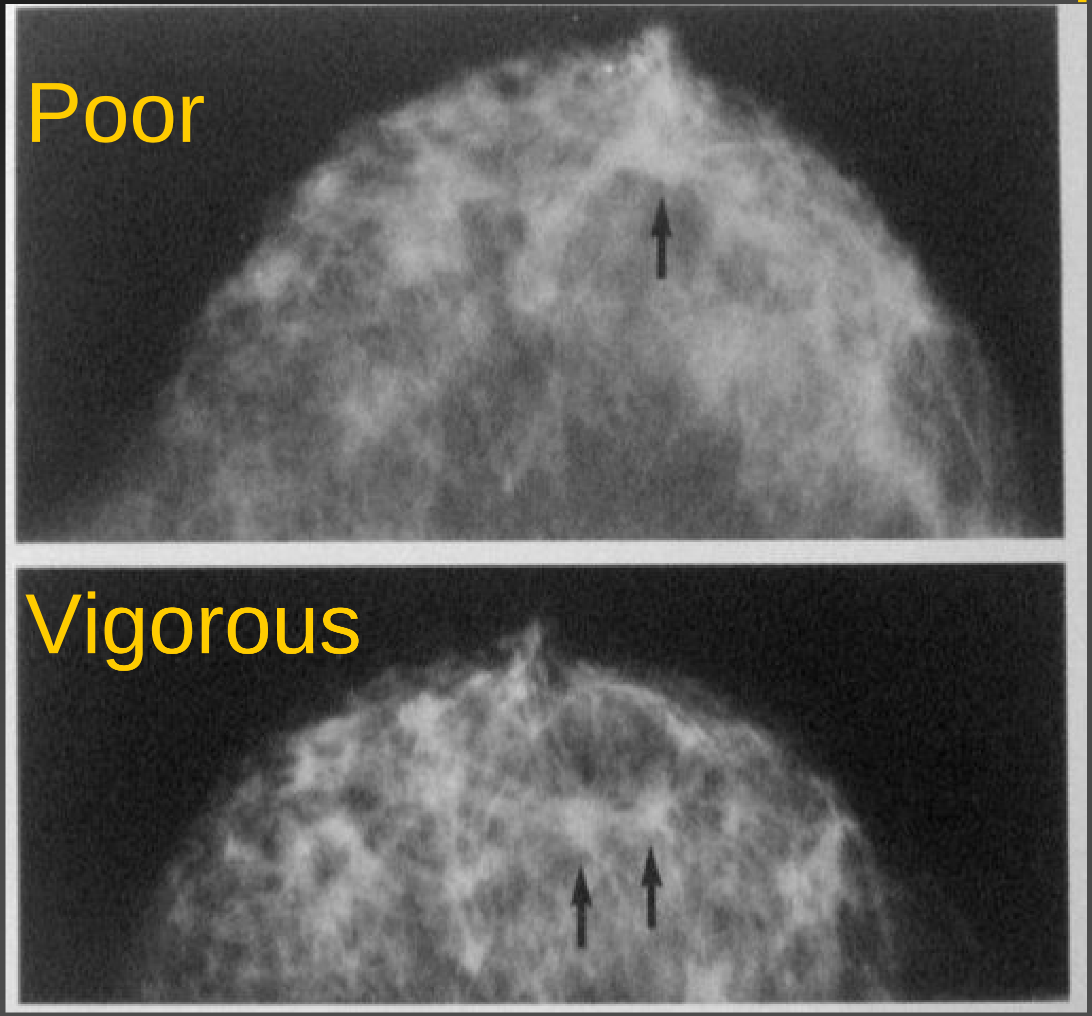
- 1949 R. Leborgne, Uruguanian radiologist first uses breast compression
- By 1970's compression devices common on dedicated mammography units



Raul Leborgne, MD

Evolution of Compression

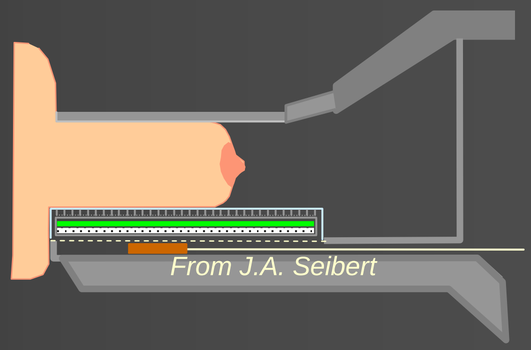
Breast Compression Improves Contrast and Conspicuity



Images from: Medical Radiography and Photography, Kodak 62:2 1986

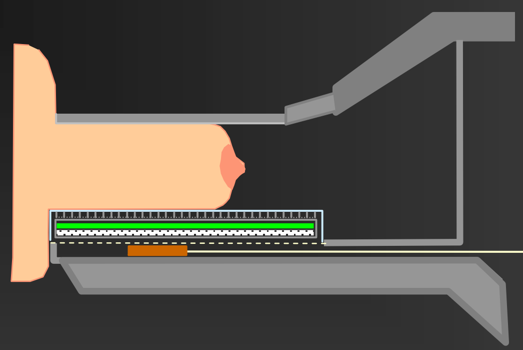
Breast Compression

Area compression



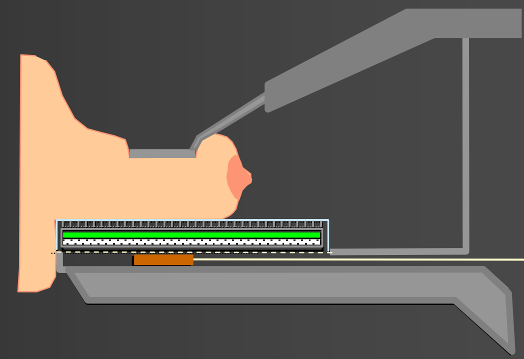
- Reduces breast thickness
  - lowers radiation dose
  - spreads breast tissues apart
  - produces a more uniform thickness
    - allows use of narrow latitude, high contrast film
- Reduces motion and geometric unsharpness
- Reduces x-ray scatter and beam hardening, thus improving contrast

Area compression



Full compression paddle:
Uniform density across image.

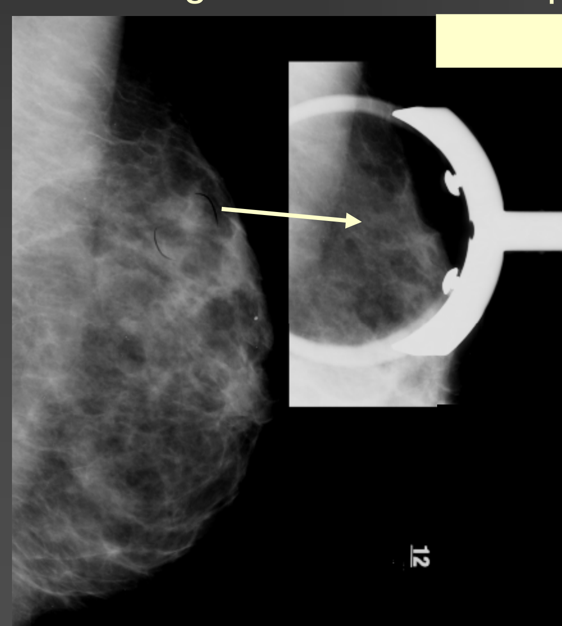
Spot compression



Spot compression paddle:
Better compression over small area

Clear polycarbonate paddle, ~0.3 cm thick

Flat, parallel geometry
Deflection < 1 cm

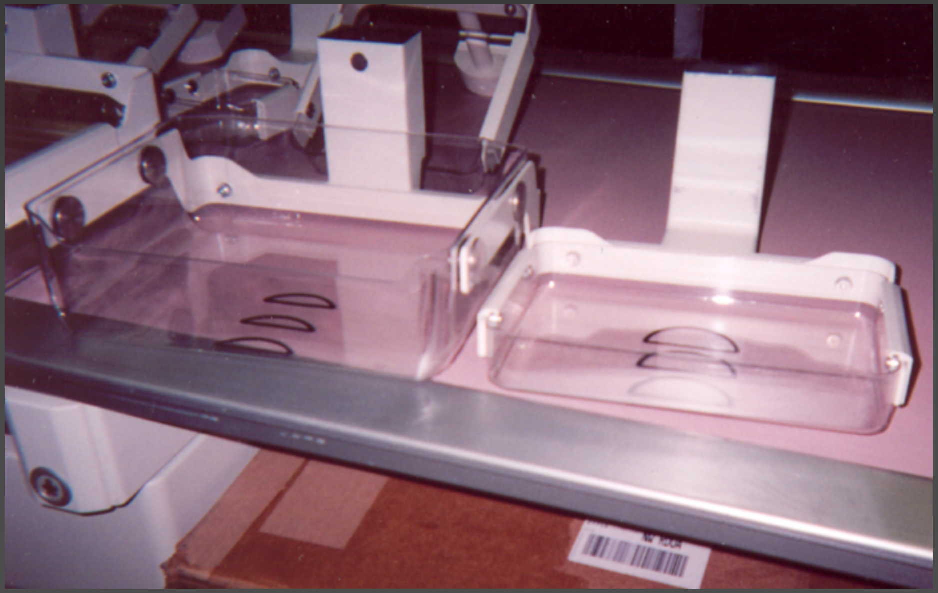


Spot paddle decreases tissue thickness

↓ superimposition of tissues

Slide courtesy of J.A. Seibert

Lorad F.A.S.T. paddle (Fully Automatic Self-adjusting Tilt) Tilts in the A-P axis.

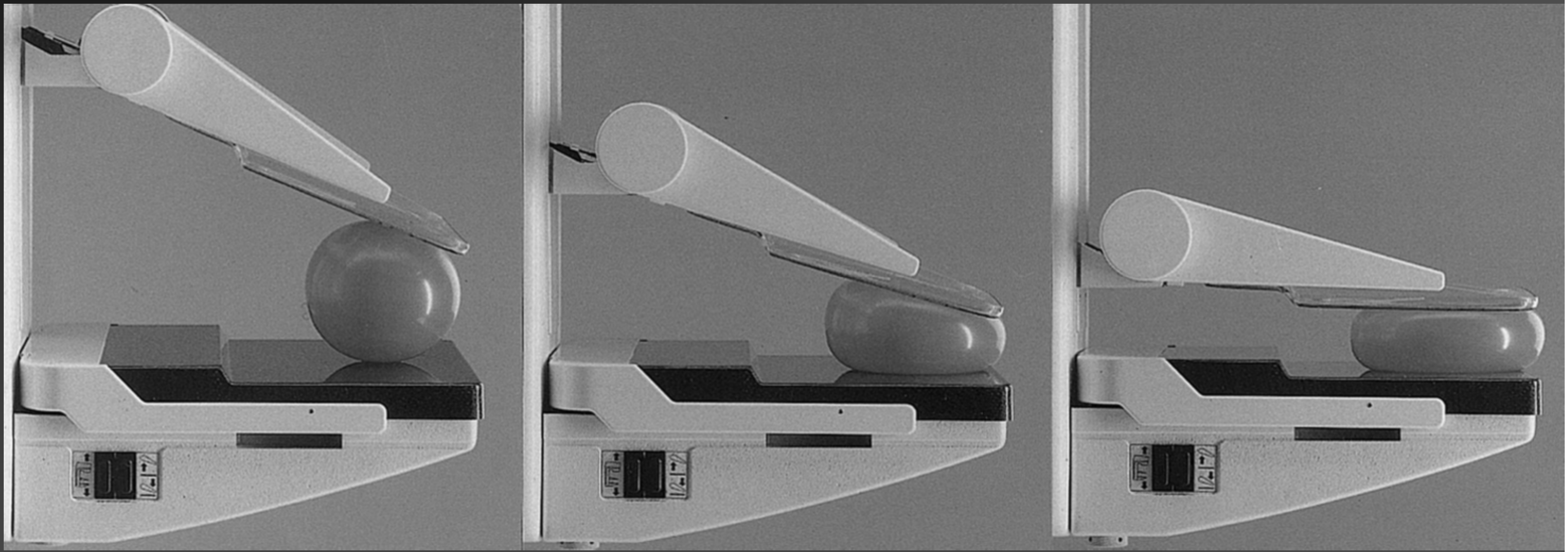


Siemens high and low edge paddles.

Flex² paddle tilts in both A-P & lateral directions

Slide courtesy D. Jacobson

Biphasic Compression Paddle



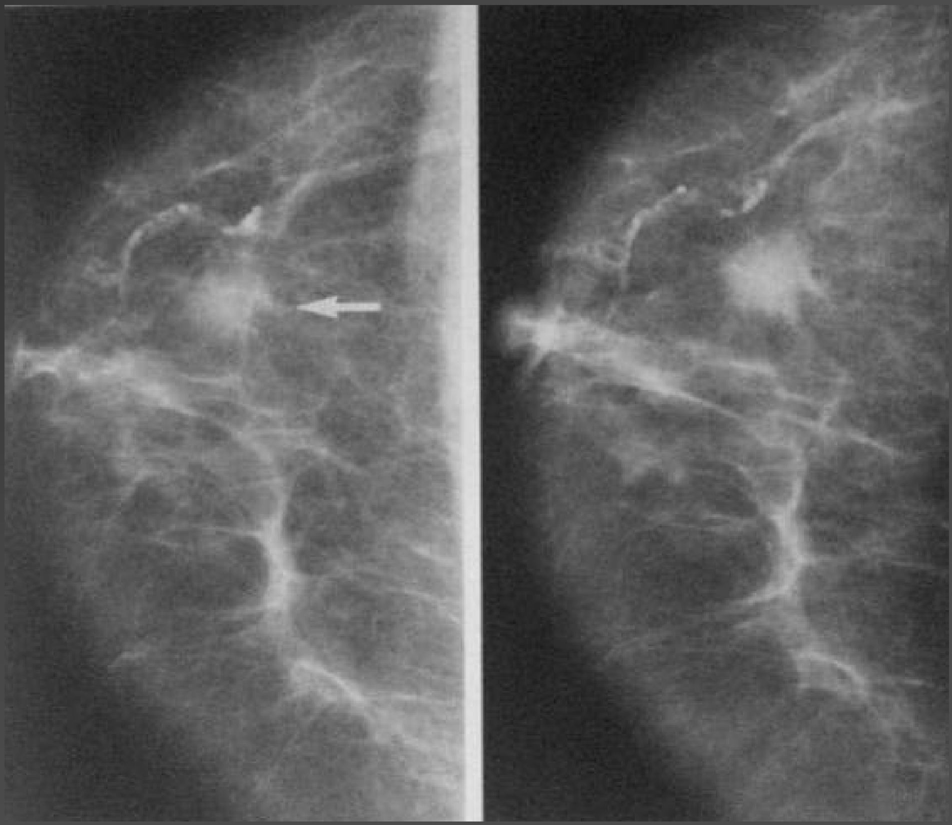
Breast biphasic compression (22.5°angled paddle, followed by progressive angle reduction.

With permission: Breast Biphasic Compression versus Standard Monophasic Compression in X-ray Mammography, Sardanelli, F. et al. Radiology 2000;217:576-580

Slide courtesy D. Jacobson

Anti-scatter Grids

- 1978
  - Philips introduces the Diagnost-U with a moving grid
- 1984
  - Leibel-Flarsheim introduces fine-line stationary grid



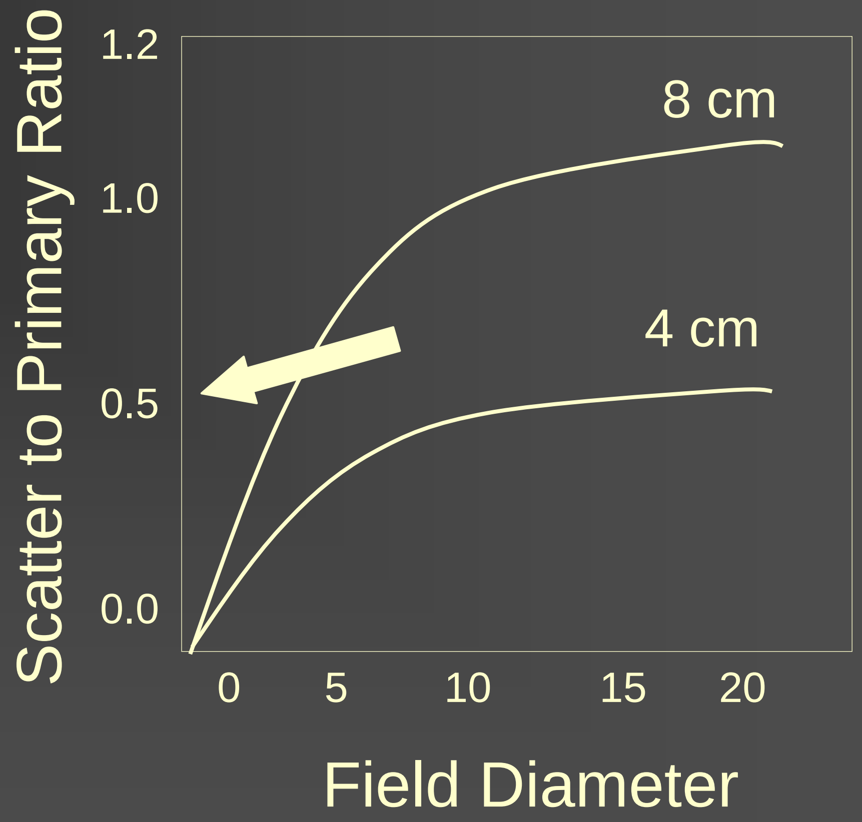
Images from: Medical Radiography and Photography, Kodak 62:2 1986

No grid
26 kVp

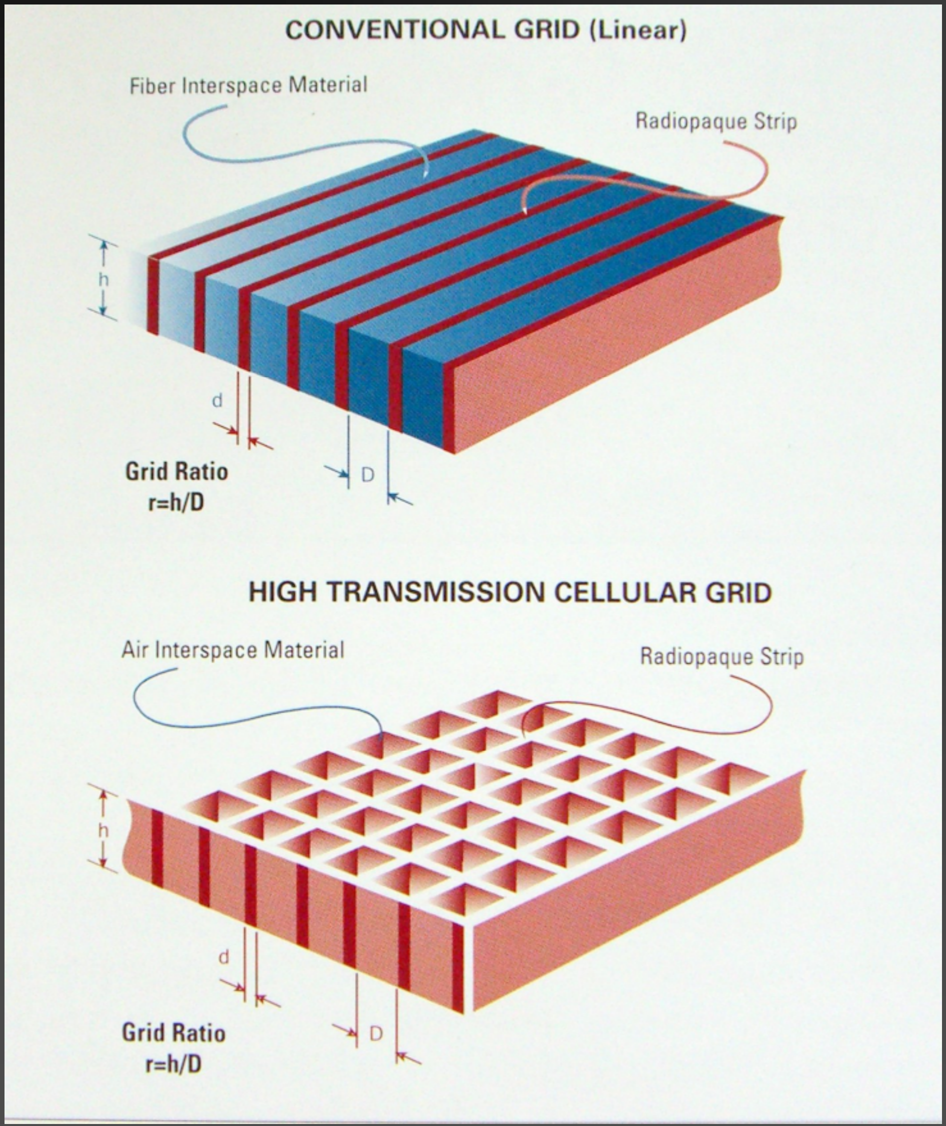
With grid
28 kVp

Scatter Severely Degrades Contrast

- Scatter to Primary Ratio
  - Field Diameter
  - Breast Thickness
- At a S/P ratio of 0.5 contrast is reduced by ~ 35%
- Anti-scatter grids are necessary



