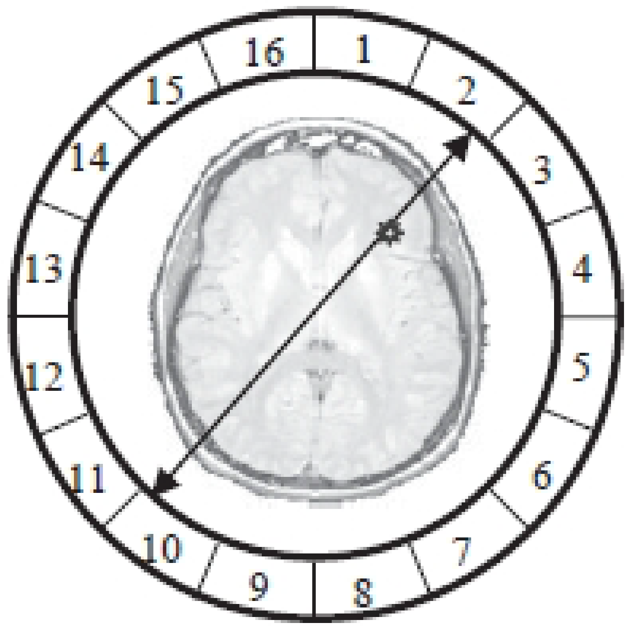


EEM 456 Introduction to Medical Imaging

Lecture Notes

The main origin of these lecture notes is the course textbook:

K. K. Shung, M. B. Smith, and B. M. W. Tsui, “Principles of Medical Imaging”, Academic Press, Inc., 1992.

Most of the supplementary figures, exercises, and text are obtained from the reference textbook:

William R. Hendee, E. Russel Ritenour, “Medical Imaging Physics”, Wiley-LISS, 2002.

Notes are supported by additional materials depending on the intended emphasis on any topic, while providing the appropriate references.

CHAPTER 1
X-RAY

I. Fundamentals of X-ray

Electromagnetic Radiation

X-ray is a form of electromagnetic (EM) energy just like radio waves or light.

Significant differences:

1) frequency or wavelength.
   Diagnostic x-rays
   (100 nm - 0.01 nm)

2) *Wave-particle duality*: It behaves as if it possessed the dual characteristics of both particles and waves.

Table I
Electromagnetic wave spectrum

Energy (eV)	Frequency (Hz)		Wavelength (m)
4×10^{-11}	10^{4}		10^{4}
4×10^{-10}	10^{5}	AM radio waves	10^{3}
4×10^{-9}	10^{6}		10^{2}
4×10^{-8}	10^{7}	Short radio waves FM radio waves and TV	10^{1}
4×10^{-7}	10^{8}		10^{0}
4×10^{-6}	10^{9}		10^{-1}
4×10^{-5}	10^{10}	Microwaves and radar	10^{-2}
4×10^{-4}	10^{11}		10^{-3}
4×10^{-3}	10^{12}	Infrared light	10^{-4}
4×10^{-2}	10^{13}		10^{-5}
4×10^{-1}	10^{14}	Visible light	10^{-6}
4×10^{0}	10^{15}	Ultraviolet light	10^{-7}
4×10^{1}	10^{16}		10^{-8}
4×10^{2}	10^{17}		10^{-9}
4×10^{3}	10^{18}	X-ray	10^{-10}
4×10^{4}	10^{19}		10^{-11}
4×10^{5}	10^{20}		10^{-12}
4×10^{6}	10^{21}	Gamma ray	10^{-13}
4×10^{7}	10^{22}	Cosmic ray	10^{-14}

Wave concept: useful in explaining reflection, scattering, refraction characteristics.

photon or quanta

Particle concept: X-ray radiation is thought to be particles traveling at the speed of light and carrying an energy given by *E=hv*.

Energy of an X-ray photon with a wavelength of 1 nm:

$E= 4.13 \times 10^{-15} \times 3 \times 10^{8}/10^{-9}=1.2\times10^{3}$ eV

h (Planck constant) $=4.13 \times 10^{-18}$ keV-sec
1 eV $=1.6 \times 10^{-19}$ joules

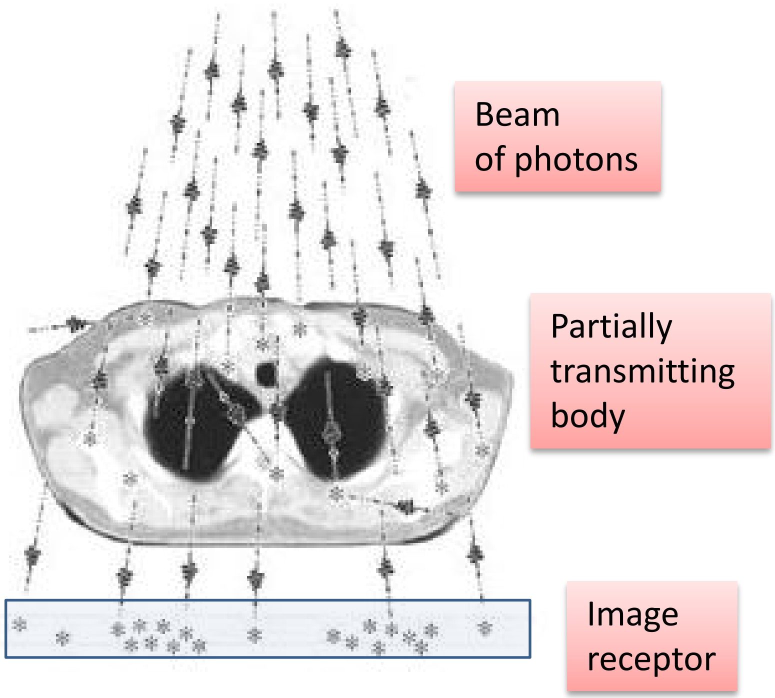
Interactions between X-rays and Matter

X-rays can interact with the orbital electrons as well as with the nuclei of the atoms.

In the *diagnostic energy range*, the intractions are more likely to involve orbital electrons, because their energy levels are too low to interact with nuclei.

Five ways that X-ray photons can interact with atoms or molecules in matter:

1) coherent scattering,
2) photoelectric effect,
3) Compton scattering,
4) pair production,
5) photodisintegration.



The *probability that each process to occur* depends on the energy (E) of the X-ray photon and the atomic number (Z) of the atom among other things.

Figure source: Wolbarst, A. B., Looking Within, University of California Press, page 13, 1999.

Coherent scattering

Occurs in low-energy radiation that does not carry enough energy to eject the orbital electrons out of the orbit or ionize the atom or molecule.

The photon is deflected into another direction (almost the same direction) losing little energy, yielding negligible change in wavelength.

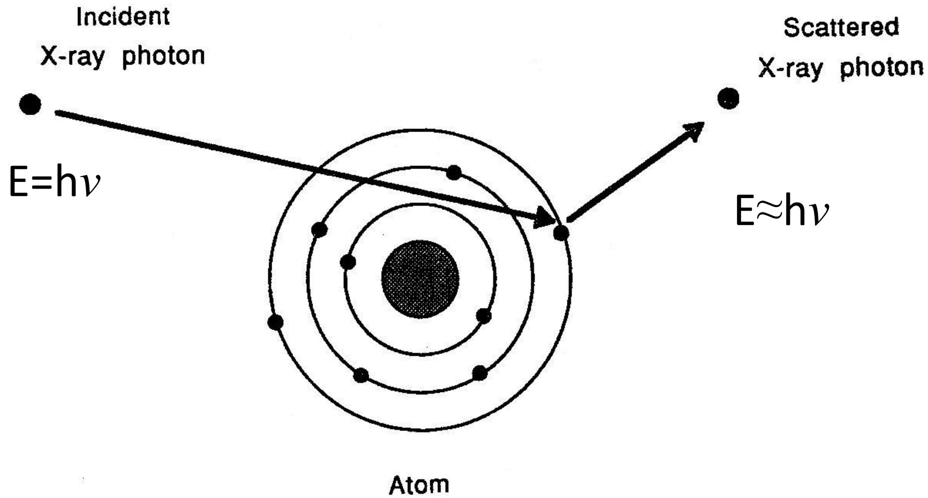


Figure 2 Coherent scattering of an X-ray photon by an atom.

This is the only interaction between X-ray and matter that does not cause ionization.

The importance of *coherent scattering* is small because little energy is deposited in the attenuating medium. However, It may reduce the resolution of scans obtained with low-energy, *γ -emitting nuclides (e.g.,* ^{125}I) used in nuclear medicine (Hendee and Ritanaur, 2002).

Photoelectric effect

- An incident X-ray photon, collides with one of the orbital electrons and ejects it from its orbit.
- The photon is *absorbed*, giving up all its energy.
- Majority of photon's energy is spent to overcome the binding energy and the rest is the kinetic energy of the escaped electron.
- The freed electron is called *photoelectron*.
- The vacancy in the orbit generated due to the escaped electron will be filled almost instantly by an electron from outer shells.
- The remaining atom now becomes a positively charged ion.

ionization

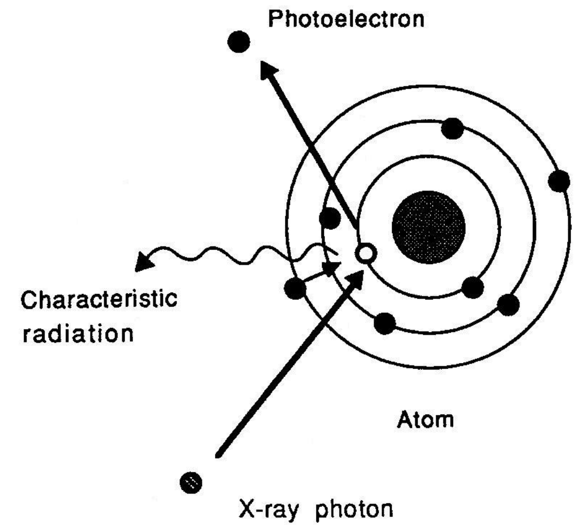


Figure 3 Photoelectric effect.

- Accompanying the *ionization*, a characteristic radiation is emitted.
- As an alternative to characteristic radiation, the *Auger effect* (energy released by an outer shell electron is transferred to an other orbital electron), may occur.
- The electron that acquires enough energy to escape is called an *Auger electron*.

Photoelectric effect

The probability for characteristic radiation to occur (fluorescent yield) is a function of the atomic number (Z) of the atom:

- Heavier atoms are most likely to emit characteristic radiation,
- Lighter atoms are most likely to emit Auger electrons.

The photoelectric effect always yields three end products:

1) characteristic radiation or Auger electrons,
2) photoelectron,
3) a positive ion

Albert Einstein (1879–1955) was best known to the general public for his theories of relativity. However, he also developed a theoretical explanation of the photoelectric effect—that the energy of photons in a light beam do not add together. It is the energy of each photon that determines whether the beam is capable of removing inner shell electrons from an atom. His Nobel Prize of 1921 mentioned only his explanation of the photoelectric effect and did not cite relativity because that theory was somewhat controversial at that time.

(Hendee and Ritanaur, 2002)

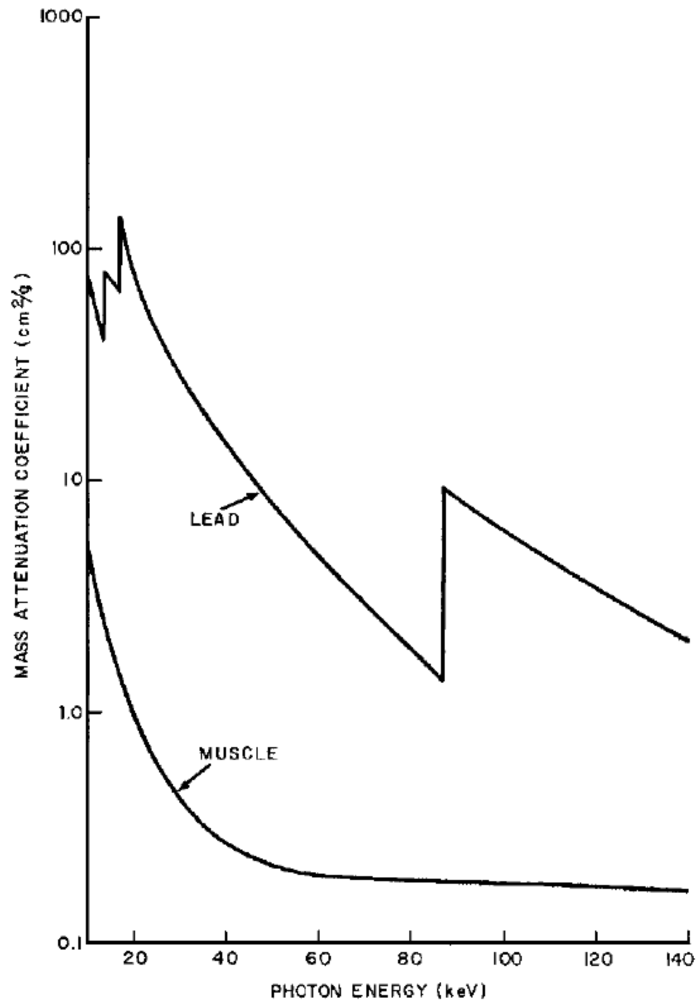
The probability for the photoelectric effect to occur is governed by the following principles:

1) The energy (E) carried by the incident X-ray photon has to be higher than the binding energy (E_b) of an orbital electron for the electron to be ejected.
2) The probability for the photoelectric effect to occur is approximately proportional Z^3 and E^{-3} once $E>E_b$.

Effects of photon energy (E)

Photoelectric
mass atenuation
coefficient (will be
defined shortly)
of lead and soft
tissue as a function of
photon energy.
K and L absorbtion
edges are depicted
for lead.

Absorbtion edges
for soft tissues occur
at photon energies
to low to be shown.



(Hendee and Ritanaur, 2002)

Effects of atomic number (Z)

At all photon energies the photoelectric attenuation coefficient for lead (Z = 82) is greater than that for soft tissue (Z_{eff}= 7.4 where Z_{eff} represents the effective atomic number of a mixture of elements.).

In general, the photoelectric mass attenuation coefficient varies with Z^3.

Example:

The number of 15-keV photons absorbed primarily by photoelectric interaction in bone (Z_{eff} = 11.6) is approximately four times greater than the number of 15-keV photons absorbed in an equal mass of soft tissue because

$$(11.6/7.4)^3 = 3.8.$$

Compton scattering

- The scattered radiation encountered in an X-ray examination is mostly due to Compton scattering.
- Only part of the energy carried by the photon is transmitted to the electron.
- The photon is scattered by the electron into other directions with a reduction in energy or an increase in wavelength.

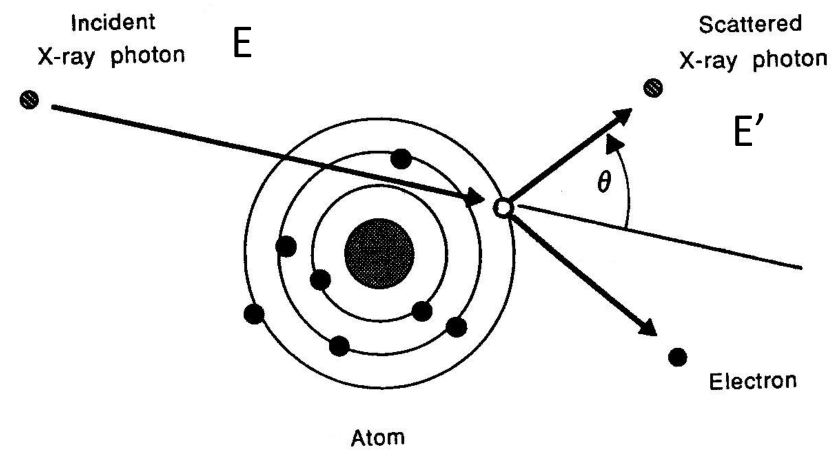


Figure 4 Compton scattering of an X-ray photon by an atom.

The amount of energy that a scattered photon may retain depends on two factors:

1) the initial photon energy E relative to the binding energy of the orbital electron,
2) the scattering angle θ.

Assuming that the electron is free and stationary before collision, the following equation is valid:

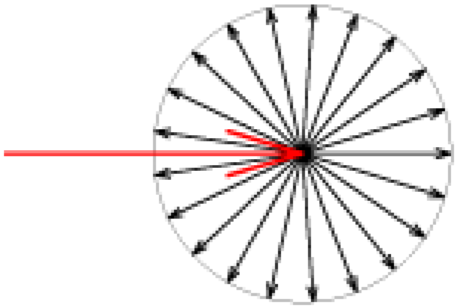
$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)}$$

m_e : rest mass of the electron equivalent to 511 keV of energy.

Compton Scattering

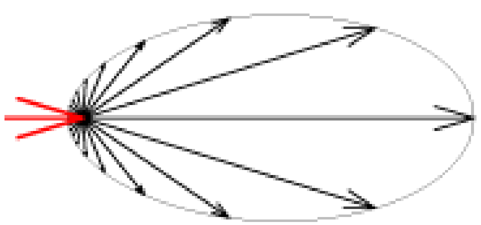
If photon energy is relatively low, the energy carried by the scattered photon is almost independent from the angle.

Isotropic scattering:
Wave scattering phenomenon where the wavelength is much larger than the size of the scatterer.



As the energy is increased, photons scattered at small angles or in forward direction carry higher energy.

Scattering is concentrated in the forward direction for wavelength much smaller than the scatterer size.



Pair production

- Nucleus is involved.

- It is the process in which the high-energy photon is completely absorbed by the nucleus and converted into two particles: an electron and a positron, a particle with the same mass as an electron but with a positive charge.

- It has little importance in X-ray radiography because very high energy photons in the order of 1 MeV are required for this interaction to occur.

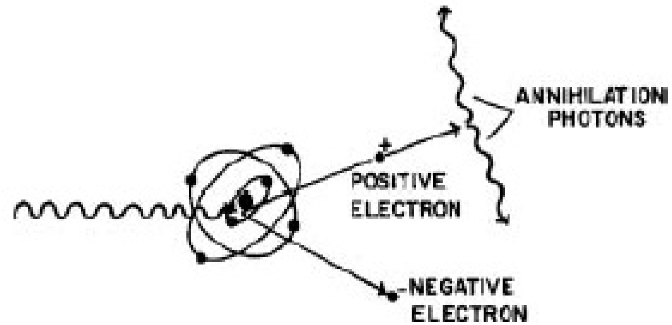


FIGURE 4-20
Pair production interaction of a high-energy photon near a nucleus. Annihilation photons are produced when the positron and an electron annihilate each other.

(Hendee and Ritanaur, 2002)

‘’Because the energy equivalent to the mass of an electron is 0.51 MeV, the creation of two electrons requires 1.02 MeV. Consequently, photons with energy less than 1.02 MeV do not interact by pair production. This energy requirement makes pair production irrelevant to conventional radiographic imaging. During pair production, energy in excess of 1.02 MeV is released as kinetic energy of the two electrons (Hendee and Ritanaur, 2002).’’

Photodisintegration

- Nucleus is involved.
- It has little importance in X-ray radiography because very high energy photons (>10MeV) are required for this interaction to occur.
- It is a process in which one or more nuclear particles or nucleons such as neutrons or protons are ejected from the nucleus by the high-energy photon.

