The Physics of Mammography

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Ownership

Statistics are for fiscal year ended June 30, 2011

Parent corporate entity: Geisinger Health System

Main campus: Danville, Pennsylvania

Founded: 1915 by Abigail Geisinger

President and CEO: Glenn D. Steele Jr., MD, PhD

Finances: $2.7 billion revenue

Employees: 14,408

Market Served:

- Central and northeastern Pennsylvania
- 2.6 million population
- 44 of Pennsylvania's 67 counties

Scope:

- Two tertiary/quaternary acute care hospitals (728 beds)
- An alcohol and chemical dependency treatment center
- Thirty-seven community practice sites
- Integrated, multidisciplinary physician practice employing approximately 880 physicians and scientists
- Healthcare insurance provider to over 270,000 members

Patient Care Profile:

- 40,425 discharges from inpatient units
- 35,464 surgery cases
- 86,271 emergency visits
- 2,778 patient air transports
- 3,131 births

History & Overview

History

- 1971 – Founded third-party clinical engineering (CE) business as part of ECRI
- 1984 – Purchased by Geisinger Health System
- 1992 – Information Technology (IT) services business launched
- 2002 – Acquired CHMC to expand IT services
- 2011 – Acquired Medical Integrated Services, Inc. and Stat Services to expand CE services

Overview

- Headquarters: Langhorne, PA
- Employees: 290
- Revenue: $46 Million
- Regional Offices:
  - Wilkes-Barre, PA
  - Danville, PA
  - Cuyahoga Falls, OH
  - Wakefield, MA
  - Jacksonville, FL
- Businesses & Geography:
  - Clinical engineering, IT, and contact center support services for healthcare, government, education, and commercial clients in the United States

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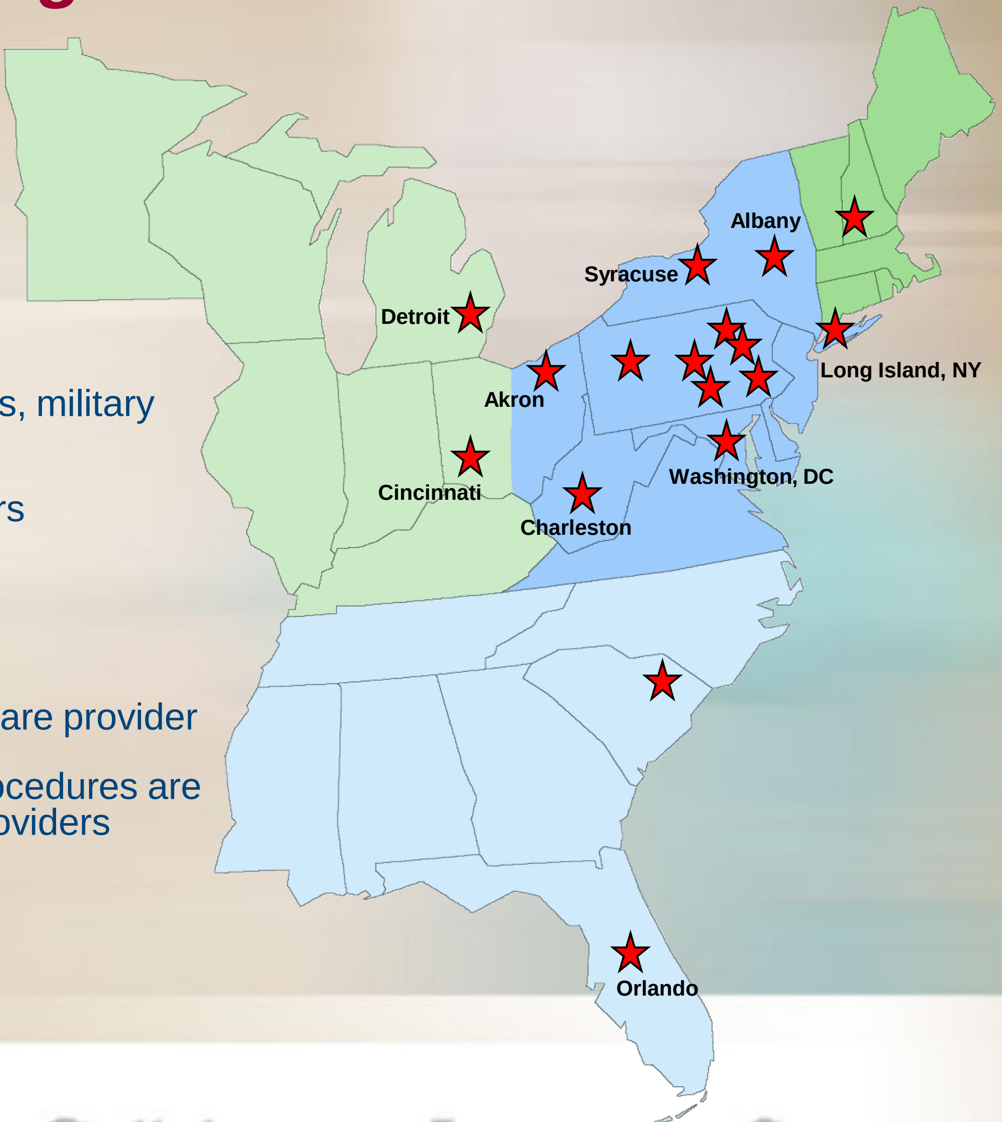
Clinical Engineering: Fast Facts

- 37+ years delivering CE services
- Over 200 healthcare clients
- Core market: Eastern U.S.
- Average client longevity - 14 years
- 130 employees - AAMI certifications, military training, OEM training
- Average employee tenure - 12 years
- State-of-the-art test equipment
- Objective and independent
- Owned by Geisinger $2.3B healthcare provider
- Interests, systems, policies and procedures are aligned with those of healthcare providers



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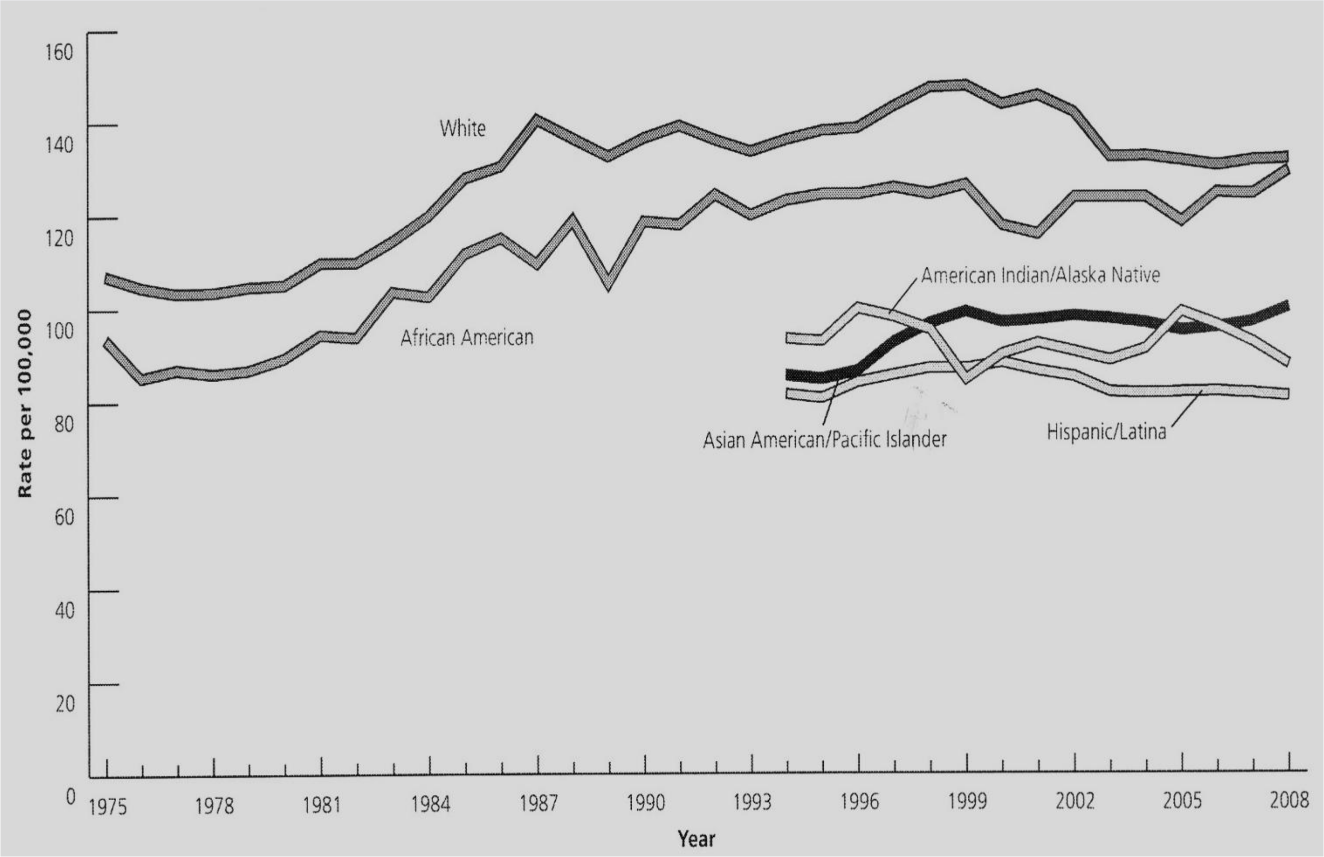
Female Breast Cancer Cases - U.S. 2011

Age	In Situ	Invasive	Deaths
<40	1,780	11,330	1,160
<50	14,240	50,430	5,240
50-64	23,360	81,970	11,620
>65	20,050	98,080	22,660
Total	57,650	230,480	39,520

Source: The American Cancer Society

Breast Cancer Incidence



Source: American Cancer Society

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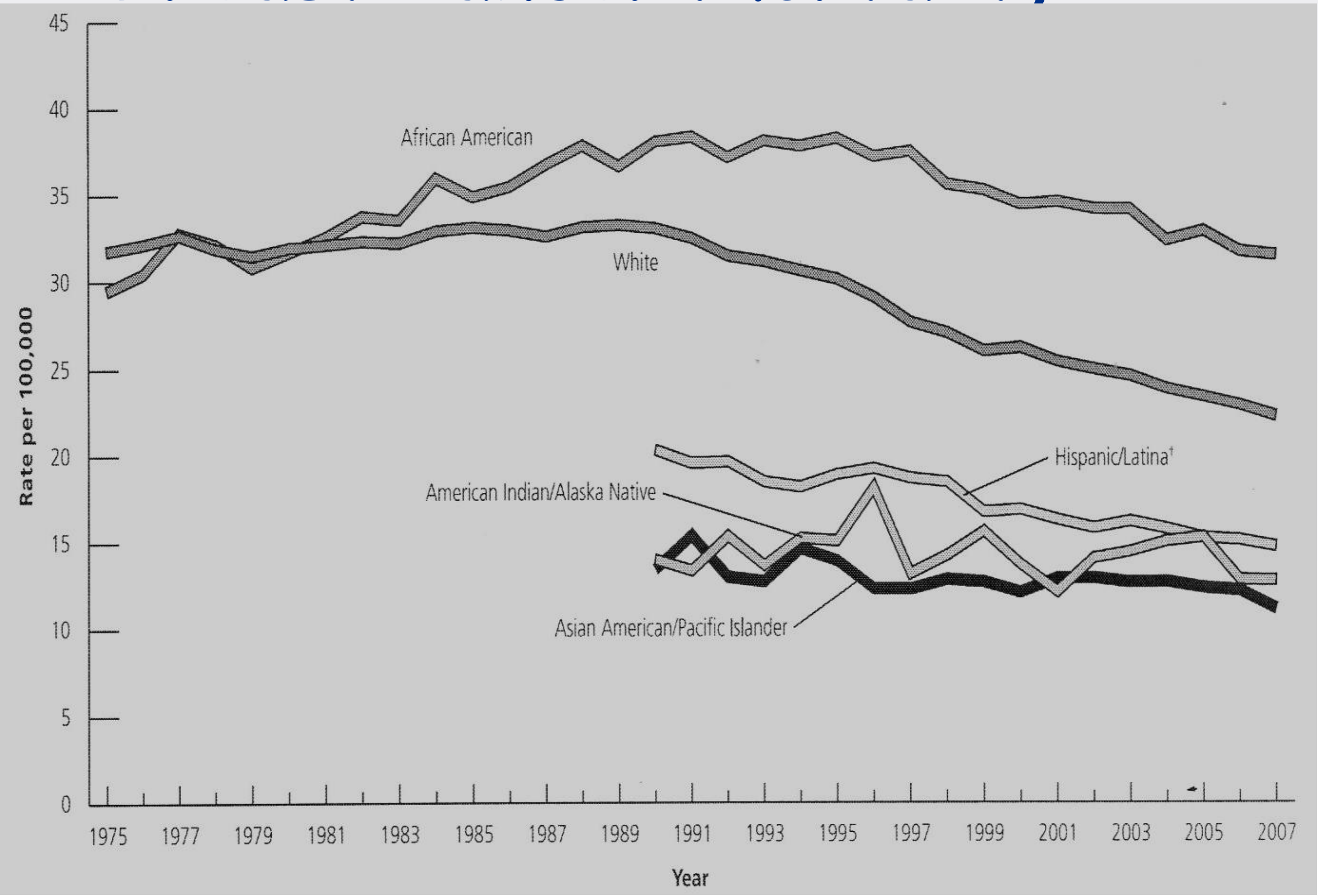
Breast Cancer Mortality



Source: American Cancer Society

The Importance of Screening Mammography

Mammography reduces the risk of dying from breast cancer.

Early detection of breast cancer by mammography also leads to a greater range of treatment options.

Source: American Cancer Society

History of the MQSA

1987

The American College of Radiology (ACR) began the Mammography Accreditation Program (MAP)

History of the MQSA

1992

The ACR produced the ACR
Quality Control Manual

Congress passed the
Mammography Quality Standards Act (MQSA)

Goals of the MQSA

The act sought to correct

(1) Poor quality equipment

(2) Lack of QA procedures

(3) Poorly trained radiologic technologists and radiologists

(4) The lack of facility inspections

History of the MQSA

All facilities were to be certified by October 1, 1994.

The ACR is designated as an accrediting body by the FDA.

In 1999 the ACR issued its revised Quality Control Manual.

MQSA Timeline

- **1987** – ACR Starts MAP
- **1992** – MQSA Passed → ACR Manual → ACR an Accrediting Body
- **1994** – All Facilities to be Certified By FDA
- **1997** – Quality Mammography Standards Final Rule
- **1999** – All Facilities Must Meet Standards → Revised ACR Manual
- **2002** – Tighter Equipment Regulations

MQSA

- States the conditions to be met to become an accrediting body.
- Quality Standards and Certification.
  Requirements for certification.
  Personnel requirements.
  Equipment requirements.
- Conduct of inspections.