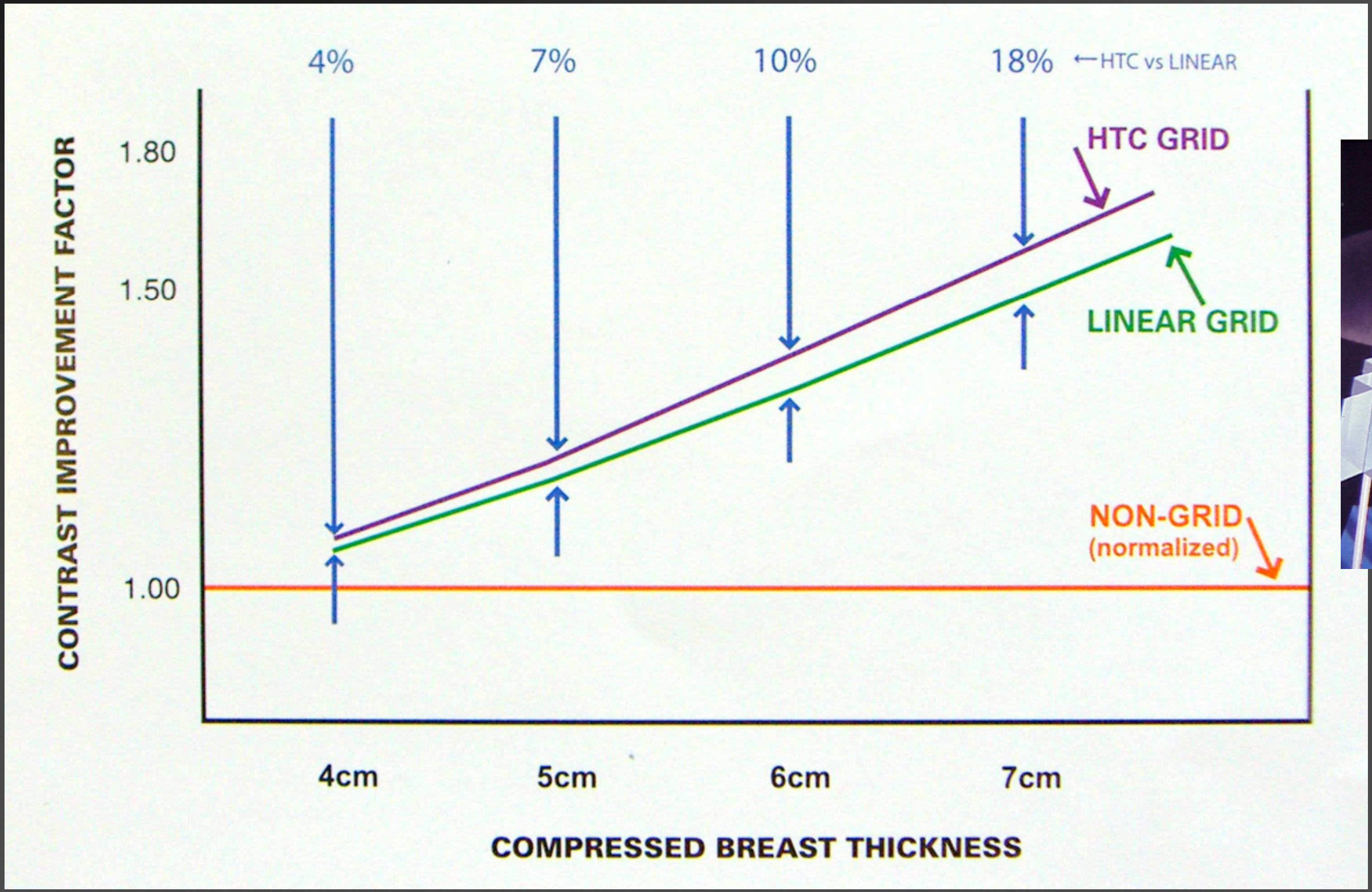
Grids

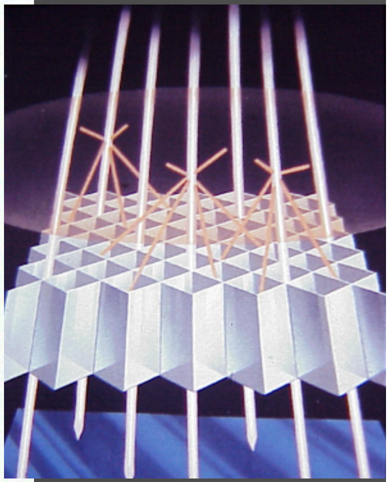


- Linear grid
  - Ratio: 5:1
  - Frequency > 30 l/cm
  - Wood, paper or carbon fiber inter-space material
  - Moved ~20 lines for blurring
- Cellular grid
  - 15 cells / cm
  - Air inter-space
  - Moved multiple of hole spacing

Figure from: http://www.hologic.com/oem/pdf/R-BI-016_Fund-Dig%20Mammo.pdf

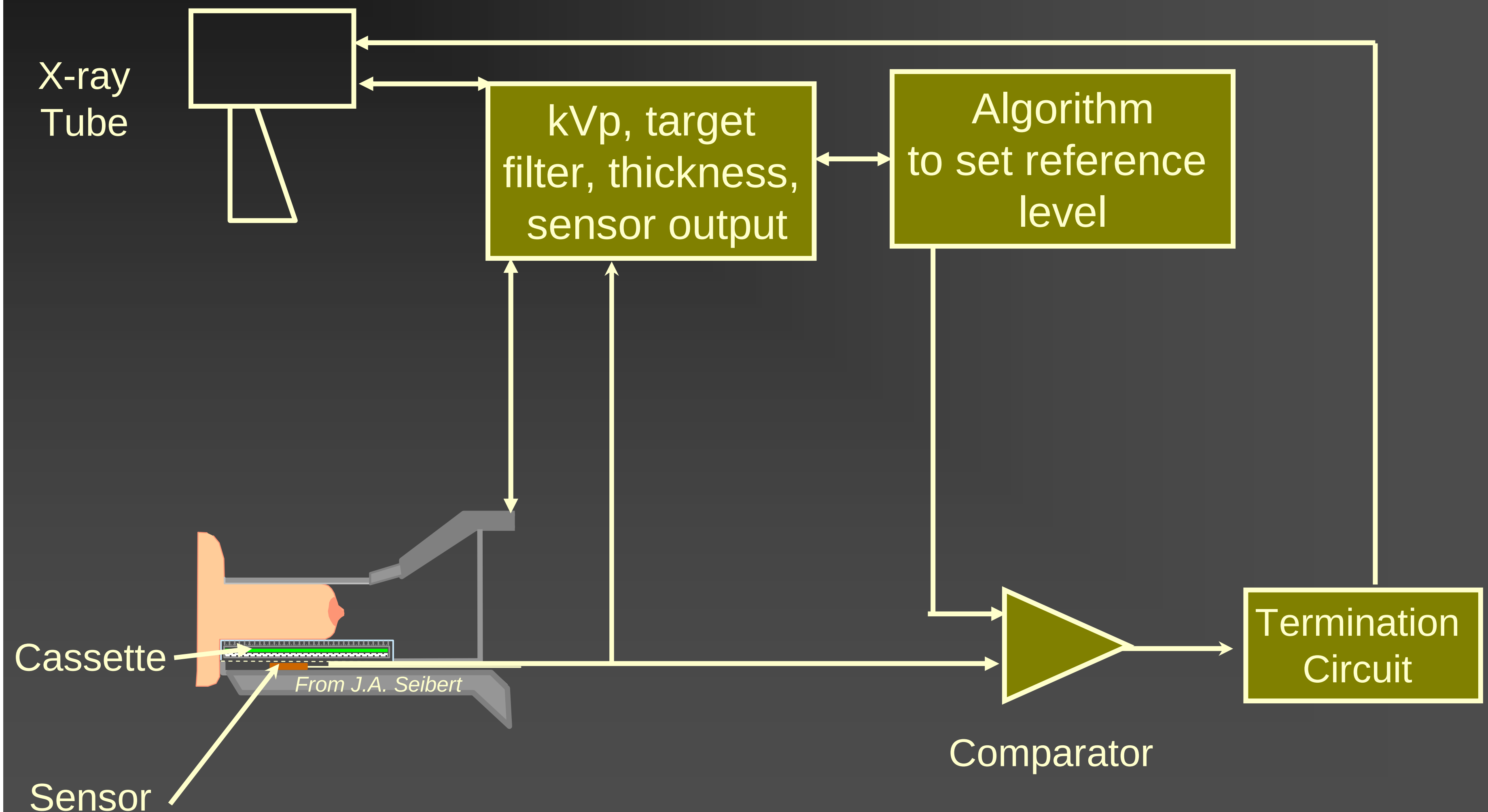
% Contrast Improvement
High Transmission Cellular Grid - HTCG





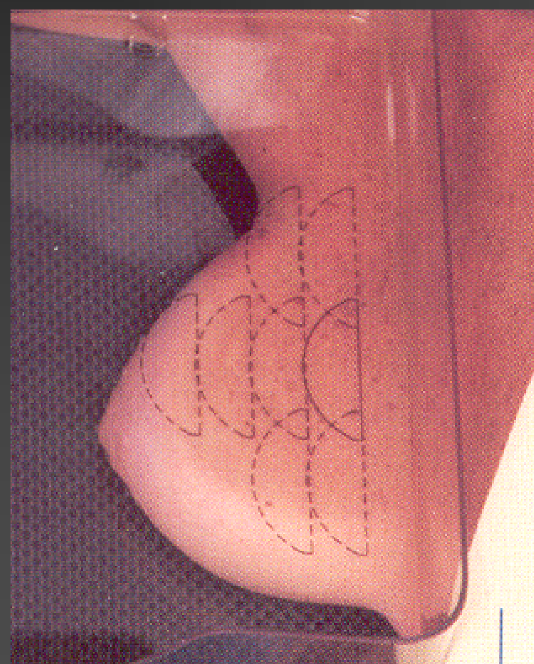
Adapted from: http://www.hologic.com/oem/pdf/R-BI-016_Fund-Dig%20Mammo.pdf

Automatic Exposure Control

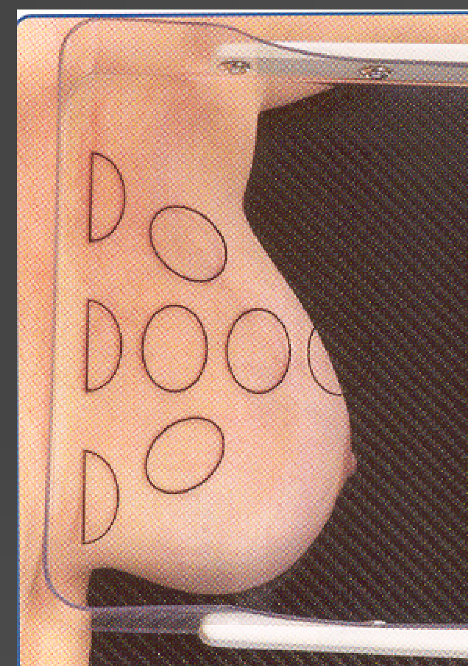


Automatic Exposure Control

- AEC sensor is located *underneath* the cassette
  - typical screen exposure is 5 to 10 mR
  - variable sensor position
  - should be under densest tissue



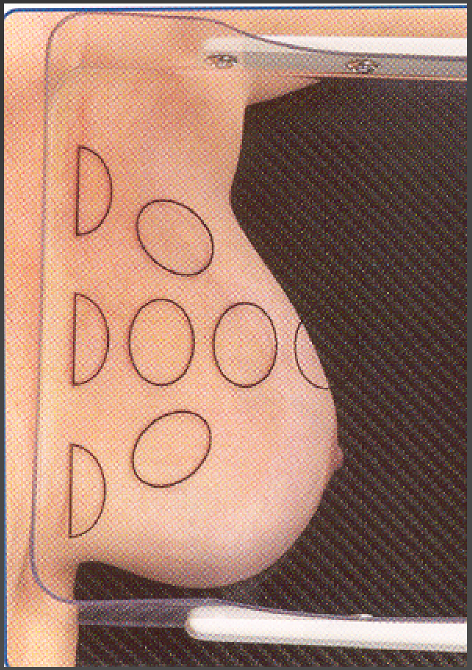
GE Instrumentarium
Vector Point



GE Instrumentarium
Diamond Autopoint

Automatic Exposure Control

- AEC sensor is located *underneath* the cassette
  - typical screen exposure is 5 to 10 mR
  - variable sensor position
  - should be under densest tissue
  - integrated signal is used to terminate the exposure



GE Instrumentarium Diamond Autopoint

AEC Modes of Operation

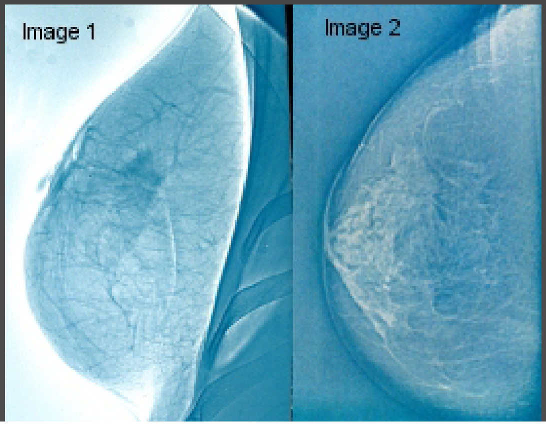
- Auto Time
  - kVp, target/filter chosen by operator
- Auto kVp
  - kVp chosen on basis of breast thickness
- Full Automatic
  - kVp, target/filter chosen by unit
- Siemens – Opdose
  - Breast thickness used to suggest kVp and target/ filter combination
- GE Instrumentarium
  - kVp adjusted during exposure to achieve exposure time of ~2 seconds
- GE DMR
  - Attenuation (100 ms) and breast thickness are used to select kVp and target/filter combination
  - Three algorithms – STD, DOSE and CNT

Mammographic Recording Systems

- 1960's non-screen industrial film
  - hand processing – 5 minutes
- 1970 Kodak RP/M non-screen film
  - 90 second processing
  - entrance skin exposure, 3 – 10 R

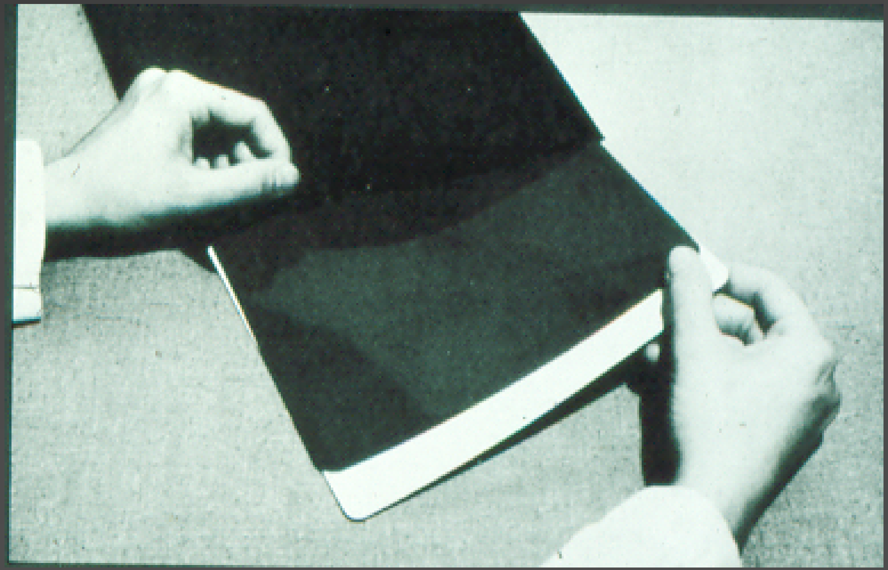
Mammography Recording Systems

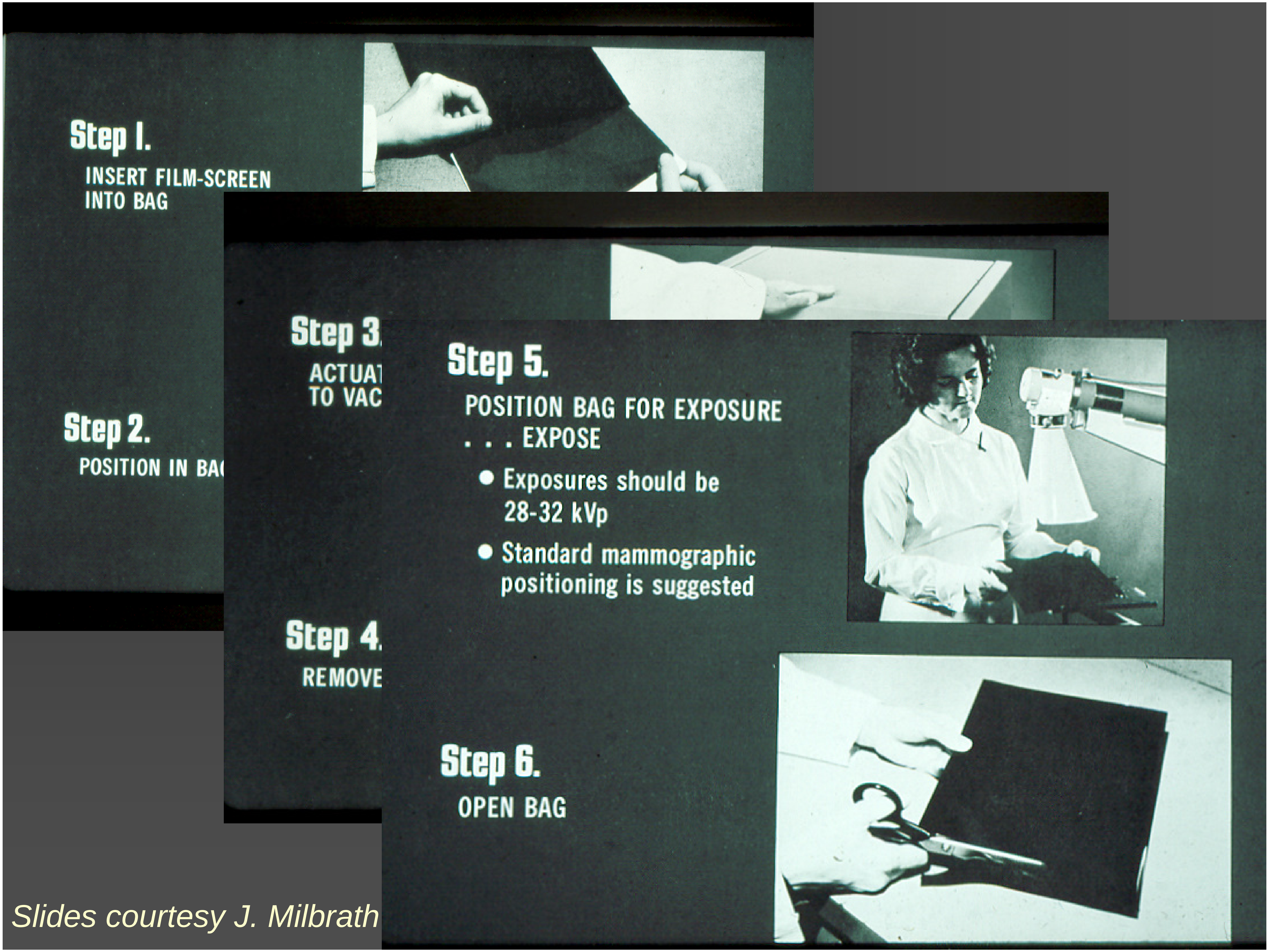
- 1950's non-screen industrial film
- 1970 Kodak RP/M non-screen film
  - 90 second processing
  - entrance skin exposure, 3 – 10 R
- 1971 Xeroradiography
  - blue powder
  - entrance skin exposure, 2 – 4 R



Mammography Recording Systems

- 1972 DuPont Lo-Dose screen-film
  - calcium tungstate screen – no cassette
  - black polyethylene vacuum bag
  - entrance skin exposure, 1 – 1.5 R





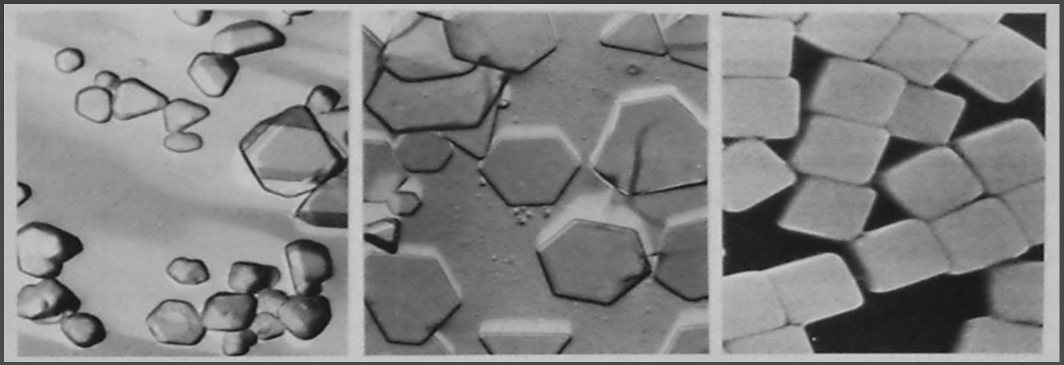
Slides courtesy J. Milbrath

Mammography Recording Systems

- 1972 DuPont Lo-Dose screen-film
  - calcium tungstate screen
  - black polyethylene vacuum bag
  - entrance skin exposure, 1 – 1.5 R
- 1976 DuPont Lo-Dose II
  - rare-earth screen, cassette
- 1976 Kodak MinR
  - rare-earth screen, cassette