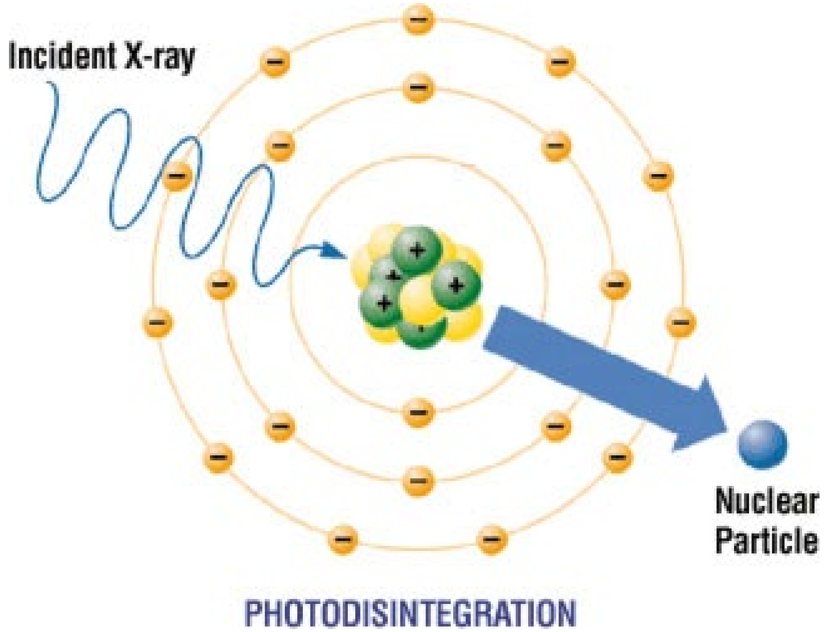


Figure source: http://qs1252.pair.com/monarchm/elsevier/mro_physics2e_v1/mod09/09s02l0109.htm

Summary

- Coherent scattering is the only interaction of the five between X-ray and matter that does not cause ionization.

- Photoelectric effect is the most desirable type of interaction in X-ray imaging because the X-ray photon is completely absorbed, producing litte scattered radiation.

- Compton scattering creates two major problems in X-ray radiography:
  - It produces the so-called background noise on the film and,
  - It is a major safety hazard for the personnel using the equipment.

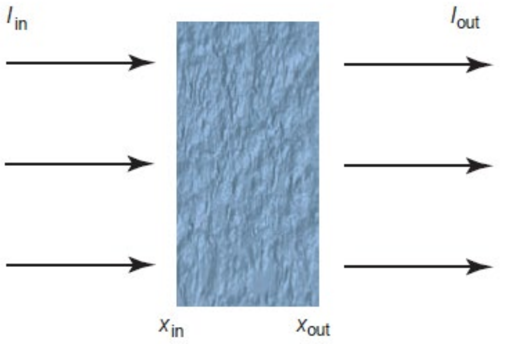
- Pair production and photodisintegration have little importance in X-ray radiography because very high energy photons are required for these interactions to occur.

- In summation, three different interactions can occur as an X-ray photon in the diagnostic range encounters an atom. Which interaction will occur depends on the energy of the photon and the binding energy of the electrons.

Attenuation

When an x ray impinges upon a material, there are three possible outcomes. The photon may

(1) be absorbed (i.e., transfer its energy to atoms of the target material) during one or more interactions;
(2) be scattered during one or more interactions; or
(3) traverse the material without interaction.



If the photon is absorbed or scattered, it is said to have been attenuated.

If 1000 photons impinge on a slab of material, for example, and 200 are scattered and 100 are absorbed, then 300 photons have been attenuated from the beam, and 700 photons have been transmitted without interaction.

Attenuation coefficient (μ) of a material?

$$\mu = \mu_{pho} + \mu_{coh} + \mu_{com}$$

$$\mu_{coh} = \rho Z^2 E^{-1}$$

$$\mu_{pho} = \rho Z^3 E^{-3}$$

$$\mu_{com} = \rho_e E^{-1}$$

$$\rho_e = N_{av} Z / A$$

ρ_e : electron density (number of electrons/gm)

N_{av}: Avagadro's number, 6.02×10^{23}

Z : Atomic number (number of protons)

A: Mass number (number of neutrons + number of protons in the nucleus)

Attenuation coefficients

Photoelectric effect and Compton scattering are the most dominant mechanisms for attenuation in the diagnostic X ray range. Coherent scattering is usually negligible.

Two mechanisms contribute to the attenuation of an X-ray beam: absorbtion and scattering. Therefore,

$$\boxed{\mu = \mu_a + \mu_s}$$

where μ_s and μ_a are respectively the fractions of the attenuation due to scattering and absorbtion.

μ_a is called X-ray *absorbtion coefficient*.

Similarly μ_a/ρ is defined as the *mass absorbtion coefficient*.

Mass attenuation coefficient, μ/ρ

To have a quantity indicating the attenuation property of the matter independent of its physical state mass atenuation coefficient is defined as the ratio of linear attenuation coefficient to density.

For instance, the linear attenuation coefficients for water, ice and water vapor at 50 keV are respectively 0.214, 0.196, and 0.00013 cm^{-1}.

However, their mass attenuation coefficients are the same, 0.214 cm^2/gm.

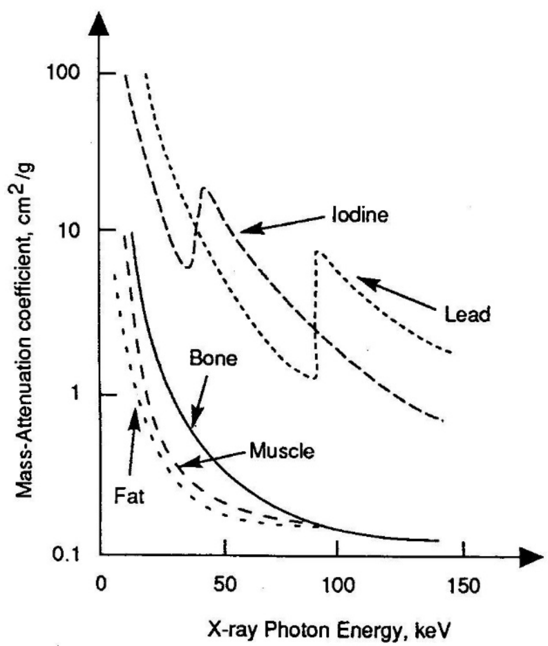


Figure 6 Mass-attenuation coefficients of several media as functions of X-ray energy.

Intensity of an X-ray Beam

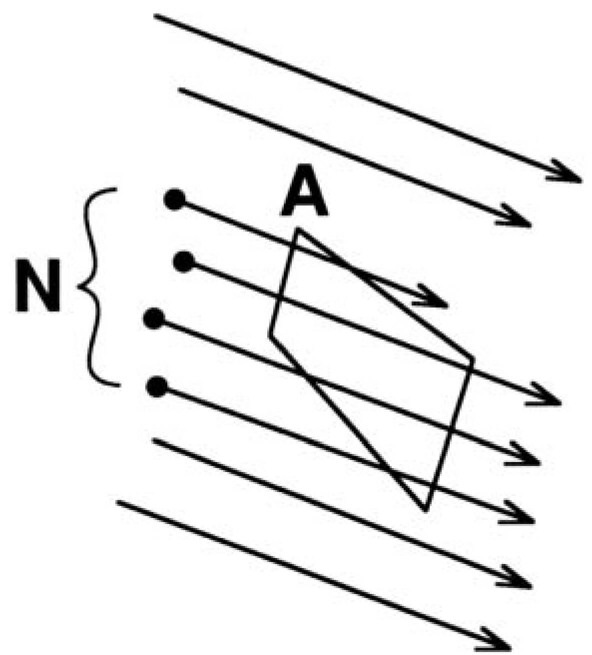
Radiation : energy in transit from one location to another.

Radiation intensity refers to a number of attributes of the output of a radiation source.

In physics and engineering, the term “intensity” is defined more specifically in terms of energy per unit area, per unit time.

A beam of radiation is shown in Margin Figure 6-1. The radiation *fluence* of the beam is defined as the number N of photons per area A*:*

$$\Phi = \frac{N}{A}$$



MARGIN FIGURE 6-1
The particle fluence of a beam of radiation is defined as the number of particles (*N*) passing through a unit area (*A*) that is perpendicular to the direction of the beam. If the beam is uniform, the location and size of the area *A* are arbitrary.

(Hendee and Ritanaur, 2002)

Intensity of an X-ray Beam

Flux ϕ is the time rate of change of fluence:

$$\phi = \frac{N}{A \cdot t}$$

If all particles or photons in the radiation beam possess the same energy, the energy fluence Ψ is simply the product of the radiation fluence Φ and the energy E per particle or photon:

$$\Psi = \Phi E = \frac{NE}{A}$$

Similarly, the photon flux ϕ may be converted to the energy flux ψ, also known as the intensity *I*, by multiplying by the energy E per particle or photon

$$I = \psi = \phi E = \frac{NE}{At}$$

Intensity of an X-ray Beam

If the radiation beam consists of particles or photons having different energies ($E_1, E_2, \ldots, E_m$), then the intensity (or energy flux) is determined by

$$I = \psi = \sum_{i=1}^{m} f_i \phi E_i$$

where f_i represents the fraction of particles having energy E_i .

TABLE 6-1 Fluence and Flux (Intensity) of a Beam of Radiation[a]

Quantity	*Symbol*	*Definition*[b]	*Units*
Particle (photon) fluence	Φ	$\frac{N}{A}$	$\frac{\text{Particles (photons)}}{\text{m}^2}$
Particle (photon) flux	ϕ	$\frac{N}{At}$	$\frac{\text{Particles (photons)}}{\text{m}^2 \cdot \text{sec}}$
Energy fluence	Ψ	$\frac{NE}{A}$	$\frac{\text{MeV}}{\text{m}^2}$
Energy flux (intensity)	ψ	$\frac{NE}{At}$	$\frac{\text{MeV}}{\text{m}^2 \cdot \text{sec}}$

[a] *Note:* These expressions assume that the number of particles or photons does not vary over time or over the area A, and that all particles or photons have the same energy.

[b] N = number of particles or photons; E = energy per particle or photon; A = area; t = time.

(Hendee and Ritanaur, 2002)

Intensity Attenuation

Assume all atoms in the material are identical and all have a cross section of σ and there are n atoms per unit volume of the material.

The total number of atoms encountered in the beam (per cm) is A (cm^2)n ($atoms/cm^3$).

The area occupied by the atoms in the beam is $An\sigma$.

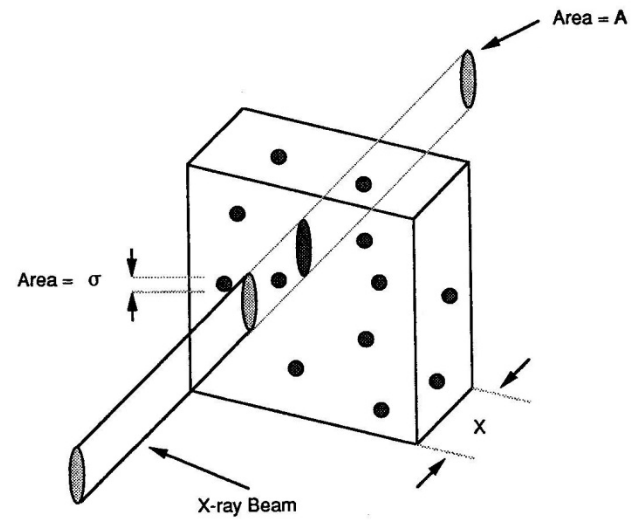


Figure 5 X-ray beam of cross-section *A* intersects medium of thickness *x*.

The probability for a photon to interact with an atom (per cm) is $An\sigma/A = n\sigma$.
The probability for a photon to interact with an atom in thickness dx is $n\sigma dx$.
The X-ray intensity removed in thickness dx is

$$dI = -n\sigma I\,dx$$

Rearranging the equation, we have

$$\frac{dI}{dx} = -n\sigma I$$

Linear attenuation coefficient, μ

Let $\mu = n\sigma$ which is the fraction of X-ray energy removed per unit thickness per unit intensity. Substituting μ into the above equation and carrying out the integration, we obtain

$$I_{out} = I_{in} e^{-\mu x}$$

where μ is called the *linear attenuation coefficient* (typically expressed in cm^{-1}). This simple law is only valid when the material is homogeneous and the beam consists of photons of a single energy. Actually, μ is a function of both the photon energy and the material, that is, $\mu = \mu(E, \text{material})$, for example:

$$\begin{aligned} \mu(10\,\mathrm{keV}, \mathrm{H_2O}) &= 5\,\mathrm{cm}^{-1} \\ \mu(100\,\mathrm{keV}, \mathrm{H_2O}) &= 0.17\,\mathrm{cm}^{-1} \\ \mu(10\,\mathrm{keV}, \mathrm{Ca}) &= 144\,\mathrm{cm}^{-1} \\ \mu(100\,\mathrm{keV}, \mathrm{Ca}) &= 0.40\,\mathrm{cm}^{-1}. \end{aligned} \tag{2.5}$$

- When a beam of single-energy photons travels through a nonhomogeneous medium, I_{out} is related to I_{in} by

$$I_{\mathrm{out}} = I_{\mathrm{in}}\, \mathrm{e}^{-\int_{x_{\mathrm{in}}}^{x_{\mathrm{out}}} \mu(x)\,\mathrm{d}x}. \tag{2.6}$$

- A real X-ray beam does not contain a single photon energy but a whole spectrum of energies. Making the intensity distribution of the incoming beam a function of the energy, that is, $I_{\mathrm{in}} = \int_0^\infty \sigma(E)\,\mathrm{d}E$, the intensity of the outgoing beam is equal to

$$I_{\mathrm{out}} = \int_0^\infty \sigma(E)\, \mathrm{e}^{-\int_{x_{\mathrm{in}}}^{x_{\mathrm{out}}} \mu(E,x)\,\mathrm{d}x}\,\mathrm{d}E. \tag{2.7}$$

photon flux at energy E

(Suetens P, 2009)

Radiation absorbed dose (rad)

- This unit defines the amount of radiation actually absorbed by the medium. 1 rad means that 0.01 joule of energy is absorbed by 1 kg of material.

- Materials have different X-ray absorbtion characteristics. The amount of energy absorbed by different materials may be different for the same amount of radiation.

- This difference depends on the *absorbtion* characteristics of the material and X-ray photon energy.

Collection of X-ray tubes

II. Generation and Detection of X-rays

A. X-ray Generation

To produce medical images with x rays, a source is required that:

1. Produces enough x rays in a short time
2. Allows the user to vary the x-ray energy
3. Provides x rays in a reproducible fashion
4. Meets standards of safety and economy of operation

Only special-purpose particle accelerators known as *x-ray tubes* meet all the requirements mentioned above. (Hendee and Ritanaur, 2002)

In X-ray tubes, X-rays are generated when electrons with high energy strike a target made from materials like tungsten or molybdenum.

High energy electrons can interact with

- **the nuclei** of the tungsten atoms producing *general radiation* (white radiation or Bremsstrahlung),
- **the orbital electrons** producing the *characteristic radiation*.

White Radiation (Bremsstrahlung)

When a negatively charged electron passes near a positively charged nucleus, the electron is attracted toward the nucleus and then deflected from its original path.

The electron may lose some energy or not.

If it does not, the process is called *elastic scattering* and no X-ray photons will be produced.

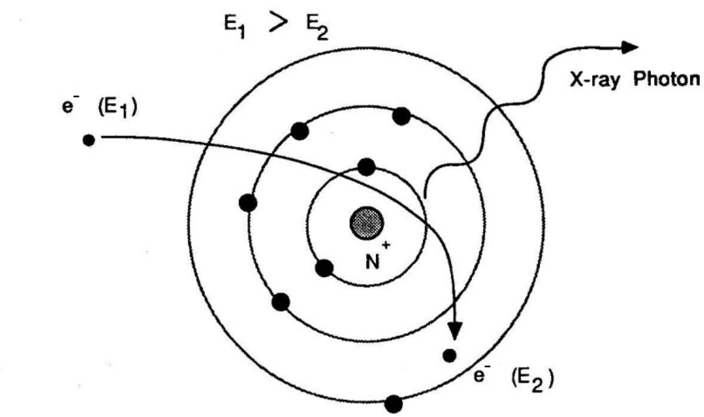


Figure 7 Deflection of high-energy electron by nucleus produces white radiation.

If it does lose some energy, the process is called *inelastic scattering* and the energy lost by the electron is emitter in the form of X-ray photon.

The radiation produced in this way is called *white radiation*.

The probability of the electron to lose energy is increased as the atomic number of the atom increases.

White Radiation/Characteristic Radiation

The electrons striking the target can interact with a number of nuclei before being stopped and the electrons may carry different energies.

Therefore, the energies of the X-ray photons generated by the process of general radiation are distributed over a wide range.

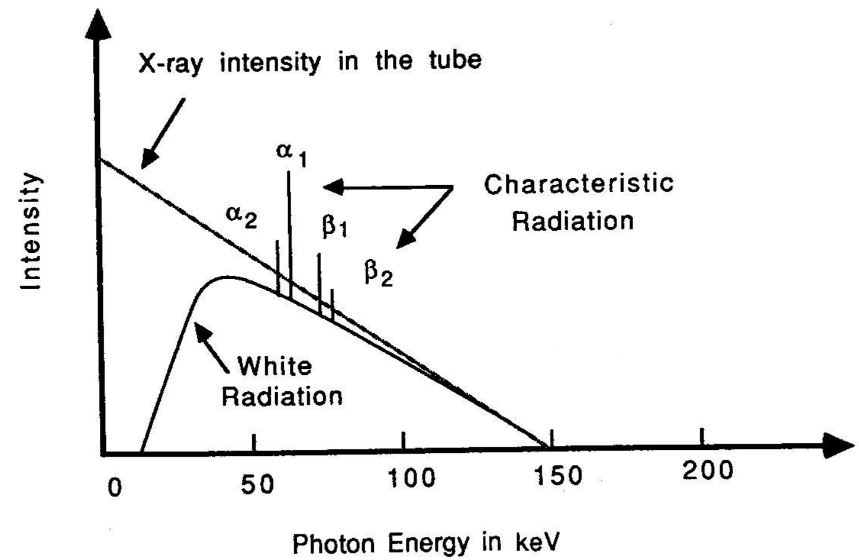


Figure 8 X-ray spectrum produced by the tungsten target of an X-ray tube.

When the electrons striking the target interact with orbital electrons in inner shells, characteristic radiation results. This process is very similar to that described in photoelectric effect. (Hendee and Ritanaur, 2002)

α_1, α_2 represent the characteristic radiations resulting from L shells falling into K shells.

β_1, β_2 represent the characteristic radiations resulting from M and N-shell electrons falling into K shells.

