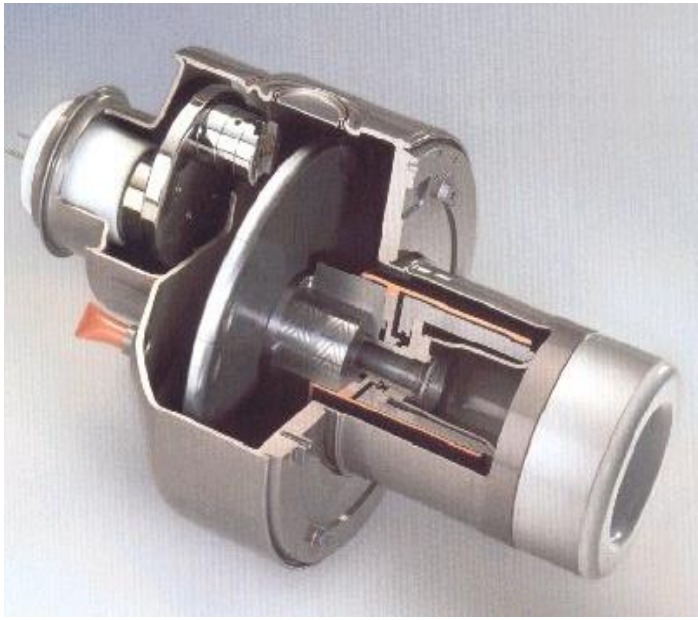
Basic elements of the x-ray assembly source

- Generator : power circuit supplying the required potential to the X-ray tube
- X-ray tube and collimator: device producing the X-ray beam



X-ray generator (II)

- Generator characteristics have a strong influence on the contrast and sharpness of the radiographic image
- The motion unsharpness can be greatly reduced by a generator allowing an exposure time as short as achievable

- Since the dose at the image plane can be expressed as :

$$D = k_0 \cdot kVp^n \cdot I \cdot T$$

  - **kVp** : peak voltage (kV)
  - **I** : mean current (mA)
  - **T** : exposure time (ms)
  - **n** : ranging from about 3 at 150 kV to 5 at 50 kV

X-ray generator (III)

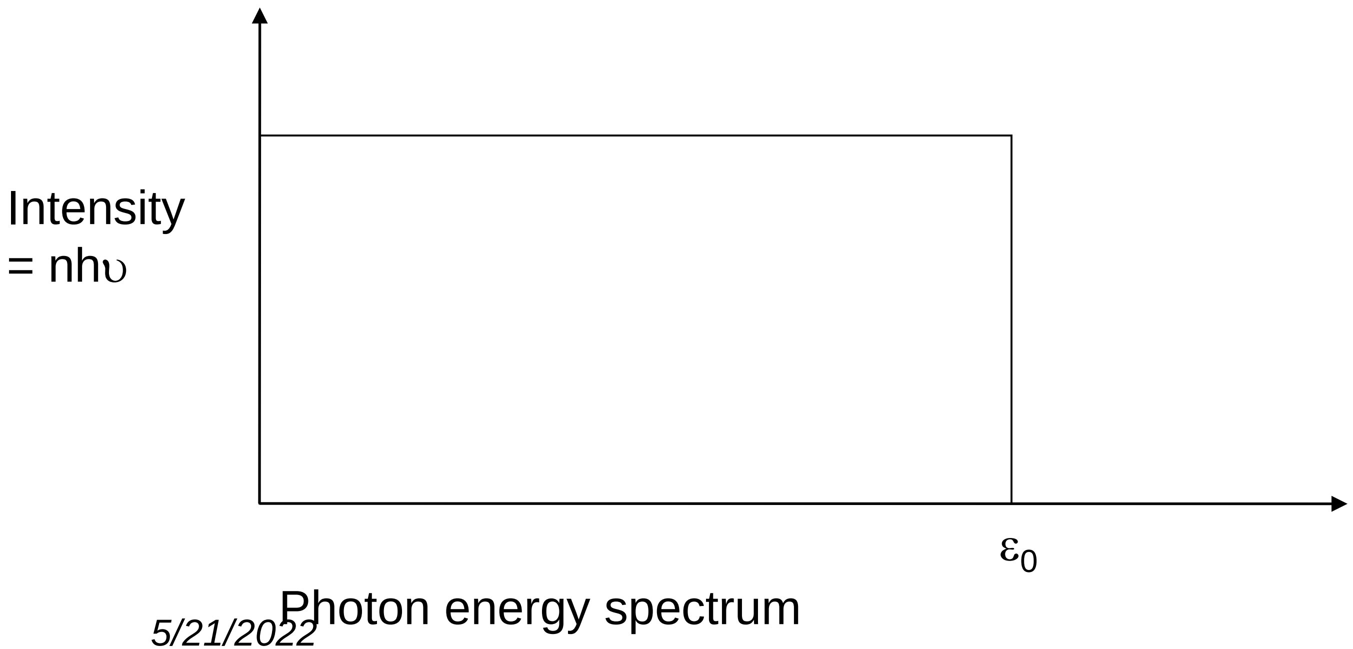
- Peak voltage value has an influence on the beam hardness
- It has to be related to medical question
  - **What is the anatomical structure to investigate ?**
  - **What is the contrast level needed ?**
- The ripple “r” of a generator has to be as low as possible