Mammography Recording Systems

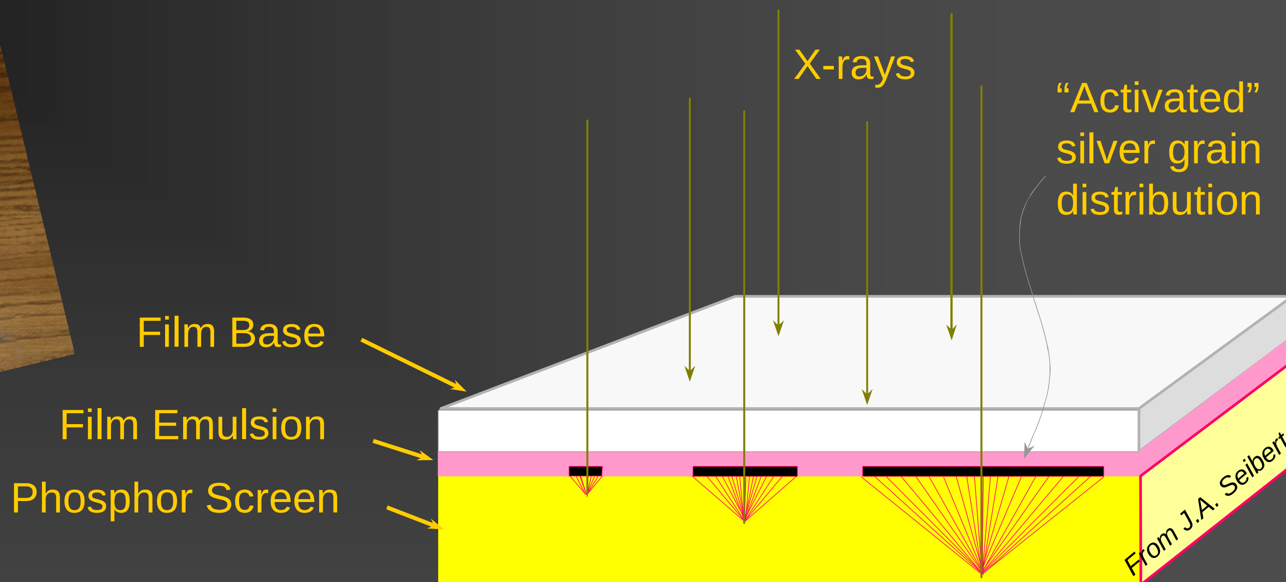
- 1983 Kodak Min- R screen-film system
  - gadolinium oxysulfide with orthochromatic film
    - (other rare earth phosphors developed)
  - significant reduction in dose compared to non-screen film
  - current films employ cubic grains



3-D Tabular Cubic

With permission: Medical Physics Publishing, "The Basics of Film Processing in Medical Imaging" by Art Haus and Susan Jaskulski

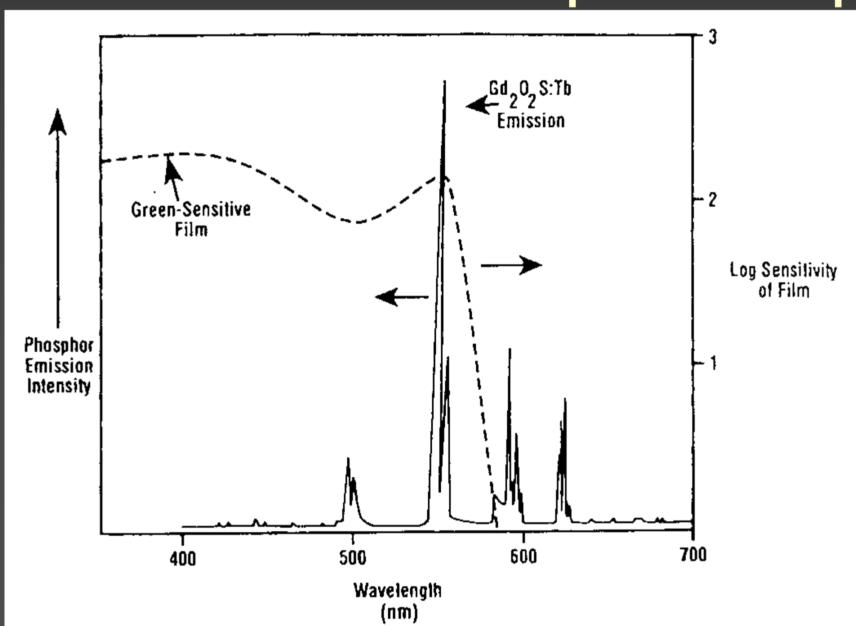
Single-sided emulsion film with a single screen underneath the film

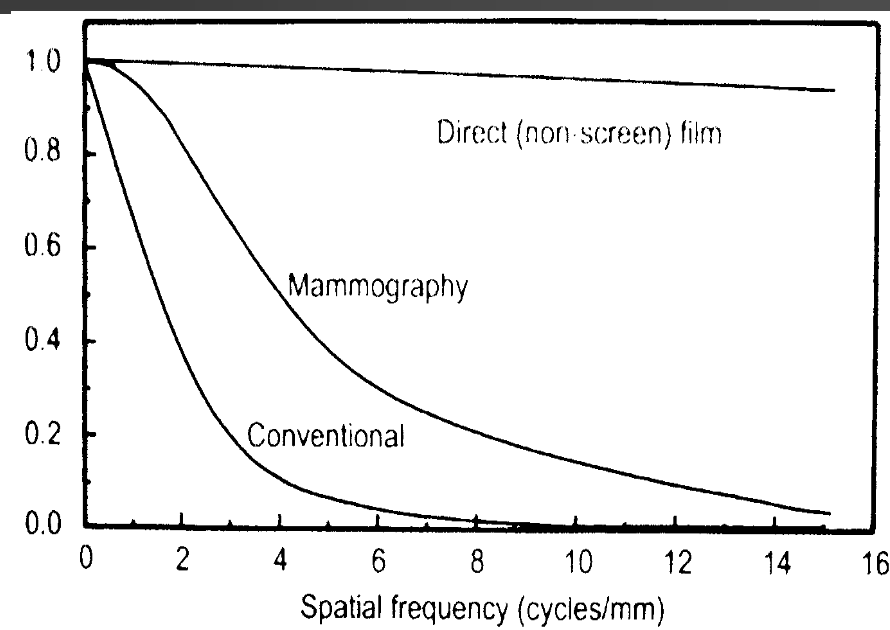


- x-ray absorption higher on entrance side of the screen
- light emission is also highest on entrance side
- light diffusion in screen is minimized which reduces blurring

Typical Screen: Gd_2O_2S:Tb

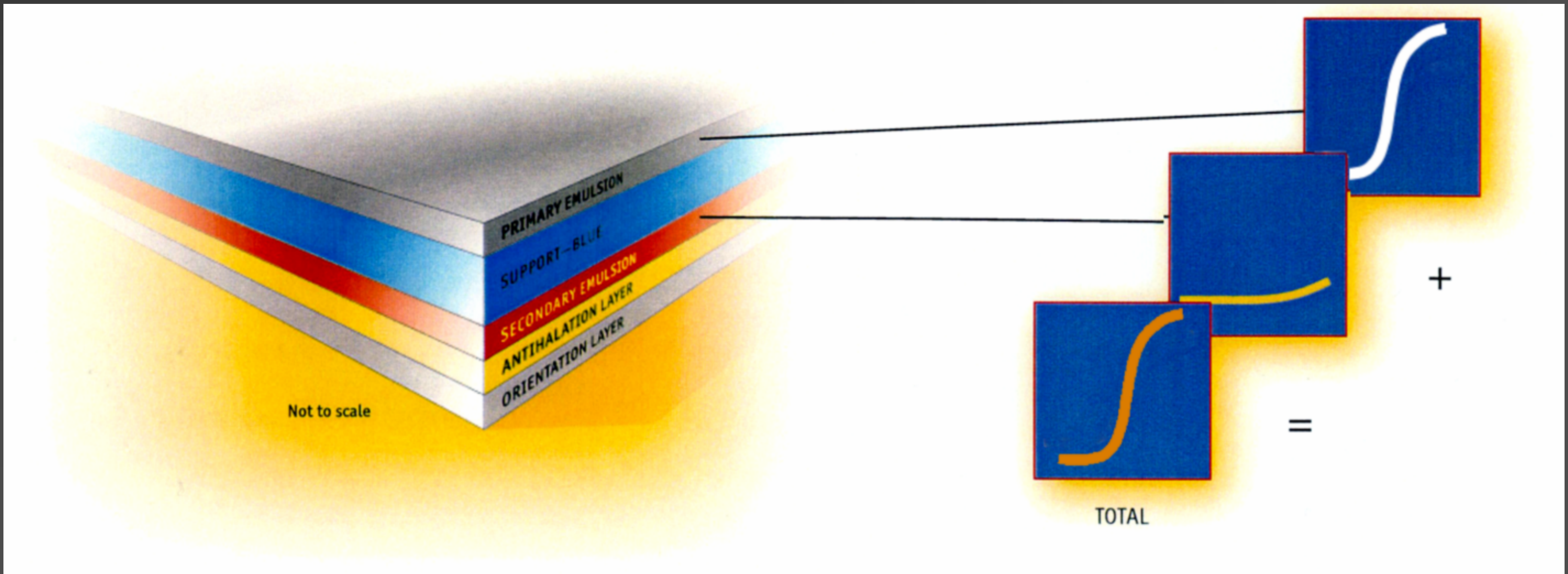
- main emission at 545 nm
  - film spectral sensitivity is matched
- conversion efficiency ~ 15 %
- x-ray absorption of 40 to 60%
- MTF ~ 10% up to 15 lp/mm





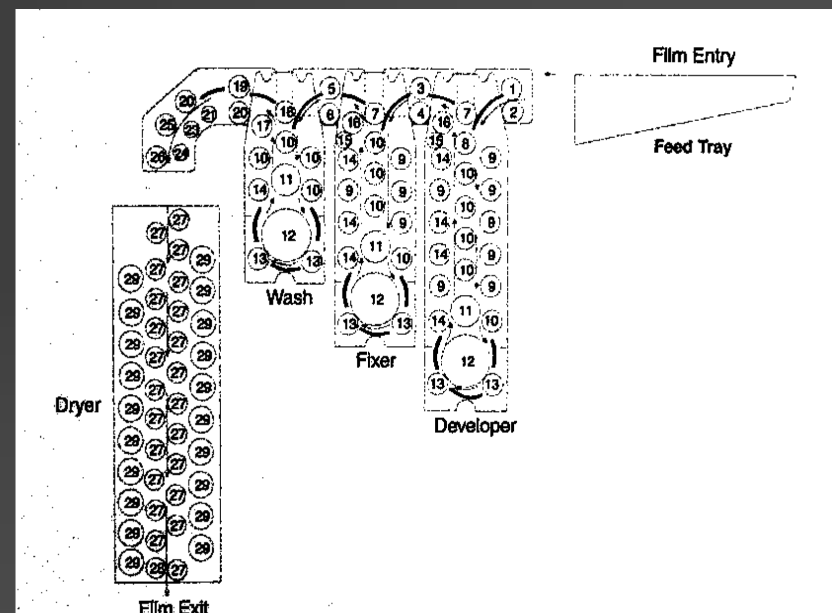
Mammography Recording Systems

- 2003 Kodak Min-R EV
  - Dual emulsion film used with a single screen
  - Asymmetric emulsion design optimizes image quality from toe to shoulder of the sensitometric curve



Film Exposure and Processing

- Latent image formation
  - Light converts AgBr complex into silver ion + electron, creates a sensitivity speck
- Processing (four steps)
  - Developer
    - Chemical amplification ~ 5 x 10^9
  - Fixer stops development
  - Washing
  - Drying

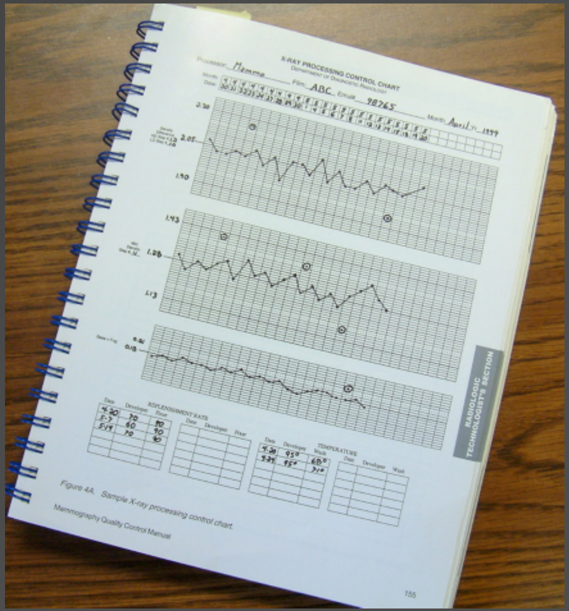


For details see: "The Basics of Film Processing in Medical Imaging" by Art Haus and Susan Jaskulski

Technologist Daily Processor Control

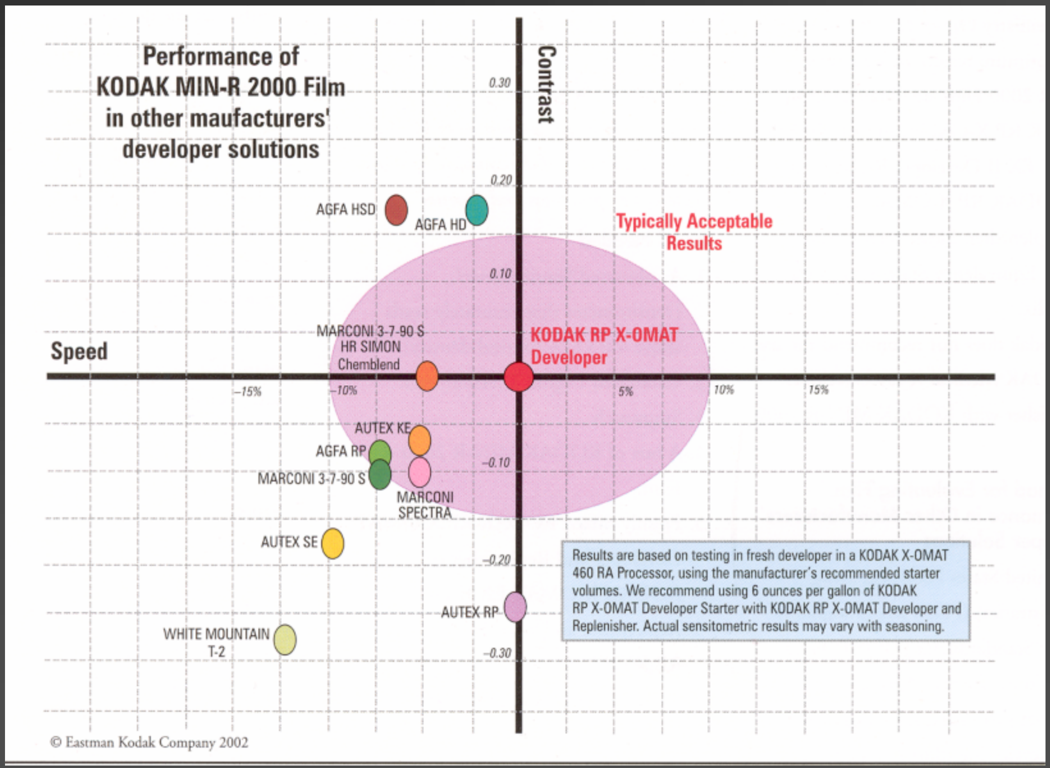
MQSA requires a processor performance test on each day that examinations are performed before any clinical films are processed

- Density Difference
  - +/- 0.15 DU
- Mid-density
  - +/- 0.15 DU
- Base + Fog
  - +/- 0.03 DU



Processing Chemistry

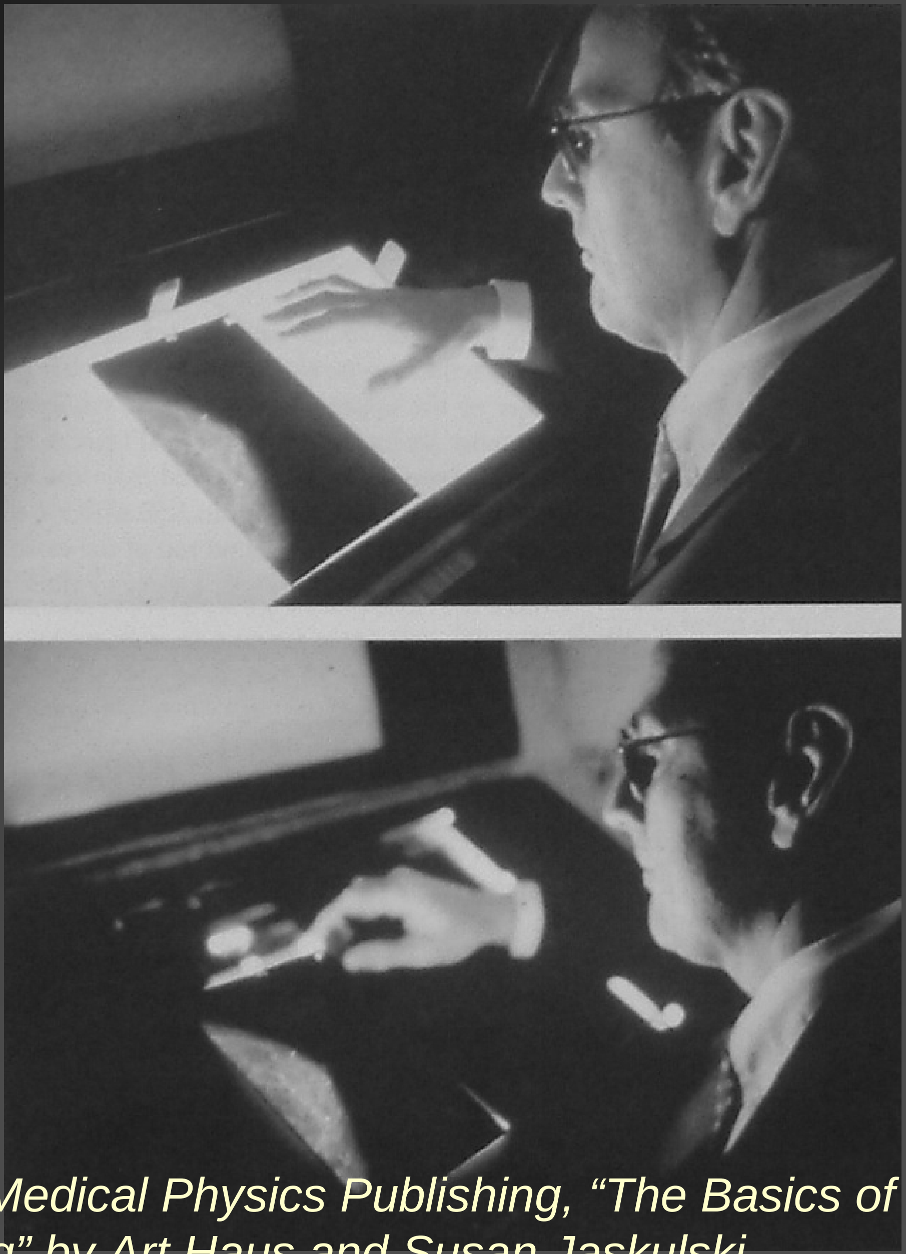
MQSA regulations require a facility to use chemical solutions that are capable of developing the films in a manner equivalent to film manufacturer’s specifications.