Inherent Filtrations in an X-ray Tube

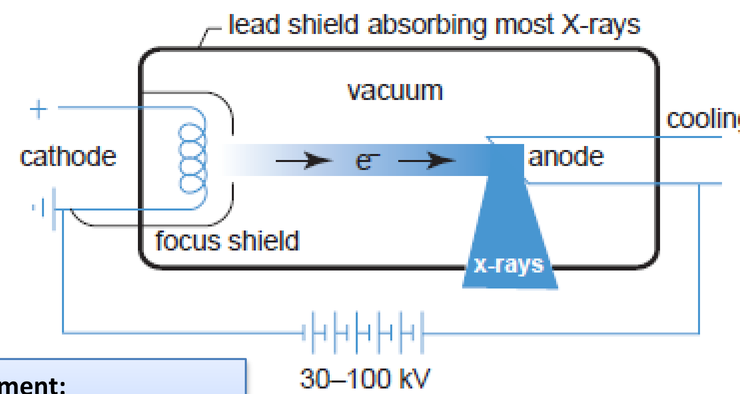
TABLE 5-1 Contributions to Inherent Filtration in Typical Diagnostic X-Ray Tube

Component	*Thickness (mm)*	*Aluminum-Equivalent Thickness (mm)*
Glass envelope	1.4	0.78
Insulating oil	2.36	0.07
Bakelite window	1.02	0.05

[a] Data from Trout, E. *Radiol. Technol.* 1963; **35**:161.

B. X-ray Generators

- A heated filament releases electrons that are accelerated across a high voltage onto a target.
- The stream of accelerated electrons is referred to as the *tube current.*
- X rays are produced as the electrons interact in the target. The x rays emerge from the target in all directions but are restricted by collimators to form a useful beam of x rays.
- A vacuum is maintained inside the glass envelope of the x-ray tube to prevent the electrons from interacting with gas molecules.
- Tungsten is desirable in X-ray application because it has a high melting point (3370°C) and little tendency to vaporize, and is strong.



Filament:
Wire Diameter: 0.2 mm
Coil diameter: 0.2 cm
Coil length: 1 cm

(Suetens P, 2009)

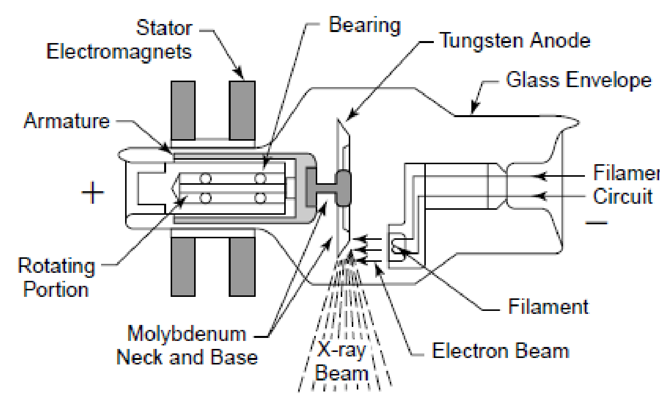


FIGURE 5-1
Simplified x-ray tube with a rotating anode and a heated filament.

(Hendee and Ritanaur, 2002)

Line Focus Principle

Most of the energy carried by the electrons bombarding the tungsten target on the anode is converted into heat (in fact, 99%).

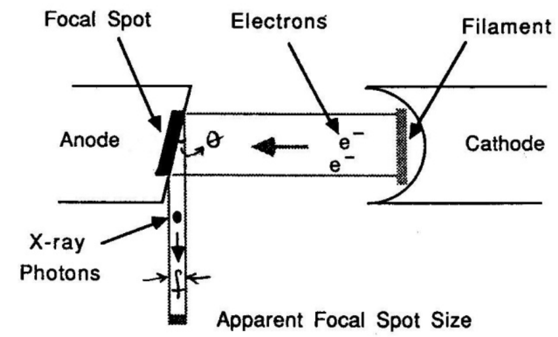


Figure 9 Basic components of an X-ray tube.

- A larger focal spot is preferred as it tolarates larger amounts of heat.

- A small focal spot is needed to generate better images.

The problem can be overcome by using the line focus principle obtained using a slanted target surface. The anode angle θ varies from 5° to 15°.

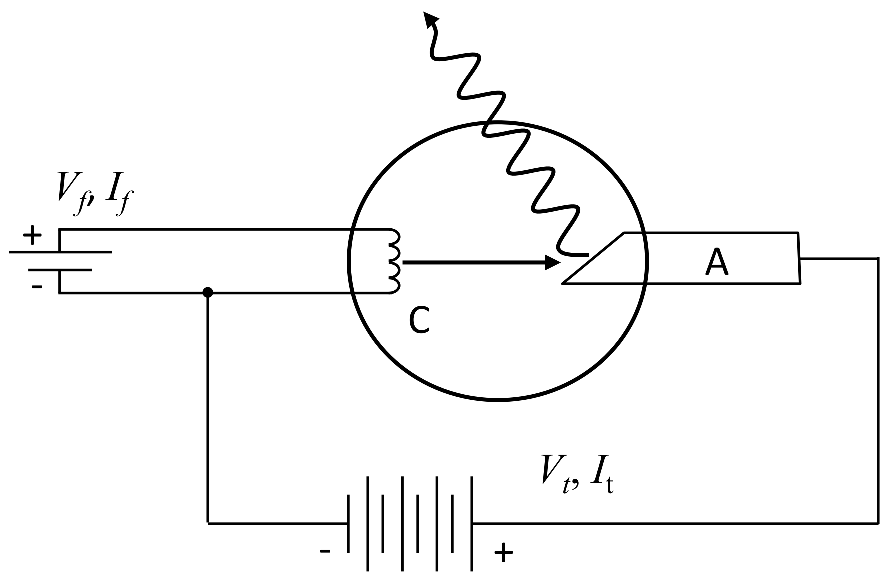
The effective focal size, *f*, is related to actual focal size, *F*, on the anode by the following equation:

$$f = F \sin\theta$$

The heat problem at the anode can be further reduced by using a rotating anode (3000 to 10000 rpm) which increases the total target area.

Electrical circuits associated with an x-ray generator

- Cathode filament C is electrically heated (V_f = ~10V / I_f = ~5 A) to boil off electrons
- Electrons are accelerated toward the anode target (A) by applied high-voltage
- kinetic electron energy: K_e
- Typically: V_t = 40 – 150 kVp, I_t = 1-1000mA
- Abrupt deceleration of electrons on target creates "Bremsstrahlung" (white radiation)



$$E_{p,\max} = h\nu = K_e = qV_t$$

X-ray Tube Ratings

Factors that affect the intensity of the X-ray beam produced by the generator:

1. Filament temperature controlled by the filament current (I_t).
2. Tube voltage (V_t).
3. The number of electrons bombarding the anode target (tube current, I_t).
4. Target Material.

Target Material The higher the atomic number, the greater the efficiency of X ray production. For example, platinum (atomic number 78) produces more white radiation than tungsten (atomic number 74) at the same tube current and potential

Tube Voltage The tube voltage V_t can be either dc or ac following a full-wave or half-wave rectification. For ac generators, it is usually measured in terms of peak voltage applied or kilovolts peak (kVp). The intensity is proportional to the square of kVp.

X-Ray Tube Ratings

Tube Current The number of X-ray photons produced depends on the number of electrons striking the target and therefore should depend on the tube current. It was found that the intensity is linearly proportional to the tube current.

Filament current The tube current increases initially as the tube voltage is increased at a fixed filament current. However, as the voltage is further increased it saturates. At this region, the tube current is limited by the filament temperature or the filament current.

These observations can be summarized by the following equation at fixed I_f:

$$\boxed{I \approx Z \cdot I_t(mA) \cdot V_t^2 \cdot F}$$

where F is the rectification factor for V_t and is one for direct current.

$$I \approx Z \cdot I_t(mA) \cdot V_t^2 \cdot F$$ radiated power (P_r)

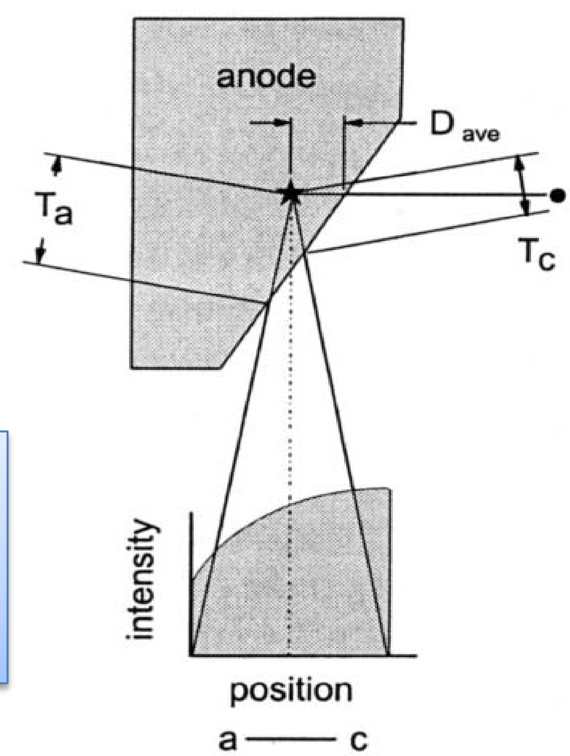
$$P_d = V_t I_t$$ deposited power

efficiency= $P_r/P_d = F\,Z\,V_t$

Efficiency of converting electron energy into x rays as a function of tube voltage.[4]

kV	**Heat (%)**	**X Rays (%)**
60	99.5	0.5
200	99	1.0
4000	60	40

The intensity leaving X-ray tube is not uniform



Heel Effect The intensity is smaller in the anode direction because photons travelling in certain direction have to travel a longer path in the anode than others.

Possible target damages

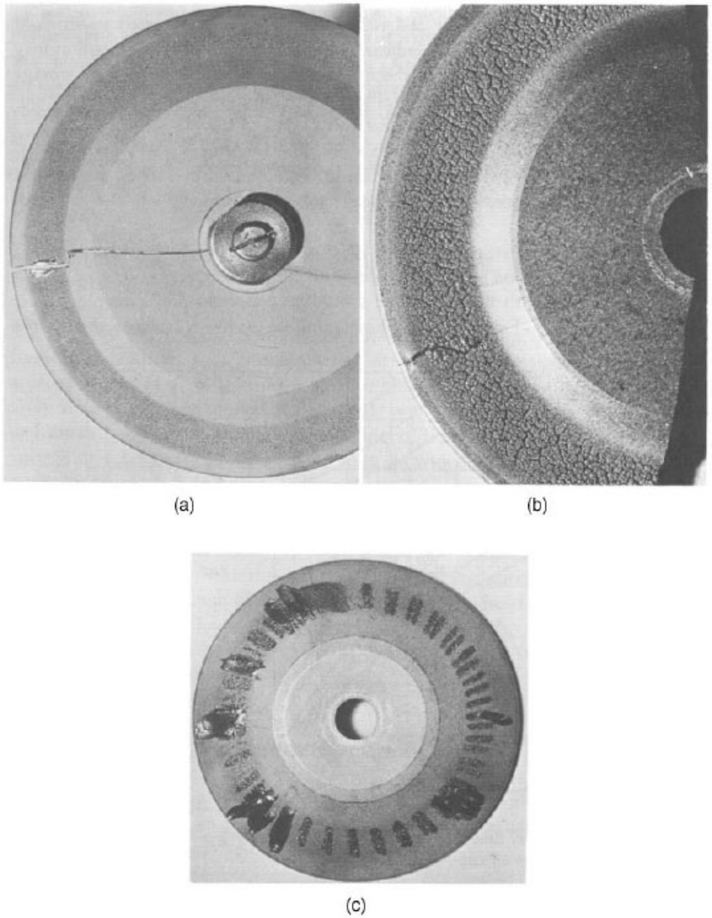
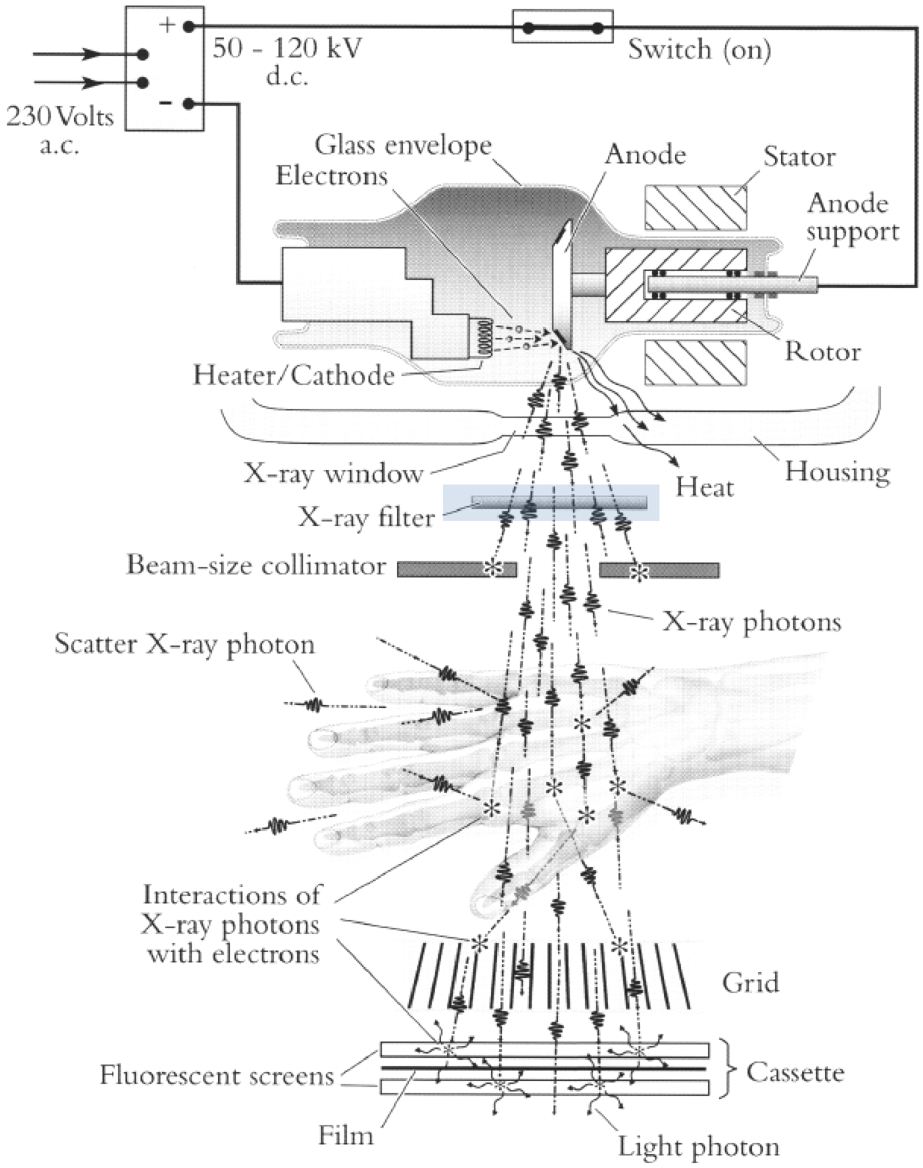


FIGURE 5-12
Rotating targets damaged by excessive loading or improper rotation of the target. **A:** Target cracked by lack of rotation. **B:** Target damaged by slow rotation and excessive loading. **C:** Target damaged by slow rotation.

(Hendee and Ritanaur, 2002)

C. Filters

- X-rays generated by X-ray tubes are *polychromatic.*
- Depending on the nature of a certain application, only a portion of the energy spectrum is desirable.
- The radiation dose to the patient can be substantially reduced by filtering out the desired portion of the X-ray spectrum.
- Thin sheets of metal placed between the X-ray source and patient are used as absorbers:
  - Aluminum is an excellent absorber for low-energy x-rays.
  - Copper is used as an aborber for high energy x-rays.



D. Beam Restrictors

- There are three types of X-ray beam restrictors:
  - Aperture diaphragms,
  - Cones and cylinders, and
  - Collimators
- The basic function of a beam restrictor is to regulate the size and shape of the beam.
- A closely collimated beam can reduce patient exposure and generate less scatter radiation.
- The aperture diagragm is basically a sheet of lead with a hole in the center whose size and shape determines those of the X-ray beam

To reduce the penumbra, the source should be made as small as possible and the diaphragm should be positioned as far away from the source as possible.

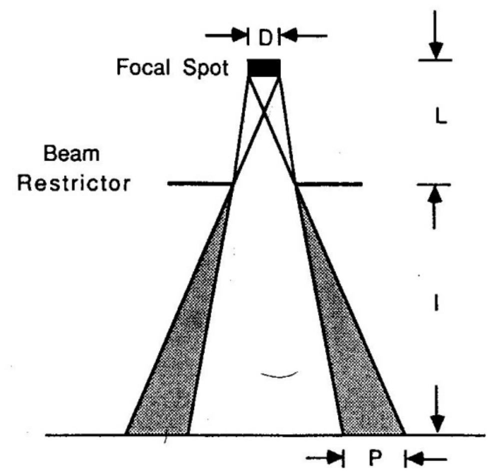


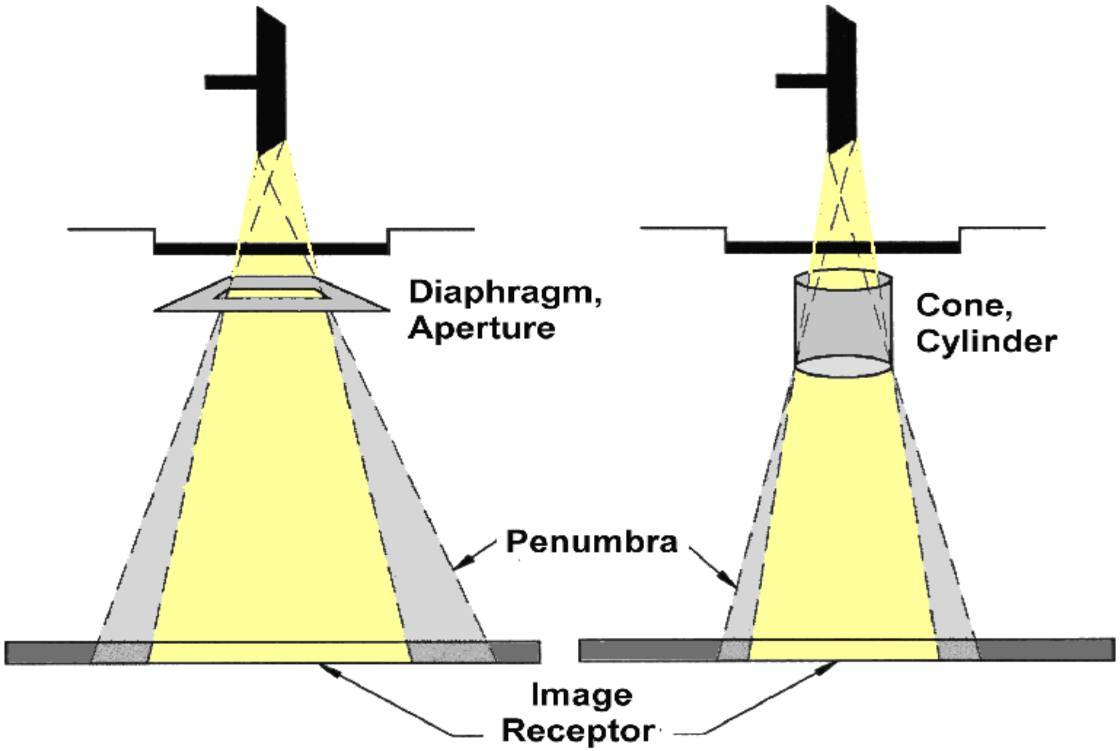
Figure 13 Effect of a beam restrictor on X-ray is illustrated. Finite aperture size results in penumbra along edges.