Technologist's QC Tests

1.	DICOM Printer QC	Weekly
2.	Detector Flat Field Calibration	Weekly
3.	Artifact Evaluation	Weekly
4.	SNR & CNR Measurements	Weekly
5.	Phantom Image	Weekly
6.	Compression Thickness Indicator	Bi-weekly
7.	Diagnostic Review Workstation QC	Weekly
8.	Viewboxes and Viewing Conditions	Weekly
9.	Visual Check List	Monthly
10.	Repeat/Reject Analysis	Quarterly
11.	Compression	Semi-annually

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Medical Physicist's Inspection

1. Mammographic Unit Assembly Evaluation
2. Collimation Assessment
3. Artifact Evaluation
4. kVp Accuracy & Reproducibility
5. Beam Quality Assessment (HVL)
6. Evaluation of System Resolution
7. Automatic Exposure Control Performance
8. Breast Entrance Exposure, AEC Reproducibility, AGD
9. Radiation Output Rate
10. Phantom Image Quality Evaluation
11. SNR/CNR Measurements
12. Diagnostic Review Workstation QC
13. Detector Ghosting

Clinical Engineer Standards

No qualifications stated in MQSA

HOWEVER

Must understand the units he/she services

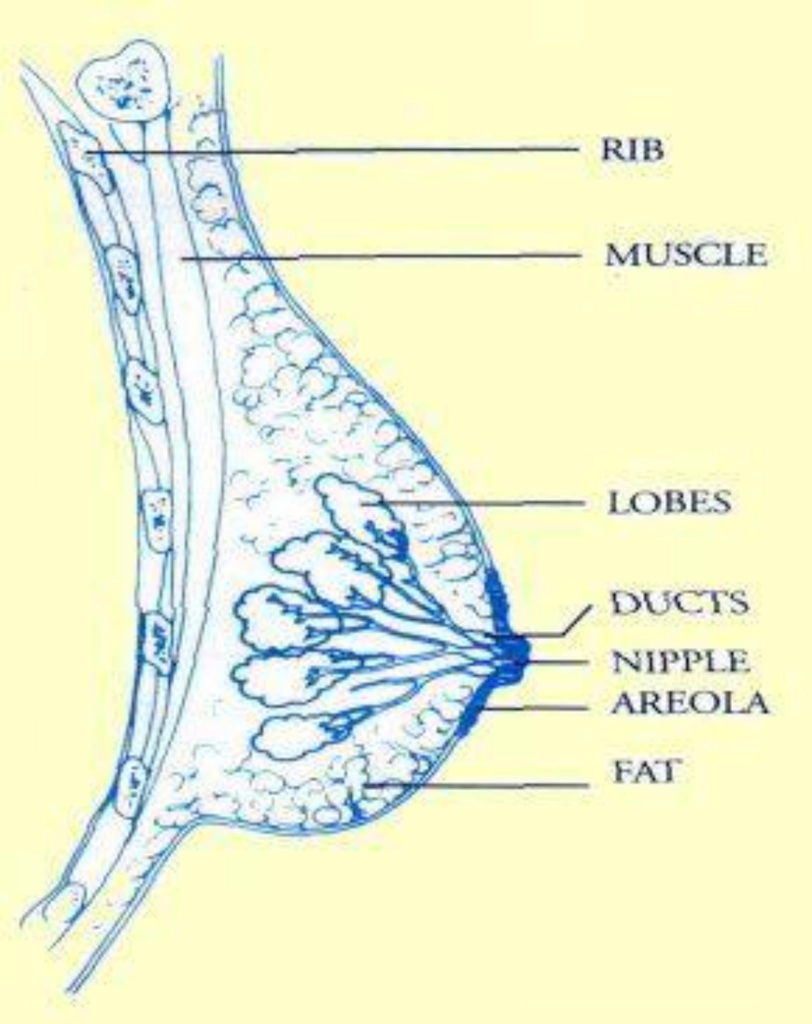
Must perform setup and calibration properly

Must do regular QA and maintenance

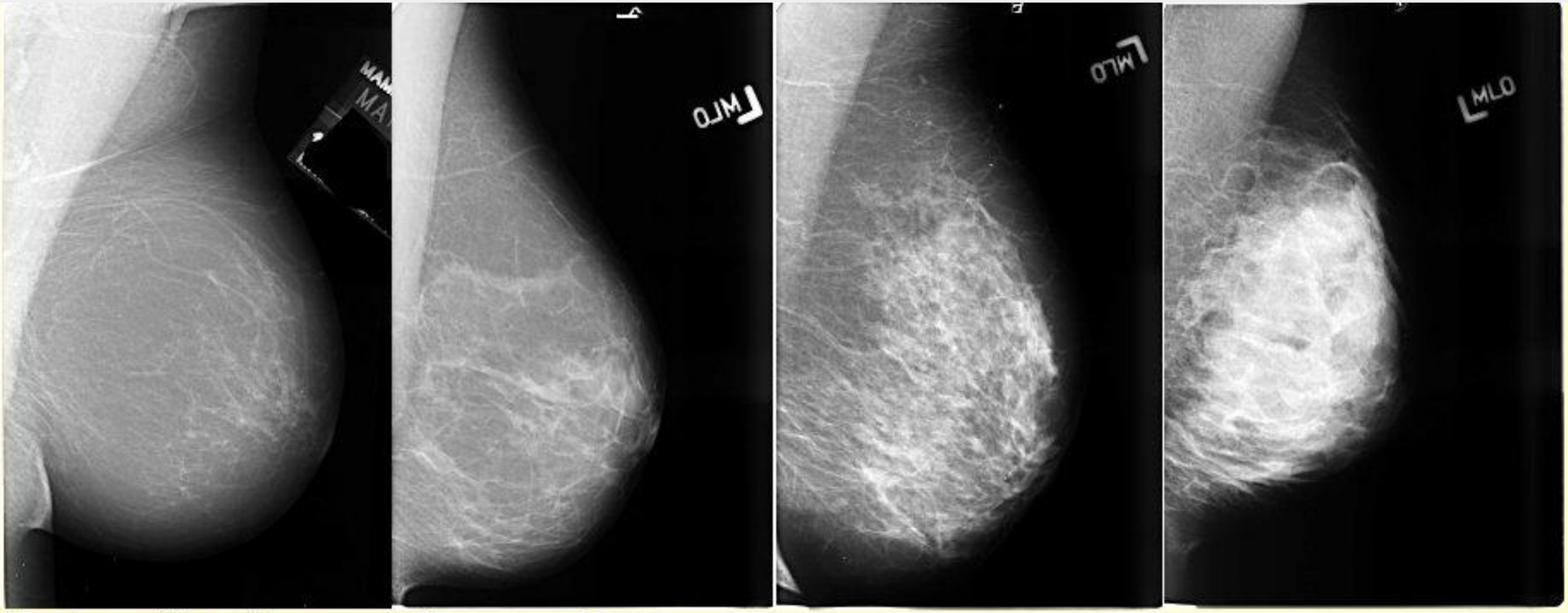
Failure of some tests requires that the machine be repaired and retested by a medical physicist prior to being used. They include:

- Average glandular dose exceeding 3 mGy
- Resolution failure
- Phantom image failure due to equipment
- SNR or CNR poor
- Collimator or blade replacement
- AEC (replacement, sensor replacement)
- X-ray tube replacement
- kVp, mA, timer adjustments

The Breast



Images of Normal Breasts

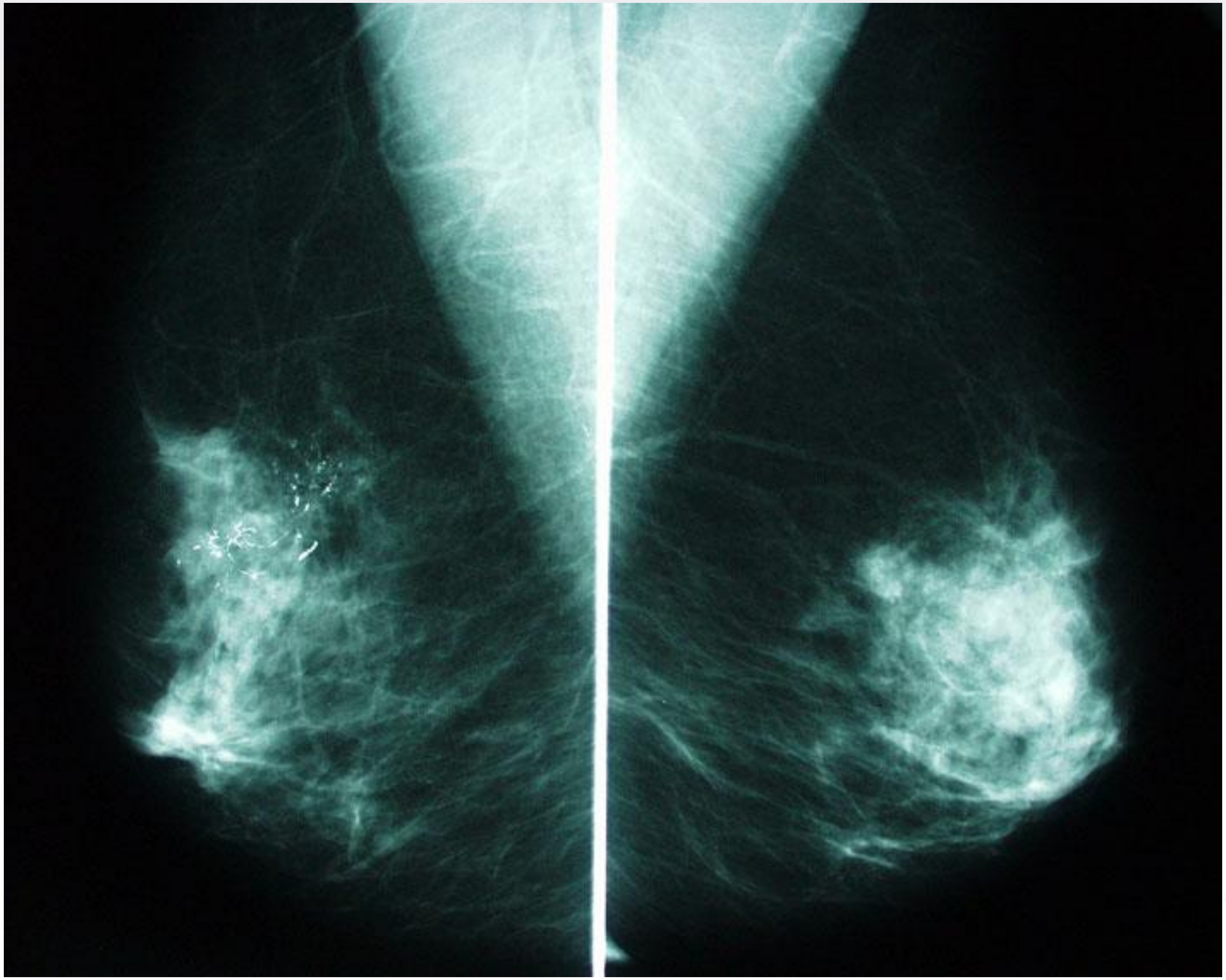


Breast composition and its mammographic appearance.[1]

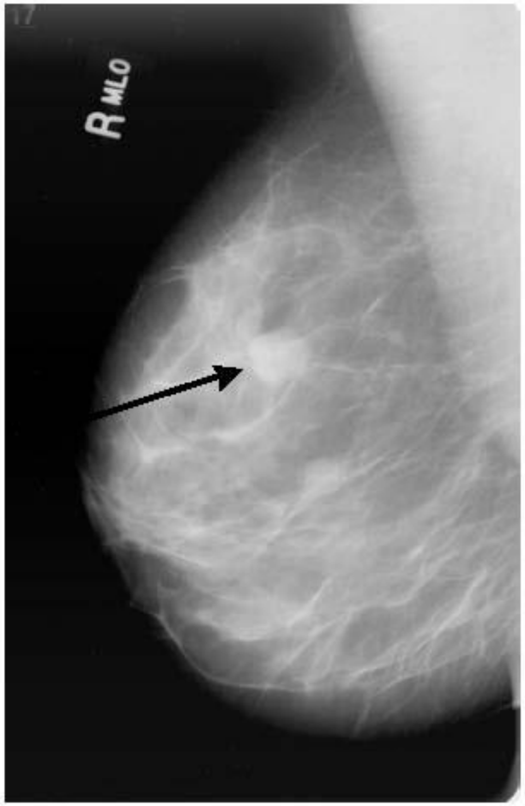
Benign Calcification

Calcifications may be as small as 0.2 mm.

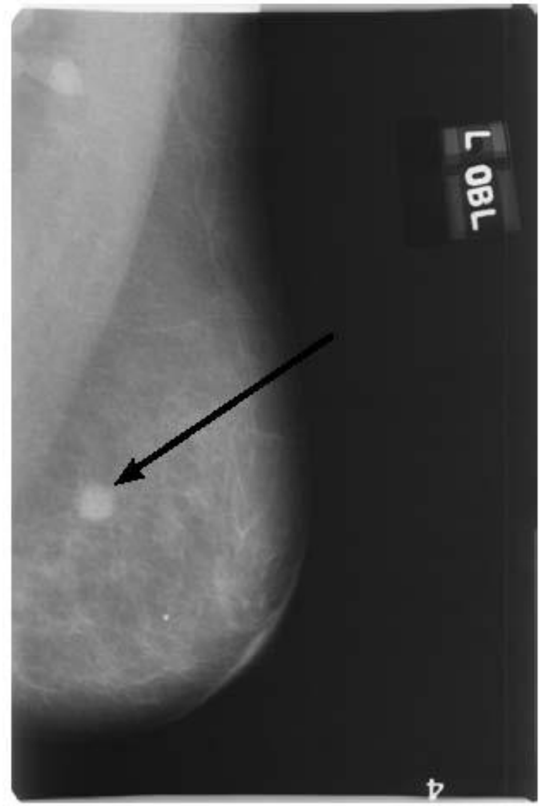
Malignant Calcification



Benign and Malignant Masses



Benign mass



Malignant mass

Digital Mammography Superior to Film Mammography

Digital mammography better than film mammography for women in any of these categories:

- Under age 50 (independent of breast density)
- Any age with very dense breast tissue
- Pre- or perimenopausal* women of any age

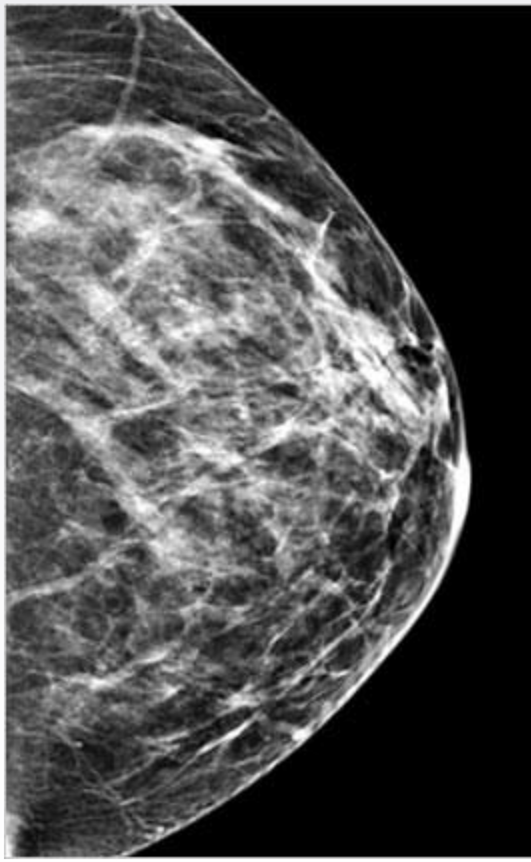
*Defined as women who had a last menstrual period within 12 months of their mammograms.