ACR Film Viewing Recommendations

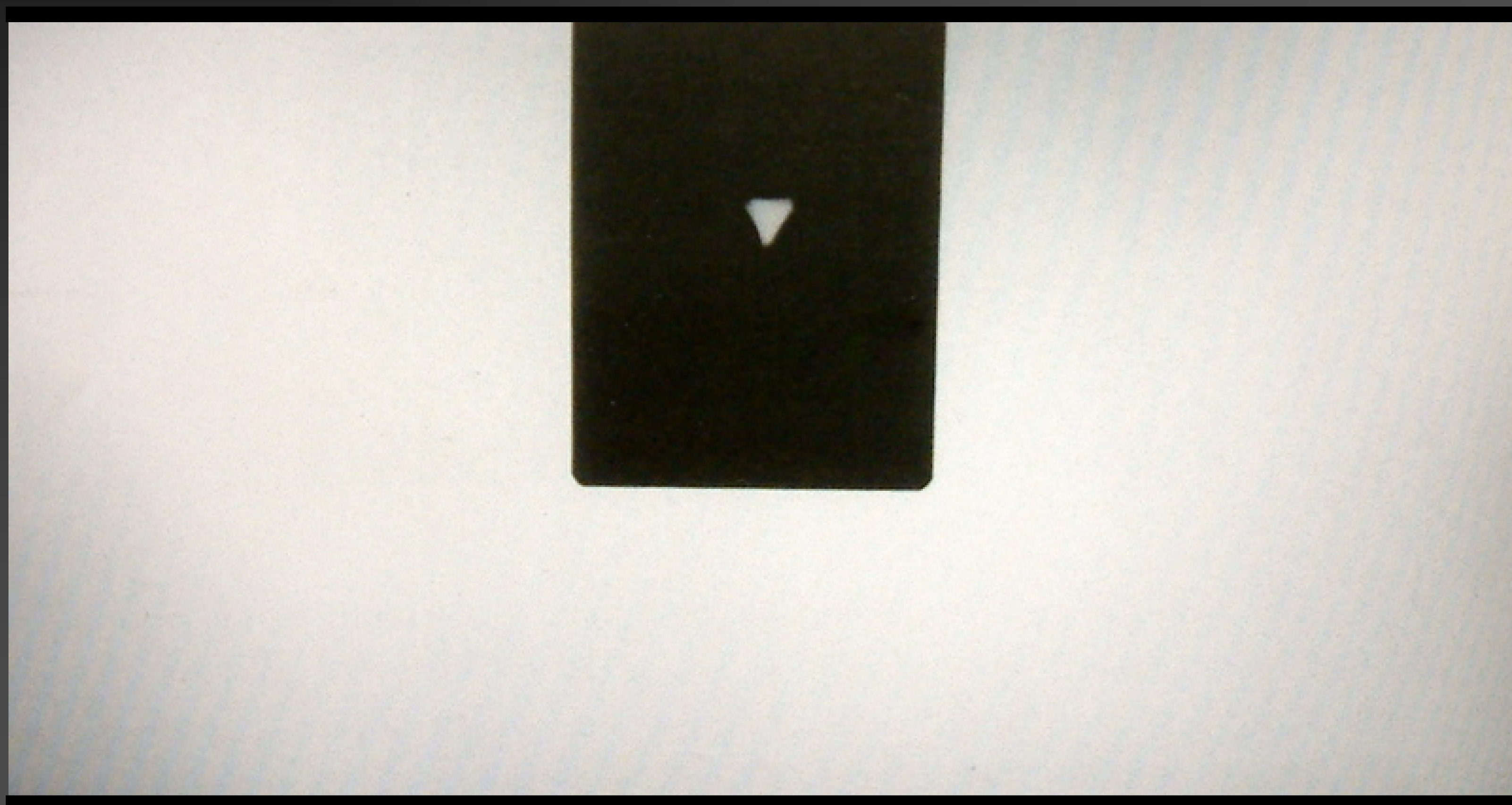
- View box luminance ~ 3000 cd/m^2
- Masking is essential to preserve visibility of low contrast objects
- Ambient light intensity < ~20 lux
- High intensity spot light should be available
- Magnifying glass should be available

Masking Is Essential



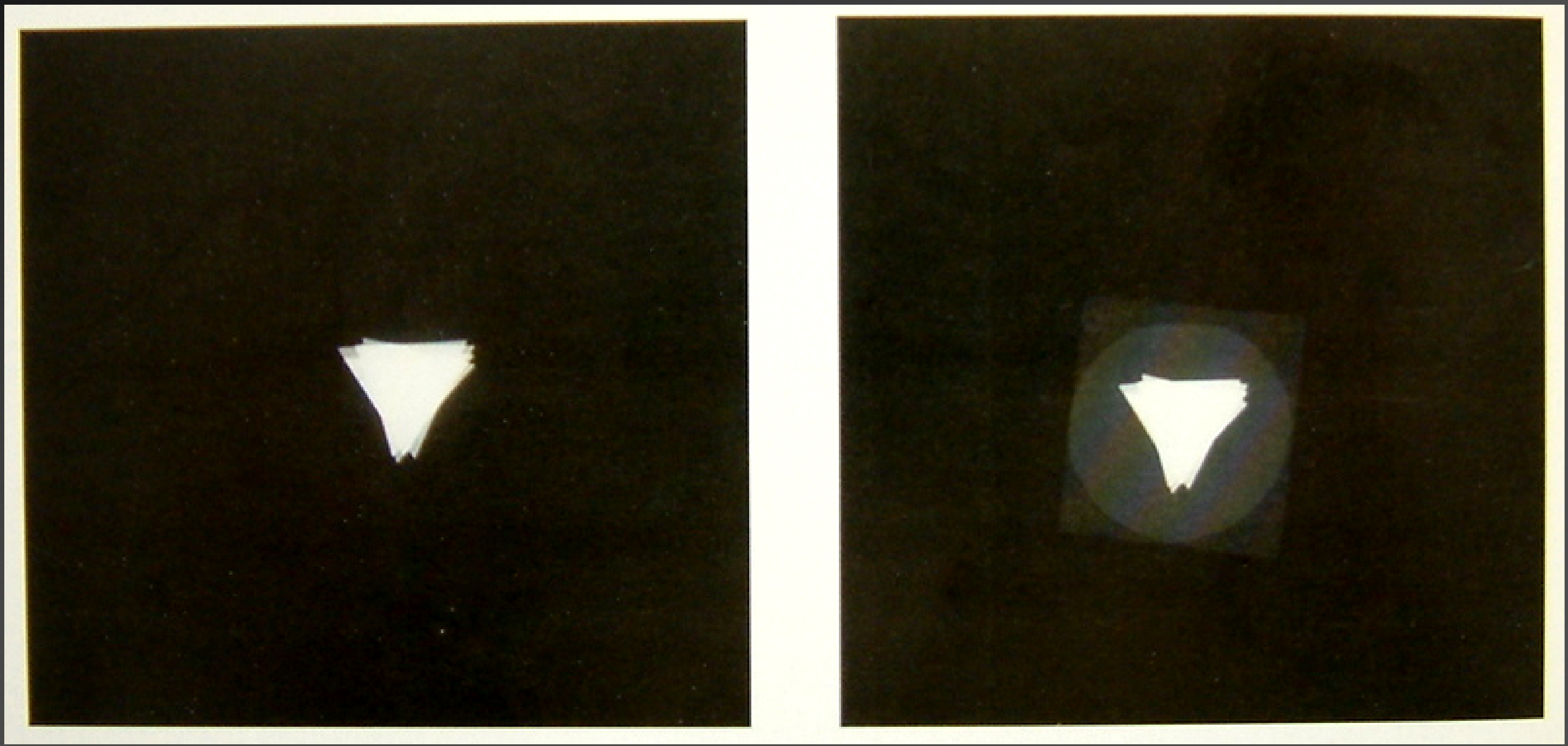
With permission: Medical Physics Publishing, "The Basics of Film Processing in Medical Imaging" by Art Haus and Susan Jaskulski

Low Contrast Test Object on Viewer



With permission: Medical Physics Publishing, "The Basics of Film Processing in Medical Imaging" by Art Haus and Susan Jaskulski

Un-Masked and Masked Test Object



With permission: Medical Physics Publishing, "The Basics of Film Processing in Medical Imaging" by Art Haus and Susan Jaskulski

Mean Glandular Dose (MGD)

$$\text{MGD (mrad)} = D_{gN} \times \text{ESE (R)}$$

- D_{gN} is the factor used to convert entrance skin exposure to mean glandular dose in mrad or mGy
  - determined by MC simulations and measurements
- D_{gN} depends on
  - hvl, kVp, target, filter, breast composition and thickness
- Maximum allowed MGD for 4.2 cm, 50% adipose, 50% gland is 300 mrad or 3 mGy

D_{gN} Conversion (mrad / R)

Mo target / Mo filter

4.5 cm breast: 50% glandular and 50% adipose breast tissue composition

kVp

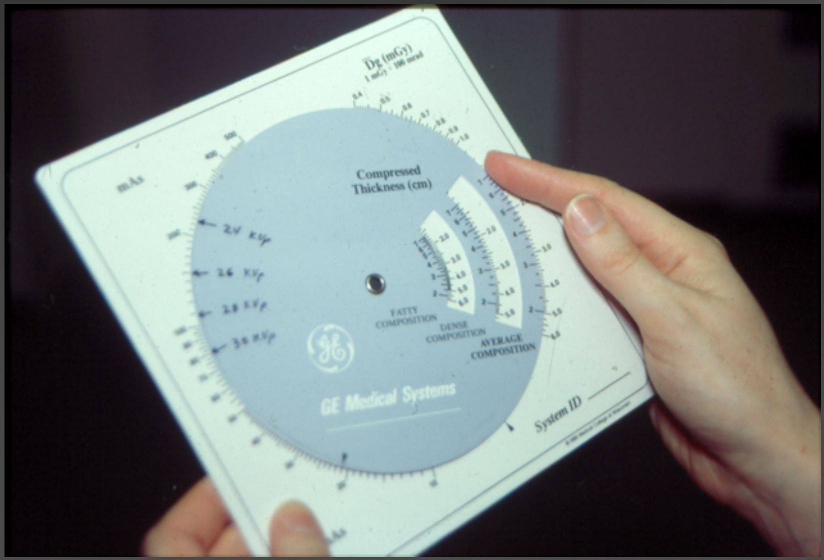
HVL (mm)	25	26	27	28	29	30	31	32
0.25	122							
0.26	126	128						
0.27	130	132	134					
0.28	134	136	138	139				
0.29	139	141	142	143	144			
0.30	143	145	146	147	148	149		
0.31	147	149	150	151	152	153	154	
0.32	151	153	154	155	156	158	159	160
0.33	155	157	158	159	160	162	163	164
0.34	160	161	162	163	164	166	167	168
0.35	164	166	167	168	169	170	171	172
0.36	168	170	171	172	173	174	175	176
0.37		174	175	176	177	178	178	179
0.38			179	180	181	182	182	183
0.39				184	185	186	186	187
0.40					189	190	191	192

ACR QC Manual 1999

Short-cut to Find MGD for MAP Phantom

$$\text{MGD (mrad)} = 0.5 \times \text{hvl (mm)} \times \text{ESE (mR)}$$

Short-cut gives MGD within 2-3% for all target and filters.



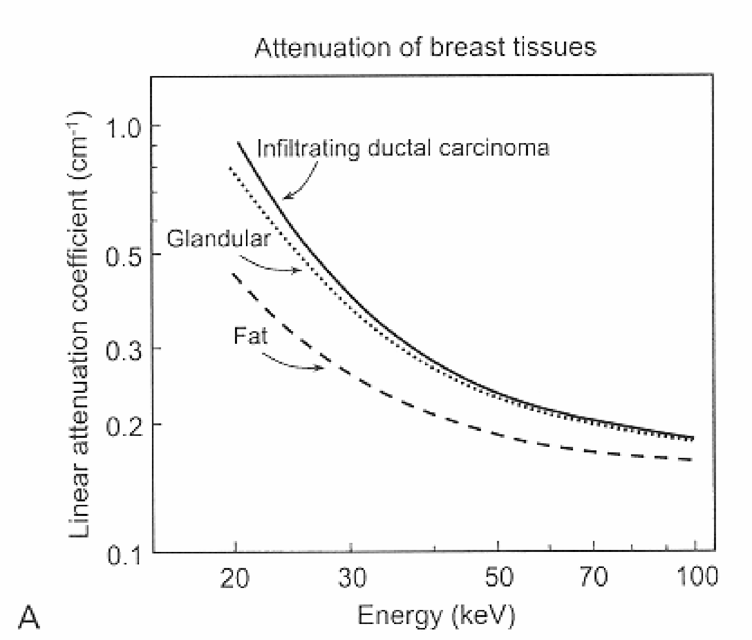
D. Jacobson, Radiographic exposure calculator and mammographic dose calculator, Radiology 1992; 182: 578.

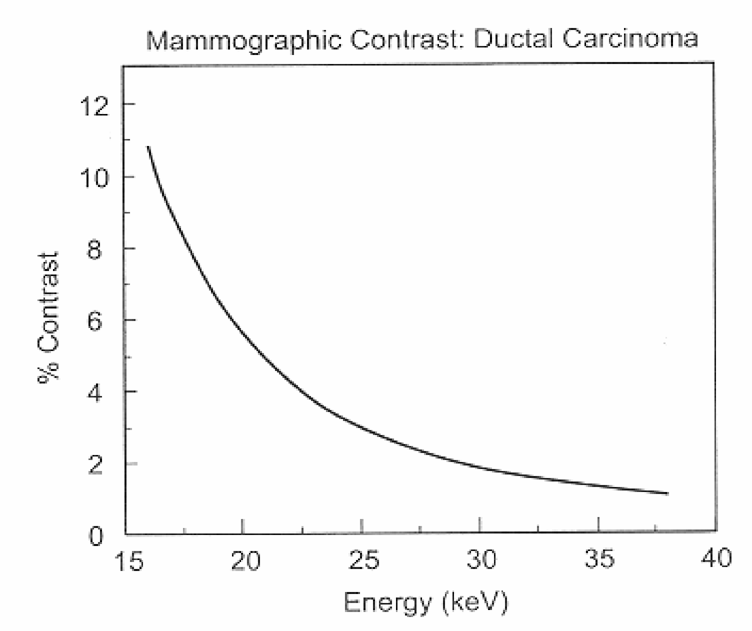

The End
SOMMERAKTION
Jeden Samstag ab 16.00 Uhr:
50% auf ALLES

The End

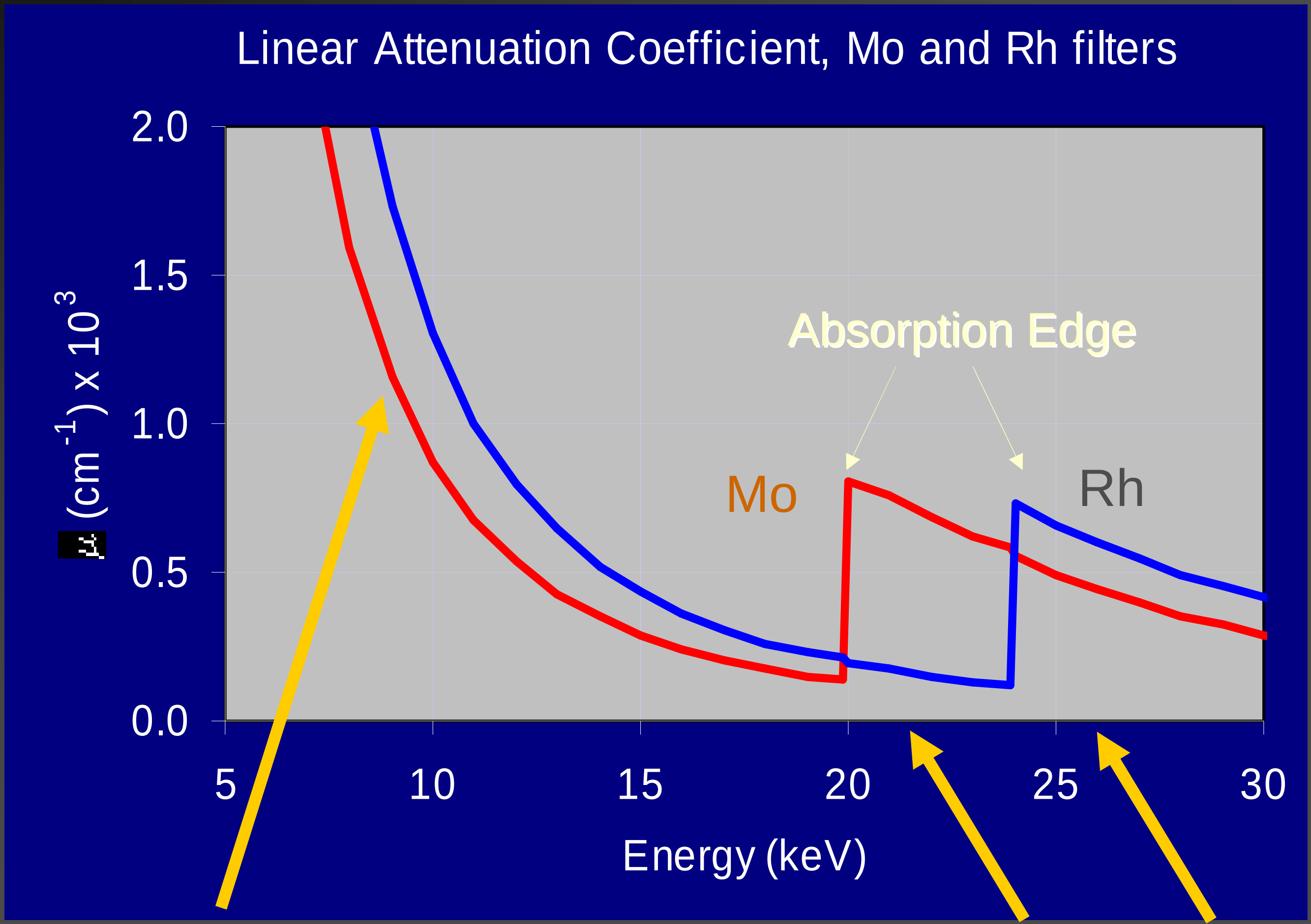
Effective Beam Energy

- inherent low subject contrast requires low effective beam energy
- Egan
  - tungsten tube, low kVp, minimal filtration
- Gros (CGR)
  - molybdenum target and fi