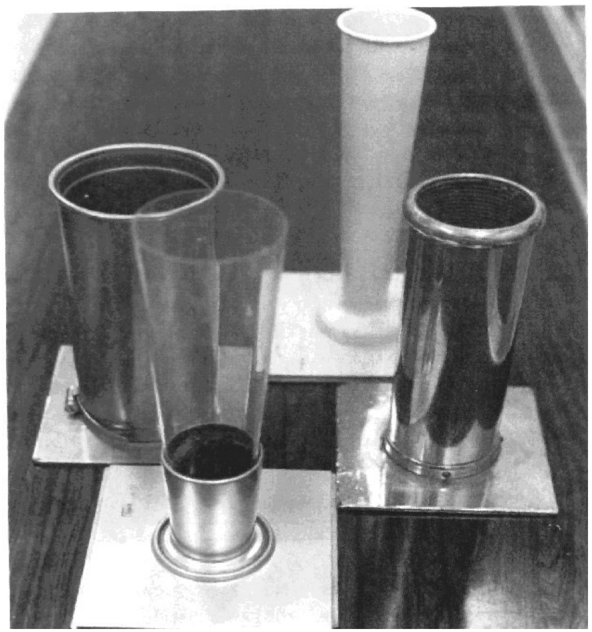
The width of the penumbra *P* is related to the source diameter by the following equation:

$$P = l\frac{D}{L}$$

D : the width of the source,
L: the distances between the source and the restrictor,
l: the distances between the restrictor and the detector.

Cones and Cylinders





Cones and cylinders are sometimes also used as beam restrictors, but they, along with the diaphragm, suffer from a major drawback:

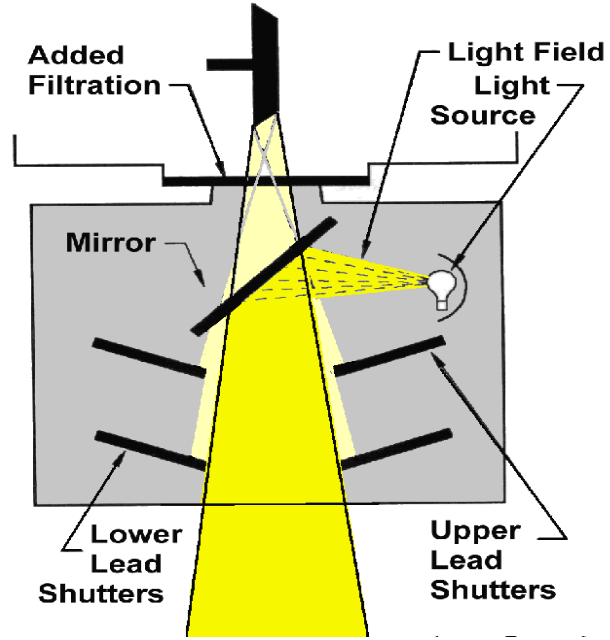
Only a limited number of beam sizes can be obtained.

Examples: dental, mammography

Collimators

- The collimator is the most popular beam restrictor for two reasons:
  - The X-ray field size is adjustable,
  - A light beam can be used to indicate the exact size of the field.

- The X-ray beam size is adjusted by the movable aperture diaphragm. The X-ray field is illuminated by a light beam from a light bulb located within the collimator the same distance from the center of the mirror as the X-ray source.



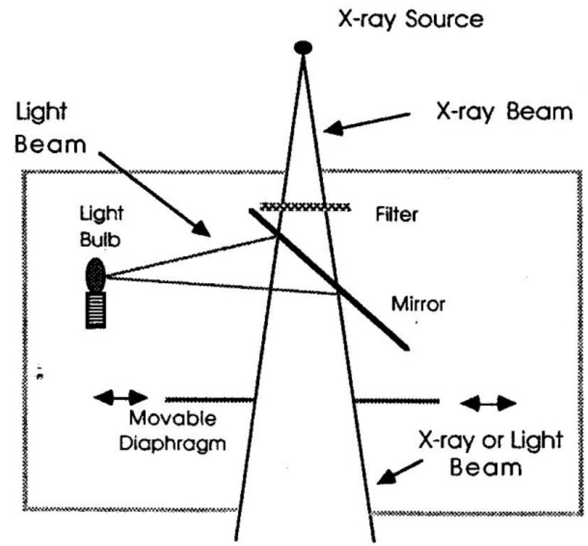


Figure 14 Physical construction of a collimator.

Collimators

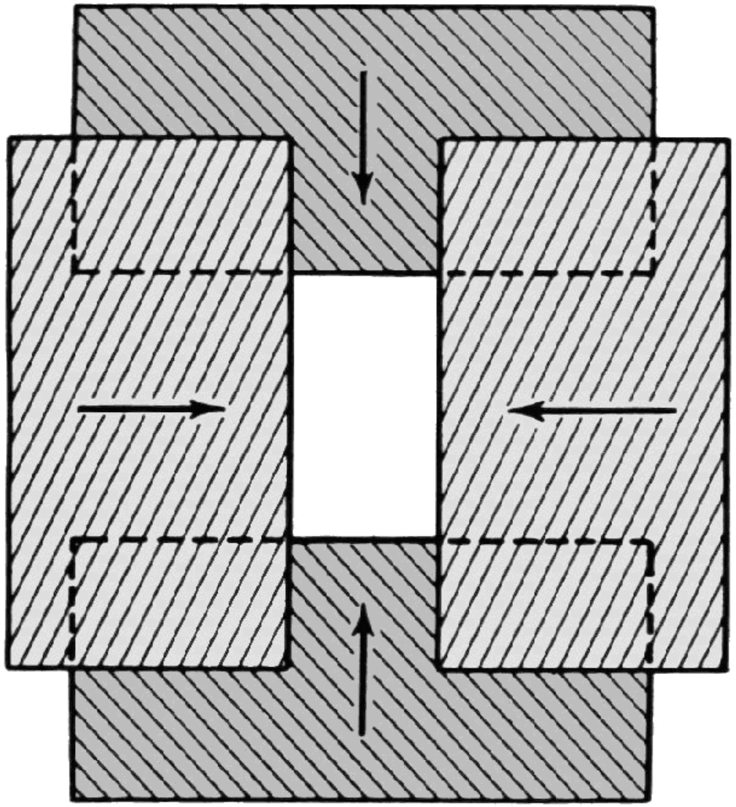


Figure source: www.hhresidents.org/files/Physics/Physics/.../radiog3-scatter.PPT

The Effect of Compton Scattering on the X-ray Image

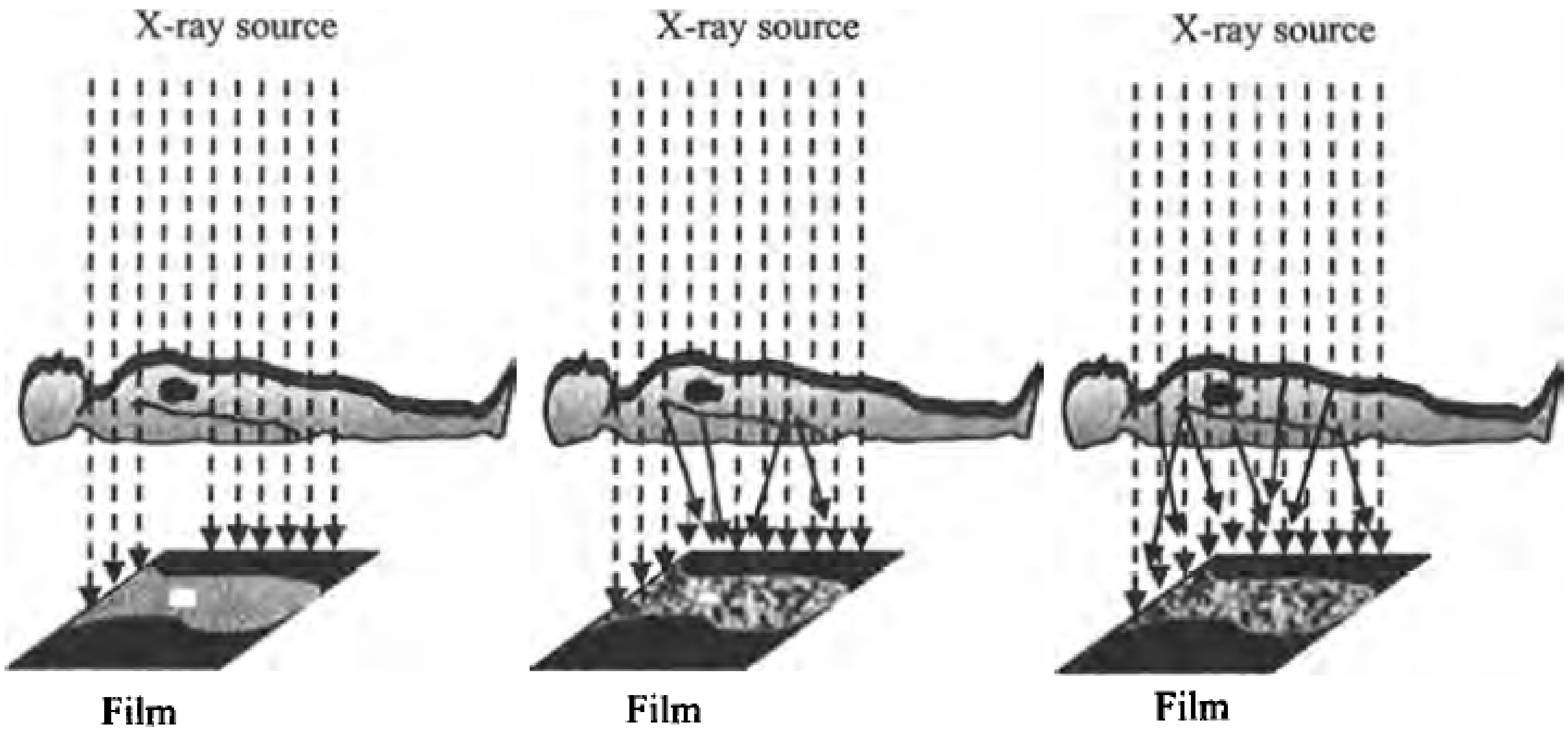
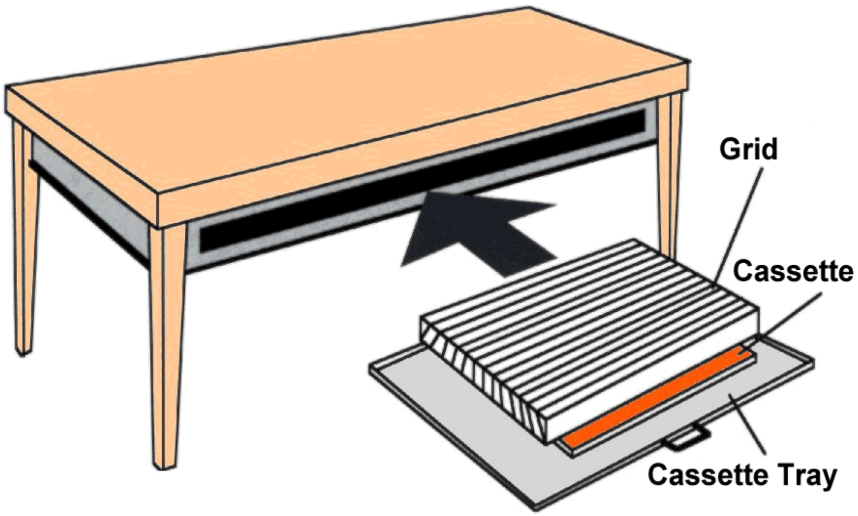
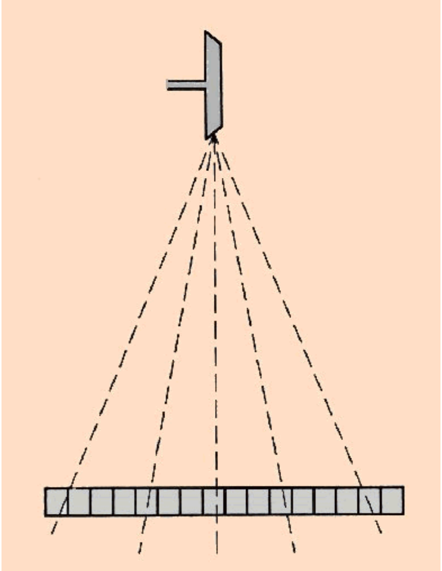


FIGURE 1.11. *The effect of Compton scattering on the X-ray image. A highly attenuating pathology is represented as a black object within the body. (Left) The ideal situation in which only photoelectric interactions occur leading to complete X-ray attenuation in the pathology. (Center) As the contribution of Compton-scattered X-rays to the image increases, the image contrast is reduced. (Right) In the case where only Compton-scattered X-rays are detected, image contrast is almost zero.*

(Webb, 2003)

Anti-scatter grid





- Scattered X-rays are noise that degrade image quality and increase patient exposure and therefore should be minimized.
- The most effective way of removing scatter radiation is the radiographic grid.
- The grid is composed of a series of lead foil strips separated by X-ray transparent spacers which are either aluminum or organic material.
- The grid blocks the scattered radiation while letting the primary radiation pass.

Figure source: www.hhresidents.org/files/Physics/Physics/.../radiog3-scatter.PPT

E. Intensifying screens, Fluorescent Screens, and Image Intensifiers

- The intrinsic sensitivity of photographic film to X-rays is very low, meaning that its use would require high patient doses of radiation to produce high-quality images.
- In order to circumvent this problem, *intensifying screens* are used to convert X-rays into light, to which film is much more sensitive.
- Compared to direct detection of X-rays by film alone, the intensifying screen/film combination results in a greater than 50-fold increase in sensitivity. The more sensitive the film, the lower is the necessary tube current and patient dose.

(Webb, 2003)

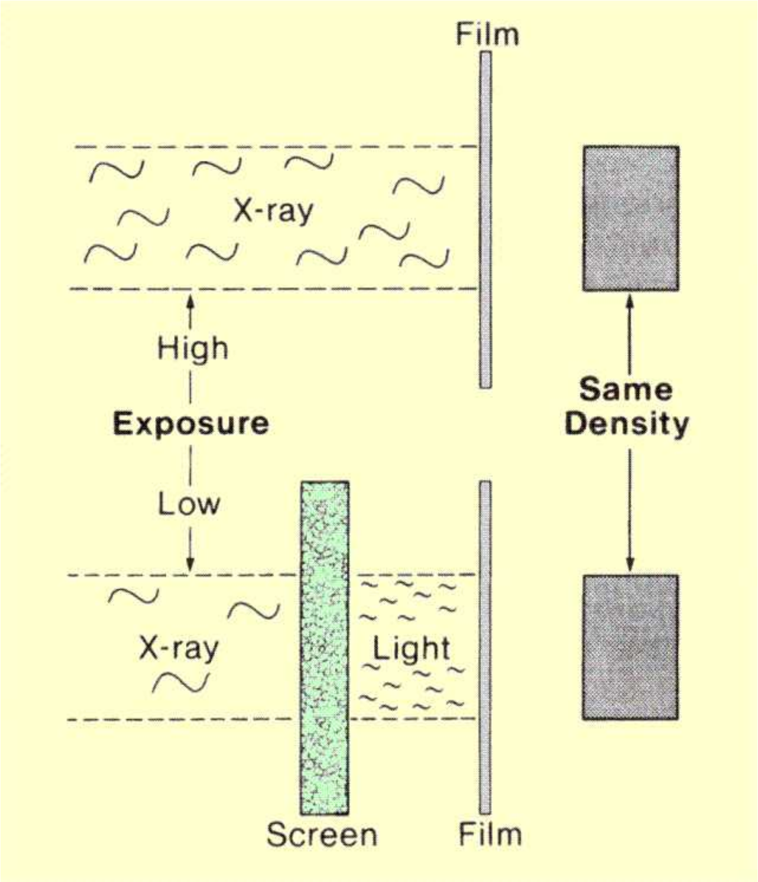


Figure source:
http://www.sprawls.org/ppmi2/FILMSCR/

Intensifying screens

Schematic of an intensifying screen/film combination

(METU, 2011)

Intensifying screens

- The phosphor layer in the screen contains a rare earth element such as gadolinium (Gd) or lanthanum (La) suspended in a polymer matrix.
- The two most common screens contain terbium-doped gadolinium oxysulfide (Gd_20_2S:Tb) or terbium-doped lanthanum oxybromide (LaOBr:Tb).
- Gd_20_2S:Tb emits light in the green part of the spectrum at 540 nm, and since Gd has a *K* -edge at 50 keV, absorption of X-rays via photoelectric interactions is very efficient.
- The compound has a high energy conversion efficiency of 20%, that is, one-fifth of the energy of the X-rays striking the phosphor layer is converted into light photons.
- LaOBr:Tb emits light in the blue part of the spectrum at 475 nm (with a second peak at 360 nm), has a *K* -edge at 39 keV, and an energy conversion efficiency of 18% (Webb, 2003).
- This compound has the advantage of using film technology that had been developed for a previously widely used phosphor, cadmium tungstate.

Image Intensifiers

- In early fluoroscopic techniques, x rays emerging from the patient impinged directly on a fluoroscopic screen.
- Light was emitted from each region of the screen in response to the rate at which energy was deposited by the incident x rays.
- The light image on the fluoroscopic screen was viewed by the radiologist from a distance of 10 or 15 in.
- A thin plate of lead glass on the back of the fluoroscopic screen shielded the radiologist from x radiation transmitted by the screen.
- The image produced on the image intensifying screen is typically very weak.
- To brighten the image, a device called the image intensifier is developed.
- Image intensifier tubes convert the x-ray image into a small bright optical image, which can then be recorded using a TV camera.