No Apparent Benefit of Digital Over Film Mammography

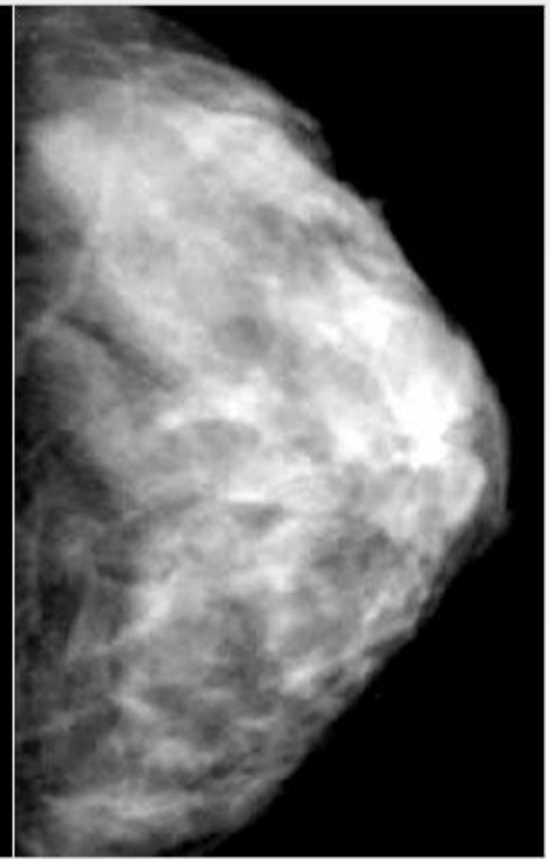
No apparent benefit of digital over film mammography for women who fit ALL of the following categories

- Over age 50
- Do not have dense or heterogeneously (very dense) breast tissue
- Those who are not still menstruating

Digital vs Film-Screen Mammograms



Digital



Film-Screen

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Physics

X-ray – Matter Interactions

Compton Scatter

Arthur H. Compton

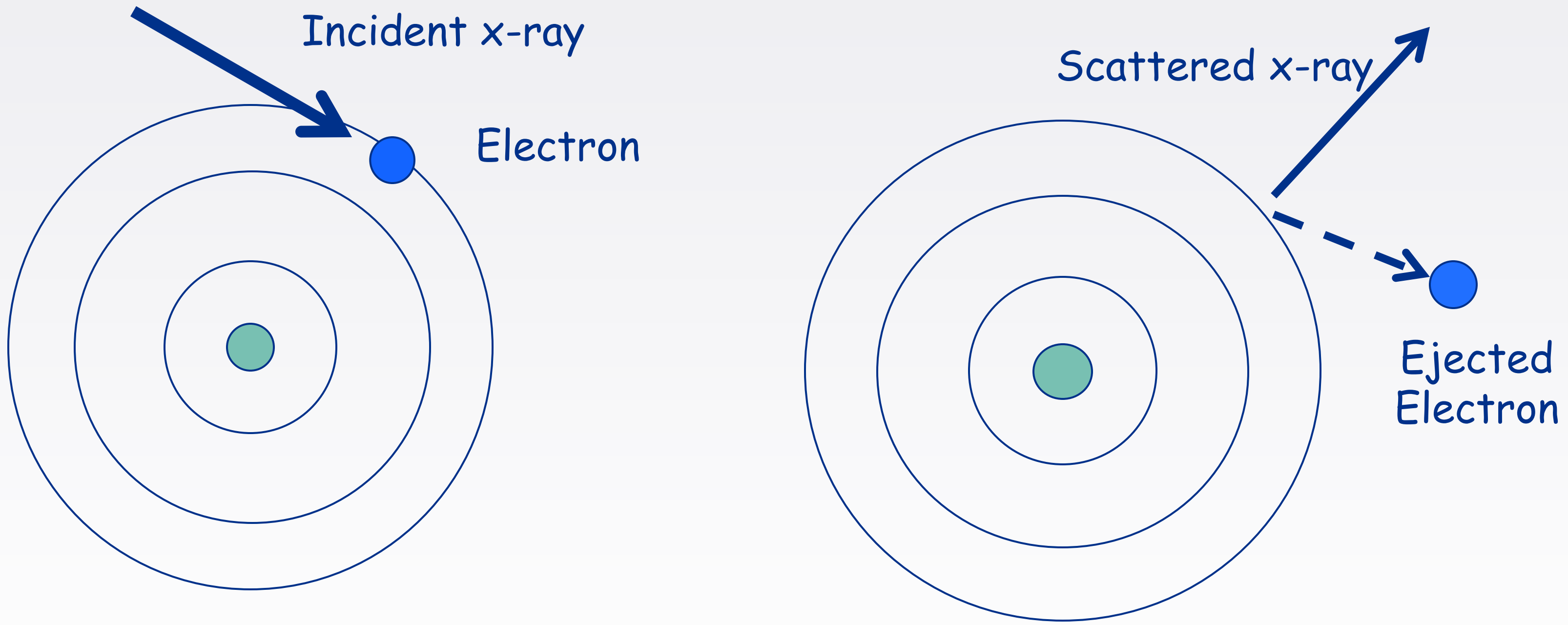
Nobel Prize, 1927

Photoelectric Effect

Albert Einstein

Nobel Prize, 1921

Compton Scatter



X-ray Interacts with Outer Shell Electron

X-ray Scatters and Electron is Ejected

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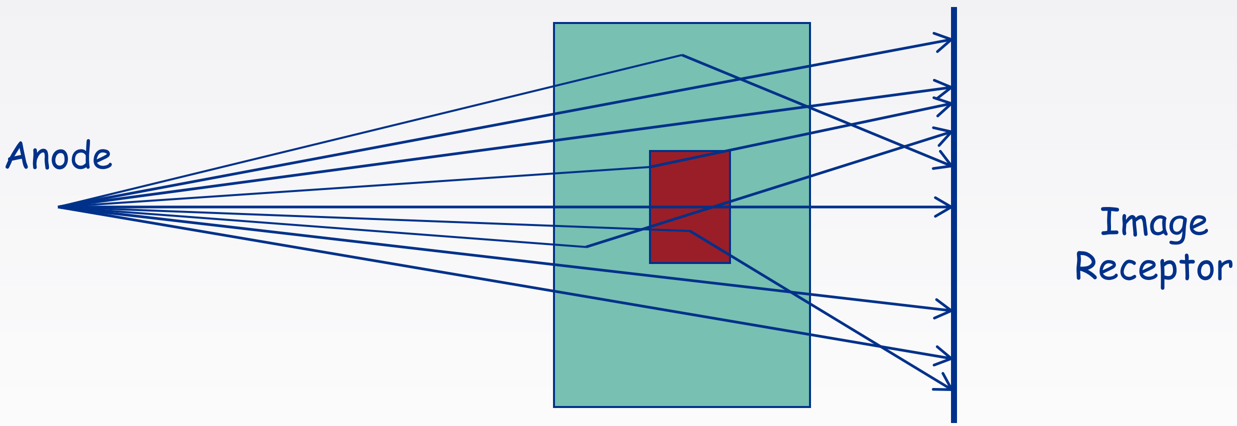
Compton Scatter

How Scatter Affects Image Quality



Compton Scatter

Factors that affect Compton Scatter

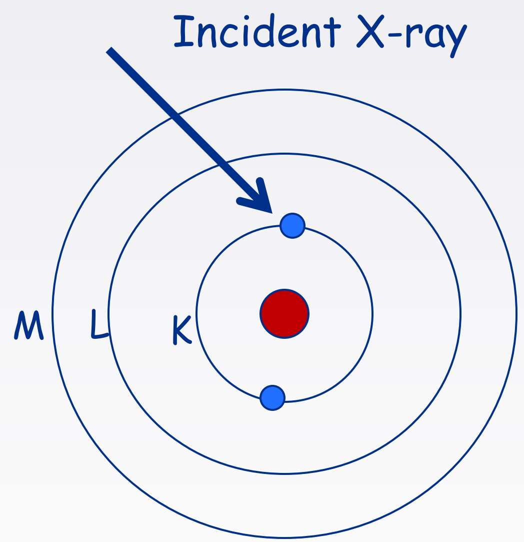
Almost independent of atomic number.

Slightly more likely to occur in bone than soft tissue.

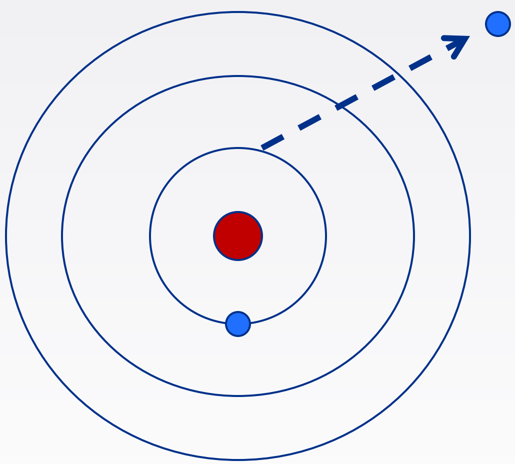
Somewhat energy dependent in the diagnostic range.

Less likely to occur than photoelectric effect at mammography energies.

Photoelectric Effect



X-ray Interacts with K-shell Electron



All X-ray Energy Given to Electron and Electron Ejected

Photoelectric Effect

Probability of Effect Occurring

Probability approximately proportional to Z^3 where Z is the atomic number of the absorber.

Probability approximately proportional to $1/E^3$ where E is the energy of the photon.

Photoelectric Effect

Probability of Photoelectric Effect in Bone Rather than Muscle

Average Atomic Number of Muscle = 7.16
Average Atomic Number of Cortical Bone = 10.83

$$P = \left(\frac{10.83}{7.16}\right)^3 = 3.5$$

Photoelectric Effect

Probability of Photoelectric Effect in Breast Rather than Adipose (Fat) Tissue

Average Atomic Number of Breast Tissue = 6.60
Average Atomic Number of Adipose Tissue = 6.02

$$P = \left(\frac{6.60}{6.02} \right)^3 = 1.3$$

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Definition

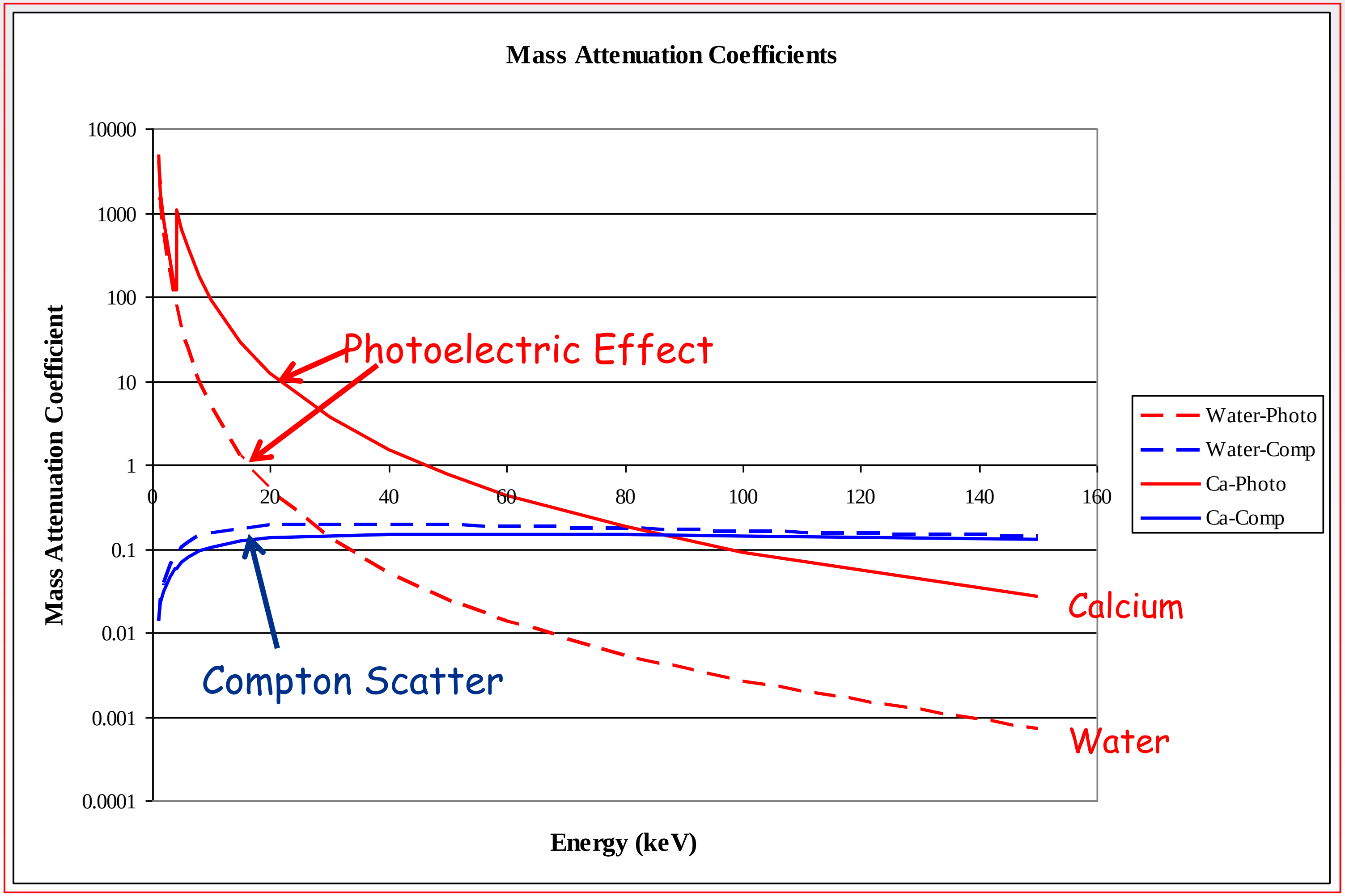
Linear Attenuation Coefficient, μ.
The fraction of photons that interact per unit thickness of absorber.