Mo and Rh attenuation filters

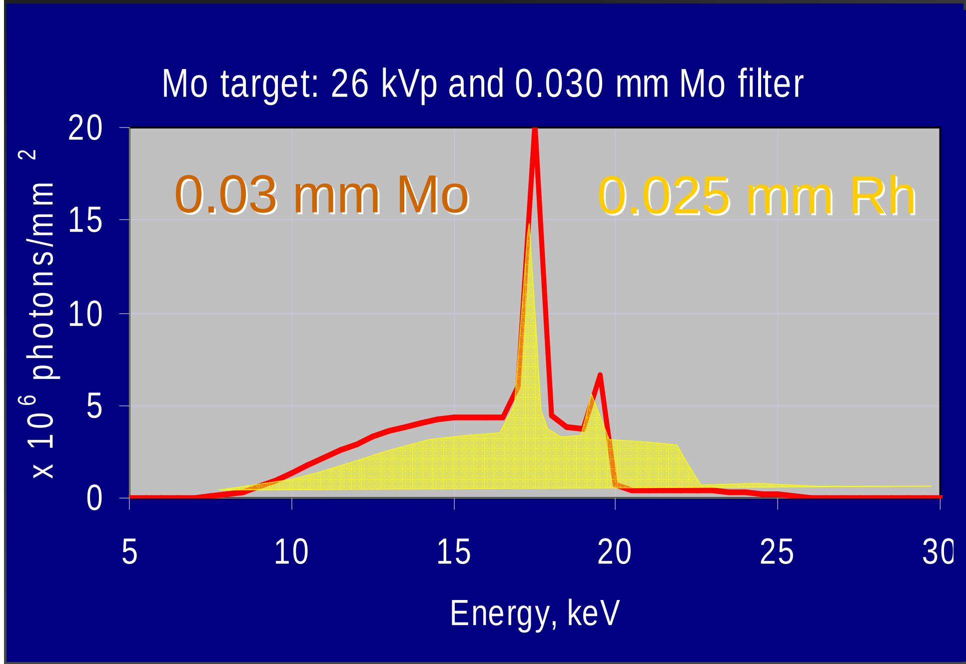


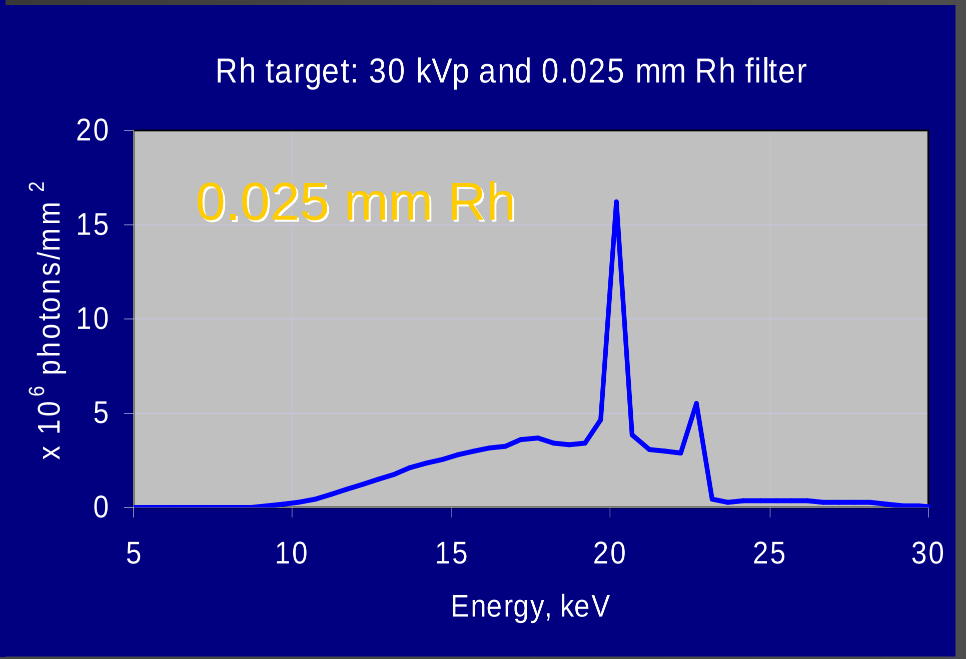
Low energy: high attenuation

High energy: high attenuation

Slide courtesy of J.A. Seibert

Filtering the spectrum



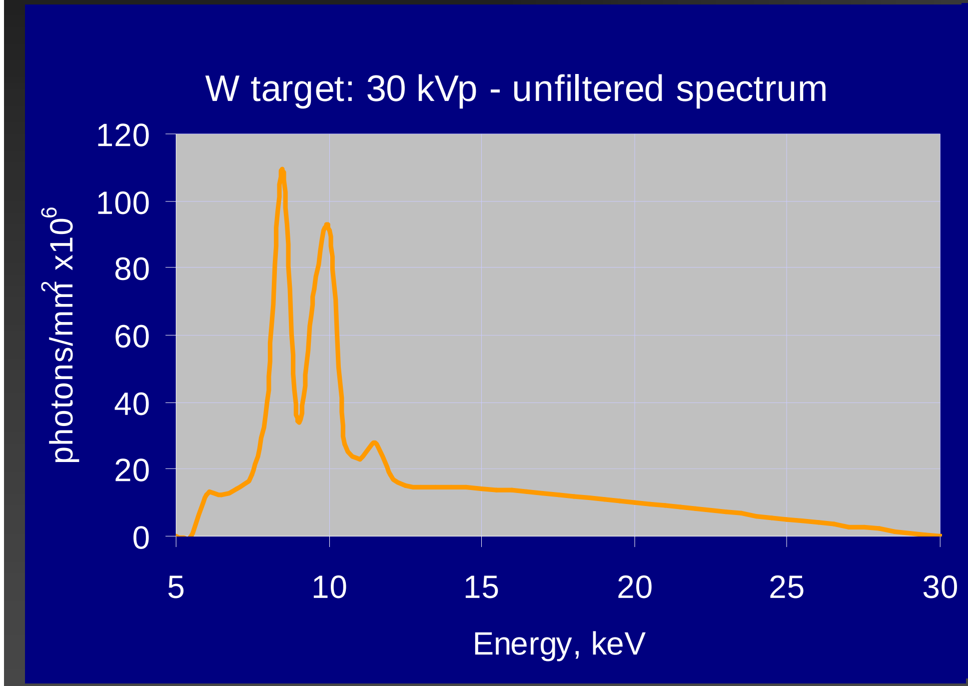


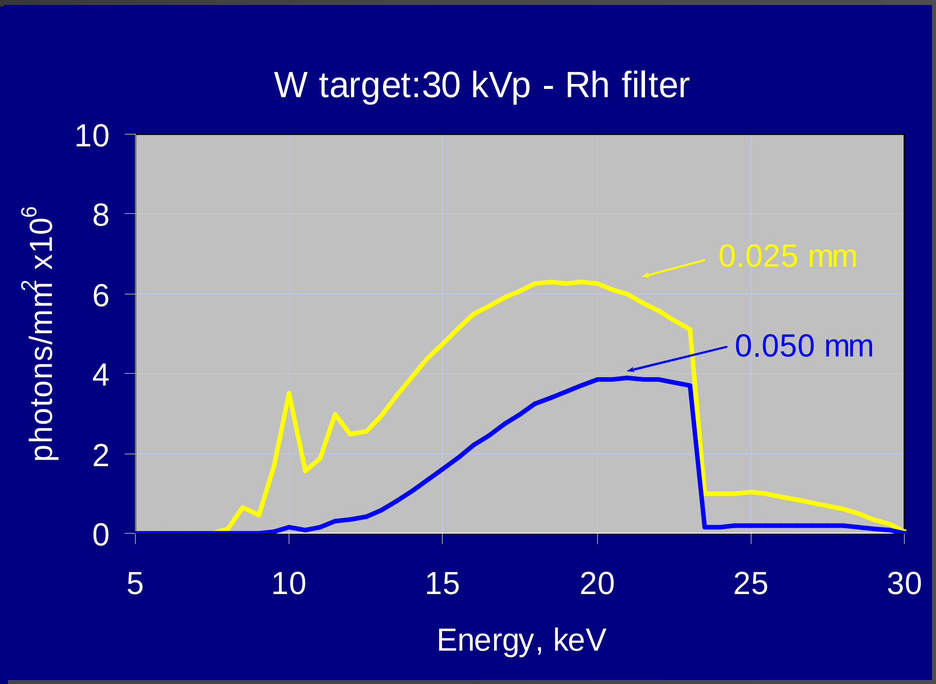
Mo target

Rh target

Slide courtesy of J.A. Seibert

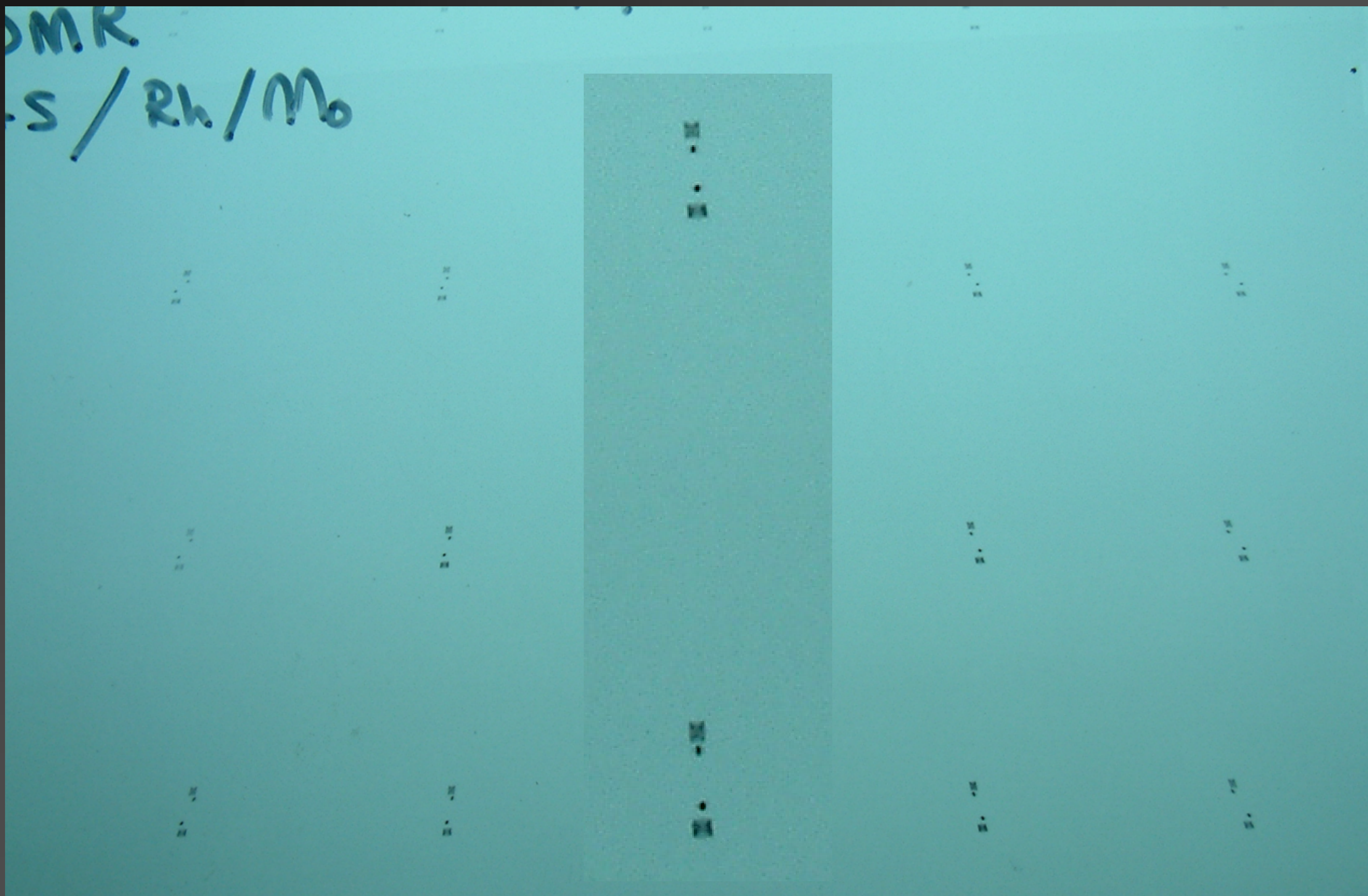
Tungsten target





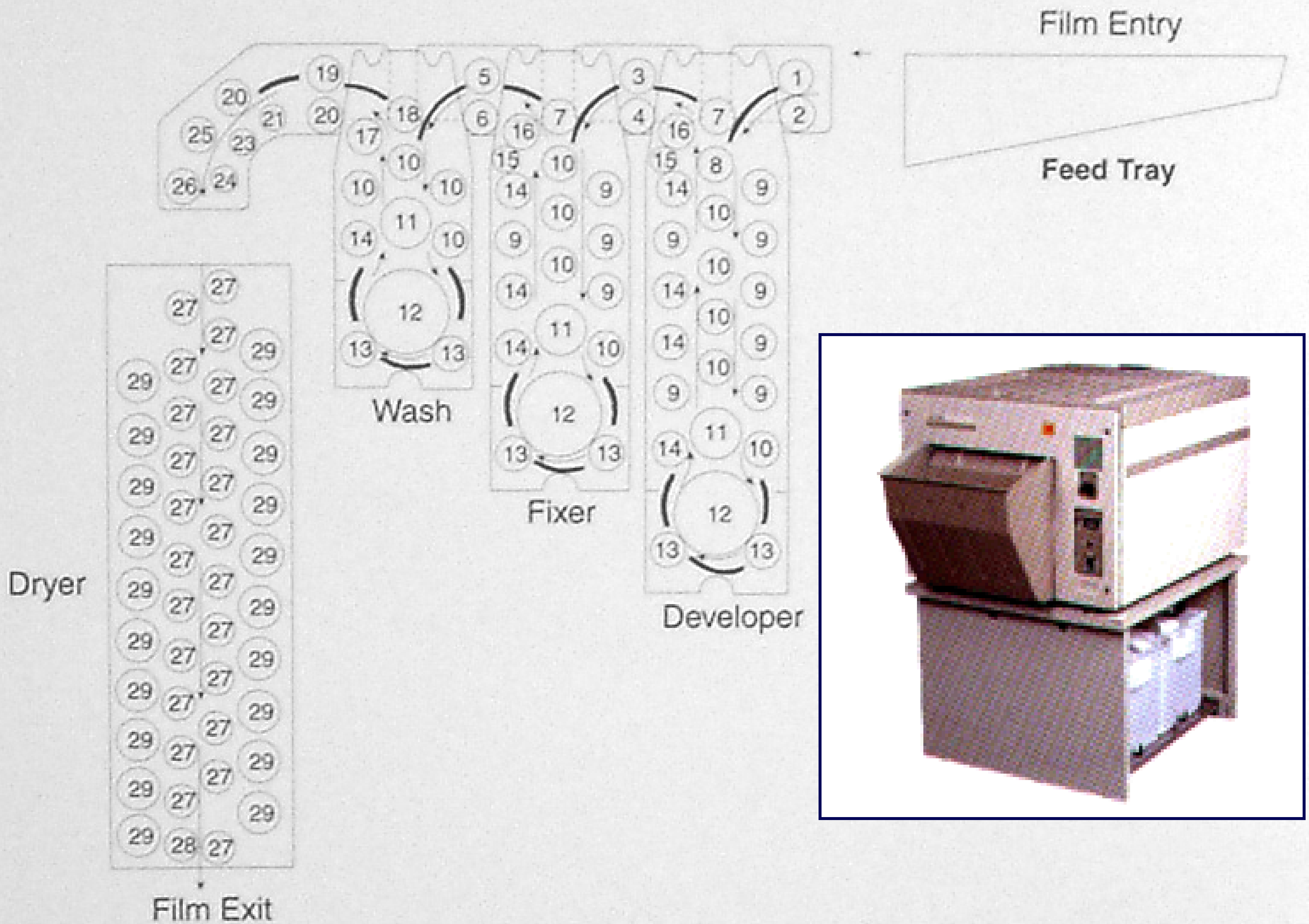
Slide courtesy of J.A. Seibert

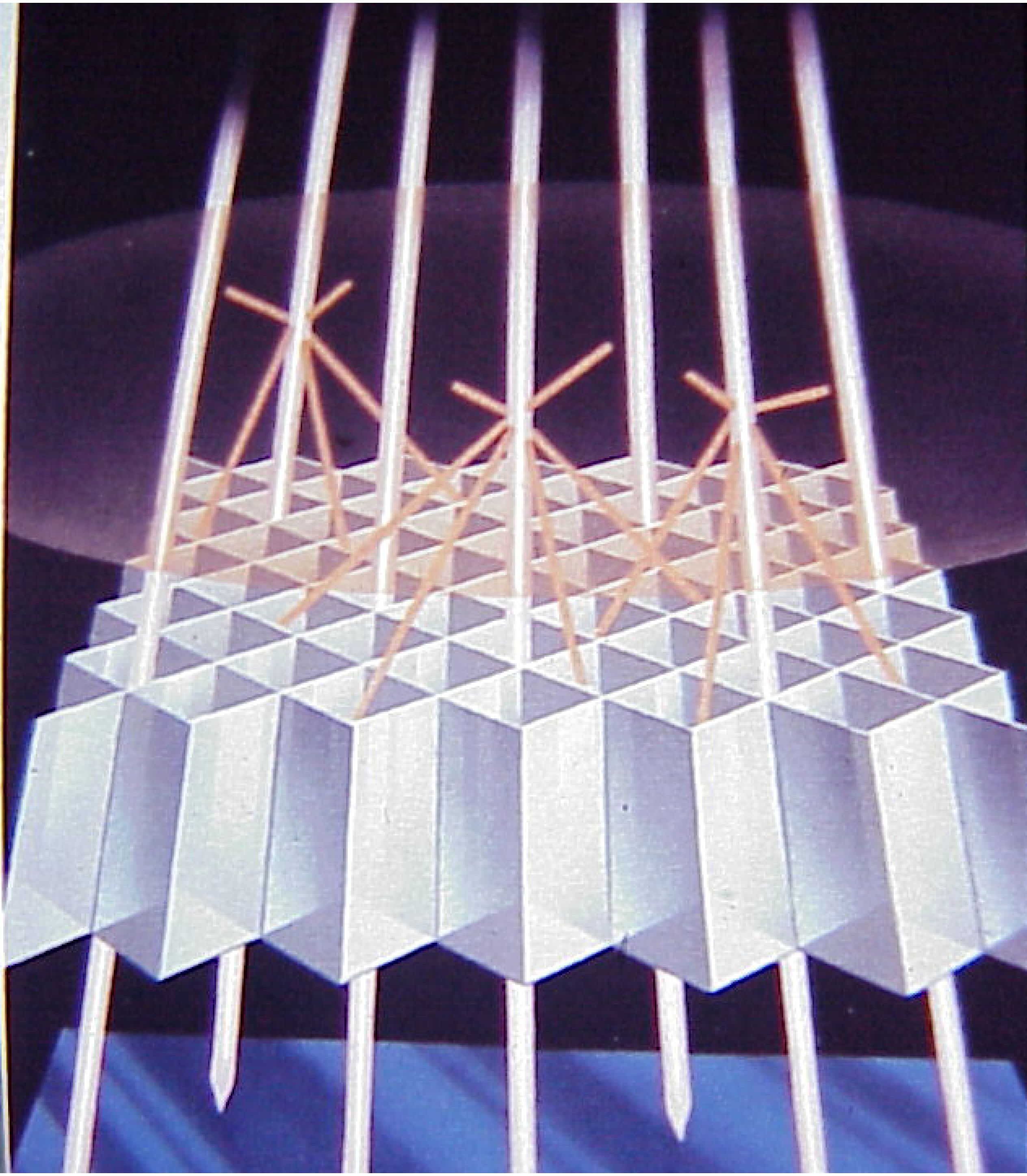
DMR Large/Small Mo/Rh Focal Spot Images

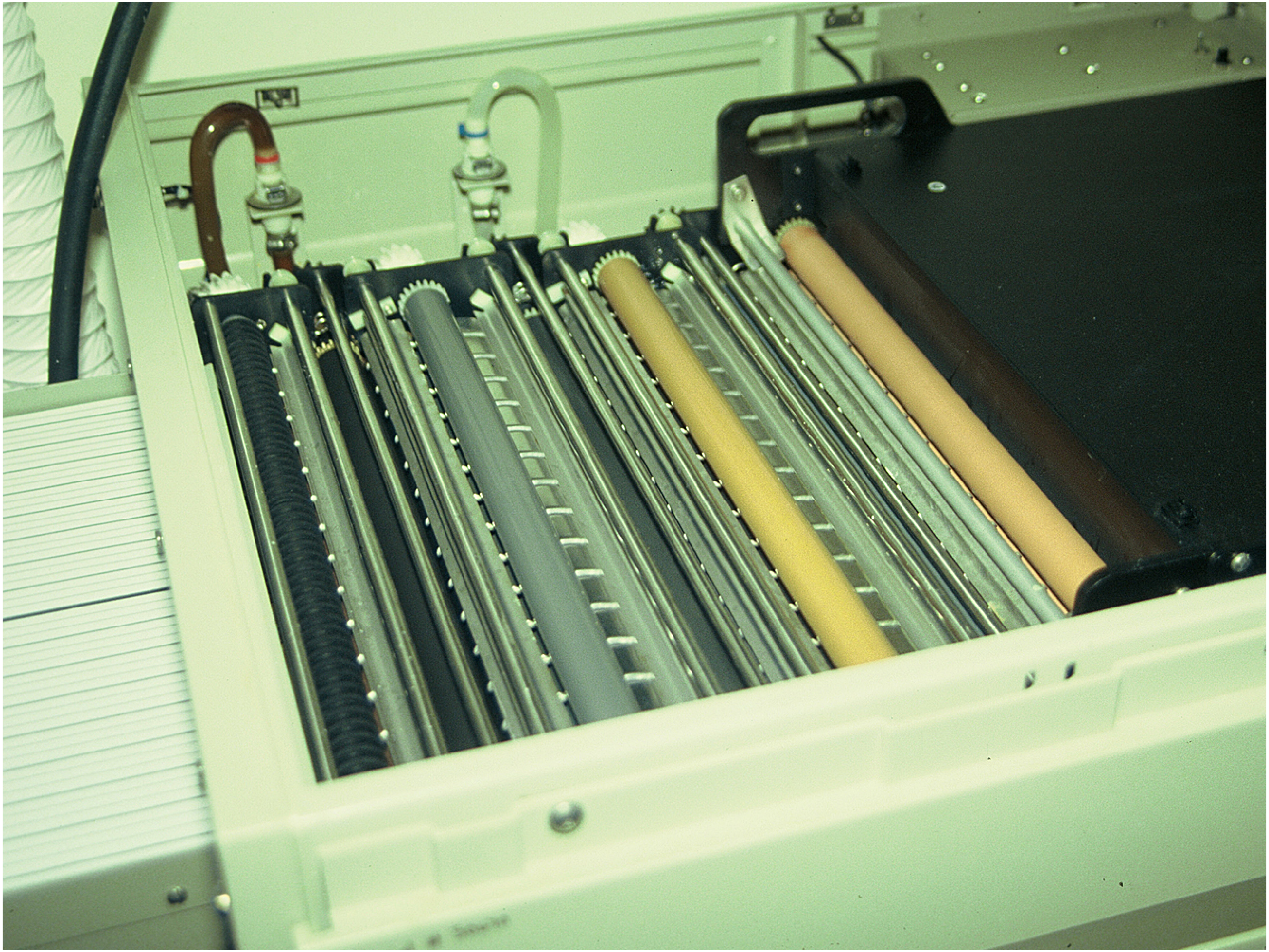


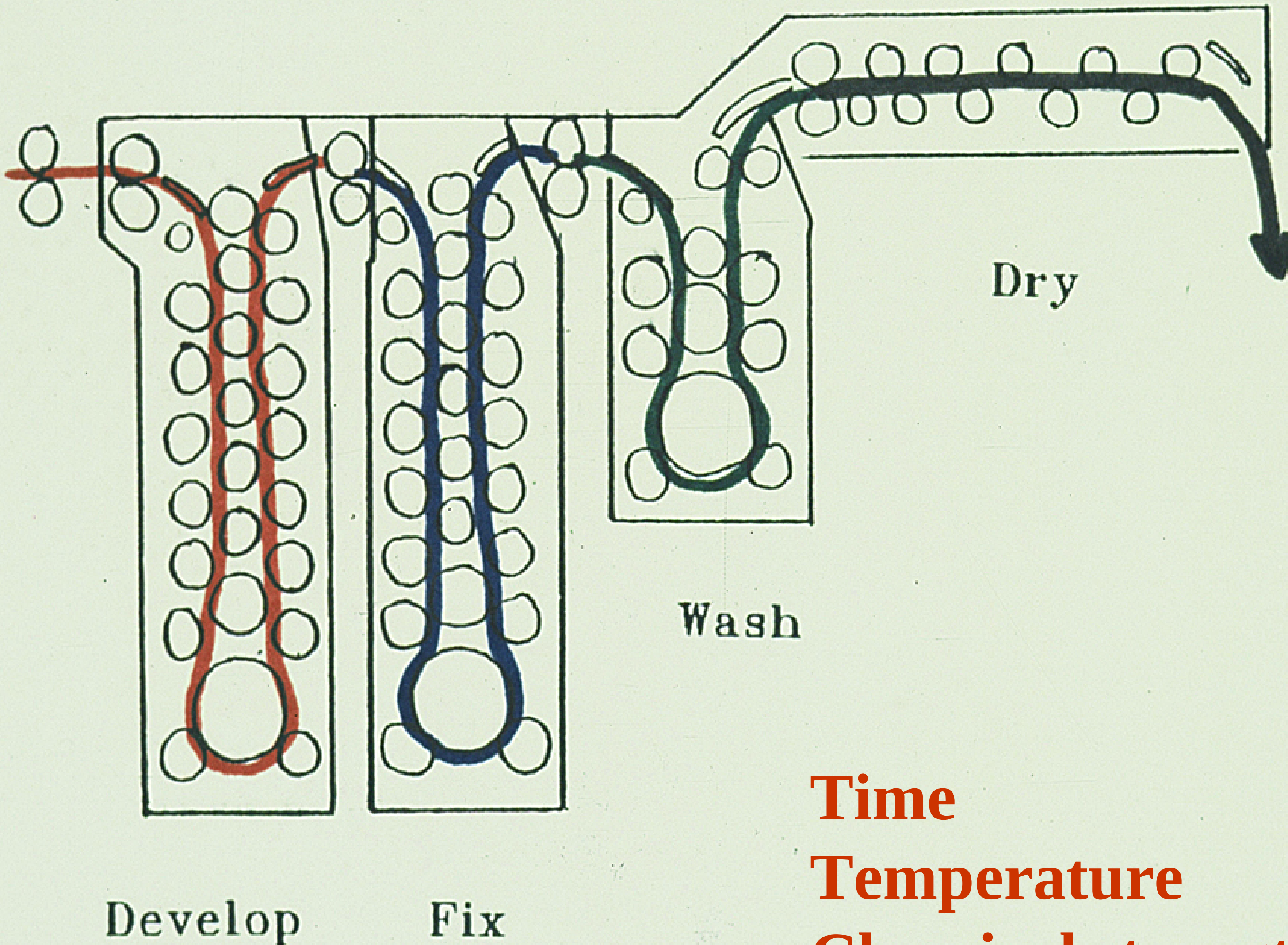
Chest Wall

Film Processing Four Steps

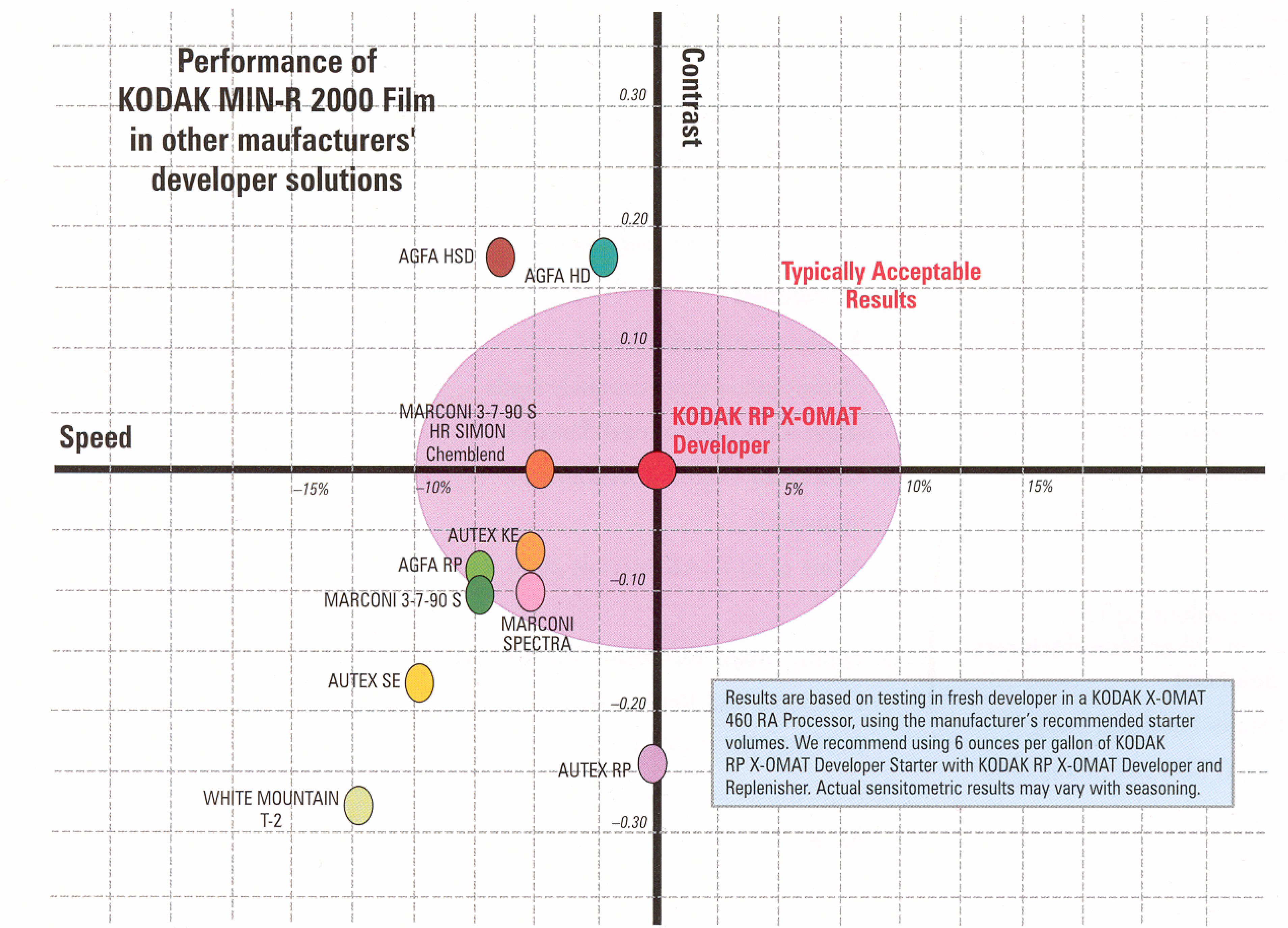




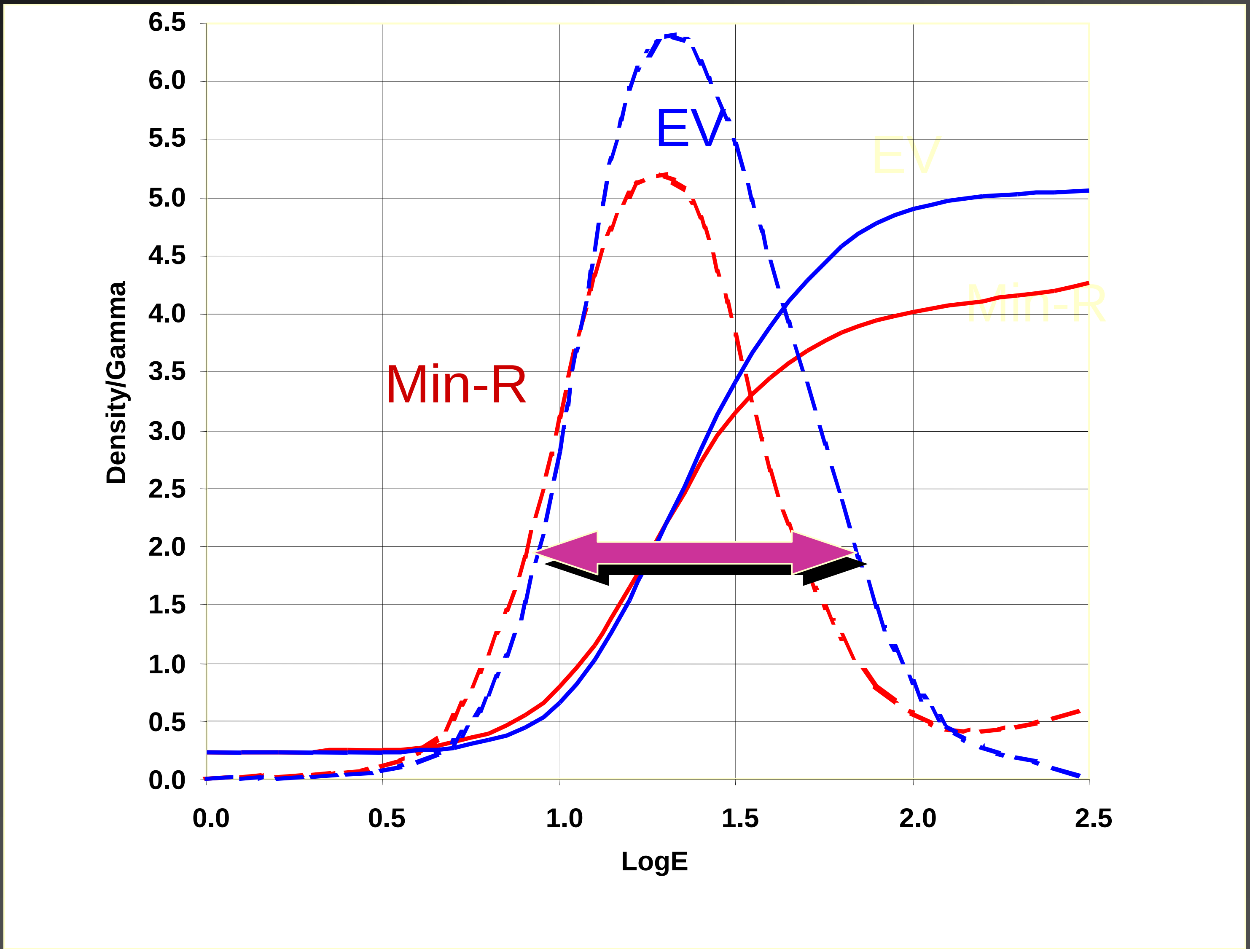




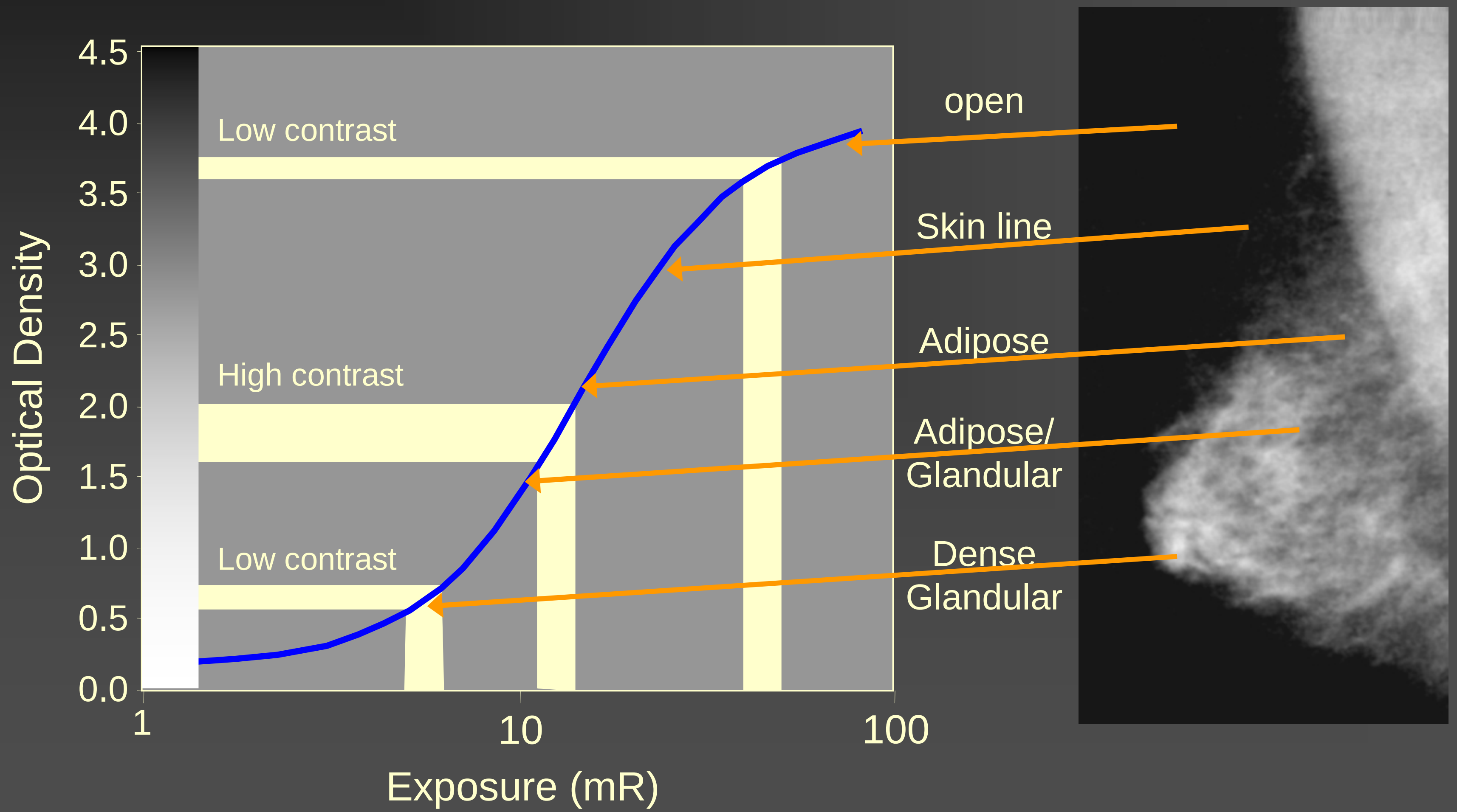
Time
Temperature
Chemical strength


Performance of
KODAK MIN-R 2000 Film
in other maufacturers'
developer solutions
Contrast
Speed
0.30
0.20
0.10
–0.10
–0.20