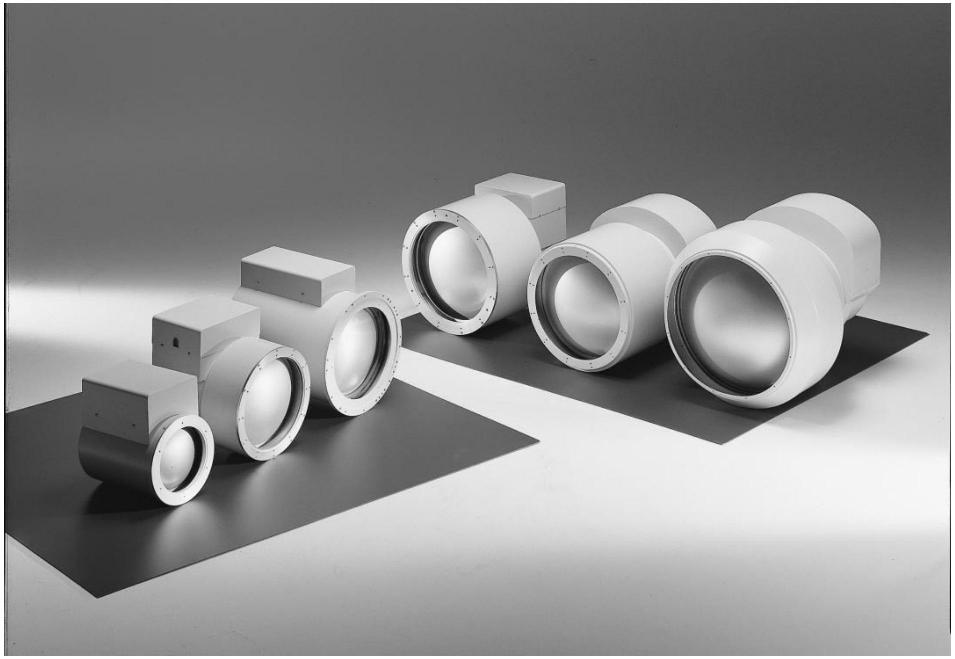
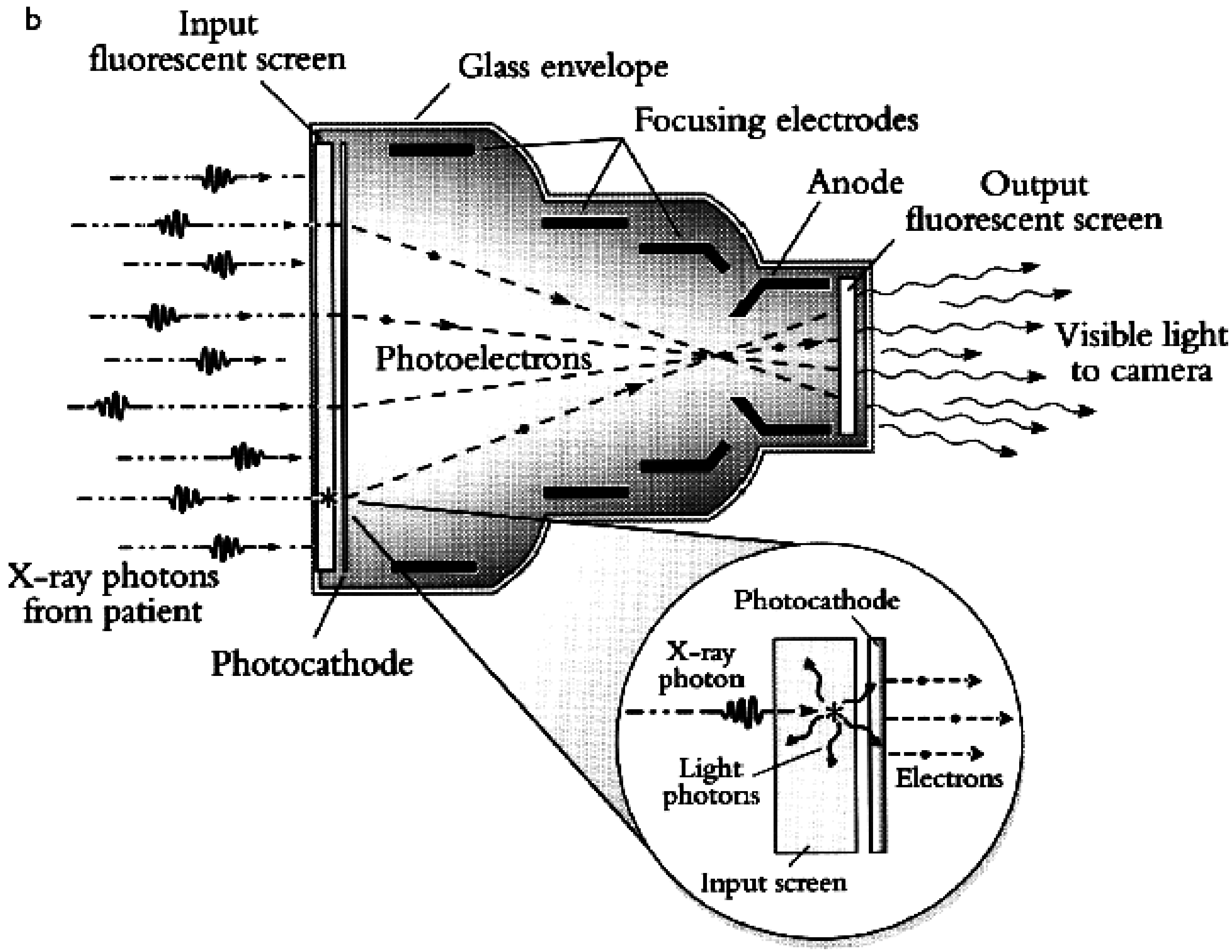


Figure source: http://sales.hamamatsu.com/assets/pdf/catsandguides/x-ray_image_intensifiers.pdf

Image intensifier is a vacuum tube with the following components:

1. Input phosphor and photocathode,
2. Focusing plates,
3. An anode, and
4. Output phosphor

Image Intensifiers

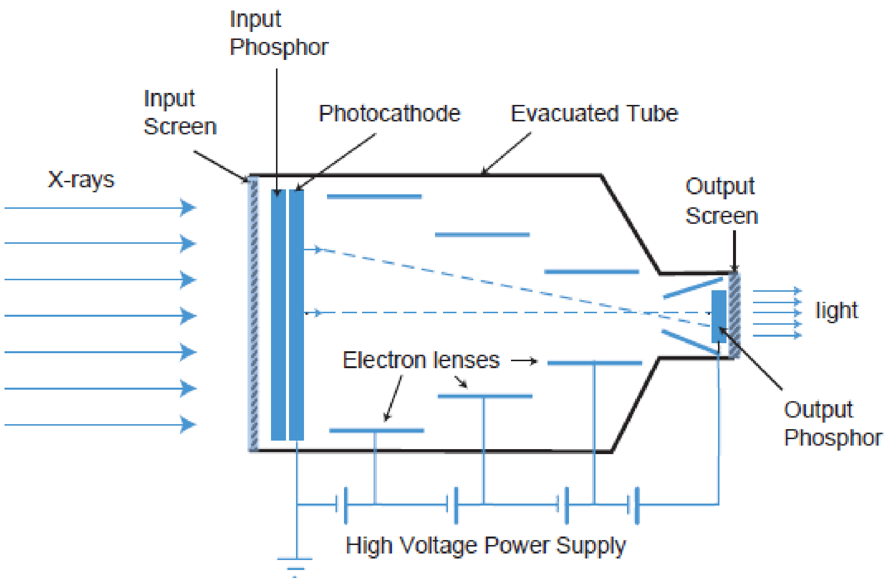


Wolbarst, 1999

Image Intensifier

Phases:

- Conversion of x-ray energy to light in the phosphorous screen (Cesium iodide, CsI)
- Emission of low-energy electrons by photoemissive layer (antimony)
- Acceleration (to enhance brightness) and focusing of electrons on output phosphorous screen (zinc cadmium sulfide, ZnCdS)



(Suetens P, 2009)

The X-ray photons that have propagated through the patient will be absorbed by the fluorescent screen of 15 to 35 cm diameter with almost spontaneous emission of ligt photons.

F. X-ray Receptors: X-ray film

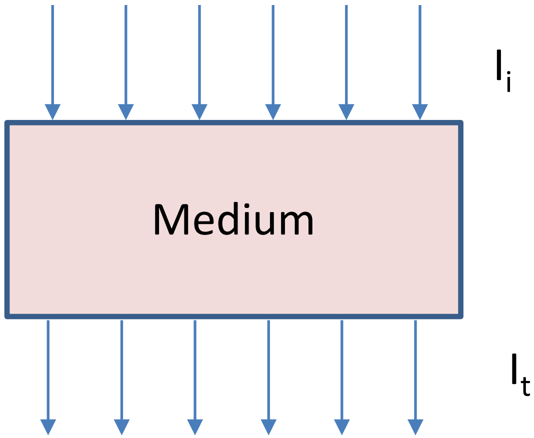
- Photographic film has low sensitivity for x-rays directly; a fluorescent screen (phosphor) is used to convert x-ray to light, which exposes the film.

- Film Composition:
  - Transparent plastic substrate (acetate, polyester),
  - Both sides coated with light-sensitive emulsion (gelatin, silver halide crystals 0.1-1 mm). Exposure to light splits ions $\rightarrow$ atomic silver appears black (negative film),

- Blackening depending on deposited energy ($E = I \times t$),

Optical density: The photographic density or optical density used to measure the film blackness is defined by the following equation:

$$D = Log_{10}(I_i / I_t)$$



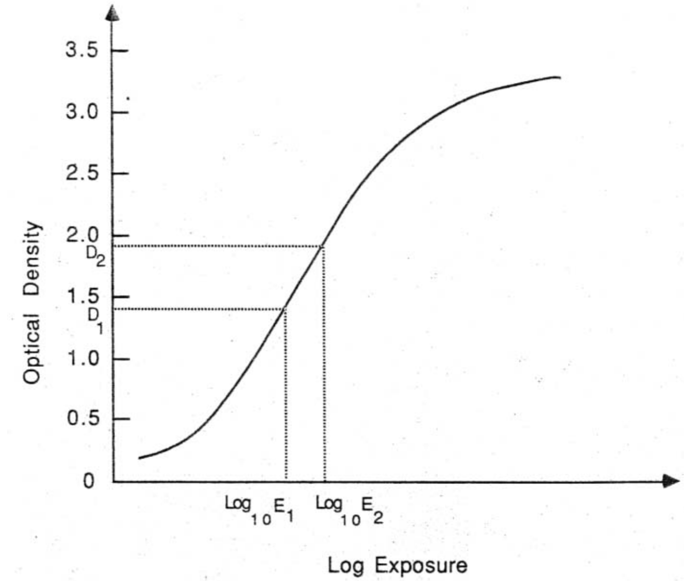
D > 2 = "black", *D* = 0.25 ... 0.3 = "transparent (white)" with standard light box (diagnostic useful range ~ 0.5 - 2.5)

X-Ray film

Characteristic curve Relationship between optical density D and film exposure, or the H and D curve, of the film.

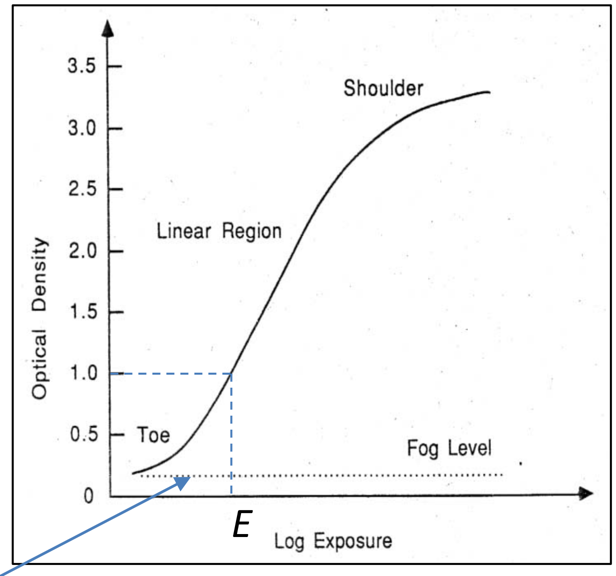
Film Gamma Film Gamma is defined as the maximum slope of the characteristic curve

$$\gamma = \frac{D_2 - D_1}{\log_{10} E_2 - \log_{10} E_1}$$



Speed Speed or sensitivity of an X-ray film-screen combination is conventionally defined as the reciprocal of the X-ray exposure in Roentgens required to produce a density of 1.0 or

$$S = 1/E$$



Film Latitude Range of log exposure that produces acceptable optical density for diagnostic purpose (usually between 0.5 and 2.5)

Silver halides developed without exposure

X-Ray Receptors: Radiation Detectors

Two types of radiation detectors are currently used for X-ray detection:

(1) Scintillation detectors,
(2) Ionization chamber detectors

Scintillation detectors Scintillation crystals Like NaI emit light photons in proportion to the absorbed X-ray photon energy.

The scintillation crystal surface is coated with a reflective material to collect the light photons.

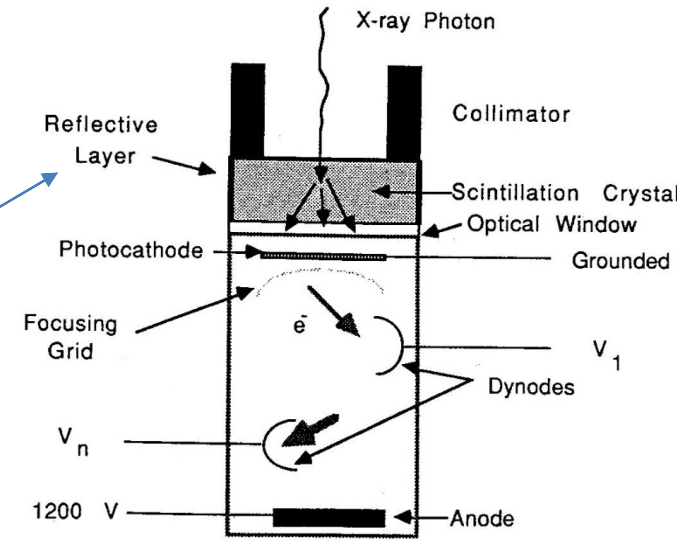


Figure 23 Physical construction of a photomultiplier tube.

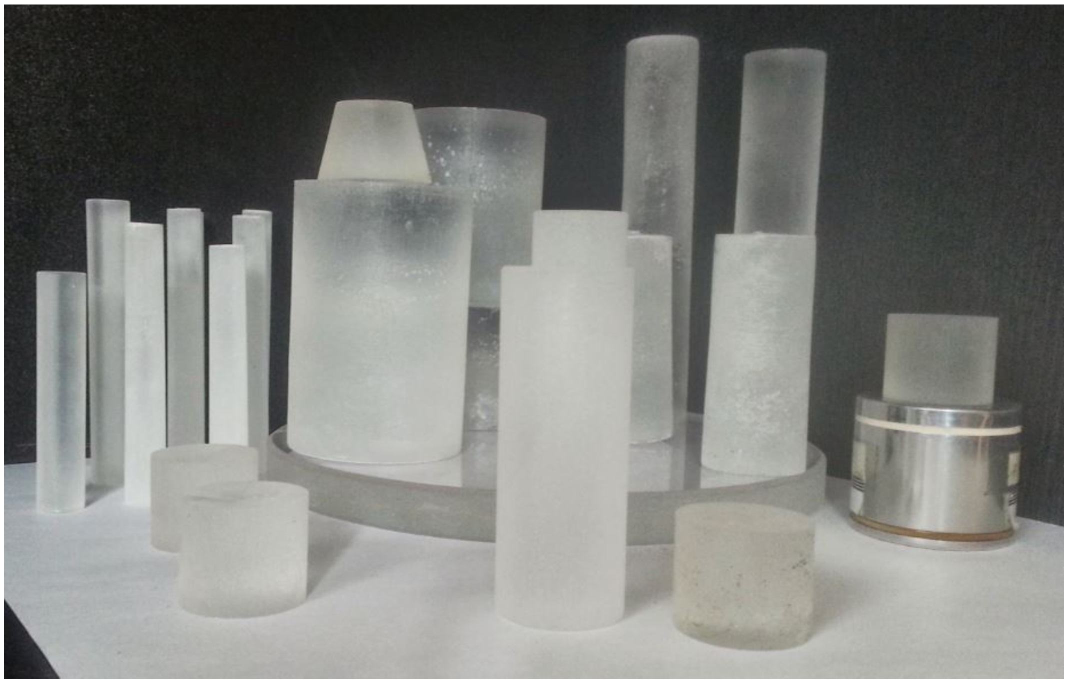
Scintillation detector
Scintillation crystal coupled to a photomultiplier tube

Photomultiplier tube consists of

- photocathode,
- an anode, and
- several intermediate electrodes called dynodes.

The number of electrons is multiplied when they propagate down the tube. The output current is proportional to the number of light photons. *Efficiency is above 85%.*

Scintillation crystals



http://mkt-intl.com/materials/single-crystals-optical-materials/scintillator-crystals/

Photomultiplier Tube Detectors

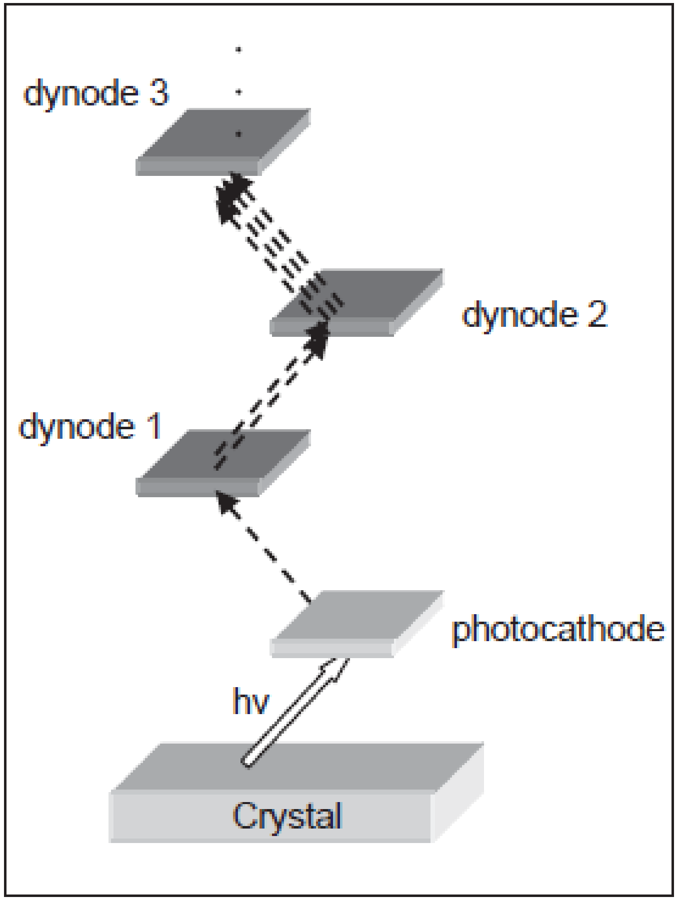


Figure 3.8

(left). The first three amplification stages in a PMT tube. (right) A commercial PMT.

Smith and Webb, 2011

Ionization chamber detectors

- It consists of a chamber filled with a gas, usually Xenon.
- Gas molecules in the chamber are ionized by X-ray photons.
- The ions are then attracted to the electrodes by a voltage difference between the electrodes, which is adjusted so as to produce a current accurately representing the energy of the X-ray photons absorbed.
- Because of the low density of gases, some of the X-rays may travel through the chamber undetected. To overcome this problem Xenon, the heaviest of the inert gases, is preferred.
- This type of device is *relatively inefficient* but *cheap*.