The mass attenuation coefficient, μ_m

$\mu_m = \dfrac{\mu}{\rho}$ where ρ is the density.

μ_m is independent of the density of the absorber.

Comparison of Photoelectric Effect and Compton Scatter



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X-ray Absorption in Matter

$$I = I_0 e^{-\mu x}$$

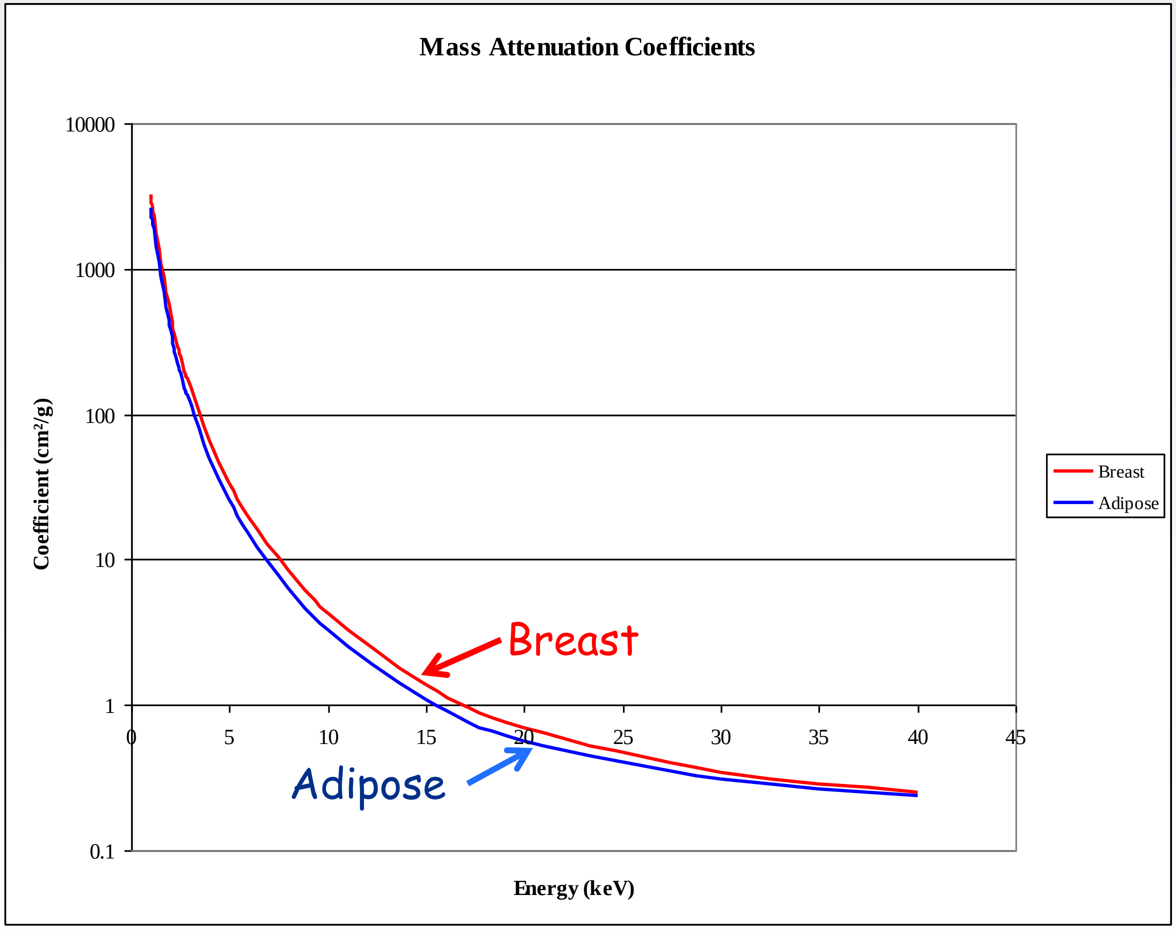
Where I_0 = intensity incident on absorber

X = thickness of absorber

μ = linear attenuation coefficient

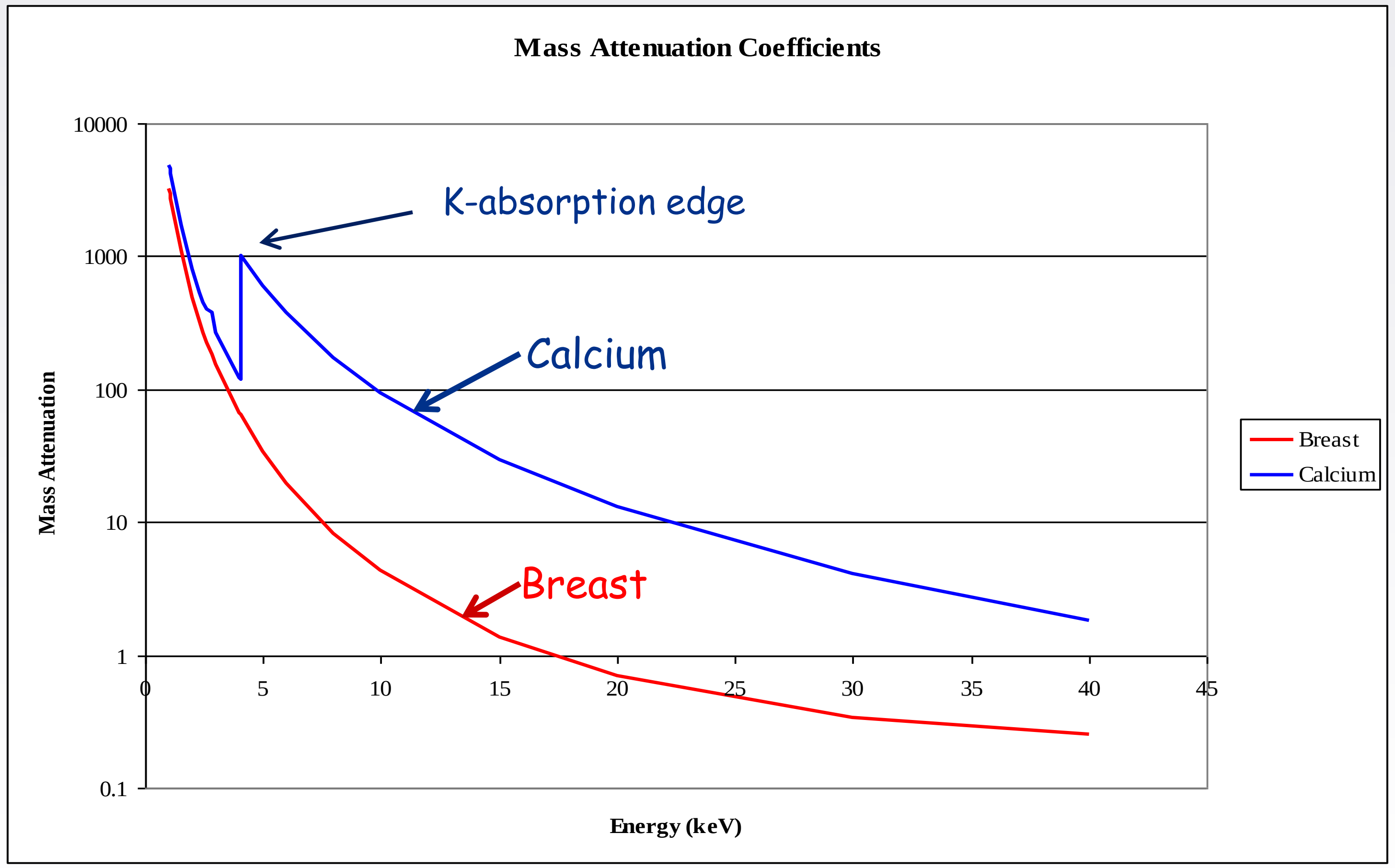
I = intensity of the exiting beam

Mass Attenuation Coefficients



Mass Attenuation Coefficients of Breast and Fat

Mass Attenuation Coefficients



Mass Attenuation Coefficients of Breast and Calcium

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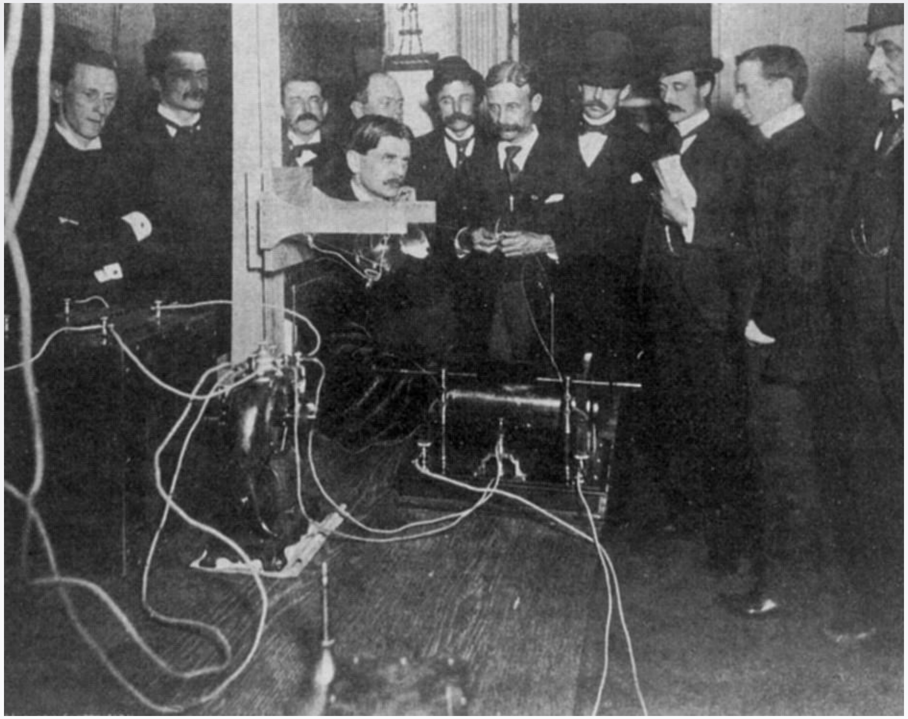
Rules for Mammography

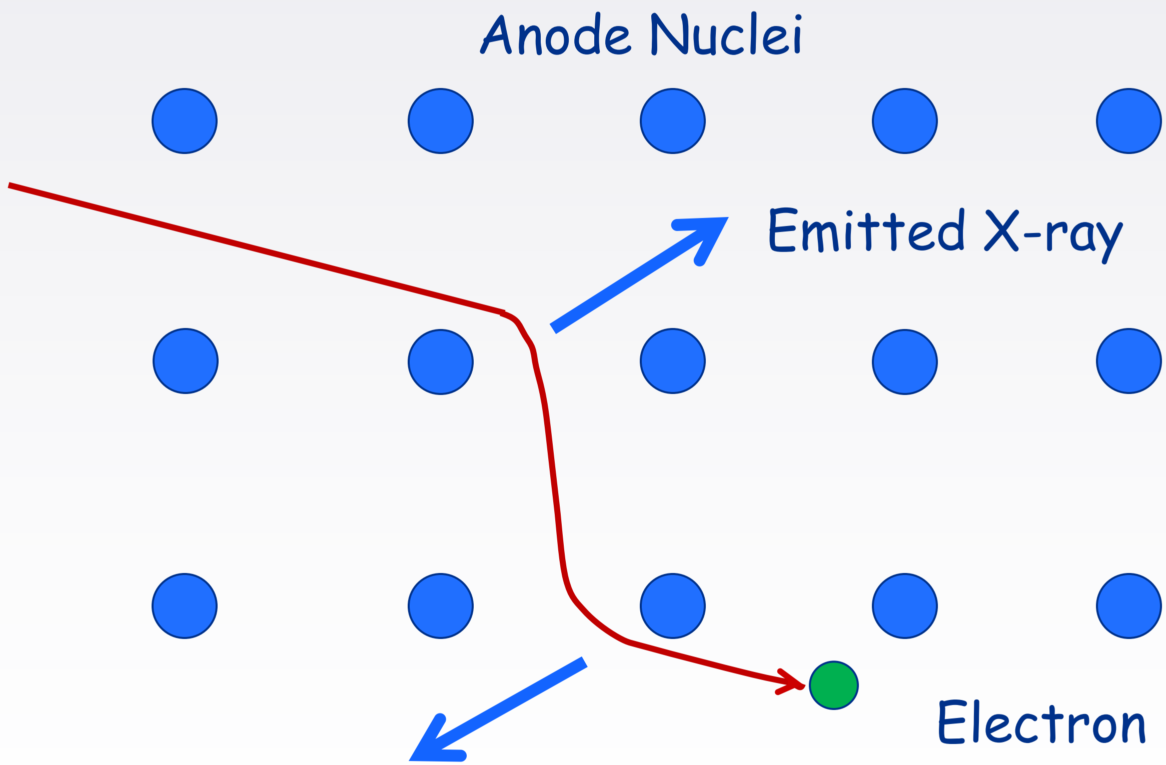
Rule 1

Mammography should be done at low kVp to produce the greatest image contrast.