–0.30
–15%
–10%
5%
10%
15%
AGFA HSD
AGFA HD
Typically Acceptable
Results
MARCONI 3-7-90 S
HR SIMON
Chemblend
KODAK RP X-OMAT
Developer
AUTEX KE
AGFA RP
MARCONI 3-7-90 S
MARCONI
SPECTRA
AUTEX SE
AUTEX RP
WHITE MOUNTAIN
T-2
Results are based on testing in fresh developer in a KODAK X-OMAT 460 RA Processor, using the manufacturer's recommended starter volumes. We recommend using 6 ounces per gallon of KODAK RP X-OMAT Developer Starter with KODAK RP X-OMAT Developer and Replenisher. Actual sensitometric results may vary with seasoning.

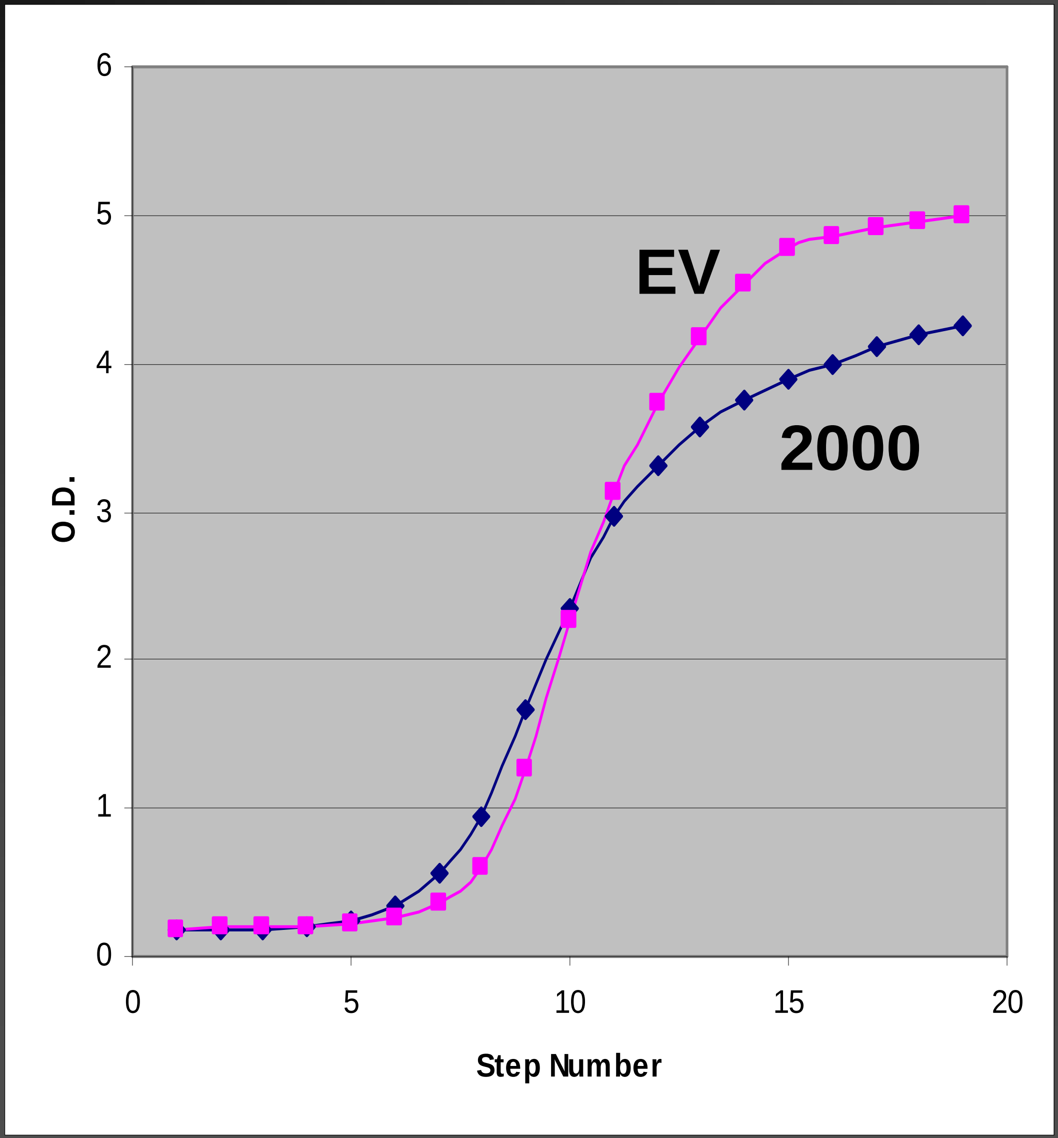
Kodak Min-R EV vs Min-R 2000



Mammography Film Response



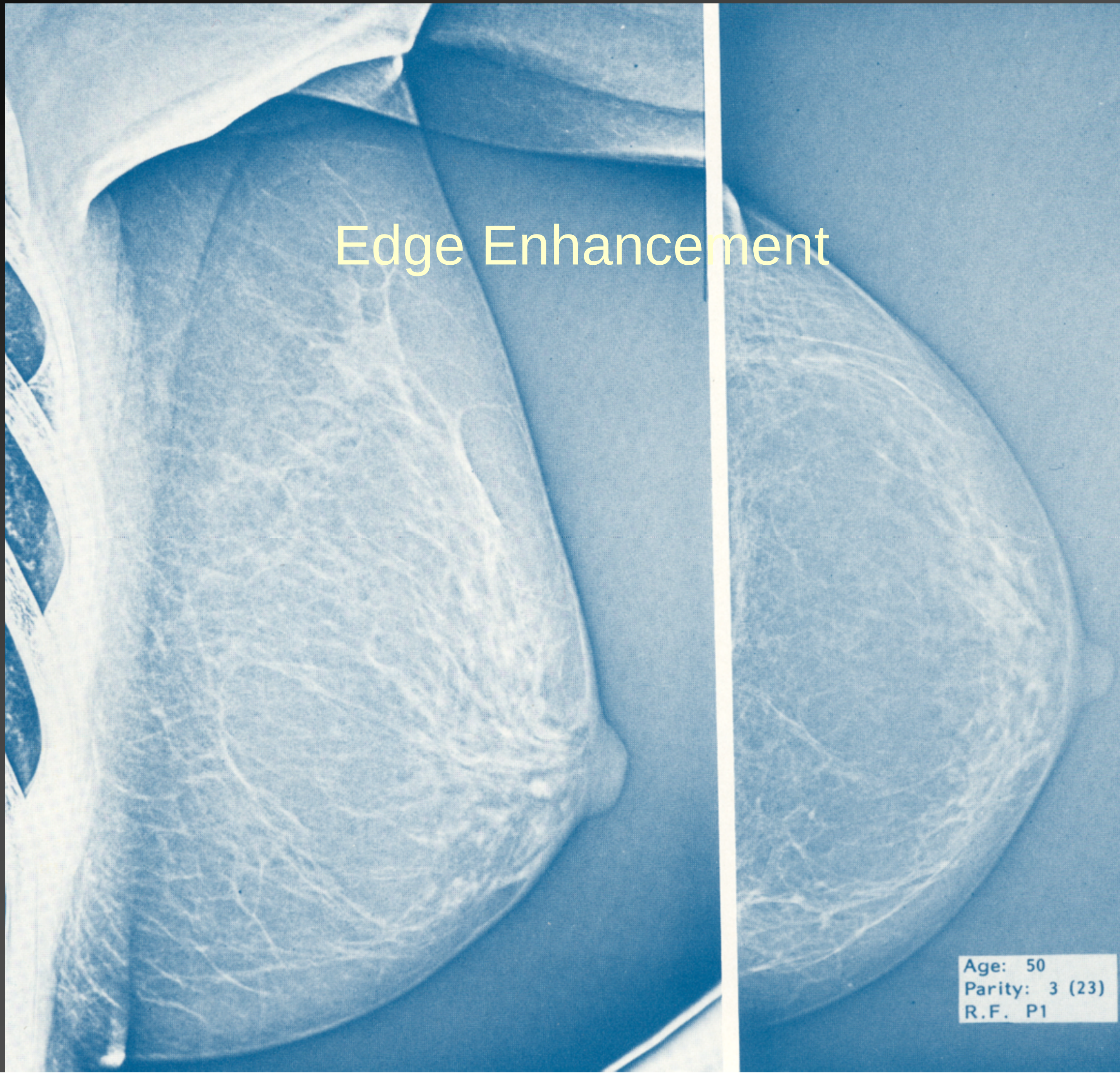
Kodak Min-R EV and Min-R 2000



X-ray generation

- X-ray tube
  - Mo, Rh, W targets
  - Mo, Rh, Al filters
  - Be tube window
  - Central axis at chest wall
  - Cathode toward chest wall of patient
- High frequency generator
  - Compact, efficient, reproducible, accurate
  - Minimal voltage ripple, excellent stability