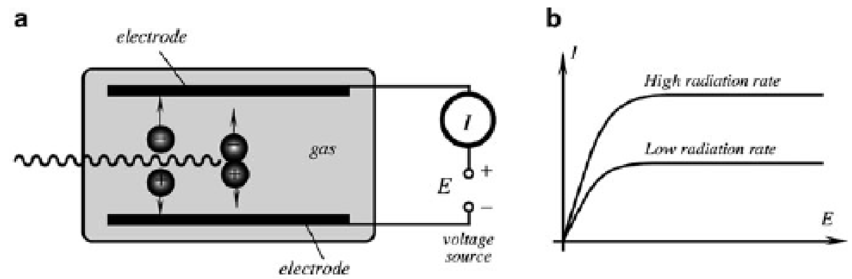


Fig. 15.3 Simplified schematic of an ionization chamber (**a**) and a current vs. voltage characteristic (**b**)

(Fraden, 2010)

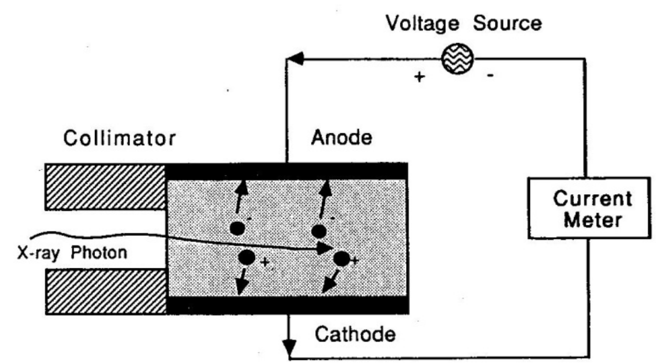


Figure 24 Physical construction of a radiation detector: ionization chamber.

III. X-ray Diagnostic Methods

A. Conventional X-RayRadiography

Most commonly used clinical procedure

- Radiologists are familiar with the procedure,
- Fully aotomated – easy to learn how to operate the machine,
- Image resolution is good,
- Performance is superior to other modalities in a number of situations.
- Lower density region appears darker (less attenuation in the object, more X-ray intensity)
- Higher density region appears lighter (more attenuation in the object, less X-ray intensity)

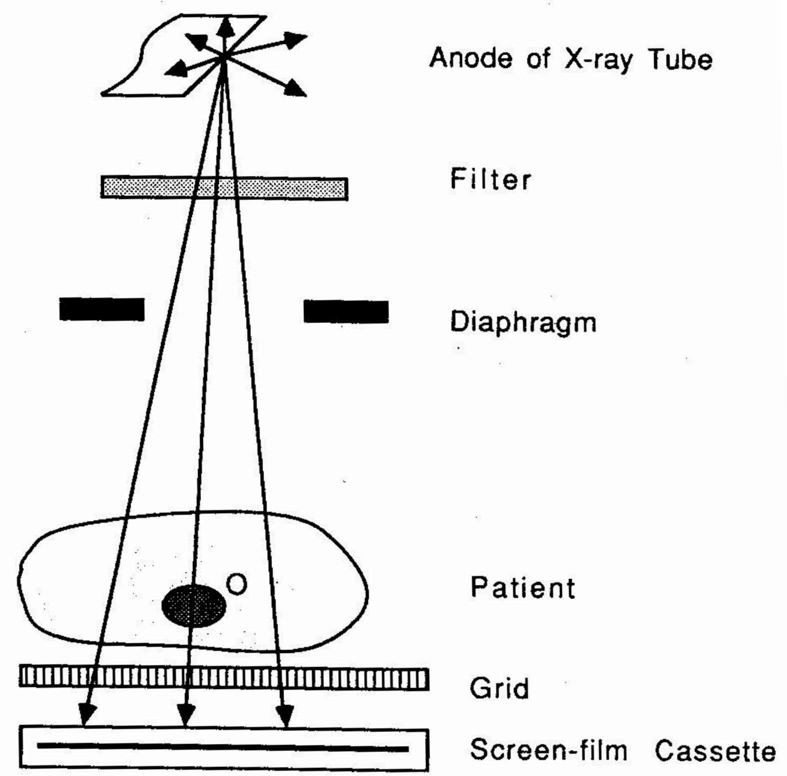
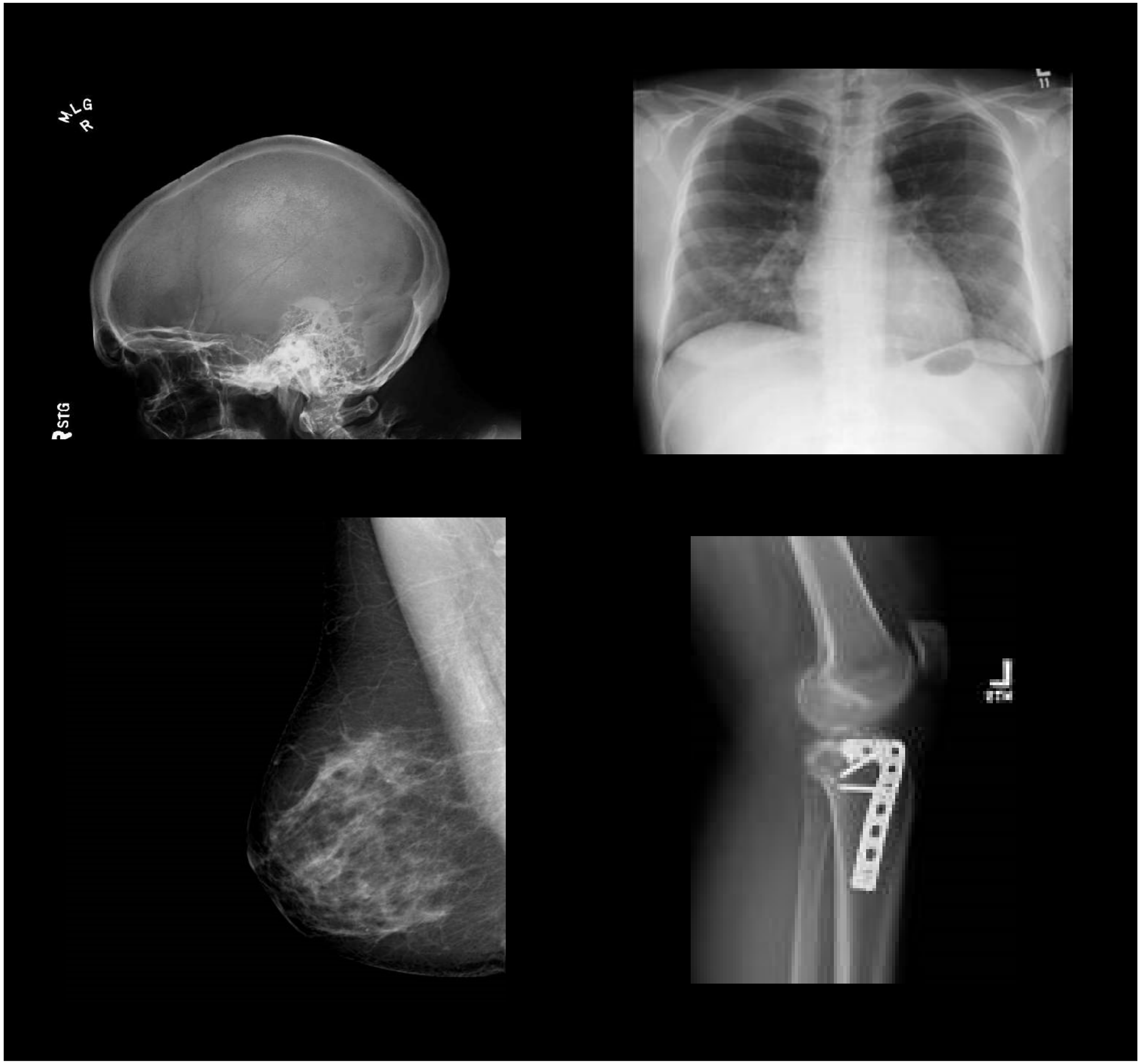
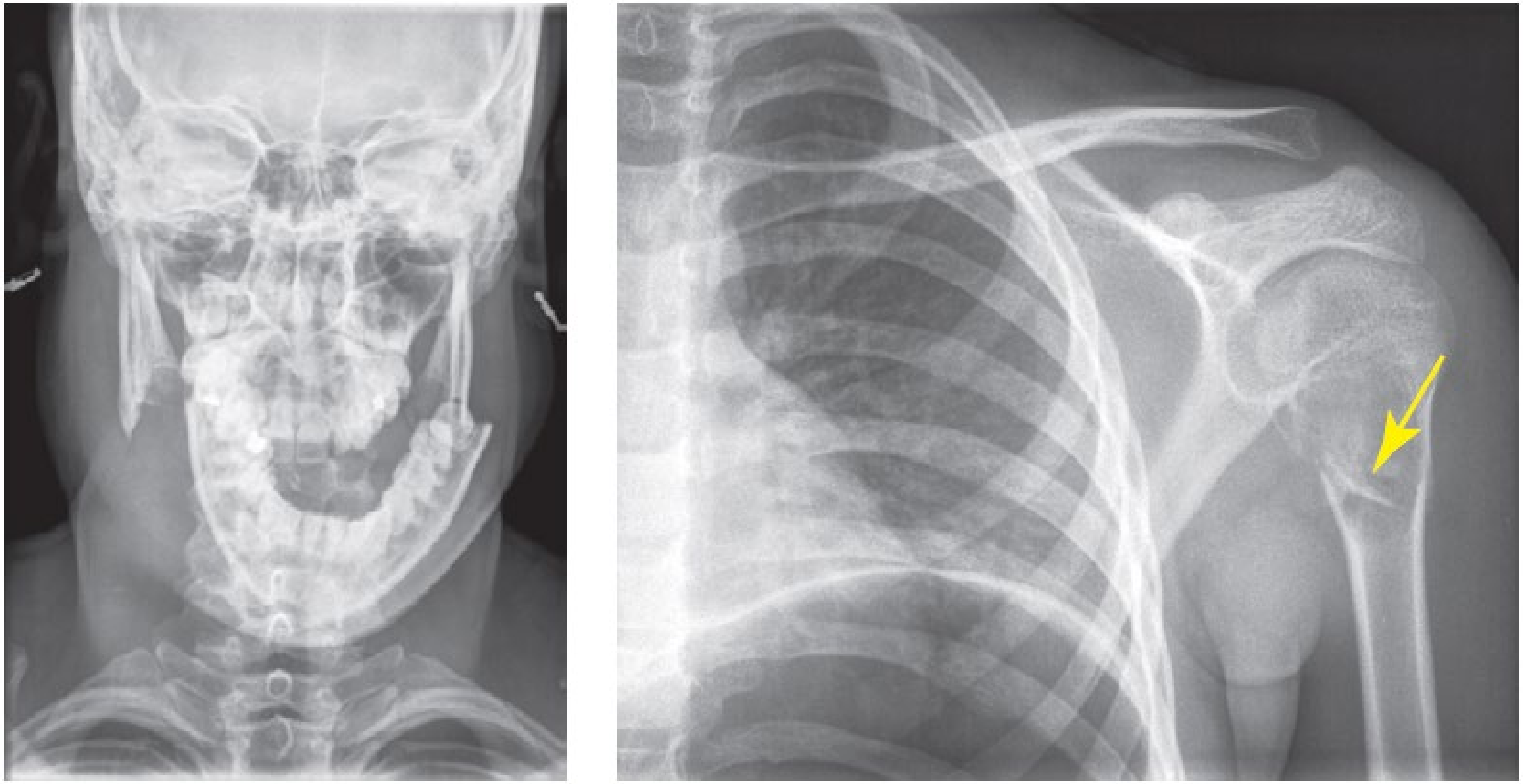


Figure 25 Basic components of a conventional radiographic system.

Conventional X-Ray Radiography

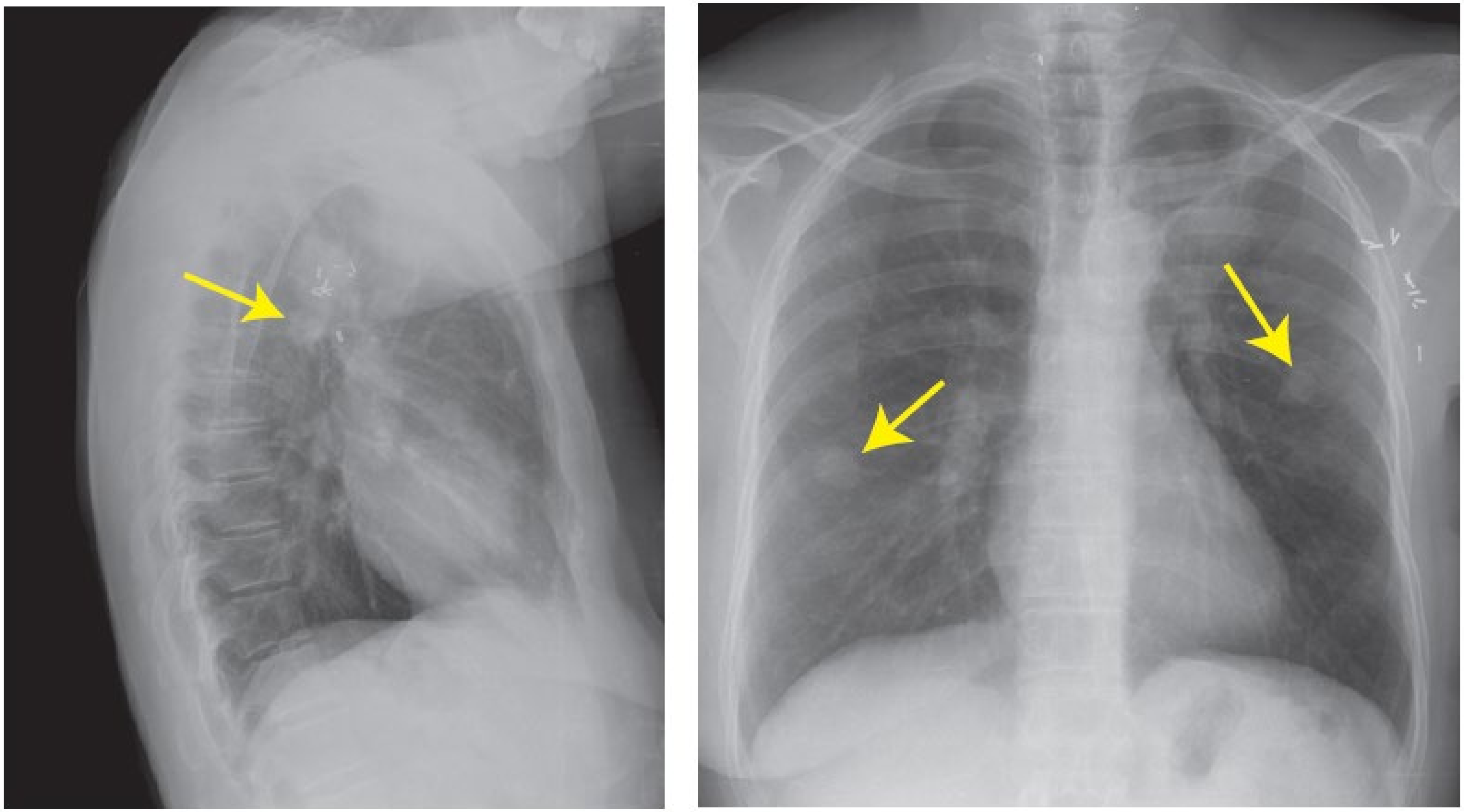




(a) (b)

Figure 2.14 **(a)** Double mandibular fracture with strong displacement to the left. **(b)** Solitary humeral bone cyst known as "fallen leaf sign". (Courtesy of Dr. L. Lateur, Department of Radiology.)

(Suetens P, 2009)



(a)

(b)

Figure 2.15 Radiographic chest image showing multiple lung metastases. (Courtesy of Professor J. Verschakelen, Department of Radiology.)

(Suetens P, 2009)

Penumbra or Geometric Unsharpness

Since the focal spot of an X-ray generator is of finite size, a blurring effect on the image of an object will result.

However, because of the focal spot size f the image is smeared or *blurred*.

The width of this blurred image, d, is defined as the geometric penumbra or geometric unsharpness.

d is related to the focal spot size f by the following equation:

$$\frac{d}{f} = \frac{t}{(S-t)}$$

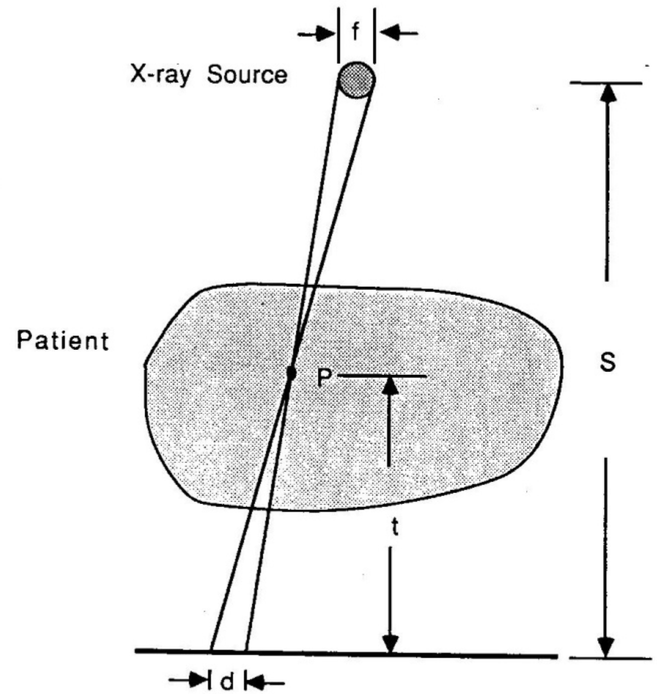


Figure 26 Finite aperture of X-ray source causes blurring of image.

To reduce the geometric unsharpness, f and t should made small and S should be large.

1. The patient is asked to lean his/her chest as tightly as possible to the film cassette,
2. X-ray generator is located as far away as possible from the patient.

Penumbra

S_0: tube-patient distance

S_1: tube-detector distance

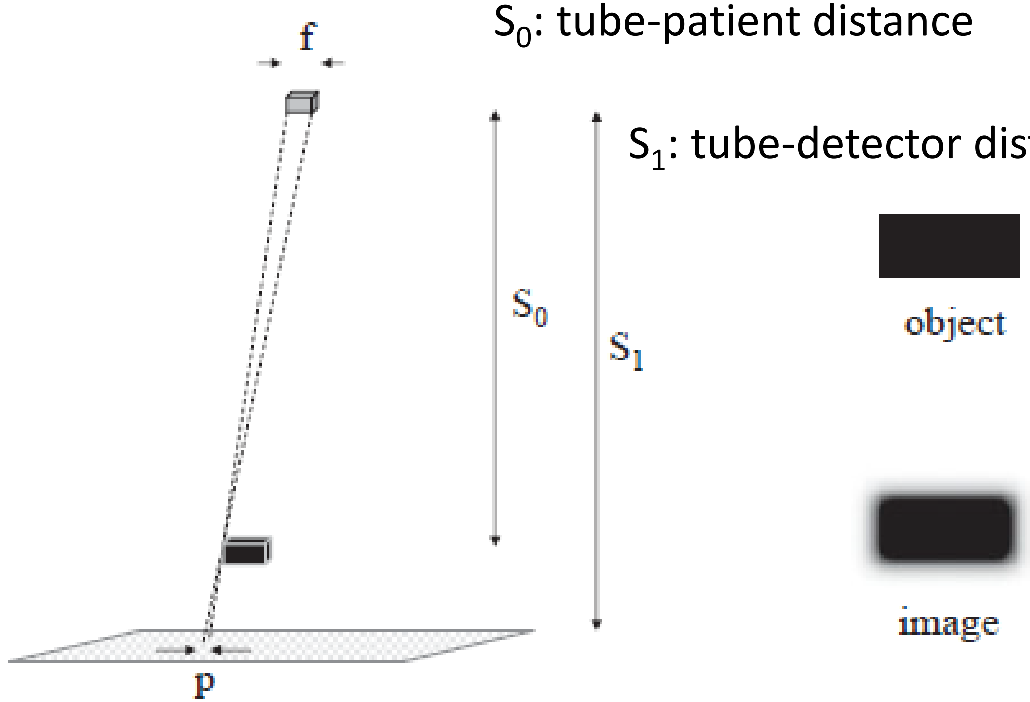


Figure 2.20

A finite effective spot size as well as the tube–patient (S_0) and tube–detector (S_1) distances determine the spatial resolution of the image. The 'geometric unsharpness' or penumbra (P) causes features and edges in the image to become blurred, as shown on the right.