Production of X-rays

Production of Bremsstrahlung



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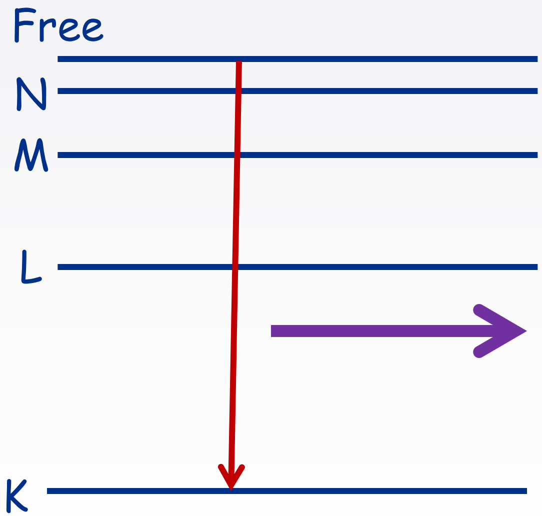
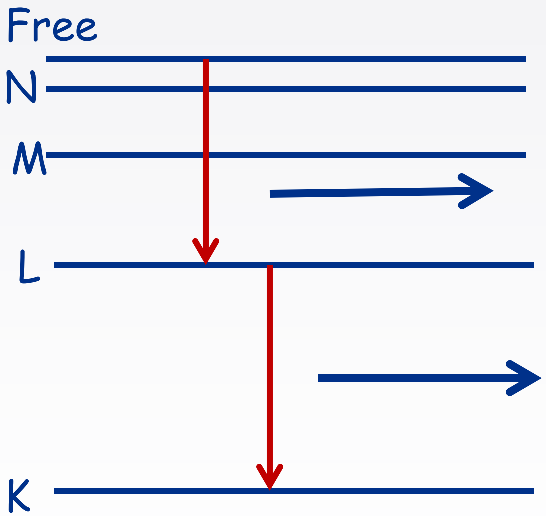
Production of Characteristic Radiation

Energy Level Diagrams



Free electron jumps to K shell with x-ray emission



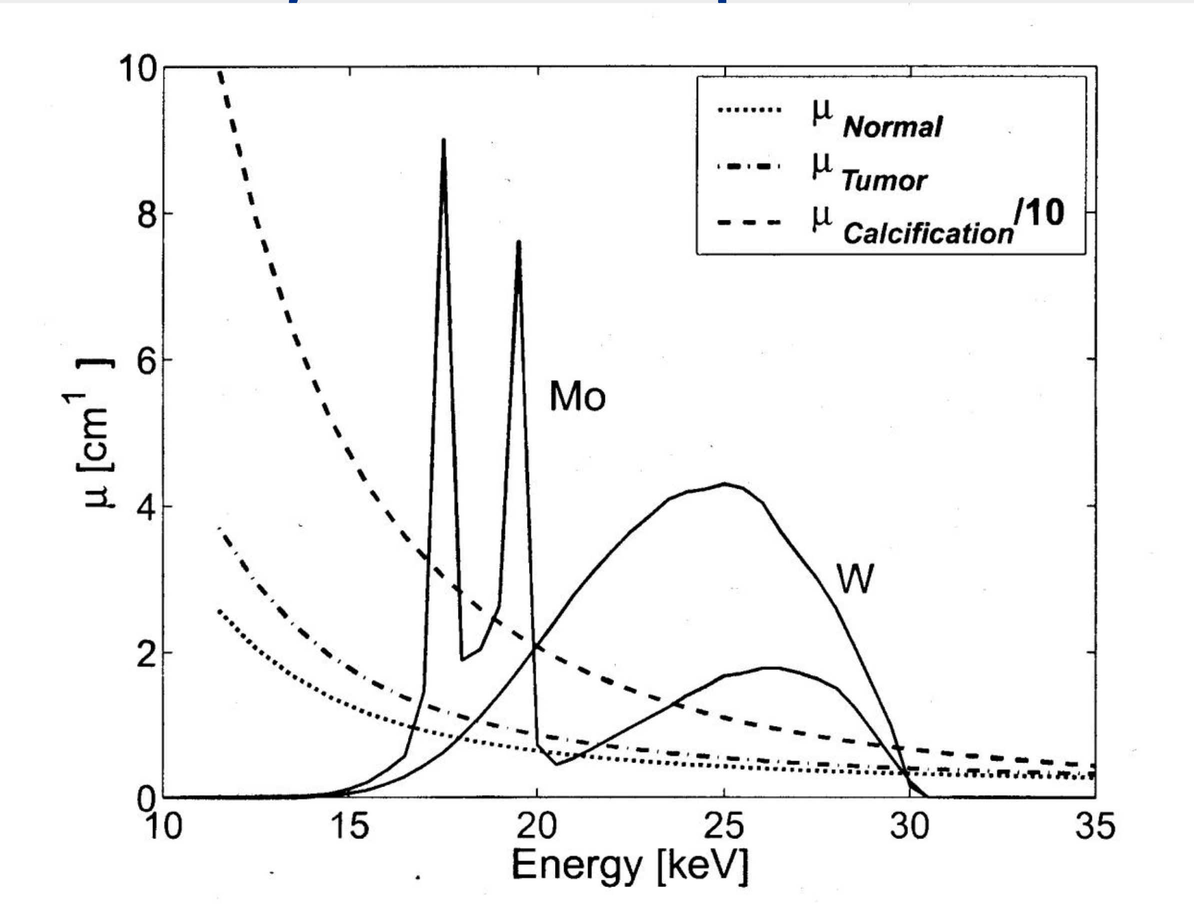
Free electron jumps to L shell then K shell with two x-ray emission

Rules for Mammography

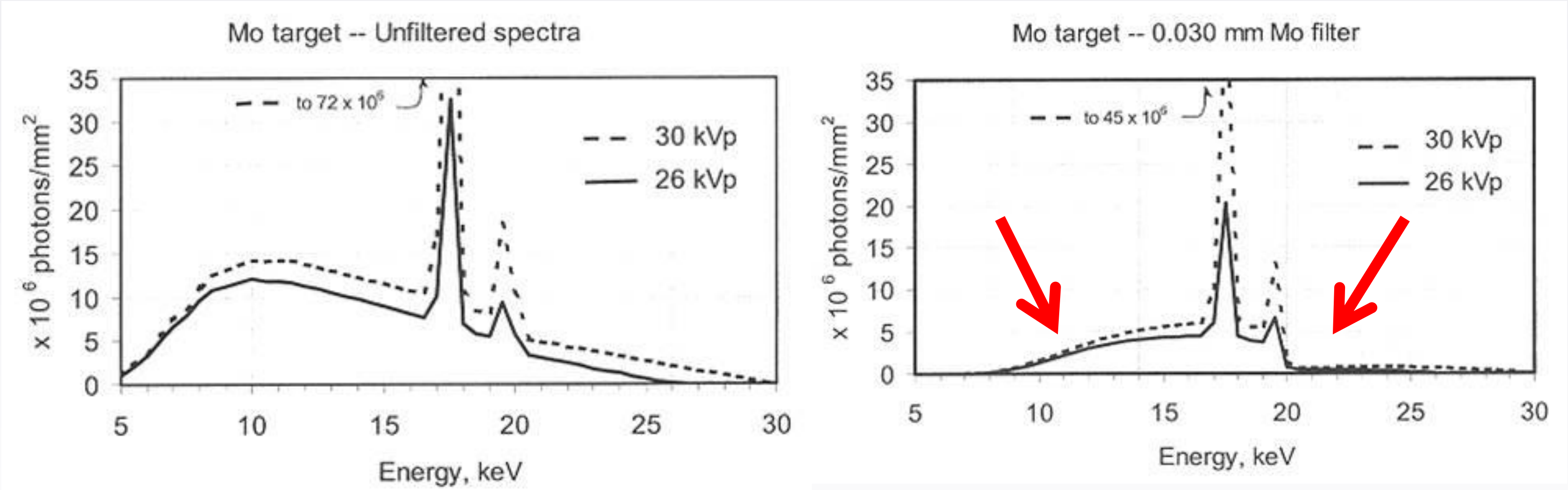
Rule 2

Find an anode material that produces a lot of x-rays in the energy range 15 to 30 keV.

Molybdenum Spectrum



Effect of Added Filtration



Note the effect of filtration on Bremsstrahlung

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Rules for Mammography

Rule 3

Use an appropriate filter to remove low energy bremsstrahlung radiation.

Image Sharpness

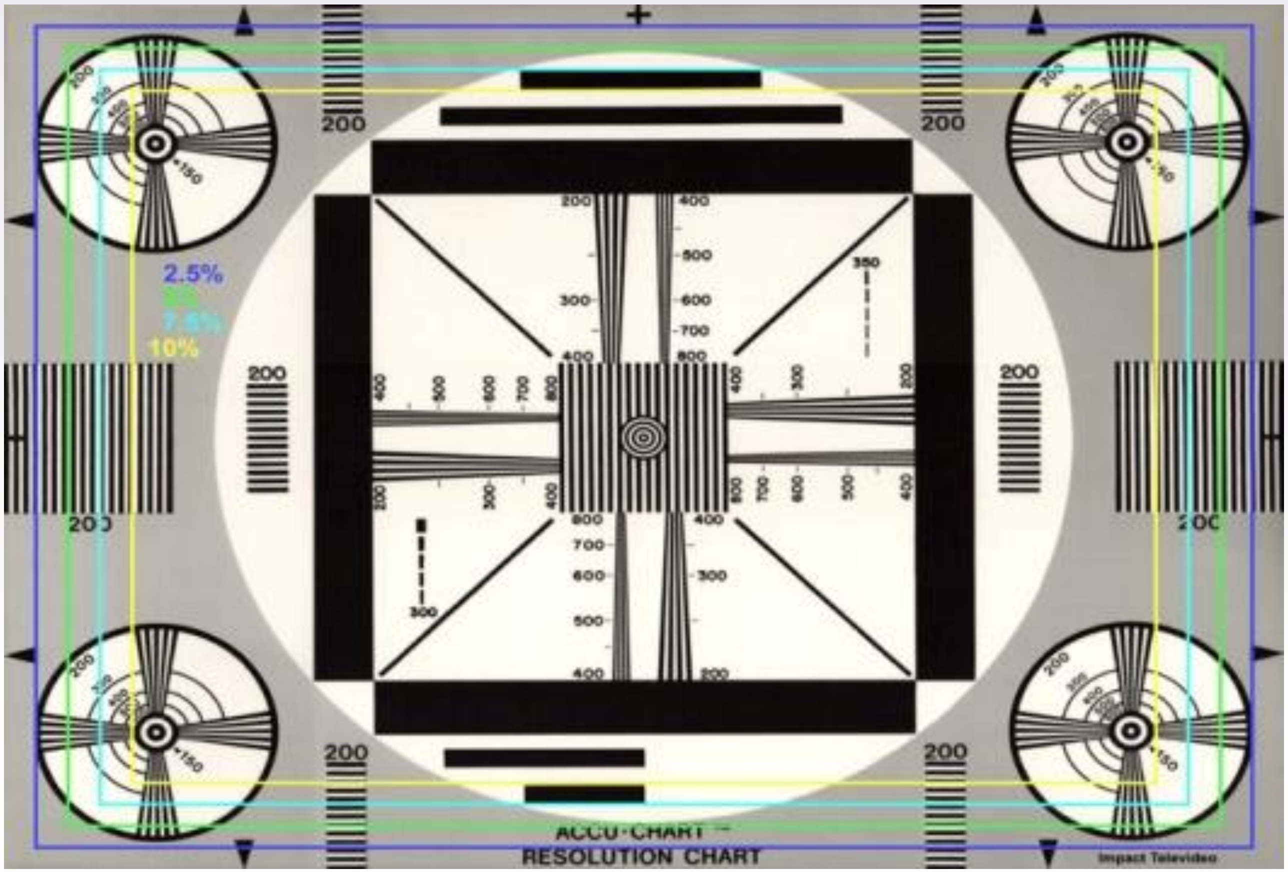


Image Sharpness

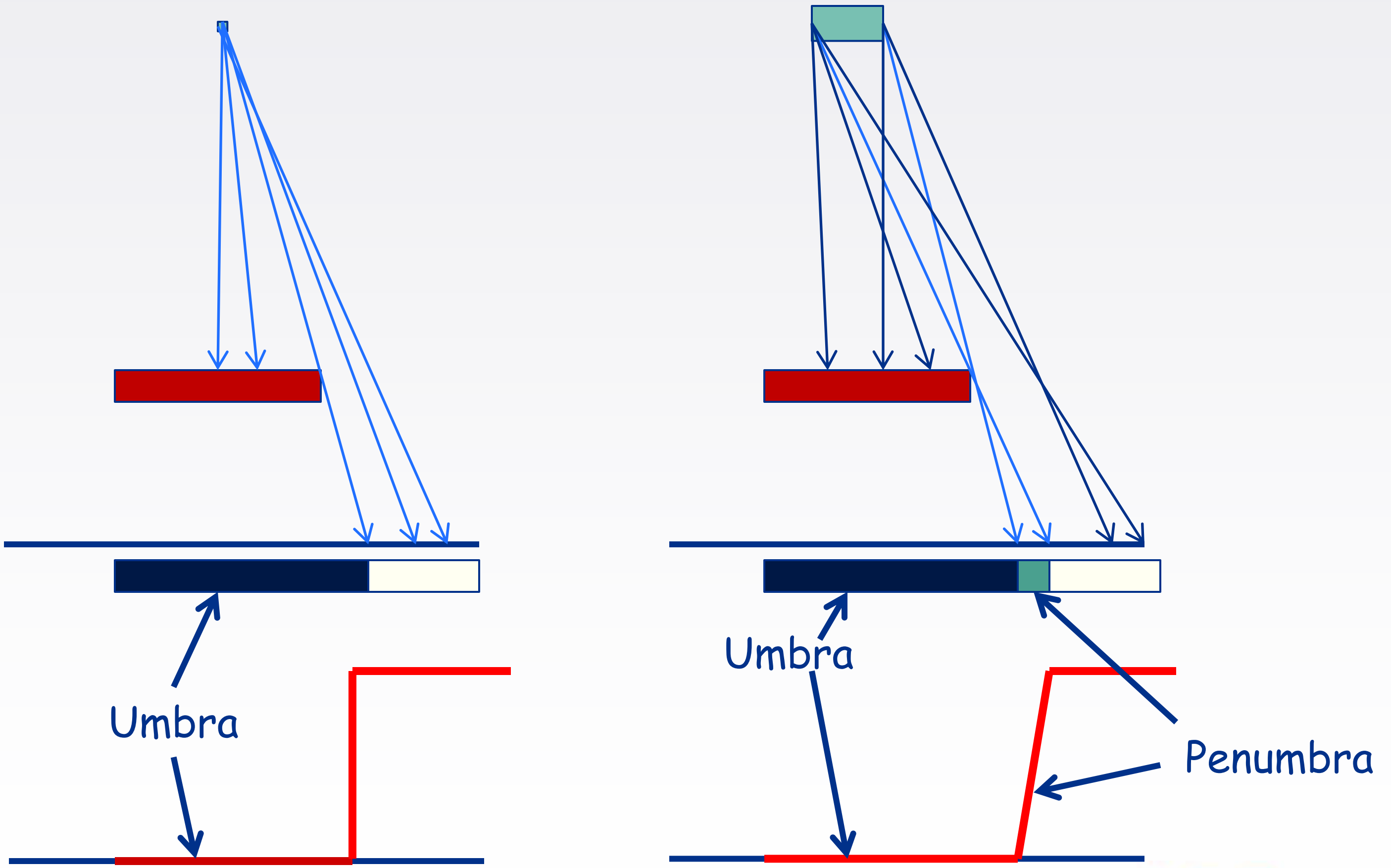
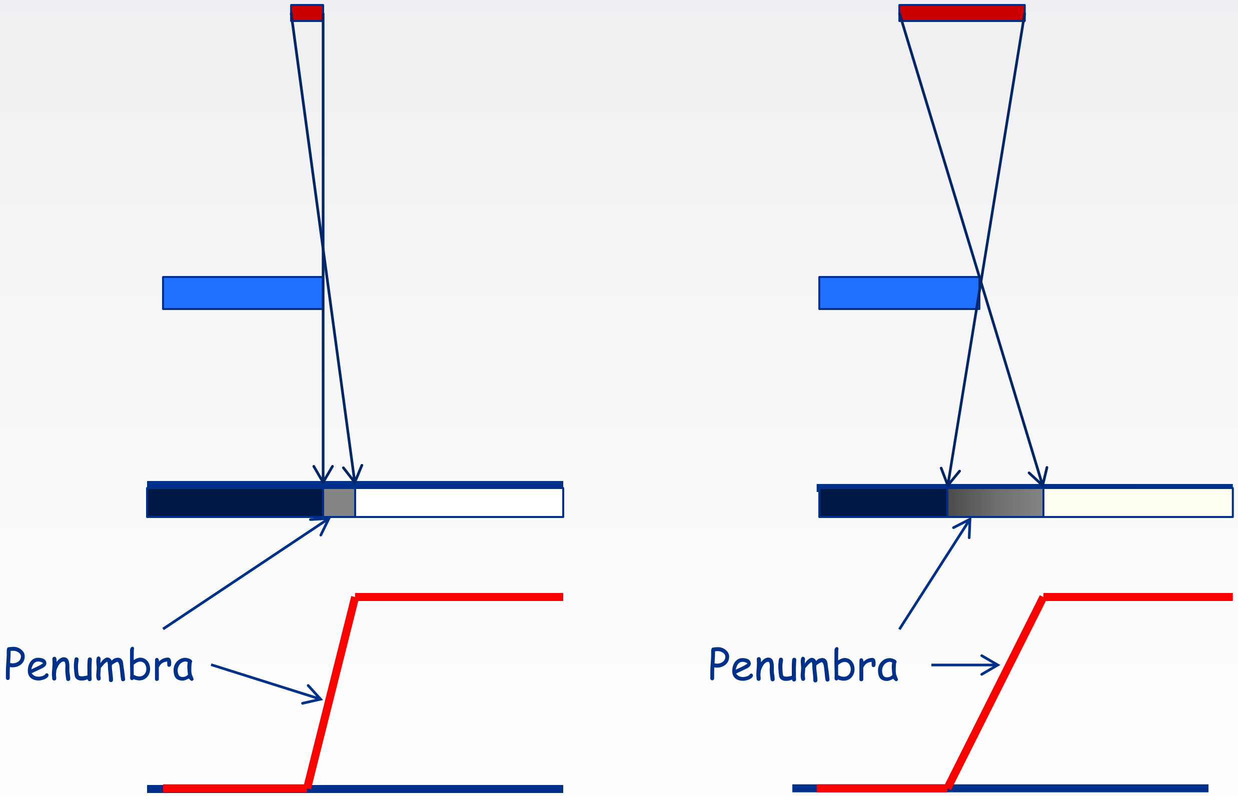