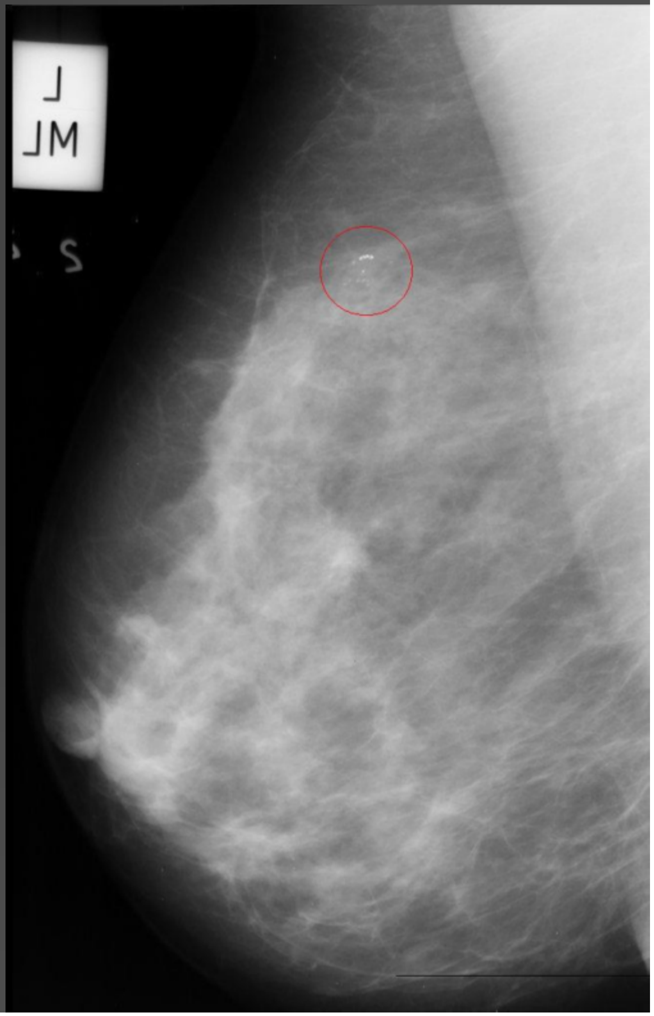
Edge Enhancement



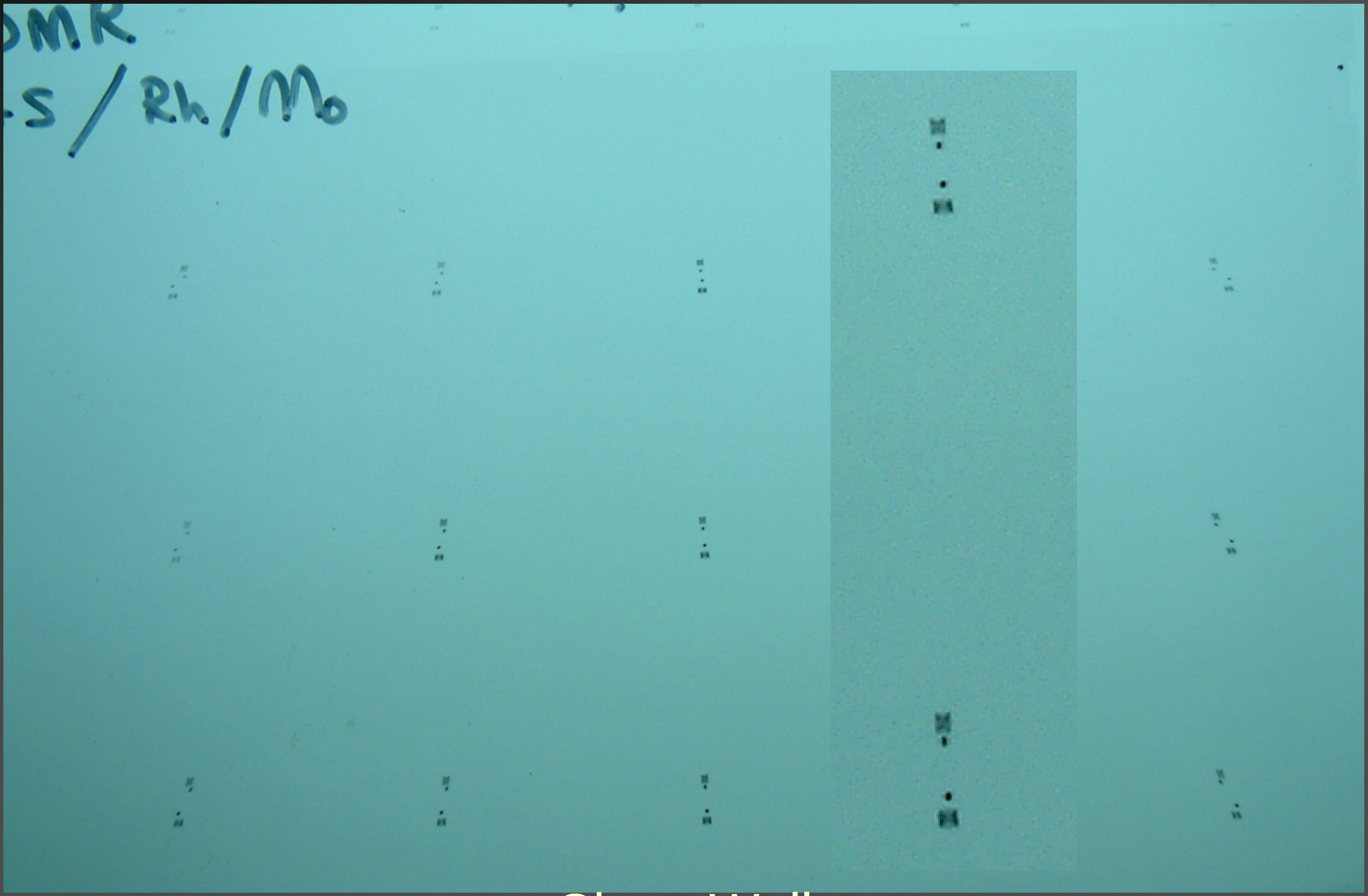
Pathognomonic Signs of Breast Cancer

Small Details With Inherent Low Subject Contrast

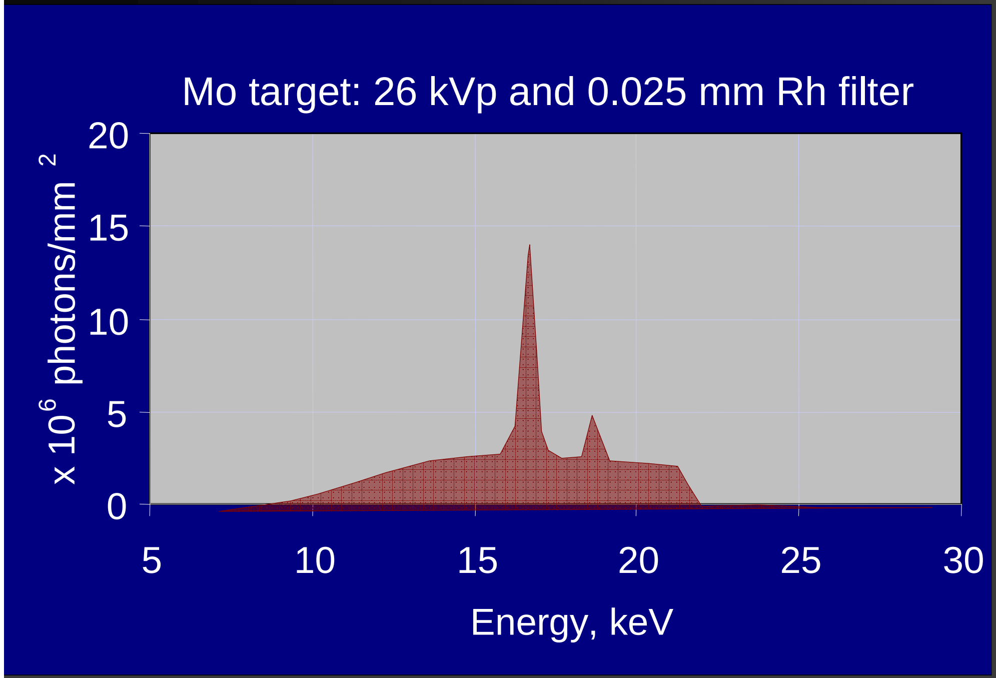
- Masses
  - spiculated
  - shape and margins are important
- Micro-calcifications
  - 100 to 300 microns
  - shape and distribution important
- Asymmetric densities
- Architectural distortions



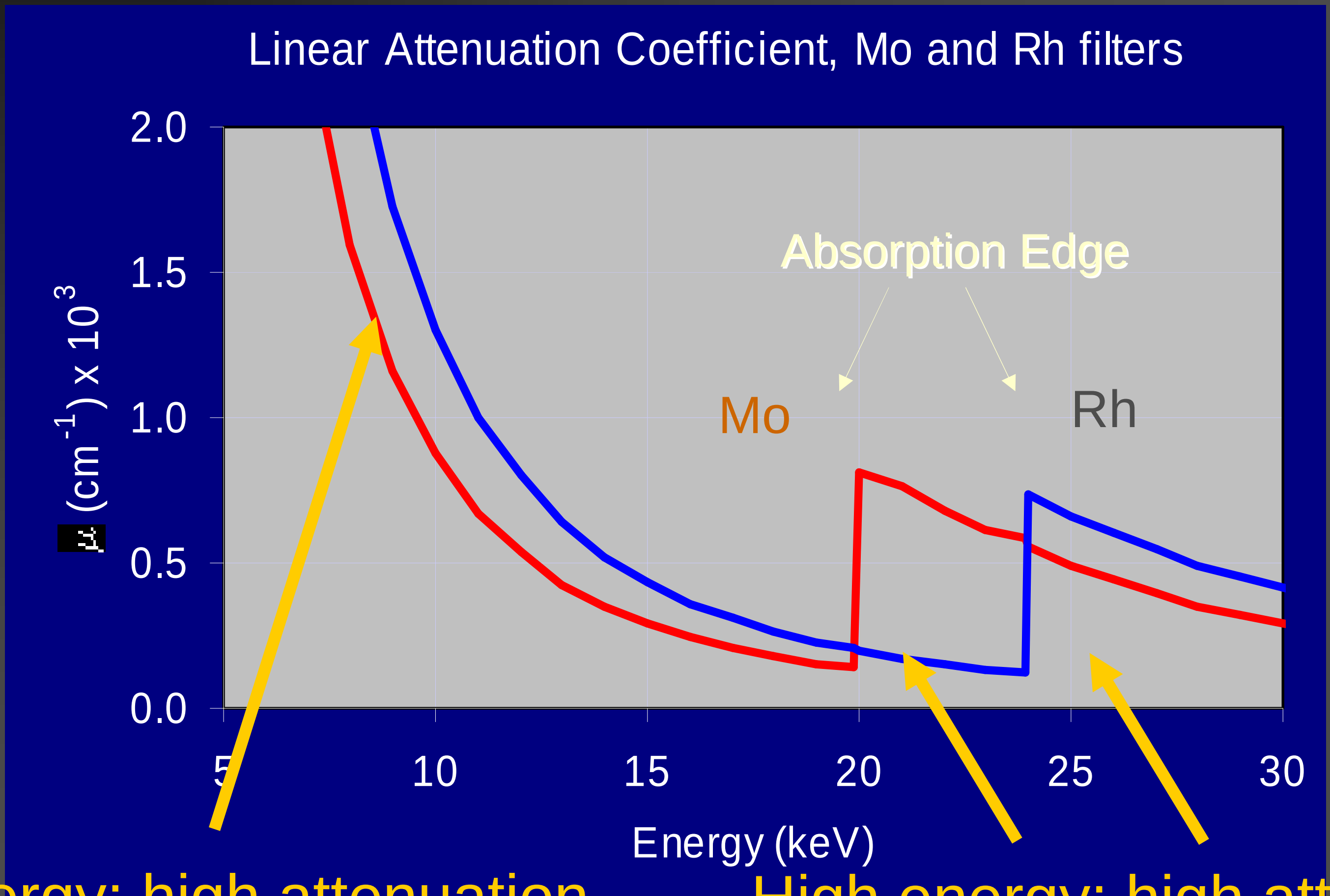
DMR Large/Small Mo/Rh Focal Spot Images



Chest Wall


Mo target: 26 kVp and 0.025 mm Rh filter
x 10^6 photons/mm ^{2}
0
5
10
15
20
5
10
15
20
25
30
Energy, keV