Smith and Webb, 2011

Field Size

As the x-ray beam leaves the focal spot, it diverges.

If the beam restrictor size is d_0, the field size d_1 at a distance S_1 from the focal spot is given by

$$d_1 = d_0(S_1 / S_0)$$

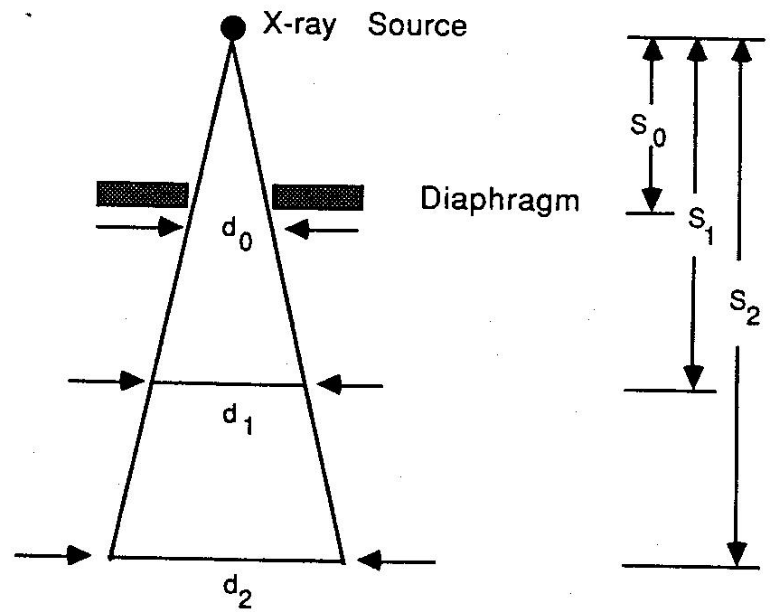


Figure 27 X-ray beam field size is proportional to distance from source.

and the relationship between the size d_2 at a distance S_2 from the focal spot and d_1 is given by

$$d_2 = d_1(S_2 / S_1)$$

It should be realized that the focal spot is finite and consequently, there will be penumbra associated with the boundaries.

The relationships hold if the film is positioned at a large distance from the source.

Film Magnification

Suppose that an object of interest, O, is located in the body of a patient and that the object is located at a distance from the film.

It can easily be shown that the size of the object, L_0, is magnified by the factor of

$$r_m = L_1 / L_0 = S_t / (S_t - t)$$

where L_1 is the size of the object on the film and S_t is the distance between the focal spot and the film.

It is apparent that if multiple objects are imaged, the sizes of these objects on the film are distorted proportionally to the distances between these objects and the film.

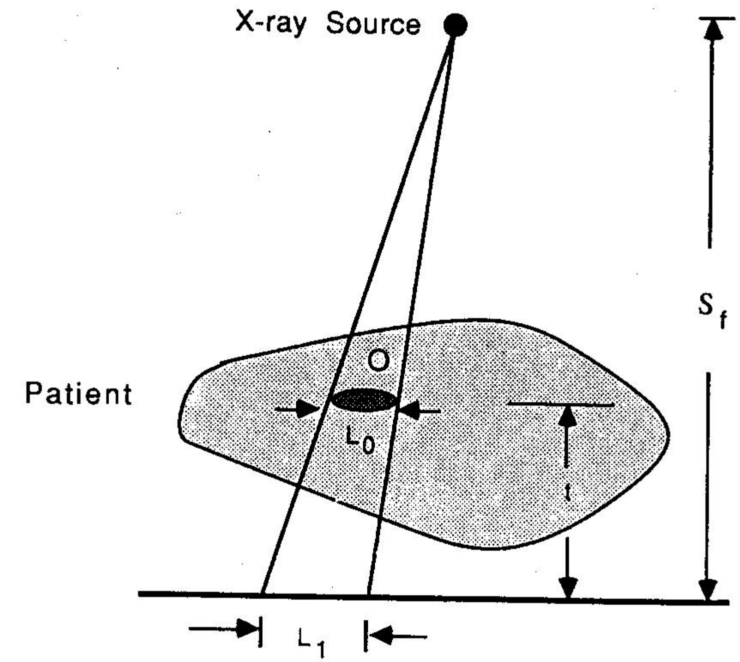


Figure 28 X-ray image of object is magnified by ratio of $S_f/(S_f - t)$.

This distortion is minimized if $S_t \gg t$.

Fluoroscopy

The X-ray images can be recorded on a film for examination or can be visualized directly on a fluorescent screen if motion of the object of interest, such as a contrast medium like barium sulfate in the digestive tract, must be studied.

In a conventional fluoroscope, the image intensifier is replaced with a fluorescent screen, yielding a weak image. The room should be darkened for examining the image. Therefore, in the modern fluoroscopes image intensifiers are used.

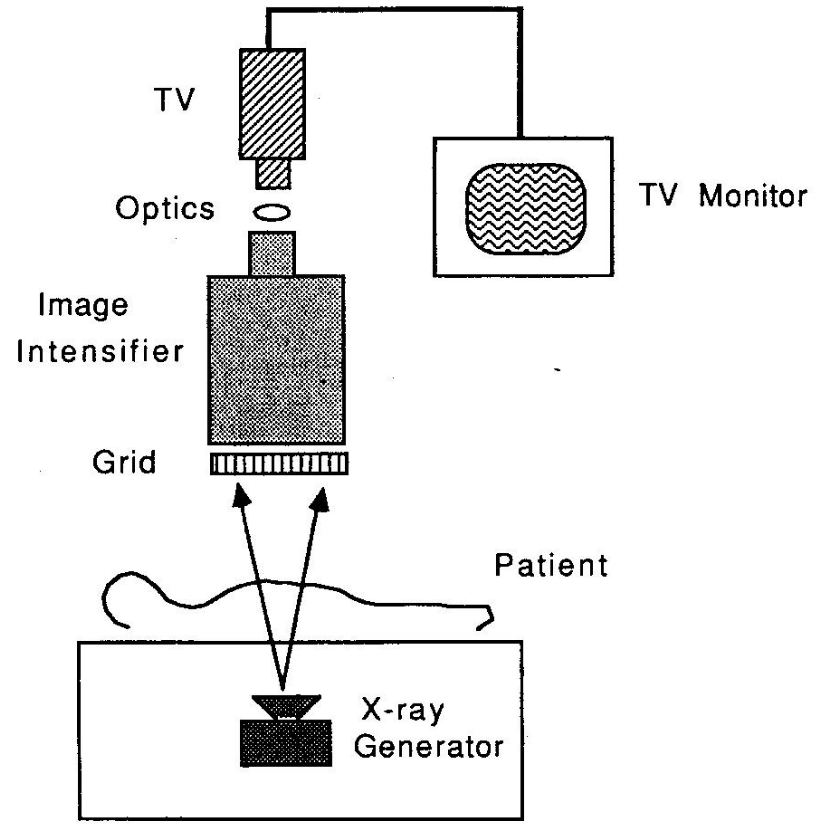


Figure 29 Basic components of fluoroscopy.

Ulcers, tumors, or obstructions in the digestive tract can be diagnosed by fluoroscopy.

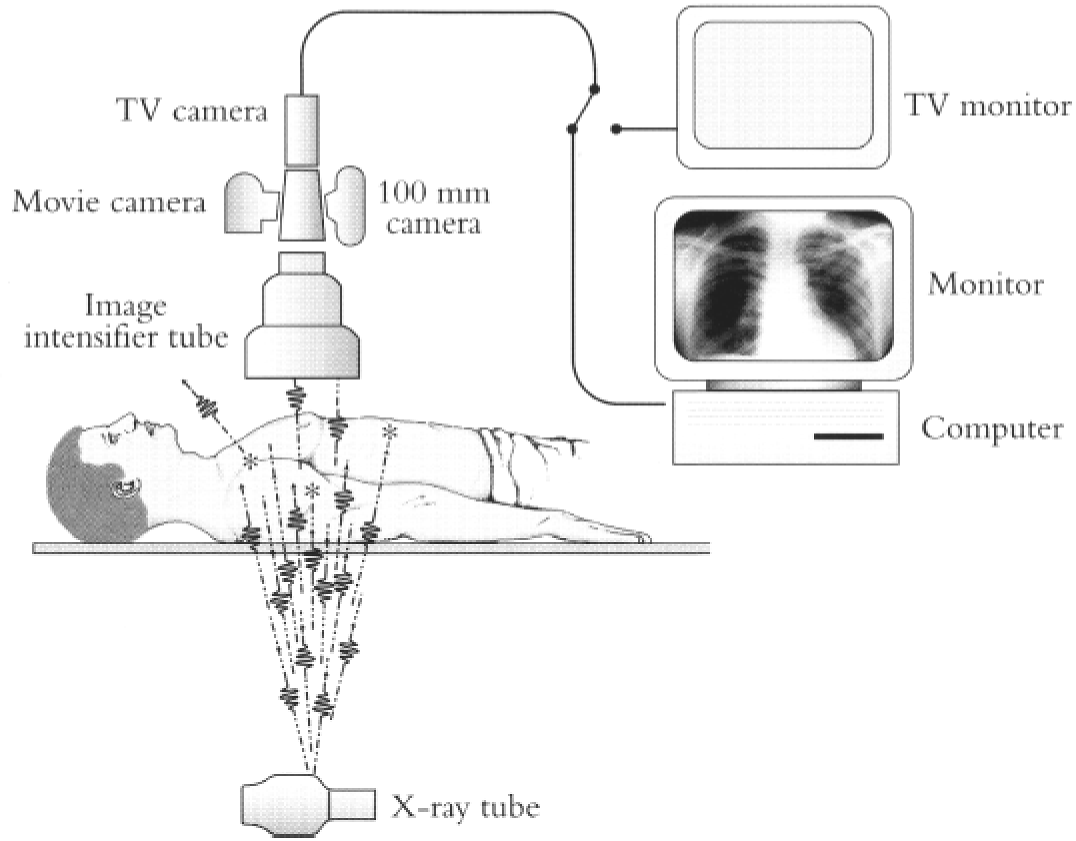


Figure 9. Fluoroscopy. The radiant energy from an X-ray tube passes through the patient, and the resulting X-ray shadows are transformed by the image intensifier into a bright image of visible light three centimeters or so in dimensions. This optical image, in turn, is captured by a 100 mm camera, a movie camera, or a video camera.

Wolbarst, 1999

Flluoroscopy Units

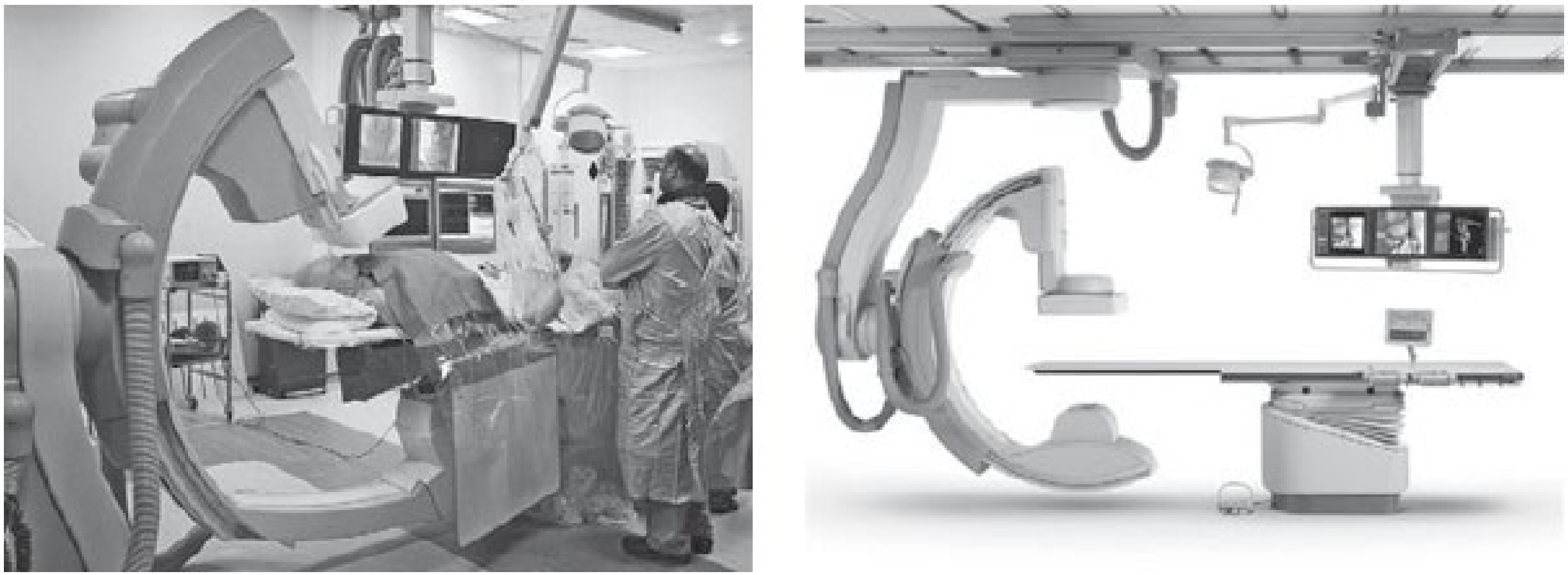


Figure 2.25

(left) A cardiac catheterization laboratory which uses a digital fluoroscopy unit to monitor placement of stents and pacemakers. (right) A neurointerventional unit, with a C-arm digital fluoroscopy unit.

Smith and Webb, 2011

Fluoroscopy

Figure 2.21

A barium sulphate enhanced image of the colon shows an adenocarcinoma (white arrows). The high attenuation of the barium sulphate produces a very high (white) image intensity.

Smith and Webb, 2011

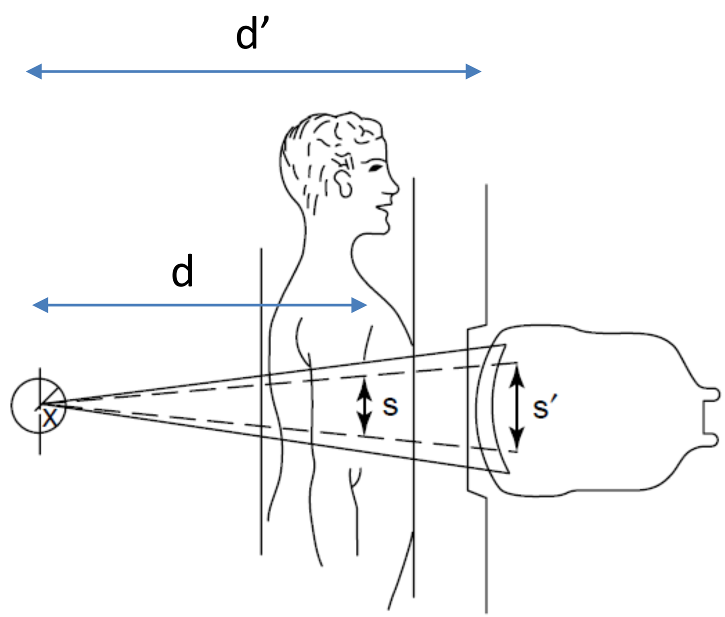
Figure 2.17 Postoperative fluoroscopic control of bone fixation with plate and screws after a complete fracture of the humerus. (Courtesy of Dr. L. Lateur, Department of Radiology.)

(Suetens P, 2009)

Size of image intensifier

$$s' = s\left(\frac{d'}{d}\right)$$

$$M = \frac{s'}{s} = \frac{d'}{d}$$



MARGIN FIGURE 14-3
An object of length s has an apparent length s' on the input screen of an image intensifier. The field of view of an image intensifier is smaller than the size of the input screen.

(Hendee and Ritanaur, 2002)

Example 14-1

An x-ray tube is positioned 45 cm below a fluoroscopic table. The input screen of an image intensifier is 15 cm in diameter and 30 cm above the table. What is the maximum length s of an object that is included completely on the screen? What is the magnification of the image? The object is 10 cm above the table.

$$s' = s\left(\frac{d'}{d}\right) \tag{14-5}$$

$$\begin{aligned} s &= s'\left(\frac{d}{d'}\right) \\ &= (15\ \text{cm})\left(\frac{10\ \text{cm} + 45\ \text{cm}}{30\ \text{cm} + 45\ \text{cm}}\right) \\ &= 11\text{cm} \end{aligned}$$

$$\begin{aligned} M &= \frac{s'}{s} \\ &= \frac{15\ \text{cm}}{11\ \text{cm}} \\ &= 1.36 \end{aligned} \tag{14-6}$$

(Hendee and Ritanaur, 2002)

C. Angiography

Angiography is a procedure involving radiographic visualization of blood vessels by injecting a nontoxic radiopaque substance such as *water-soluble organic compounds of iodine* into the blood stream.

It is useful for demonstrating vessel constriction and vascular tumors.

- A bolus of a contrast medium is injected into the artery or vein, usually catheterization.
- The medium is then rapidly diluted in the blood circulation.
- A series of images are taken immediately after the injection.

Angiography remains the ‘’gold standard’’ for diagnosing a number of clinical disorders: Coronary stenosis, pancreatic disease, abdominal aortic aneurysm, and venous thrombosis.