$$r = [(kV - kV_{min})/kV] \times 100\%$$

Thin Target X-ray Formation

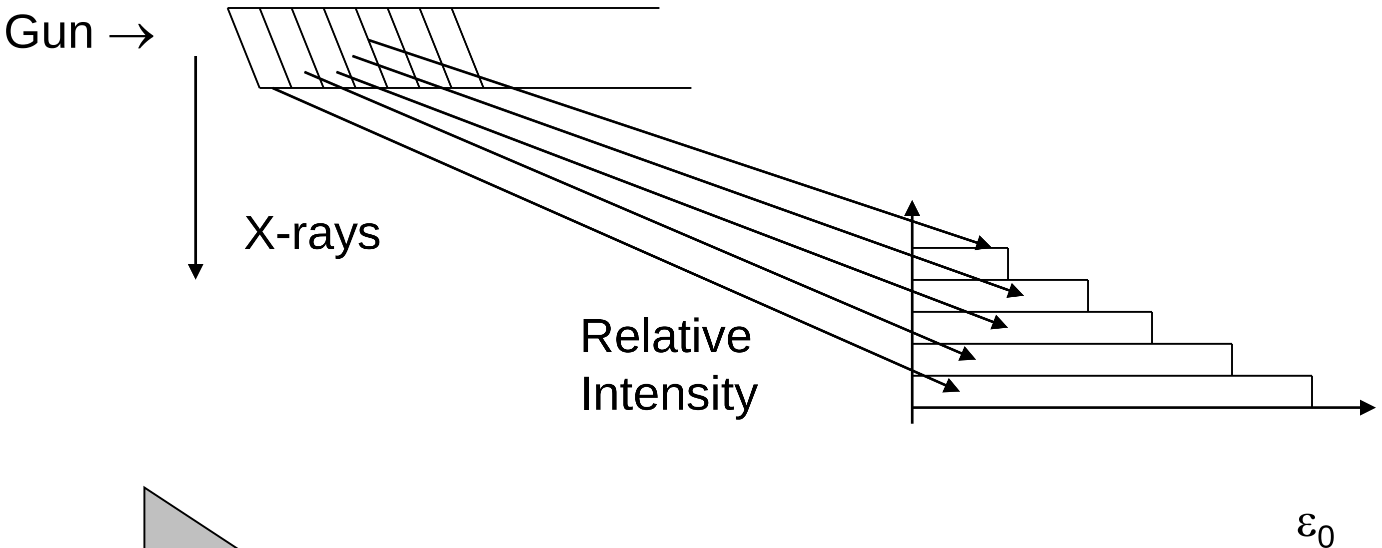
Interestingly, this process creates a relatively uniform spectrum.

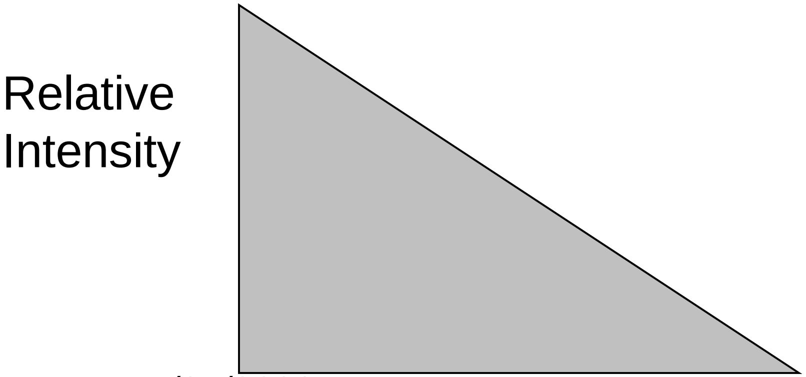
Maximum energy is created when an electron gives all of its energy, ε_0 , to one photon. Or, the electron can produce n photons, each with energy ε_0/n. Or it can produce a number of events in between. Power output is proportional to $\varepsilon_0{}^2$