Image Sharpness

Effect of Focal Spot Size



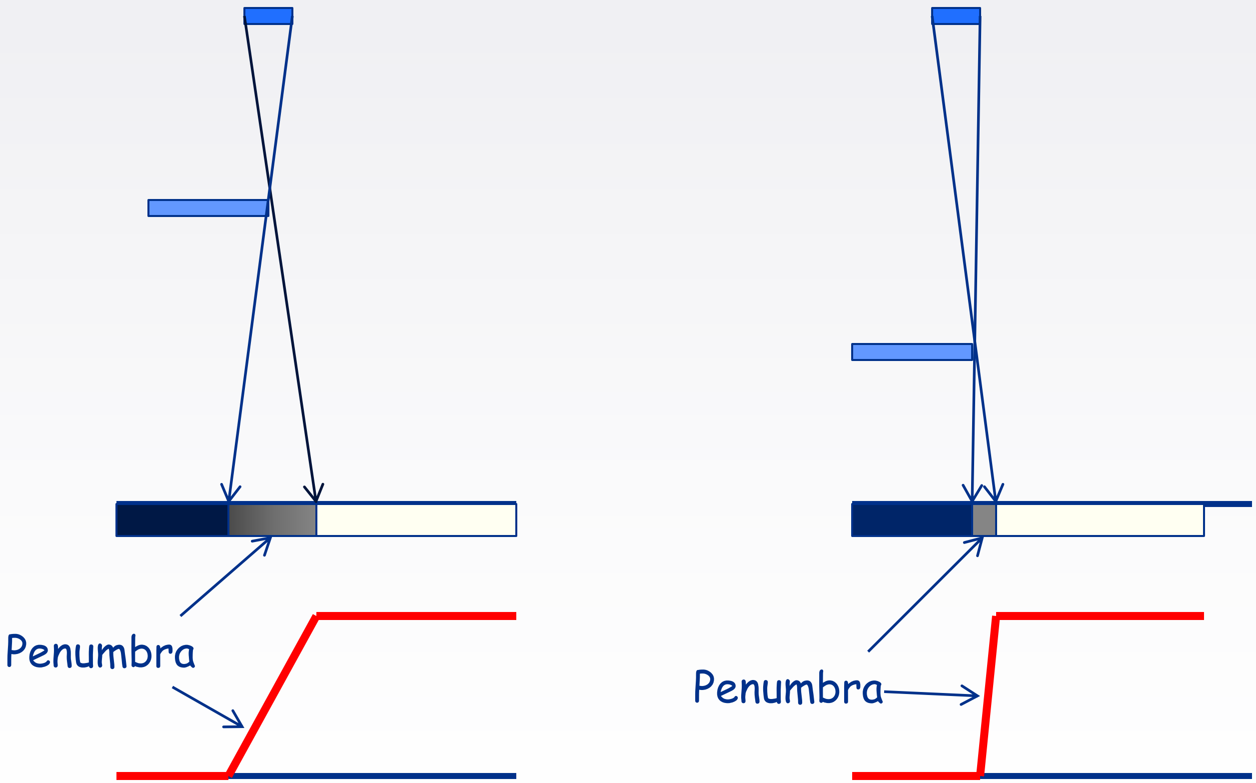
Rules for Mammography

Rule 4

To obtain a sharp image, the size of the focal spot must be small.

Image Sharpness

Effect of Object to Image Receptor Distance on Sharpness



Rules for Mammography

Rule 5

To obtain a sharp image, the object to image receptor distance must be small.

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Reasons for Breast Compression

1. Brings breast tissue closer to the image receptor to increase sharpness.

2. Thinner breast requires less technique, which reduces exposure.

3. Reduces scatter to improve image contrast.

Reasons for Breast Compression

4. Breast is immobilized, which reduces motion blurring.

5. Reduces overlaying of objects because breast tissue is spread out.

6. Evens out breast thickness to produce a uniform image density.

Rules for Mammography

Rule 6

Mammography machines must have a means for compressing the breast.

Beam Penetration

- X-ray photons must be energetic enough to penetrate the breast.
- They must not be too energetic or image contrast will suffer.
- Beam penetration is estimated by measuring the half value layer (HVL)

ACR Formulas for HVL Limits

$$\text{Minimum HVL} = \frac{kVp}{100} + 0.03$$

$$\text{Maximum HVL} = \frac{kVp}{100} + C$$

ACR Recommended HVL Limits

ACR Acceptable HVL Range					
	Minimum		Maximum HVL		
kVp	HVL	Mo/Mo	Mo/Rh	Rh/Rh	W/Rh
25	0.28	0.37	0.44	0.47	0.55
26	0.29	0.38	0.45	0.48	0.56
27	0.30	0.39	0.46	0.49	0.57
28	0.31	0.4	0.47	0.5	0.58
29	0.32	0.41	0.48	0.51	0.59
30	0.33	0.42	0.49	0.52	0.60

Rules for Mammography

Rule 7

The machine must have a means of producing a beam of adequate quality as measured by the HVL. The HVL must meet the recommendations of the ACR.

Rules for Mammography

Rule 8

The machine must produce an adequate output, i.e. exposure rate, so that exposure times are short.

In fact, the output must be at least 800 mR/s at 28 kVp for a Mo/Mo machine.

Noise

Noise is the random variation in the signal.

Sources

Quantum Noise

Detector Noise

Electronic Noise

Noise Computation

Quantum Noise

$$\sigma = \sqrt{N}$$

Relative Noise

$$\frac{\sqrt{N}}{N}$$

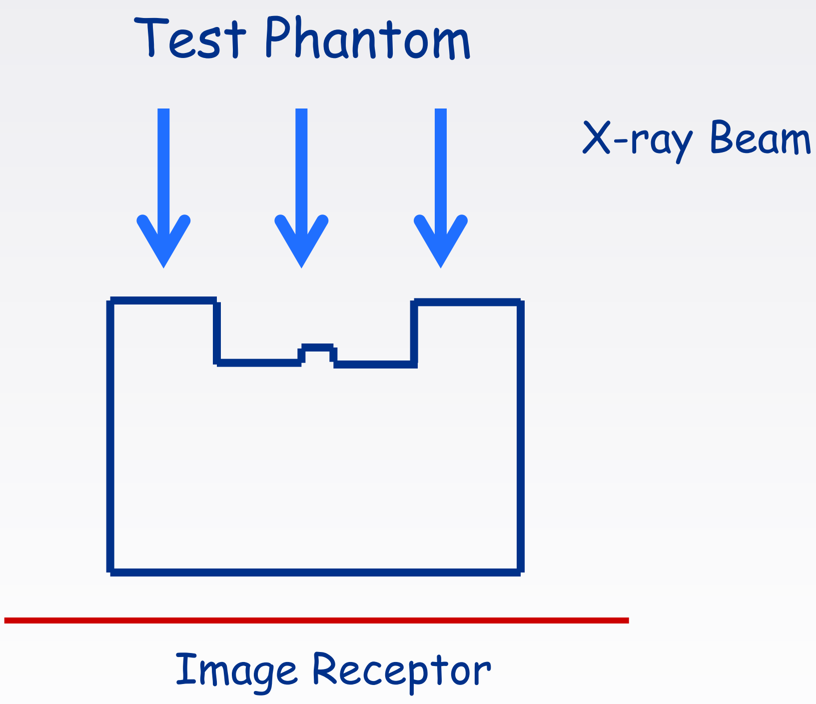
SNR (Signal to Noise Ratio)

$$\sqrt{N}$$

Noise Computation Example

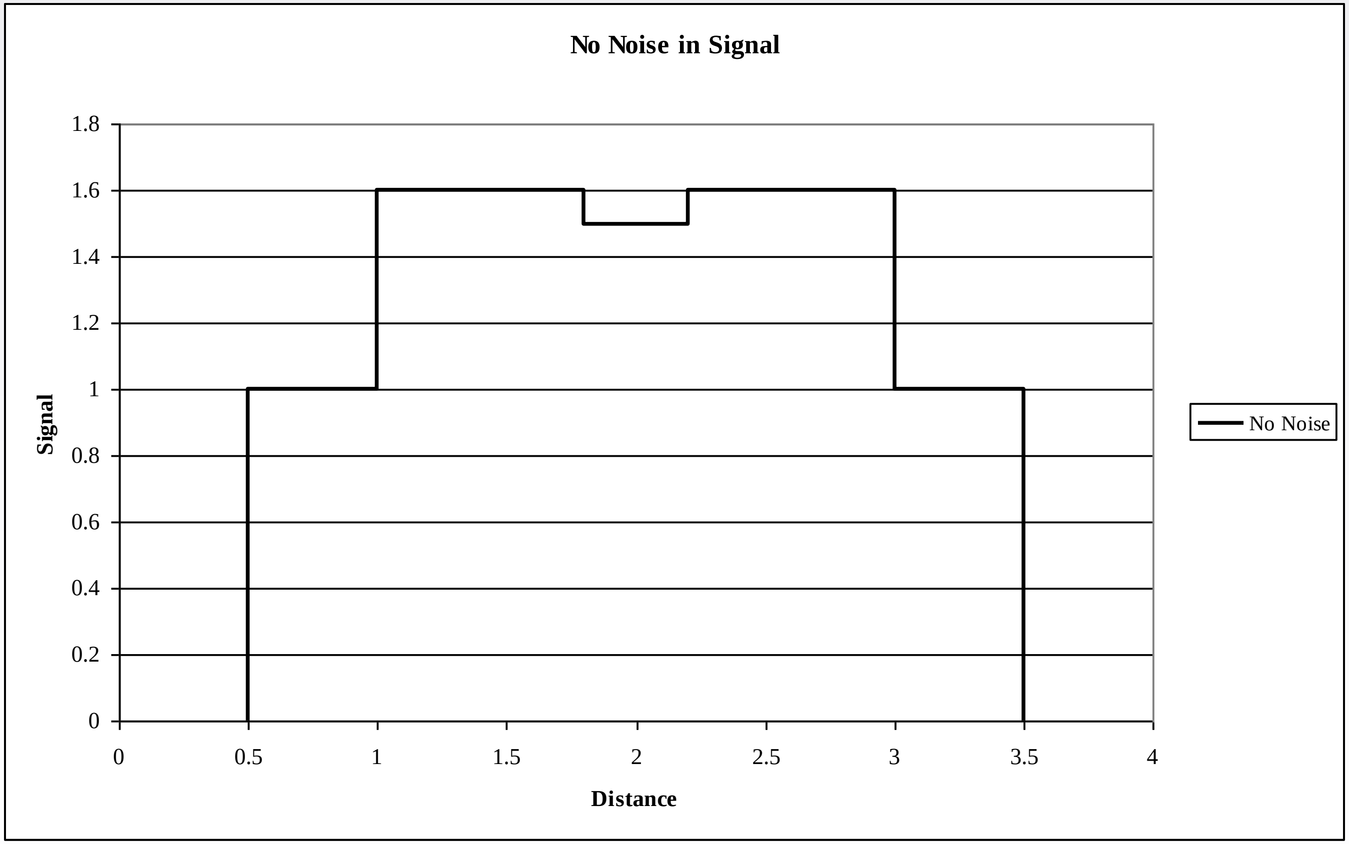
Number of Absorbed Photons	Noise	Percent Relative Noise
10^2	10	10
10^3	31.6	3.16
10^4	100	1
10^5	316.2	.31
10^6	1000	.1