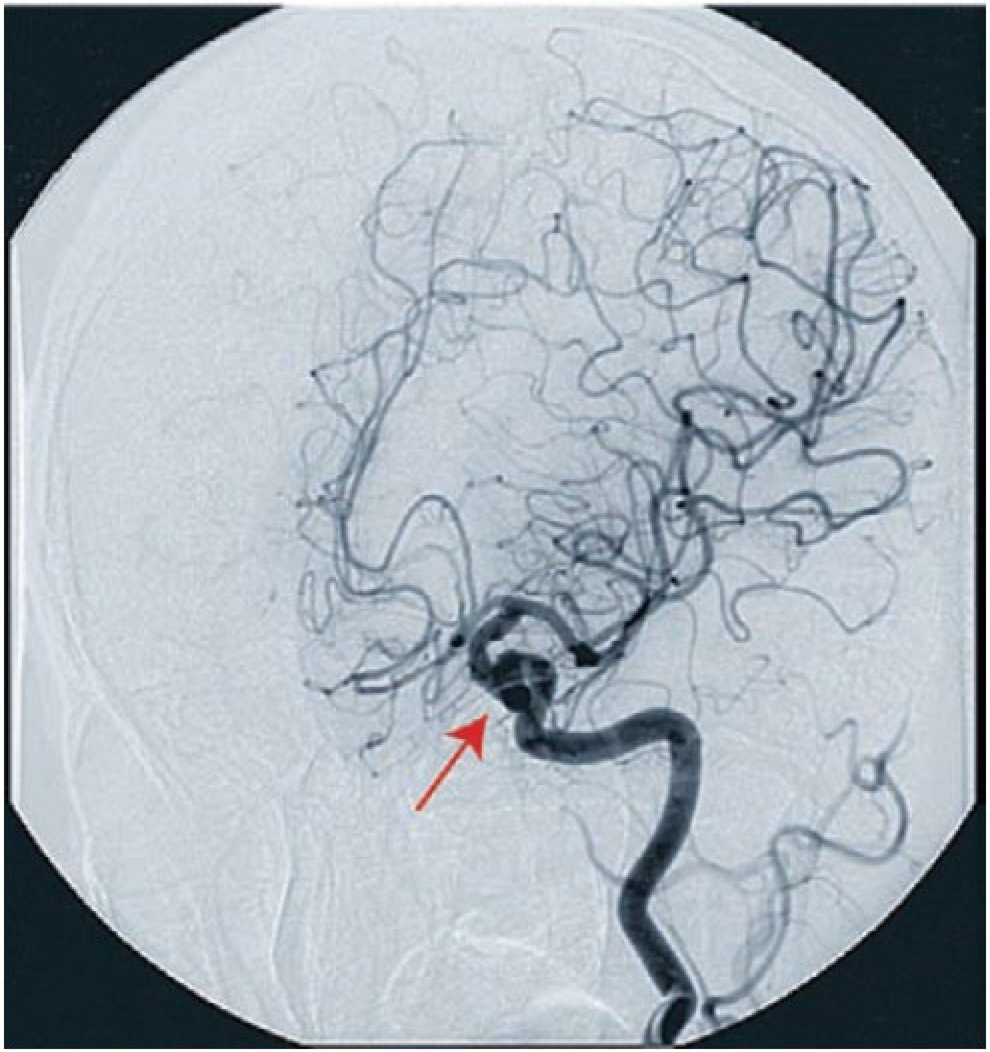


Figure 2.18 Cerebral angiogram showing an aneurysm or saccular dilation of a cerebral artery. (Courtesy of Professor G. Wilms, Department of Radiology.)

(Suetens P, 2009)

D. Mammography

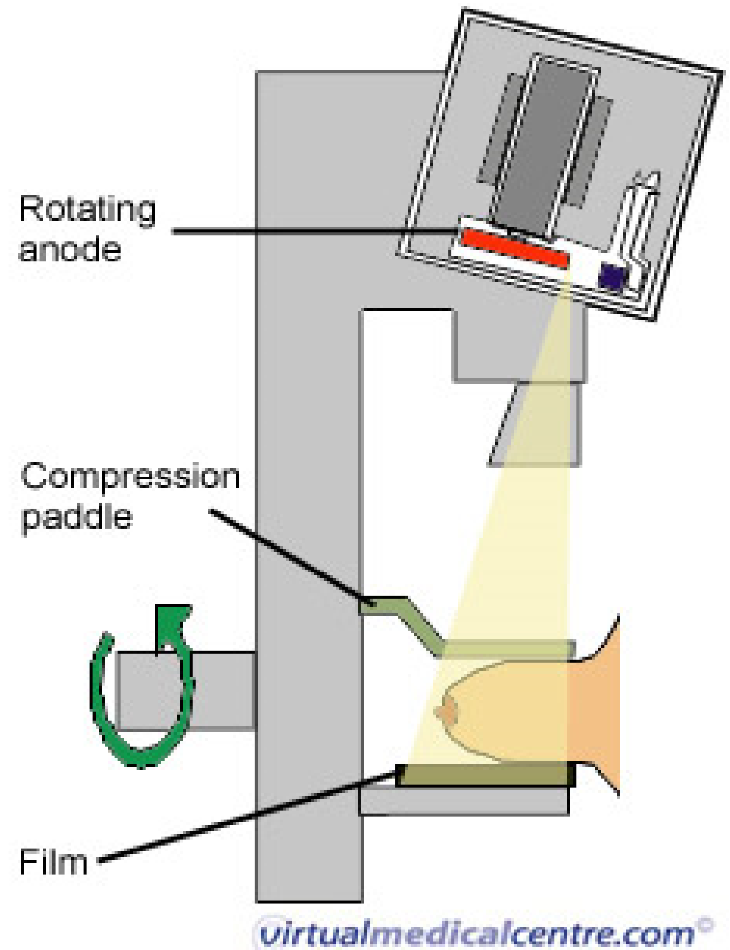
X-ray mammography is the radiographic examination of the breast perfromed with or without the injection of contrast medium.

The requirements for mammography are different from ordinary X-ray examination for the following reasons:

(1) Low-energy X-rays (~20 keV) should be used because the breast is composed of soft tissues. Modern mammography uses molybdenum (Mo) with an atomic number of 42 as anode material.

(2) mammography needs spatial resolution better than 0.1 mm to be able to visualize microcalcification and trabeculae. Thus single –emulsion is preferred.

(3) Exposure time should be short to avoid artifact due to patient motion.



Mammography

Mammography requires *compression* of the breast for several reasons. Among the most important are:

(1) Maintaining a more uniform X-ray radiation on the breast;
(2) diminishing motion artifact and reducing radiation dosage since the breast tissue that needs to be penetrated is thinner.

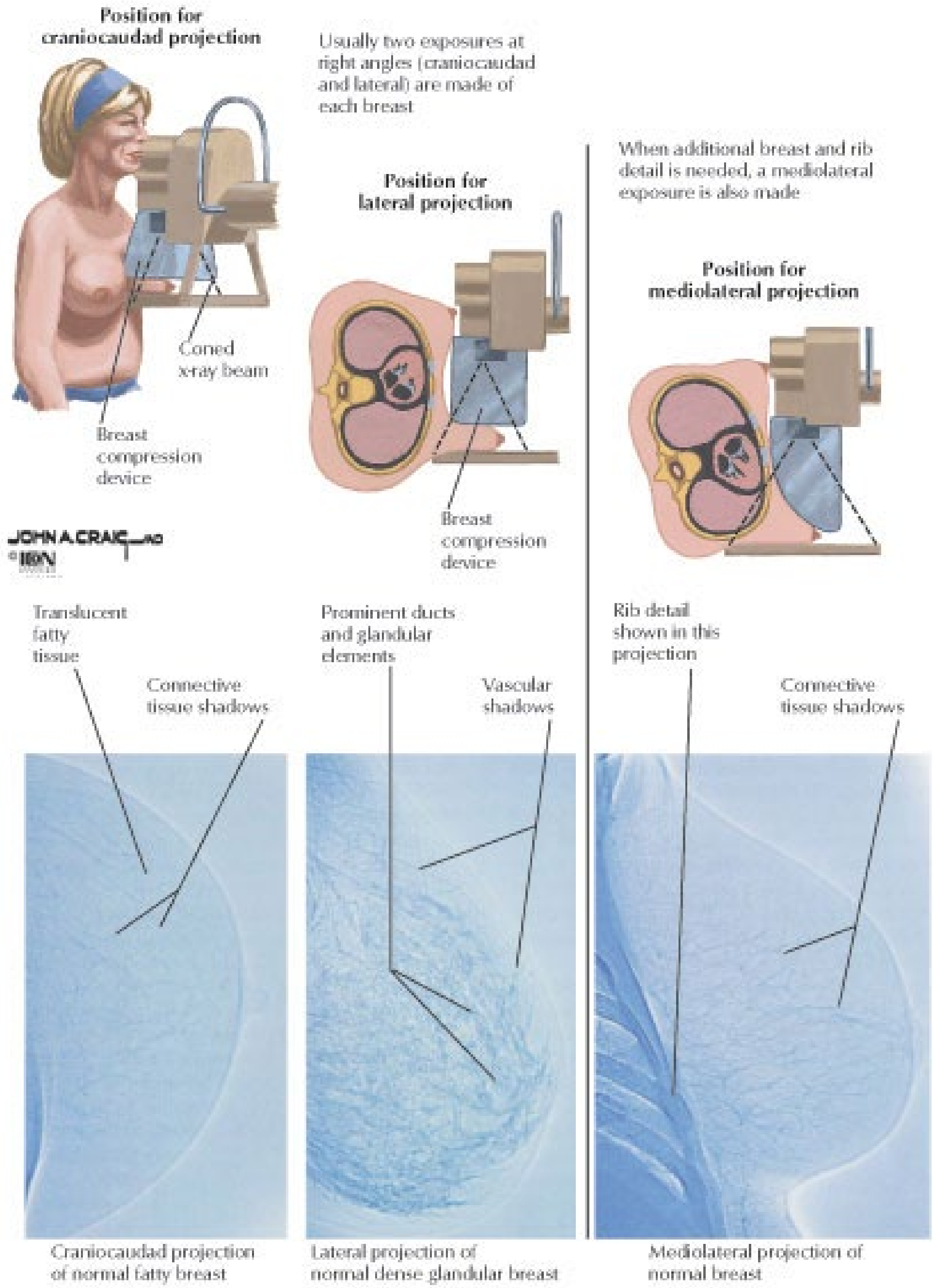
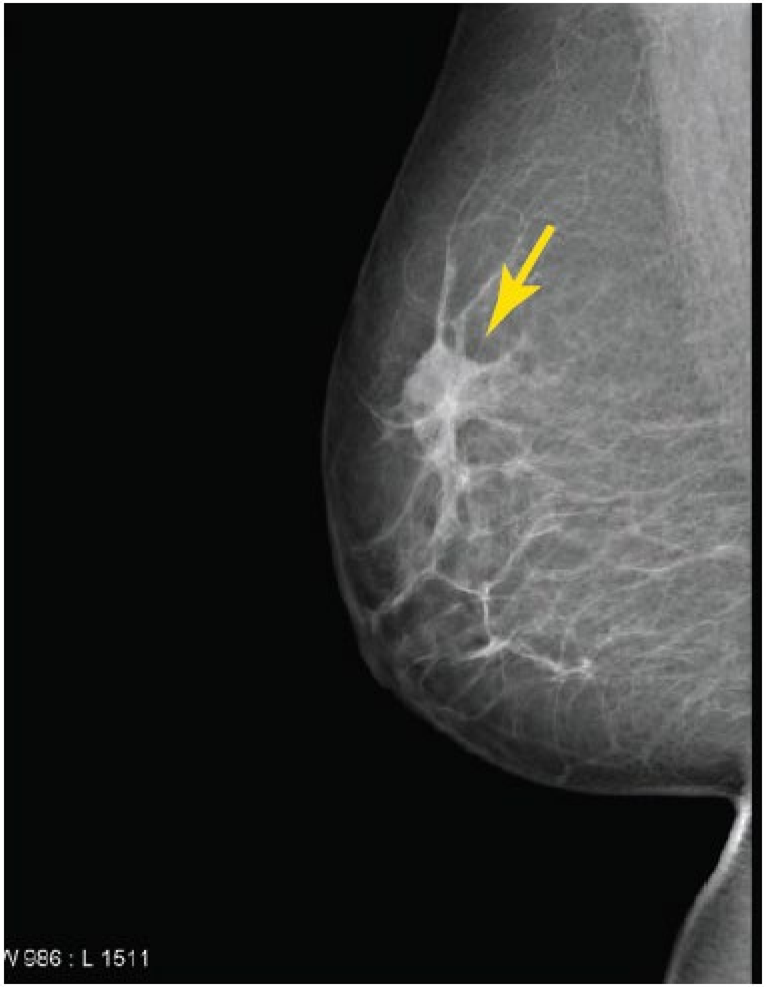
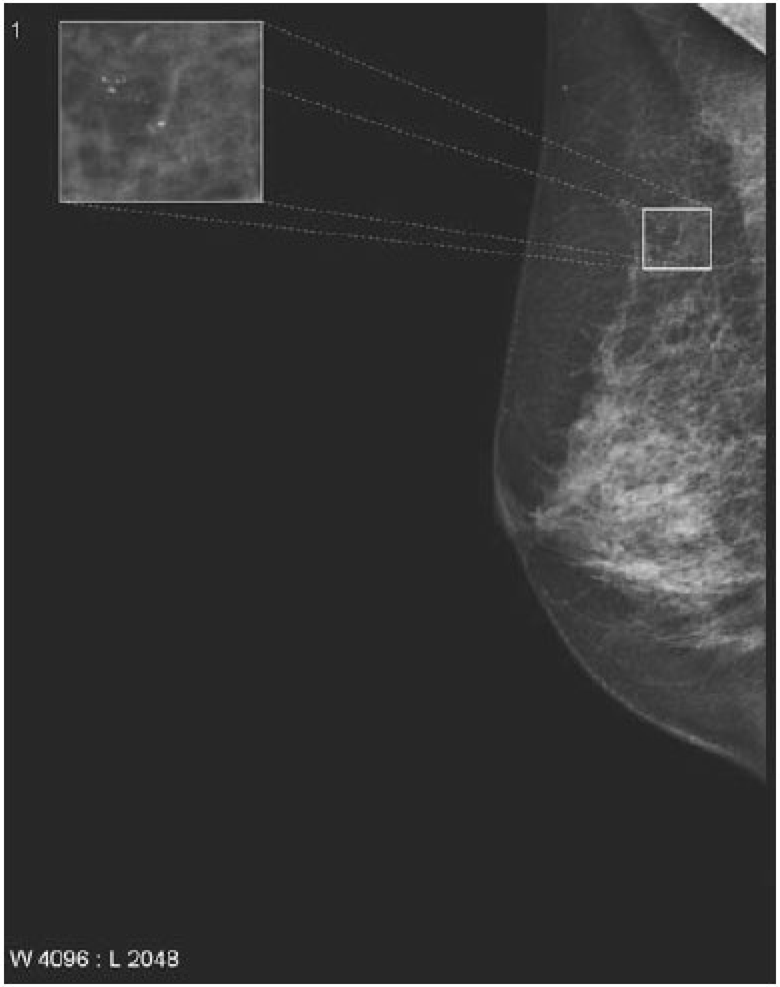


figure source: healthgiants.com



(a)



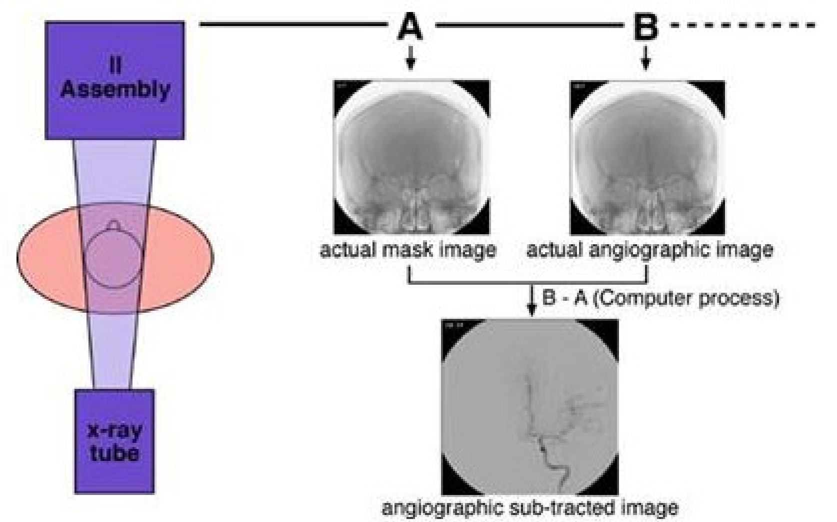
(b)

Figure 2.16 **(a)** Dense opacity with spicular border in the cranial part of the right breast; histological proven invasive ductal carcinoma. **(b)** Cluster of irregular microcalcifications suggesting a low differentiated carcinoma. (Courtesy of Dr. Van Ongeval, Department. of Radiology.)

(Suetens P, 2009)

E.Image Subtraction

- Image subtraction is a procedure that is used to suppress background information on an image.
- It is achieved either digitally or by photographic process on the X-ray film.
- It is partcularly useful in angiography because the image of the blood vessels is often masked by images of bone or soft tissue surrounding the vessels.



http://healthinformatics.wikispaces.com/Digital+subtraction+Angiography+-+DSA

F. Conventional X-ray Methods

Conventional X-ray methods (radiography) have a number of limitations:

1. Conventional X-ray is a 2D projection of a three dimensional structure.
    - Many planes are superimposed on one.
    - The depth information is lost.
    - the confusion of overlapping planes makes the detection of subtle abnormalities very difficult.
2. Conventional X-ray cannot differentiate between soft tissues.

3. Conventional X-ray can not be used to measure in a quantitative way the densities of the various tissues being interrogated.

A partial solution to these problems is to use the tomographical imaging technique, or tomography (the Greek term *tomo* means cut).

X-ray tomography is a special X-ray technique that blurs out ındesirable images of superimposed structures in order to accentuate the images of principle interest.

Conventional tomography

The film moves in syncronization with the motion of the X-ray tube, but in the opposite direction.

The fulcrum plane is the only plane in sharp focus. All planes above and below this plane are blurred.

The nature and degree of deblurring is determined by the distance of each plane from the focused plane and by the extent and type of the motion undertaken.

The arrangement is termed ‘linear tomography’ in which the source and detector move linearly in opposite directions.

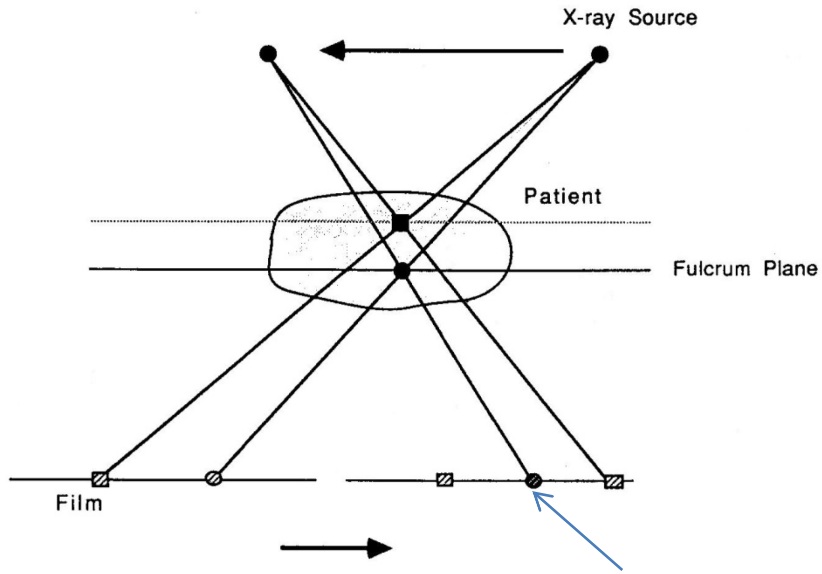


Figure 36 Conventional tomography.

image of circle remains in sharp focus

no reconstruction algorithm is required.