Thick Target X-ray Formation

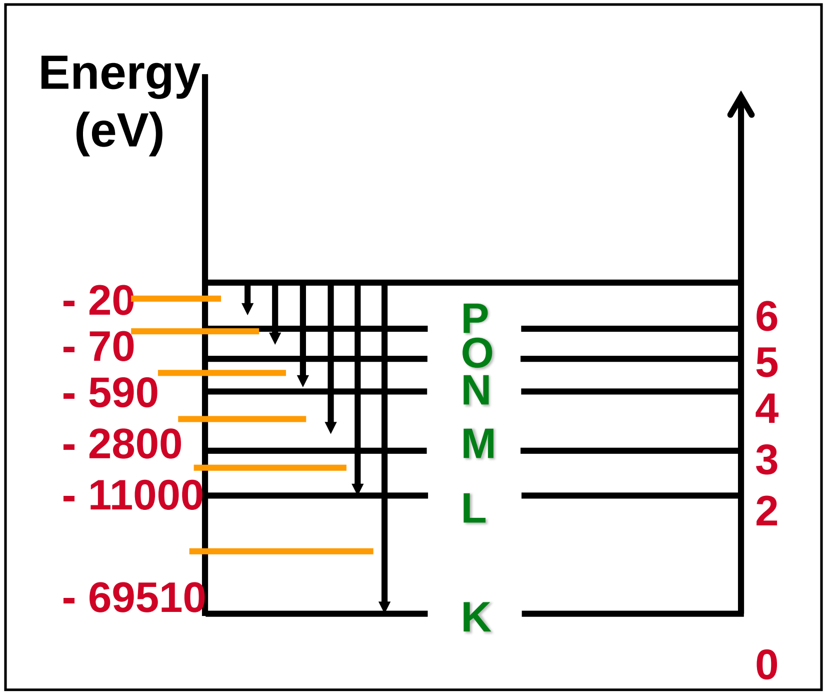
We can model target as a series of thin targets. Electrons successively loses energy as they moves deeper into the target.

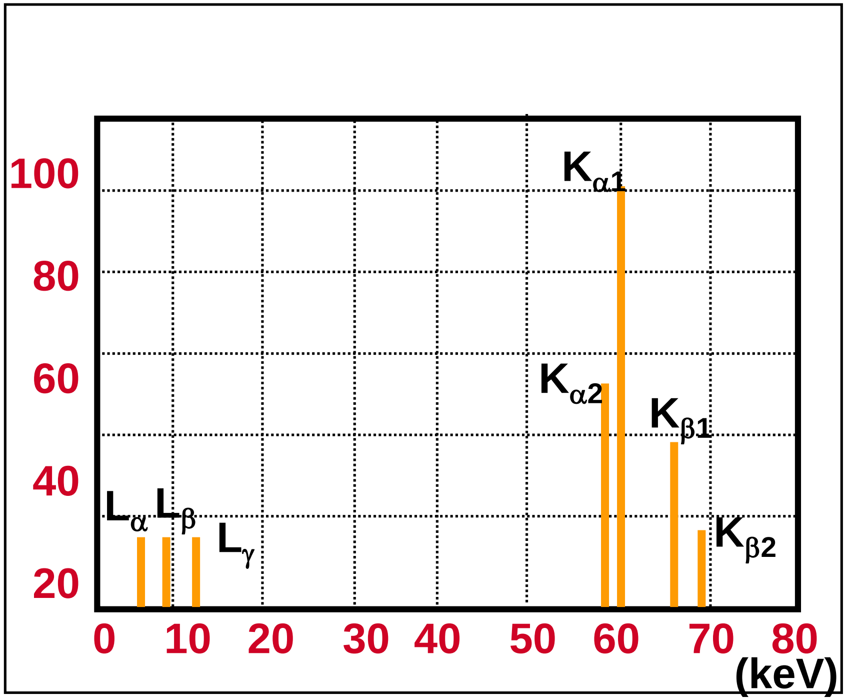




Each layer produces a flat energy spectrum with decreasing peak energy level.

Spectral distribution of characteristic X-rays (II)