Noise Example



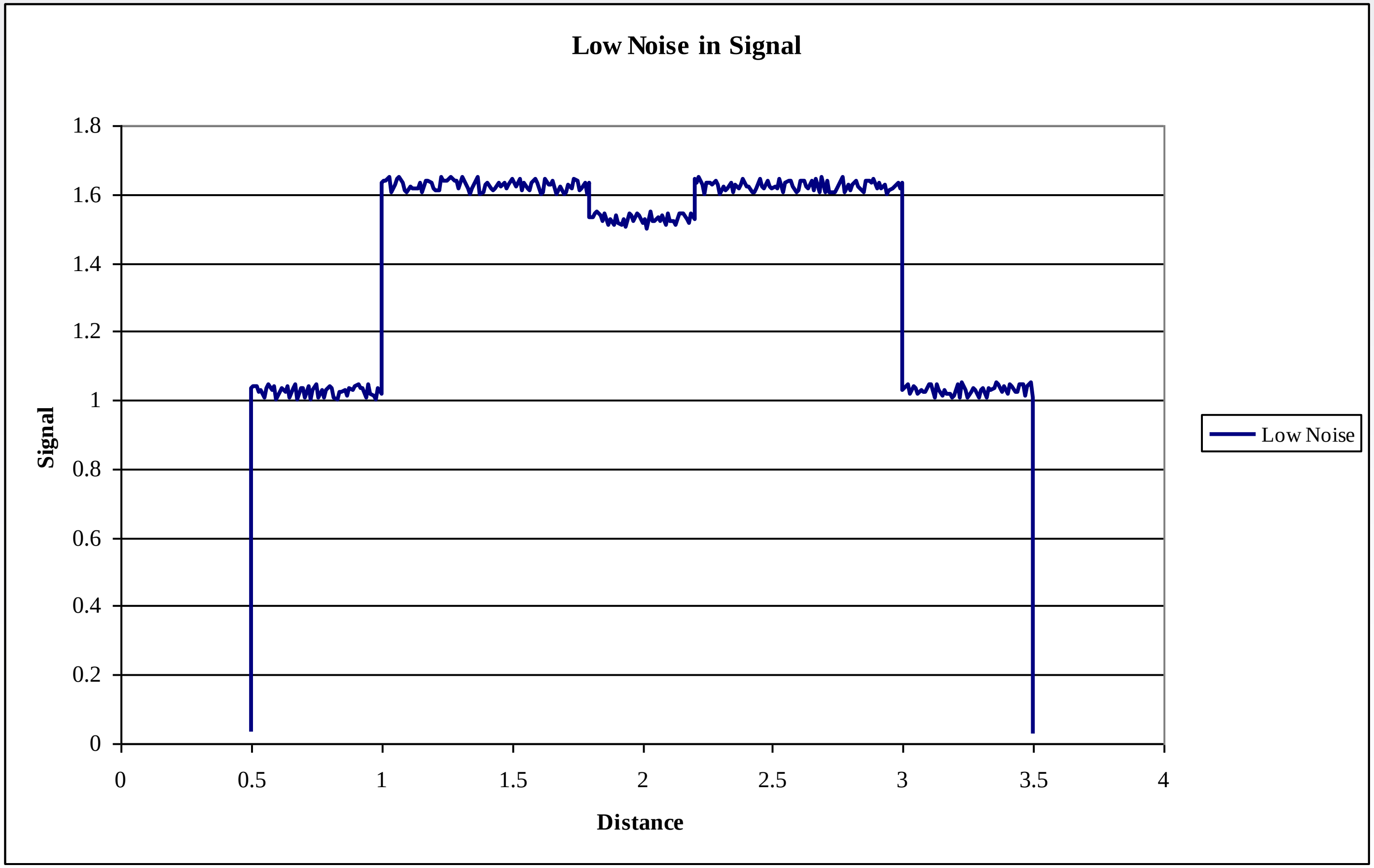
Noise Example

Perfect Noiseless Image



Noise Example

Low Noise Image



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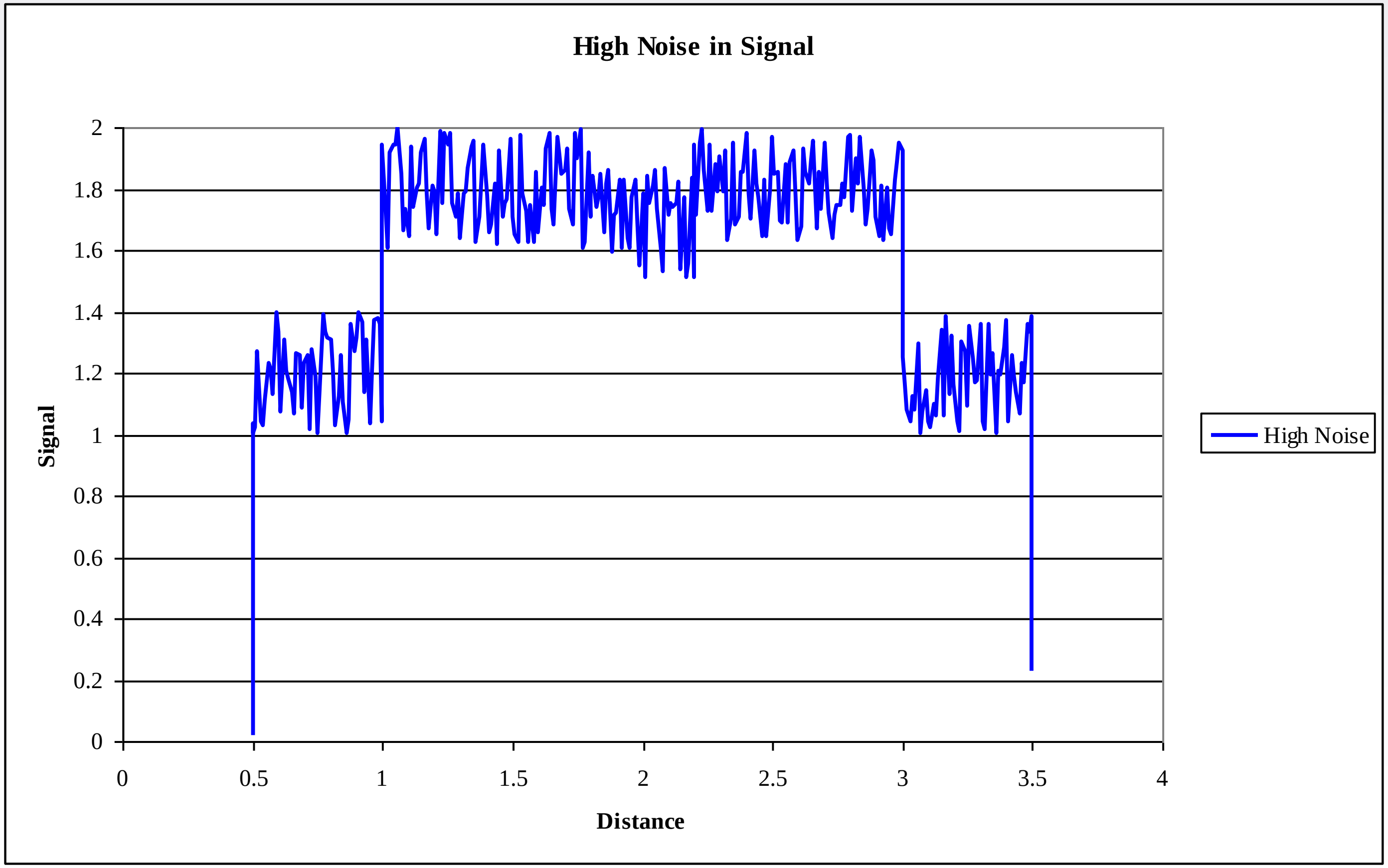
Noise Example

High Noise Image



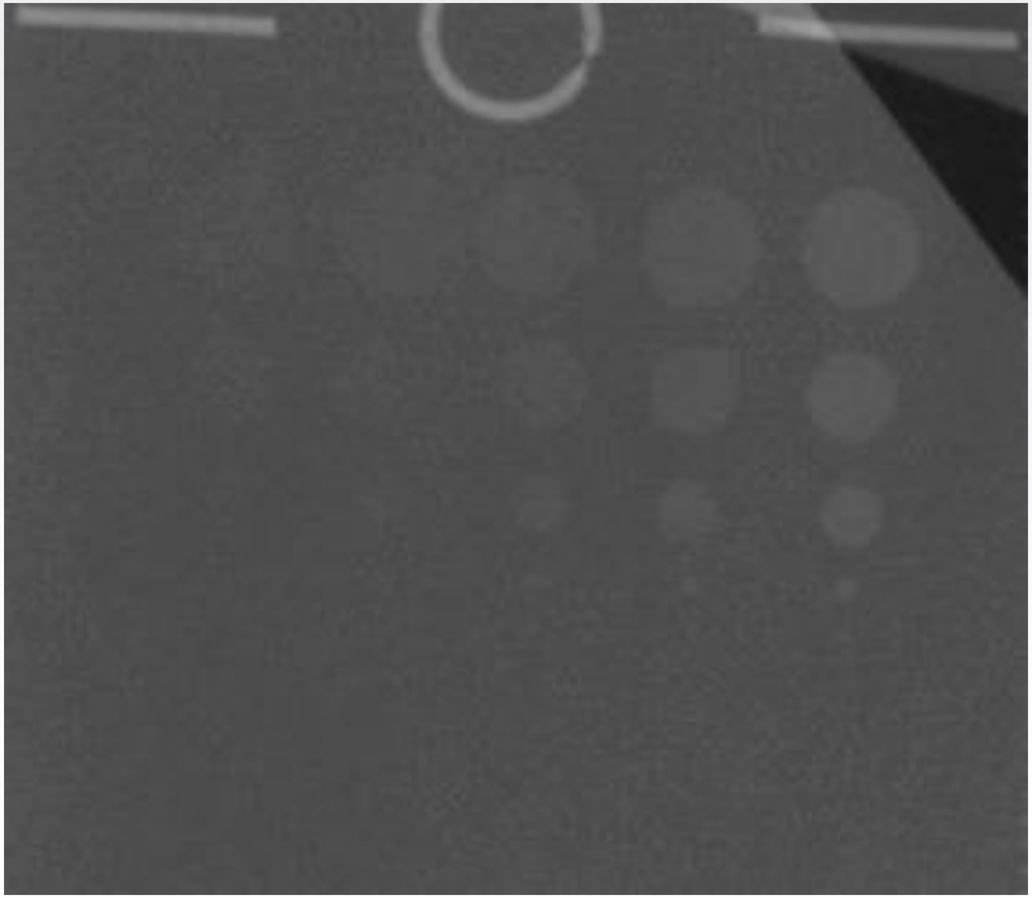
Noise Example

Low Noise Image
Noise = 0.0148
SNR = 67.6

High Noise Image
Noise = 0.1094
SNR = 9.1

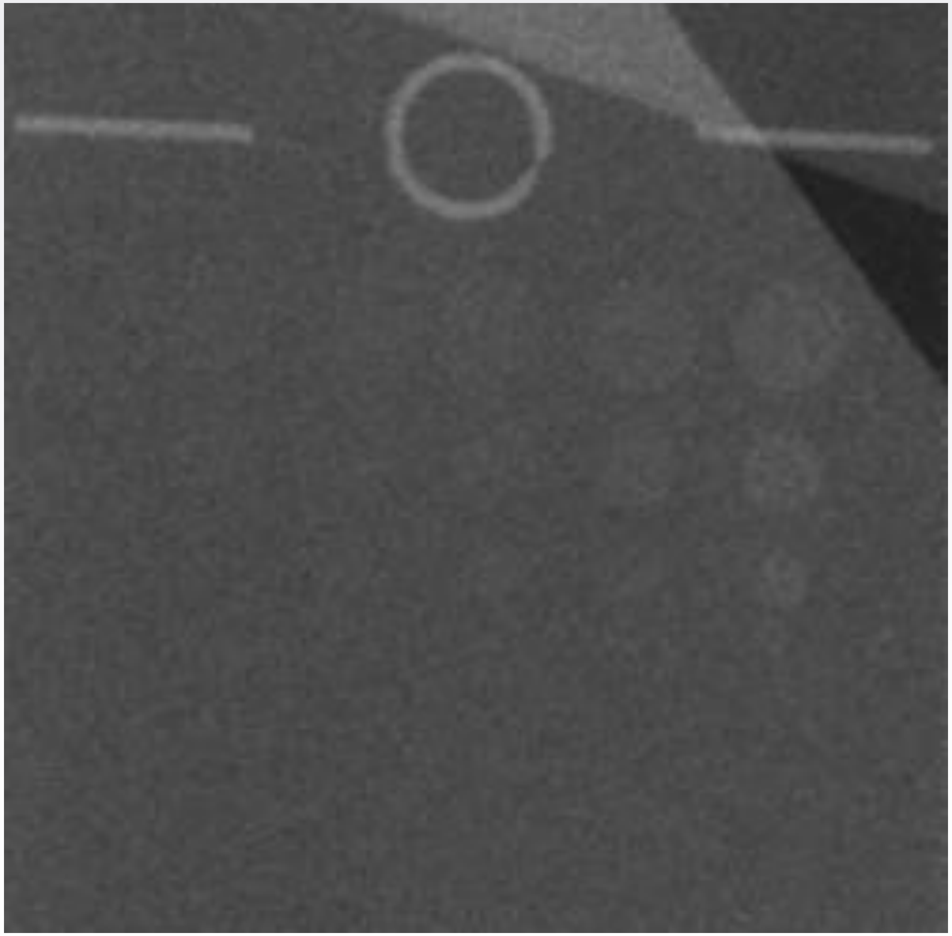
Phantom Image

Low Noise Image



Phantom Image

High Noise Image



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Rules for Mammography

Rule 9

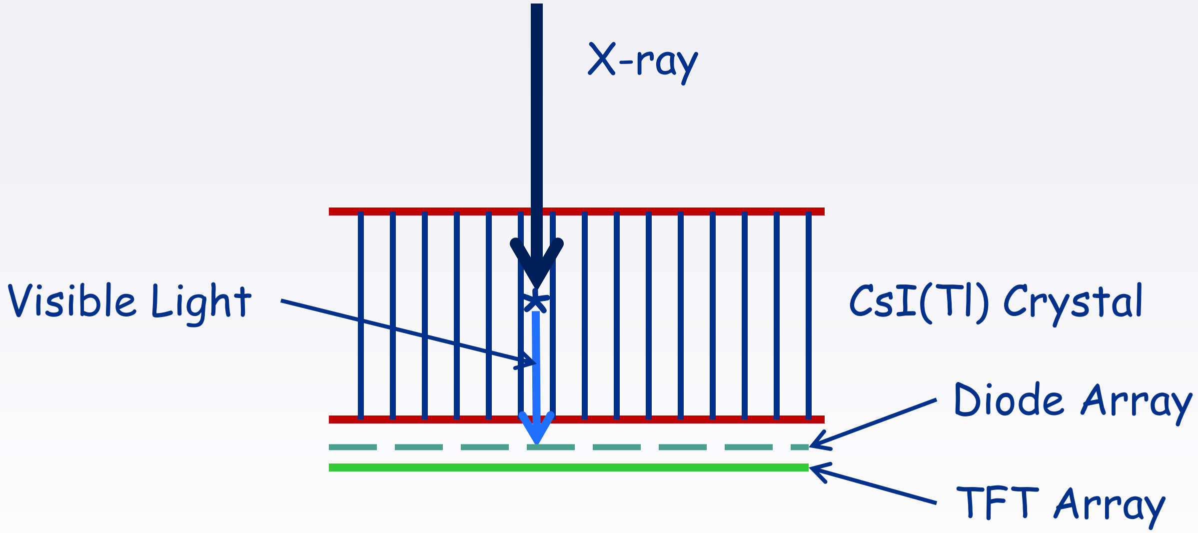
Image noise must be low enough so that small details will not be lost.