Mo and Rh attenuation filters

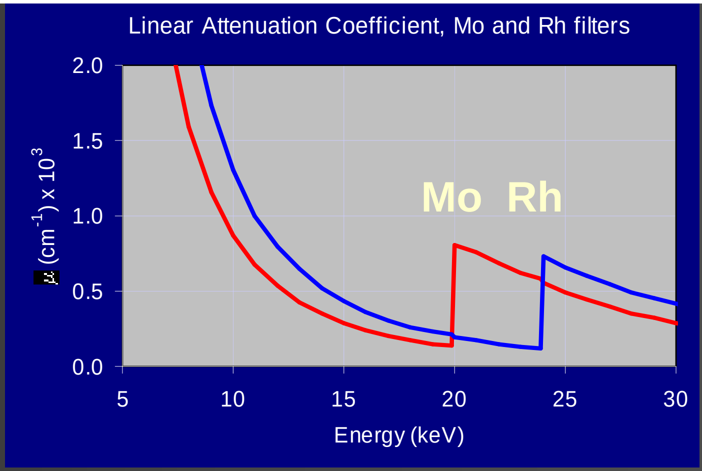


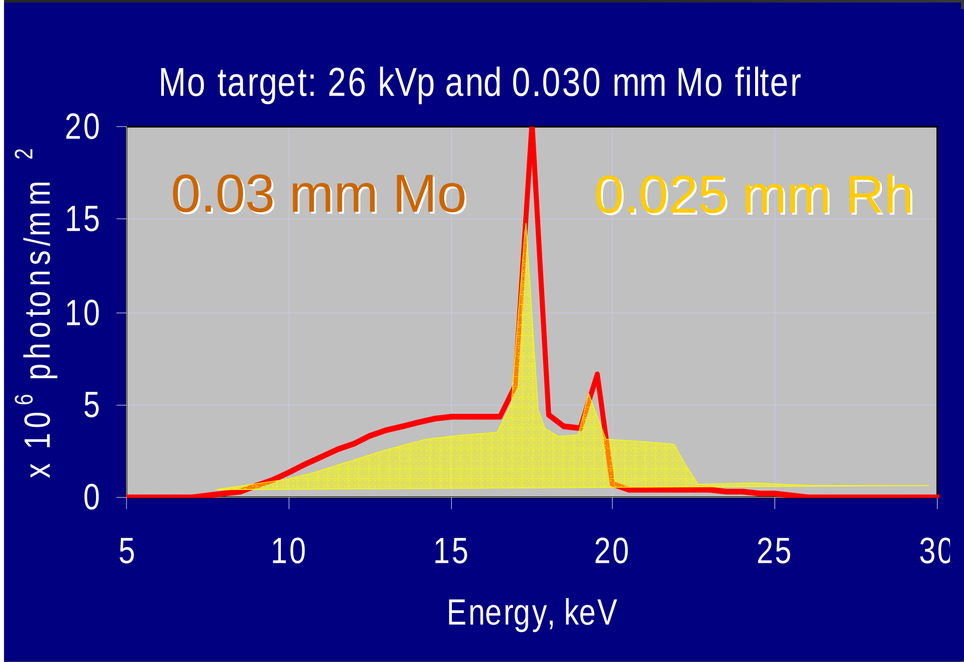
Low energy: high attenuation

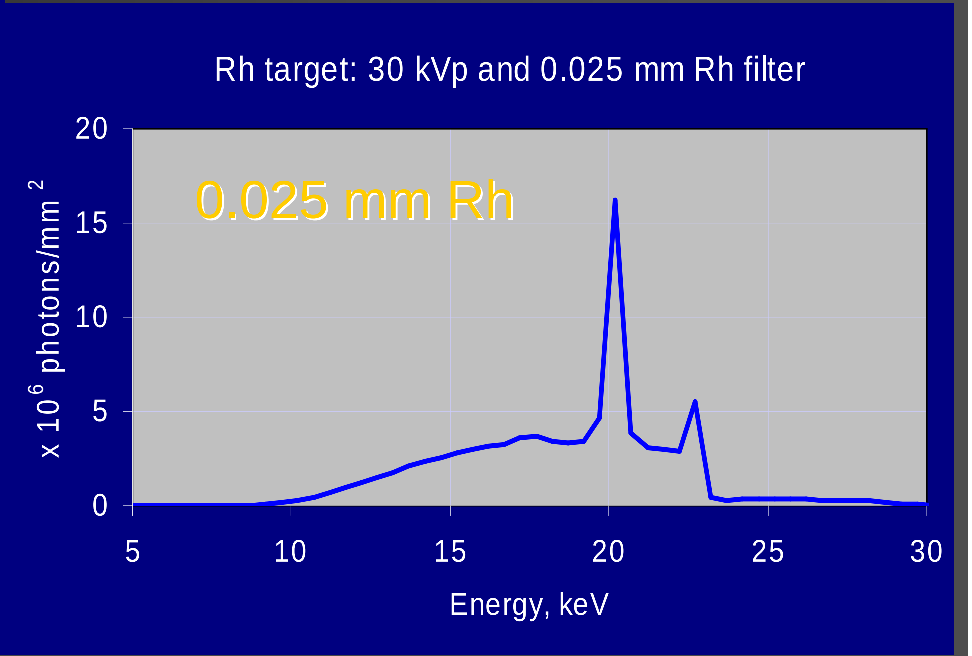
High energy: high attenuation

Slide courtesy of J.A. Seibert

Filtering the spectrum



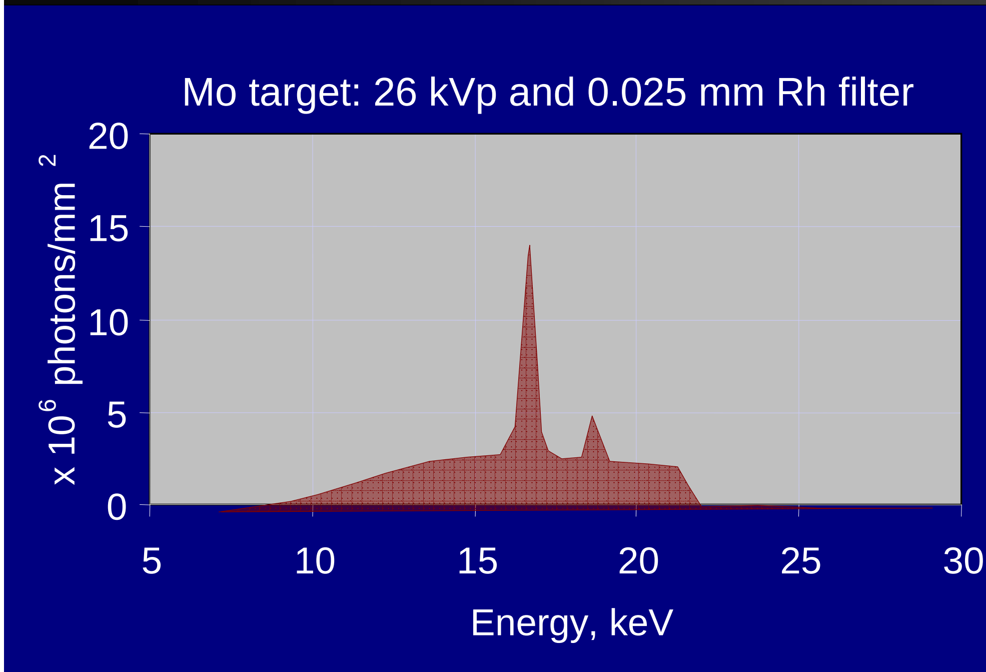


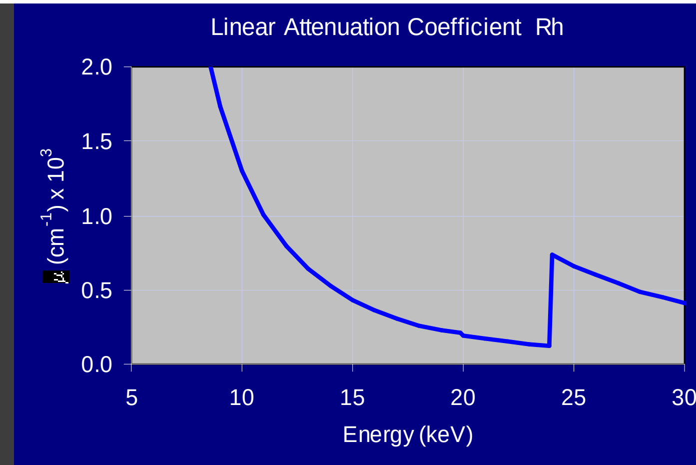


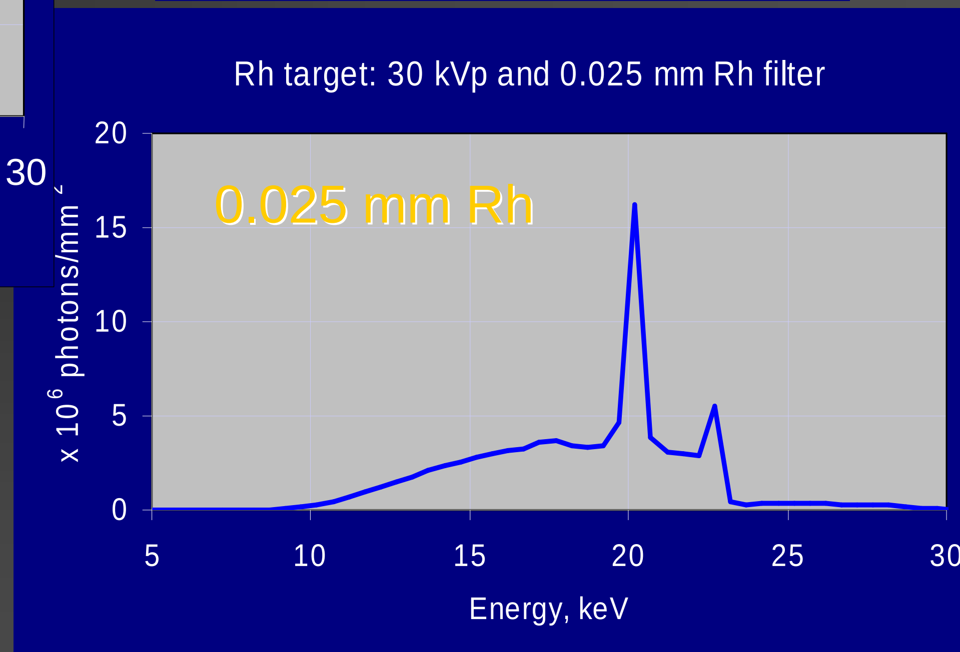
Mo target

Rh target

Slide courtesy of J.A. Seibert





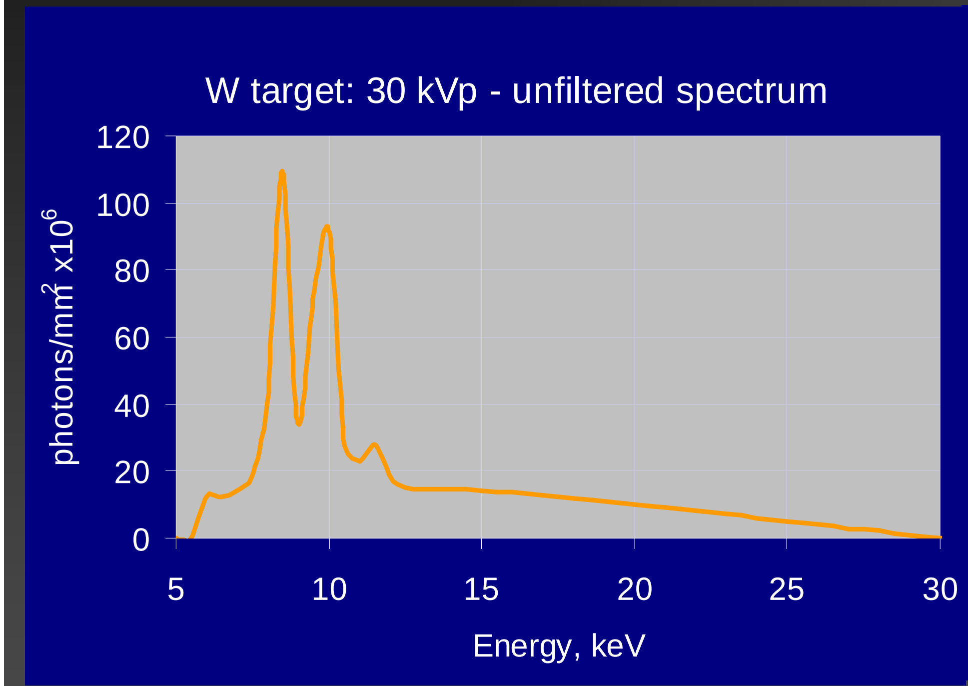


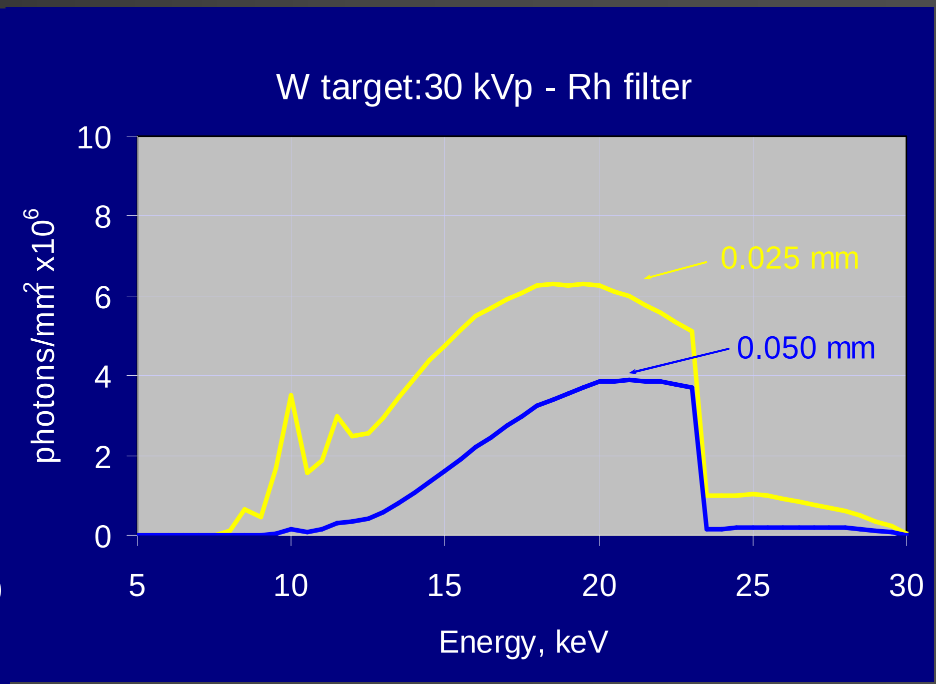
Mo target

Rh target

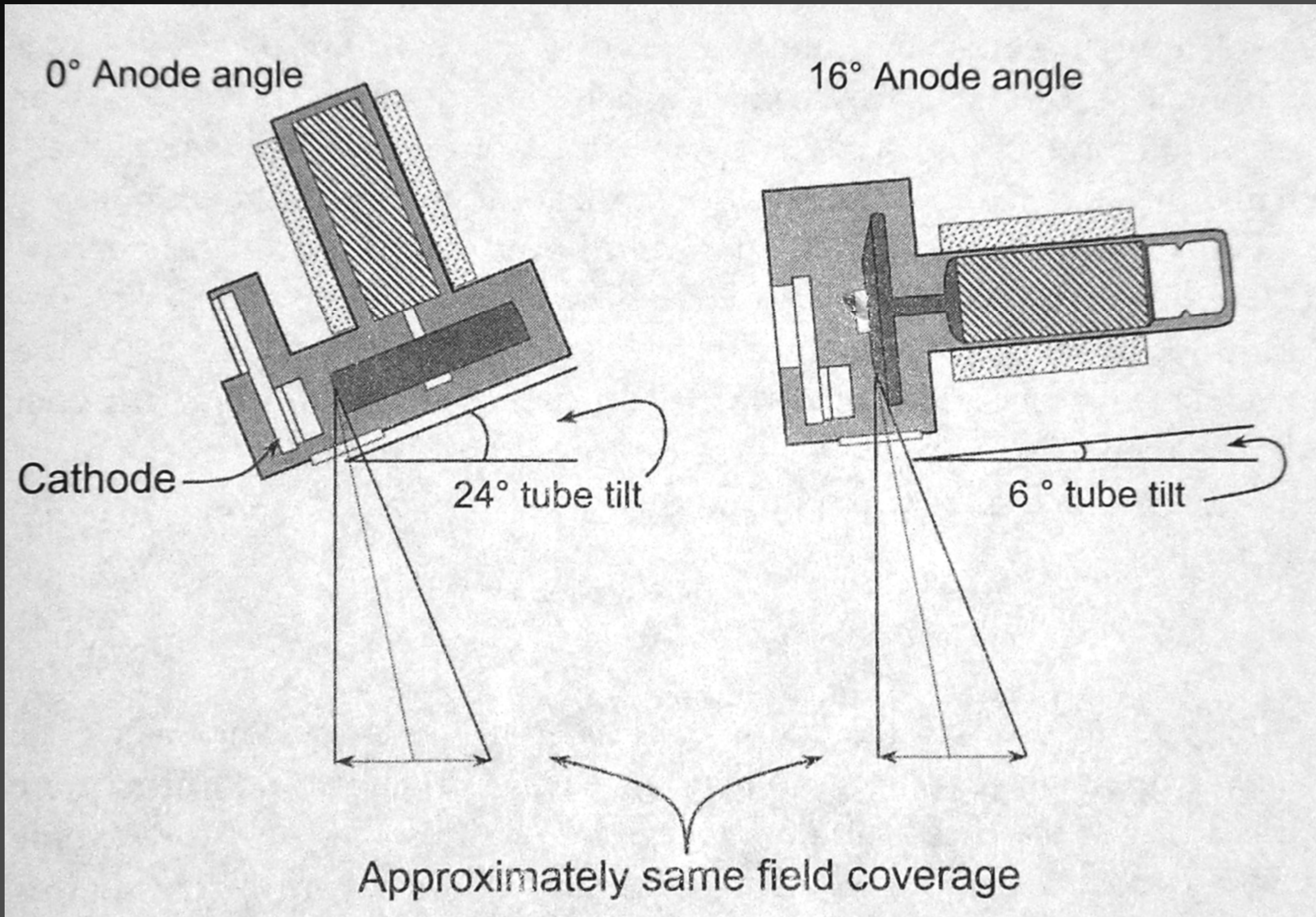
Slide courtesy of J.A. Seibert

Tungsten Target





Slide courtesy of J.A. Seibert

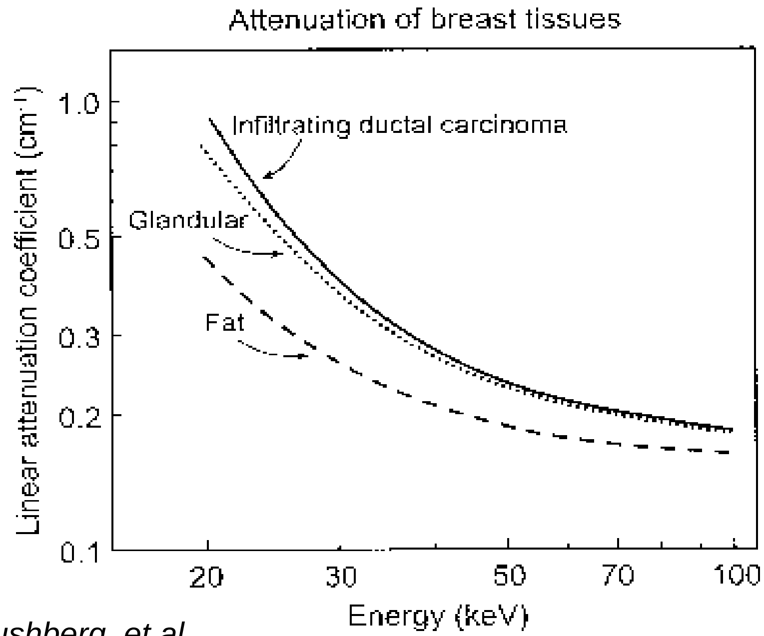


0° Anode angle
16° Anode angle
Cathode
24° tube tilt
6 ° tube tilt
Approximately same field coverage

Topics

- Milestones in Mammography
- The Dedicated Mammography Unit
- Physics of Mammography
  - Subject contrast
  - Target/filter consideration
  - Mammography X-Ray Tube
  - Collimation and scatter rejection
- Film/Screen Characteristics
- Film Viewing
- Mean Glandular Dose

Subject Contrast – Inherently Low



From; Bushberg, et al

- Attenuation properties of gland and cancer are similar and provides little subject contrast
- Micro-calcifications because of size also provide little contrast
- Moreover subject contrast decreases with energy

Subject Contrast Decreases With Increasing Photon Energy

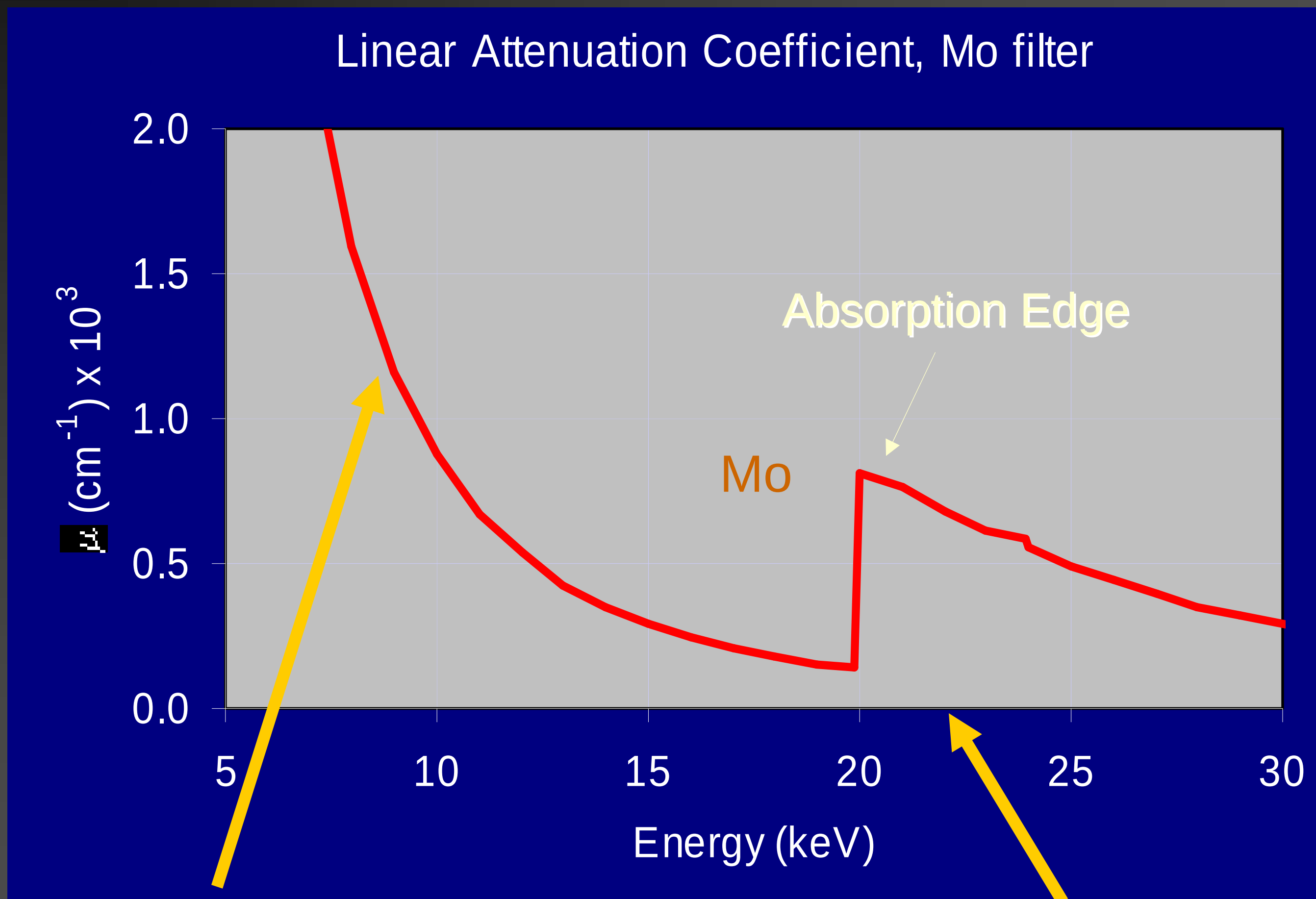
From; Bushberg, et al

Optimum beam energy would be a mono-energetic beam of 15 to 25 keV

Photon Energy to Optimize Contrast at Reasonable Doses is ~ 20 keV

- Mono-energetic beams are not available
- Optimal beams are achieved by use of k-edge filters with molybdenum or rhodium targets
- OBSERVATION
  - A k-edge filter of the *same* element as the target shapes the x-ray beam spectrum to give a quasi mono-energetic beam by reducing the low- and high-energy x-rays in the spectrum

Mo attenuation



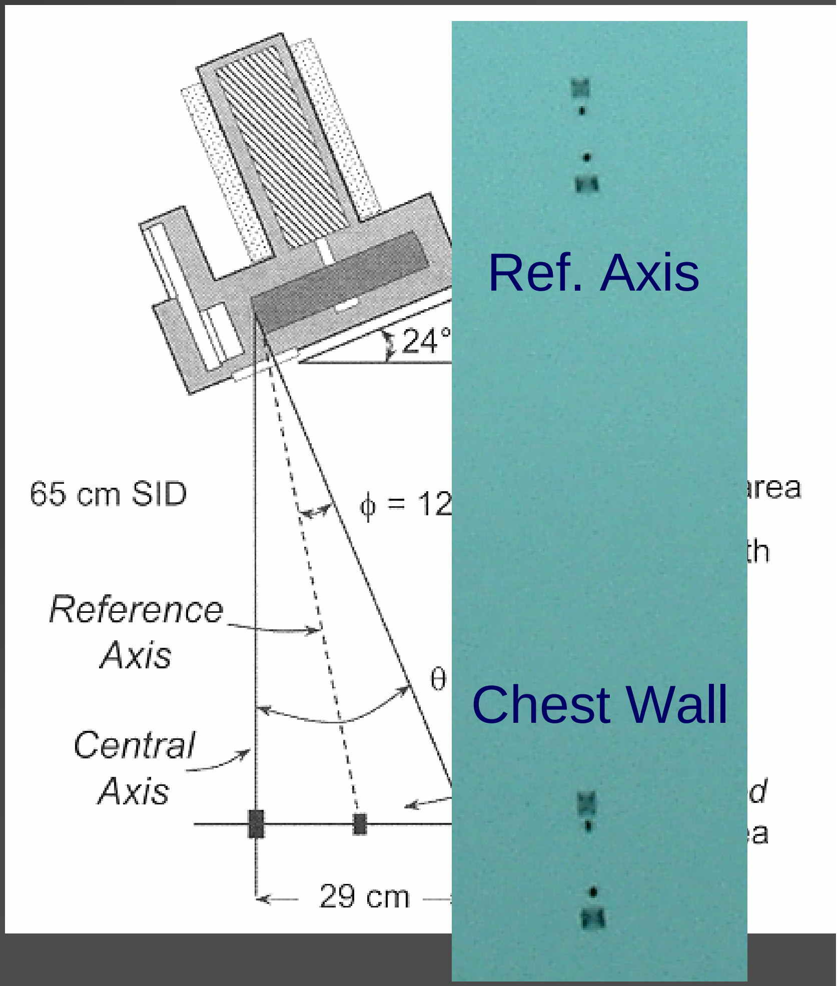
Low energy: high attenuation

High energy: high attenuation

Slide courtesy of J.A. Seibert

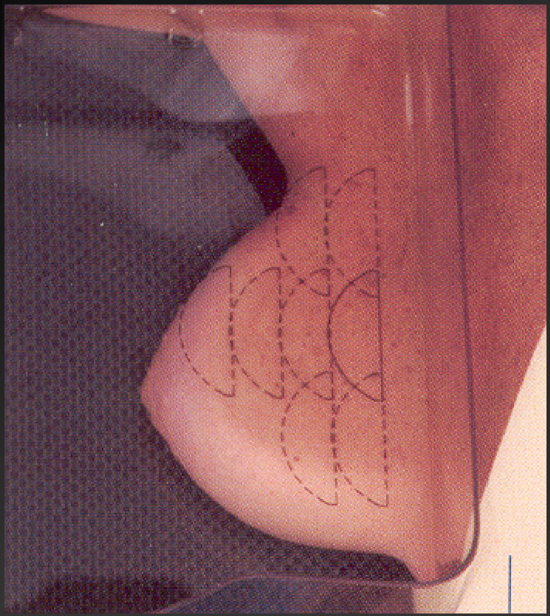
Mammography X-ray Tube

- Projected focal spot sizes
  - 0.3 mm – contact mode
  - 0.1 mm – mag mode
- Central axis and cathode at chest wall
- Projected focal spot size varies along the anode cathode axis
- Focal spot largest at chest wall
- Focal spot size specified on reference axis
- Line pair resolution test is used instead of direct measurement of focal spot size

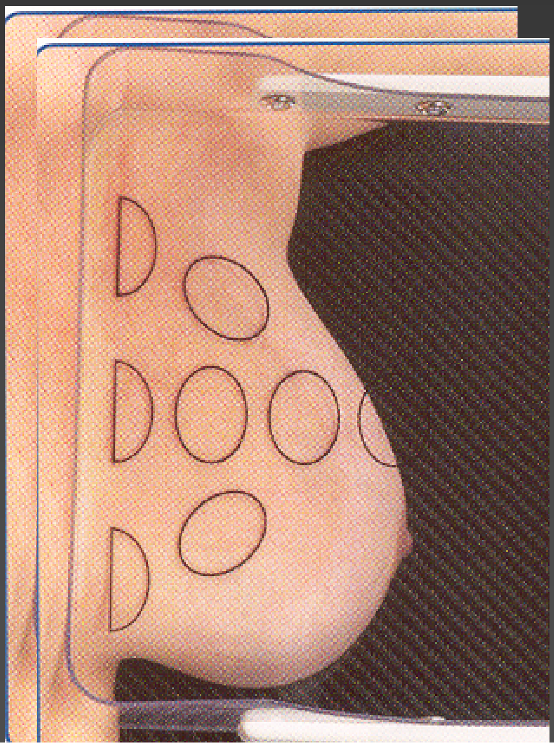


Mammography Recording Systems

- 1972 DuPont Lo-Dose screen-film
  - calcium tungstate screen
  - black polyethylene vacuum bag
  - entrance skin exposure, 1 – 1.5 R
- 1976 DuPont Lo-Dose II
  - rare-earth screen, cassette
- 1976 Kodak MinR
  - rare-earth screen, cassette



GE InstrumentariumVectorPoint
Can be moved off the A-P centerline



8 independent AEC sensors one is chosen at start of exposure

All are multiplexed to a single programmable amplifier

Automatic Exposure Control

- AEC detector is located *underneath* the cassette
  - typical screen exposure is 5 to 10 mR
  - variable sensor position
  - should be under densest tissue
- Modes of operation
  - fixed kVp and target/filter: auto time
  - fixed target/filter: auto kVp and time
  - auto kVp, target/filter and time
- Technique determined using test shot of 100 ms
- Breast thickness transducer is important in some systems