Digital Detectors

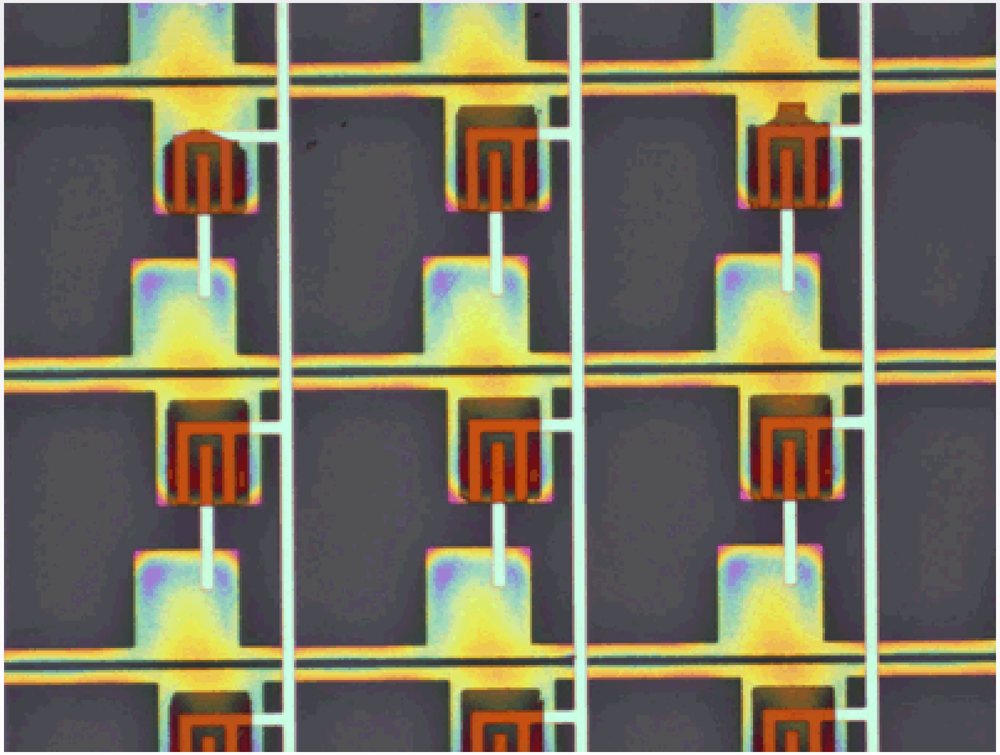
Indirect Conversion Detectors

Direct Conversion Detectors

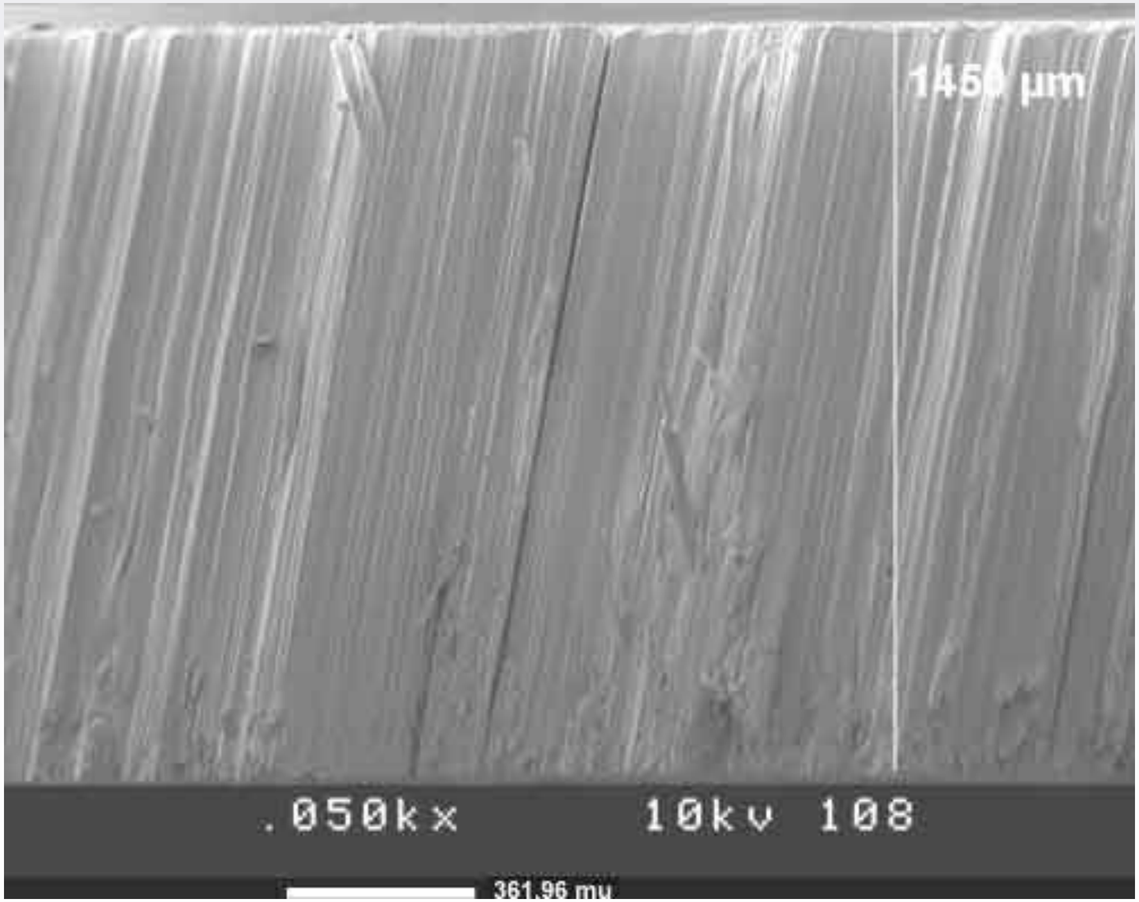
Indirect Conversion Detector



Thin Film Transistor Array



CsI(Tl) Crystals



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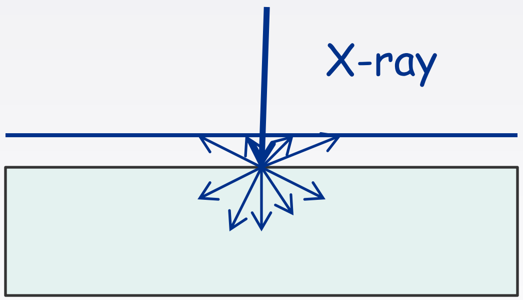
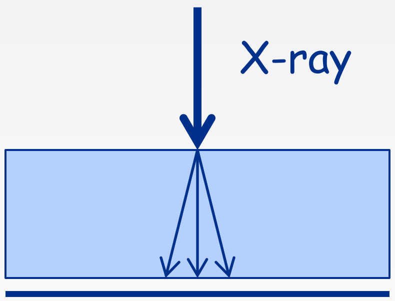
Comparison: Film/Screen and Indirect Conversion Digital

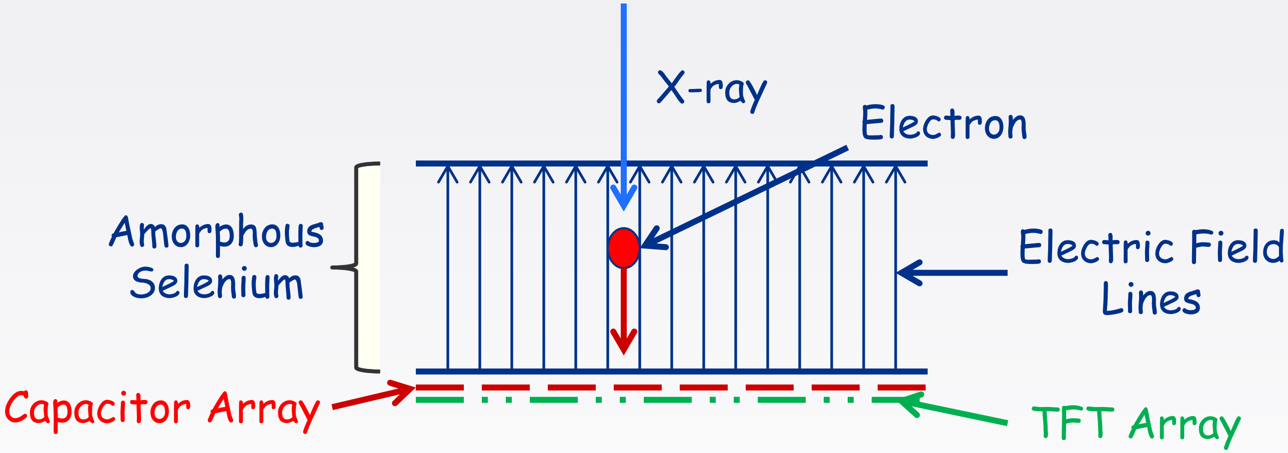


Film-Screen System

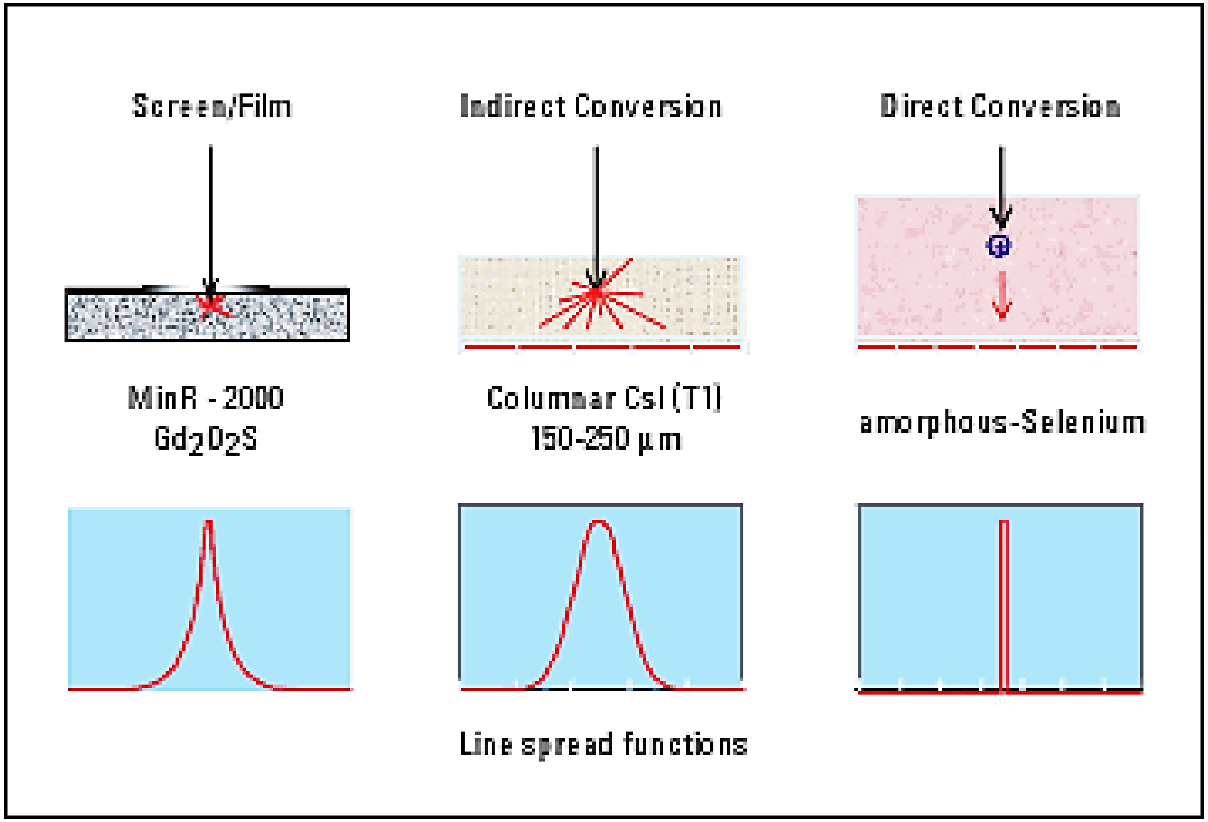


Indirect Conversion Digital

Direct Conversion Detector



Typical Line Spread Functions



Source: Fundamentals of Digital Mammography: Physics, Technology, and Practical Considerations by Andrew P. Smith, Ph.D.

The Laws of Nature

1. You can't win.
2. Most of the time, you can't break even.
3. The best you can do is to not fall too far behind.

Trade-offs

1. Increased SID sharpens images but restricts arm motion.

2. Small focal spots sharpen images but restrict mAs.

3. Breast compression is very important but….Ouch!

4. Image noise must be kept low but leads to higher patient dose.

5. Higher kVp produces better penetration and lower dose but contrast is reduced.

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Summary of Mammography Physics

1. Mammography must be done at low kVp for good contrast.

2. Anode materials must produce characteristic radiation in the 15 to 30 kVp range.

3. The appropriate filter must be used to remove low energy bremsstrahlung.

4. Use a small focal spot for a sharp image.

Summary of Mammography Physics

5. Compress the breast to sharpen the image and improve contrast.
6. The beam quality as measured by the HVL must not be too high or too low.
7. The machine must have adequate output to prevent patient motion.
8. Image noise must be kept low so small details will not be lost.

Thank you