Thick Target X-ray Formation

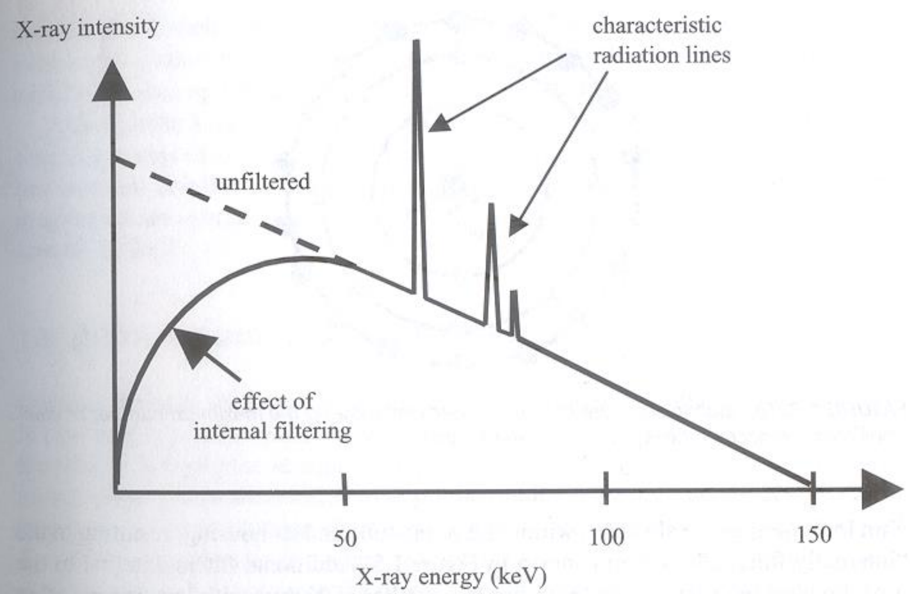


FIGURE 1.5. *A typical X-ray energy spectrum produced from a tube with a kV_p value of 150 keV, using a tungsten anode. Low-energy X-rays (dashed line) are absorbed by the components of the X-ray tube itself. Characteristic radiation lines from the anode occur at approximately 60 and 70 keV.*

Andrew Webb, Introduction to Biomedical Imaging, 2003, Wiley-Interscience.

(

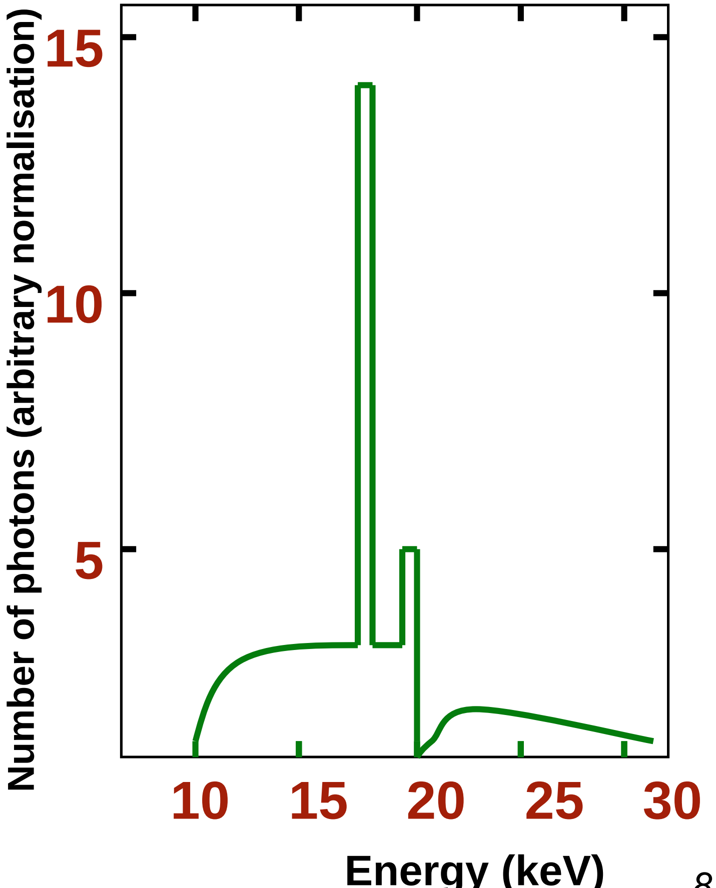
Lower energy photons are absorbed with aluminum to block radiation that will be absorbed by surface of body and won't contribute to image.

The photoelectric effect will create significant spikes of energy when accelerated electrons collide with tightly bound electrons, usually in the K shell.

Factors influencing the x-ray spectrum

- tube potential
  - kVp value
- wave shape of tube potential
- anode track material
  - W, Mo, Rh etc.
- X-ray beam filtration
  - inherent + additional

X-ray spectrum at 30 kV for an X-ray tube with a Mo target and a 0.03 mm Mo filter



Interaction of radiation with matter
Radiation Contrast

Stopping power

- Loss of energy along track through collisions
- The linear stopping power of the medium

$$\mathbf{S = \Delta E / \Delta x} \quad [\mathrm{MeV.cm^{-1}}]$$

  - ΔE: energy loss
  - Δx: element of track
- for distant collisions : the lower the electron energy, the higher the amount transferred
- most Bremsstrahlung photons are of low energy
- collisions (hence ionization) are the main source of energy loss
- except at high energies or in media of high Z

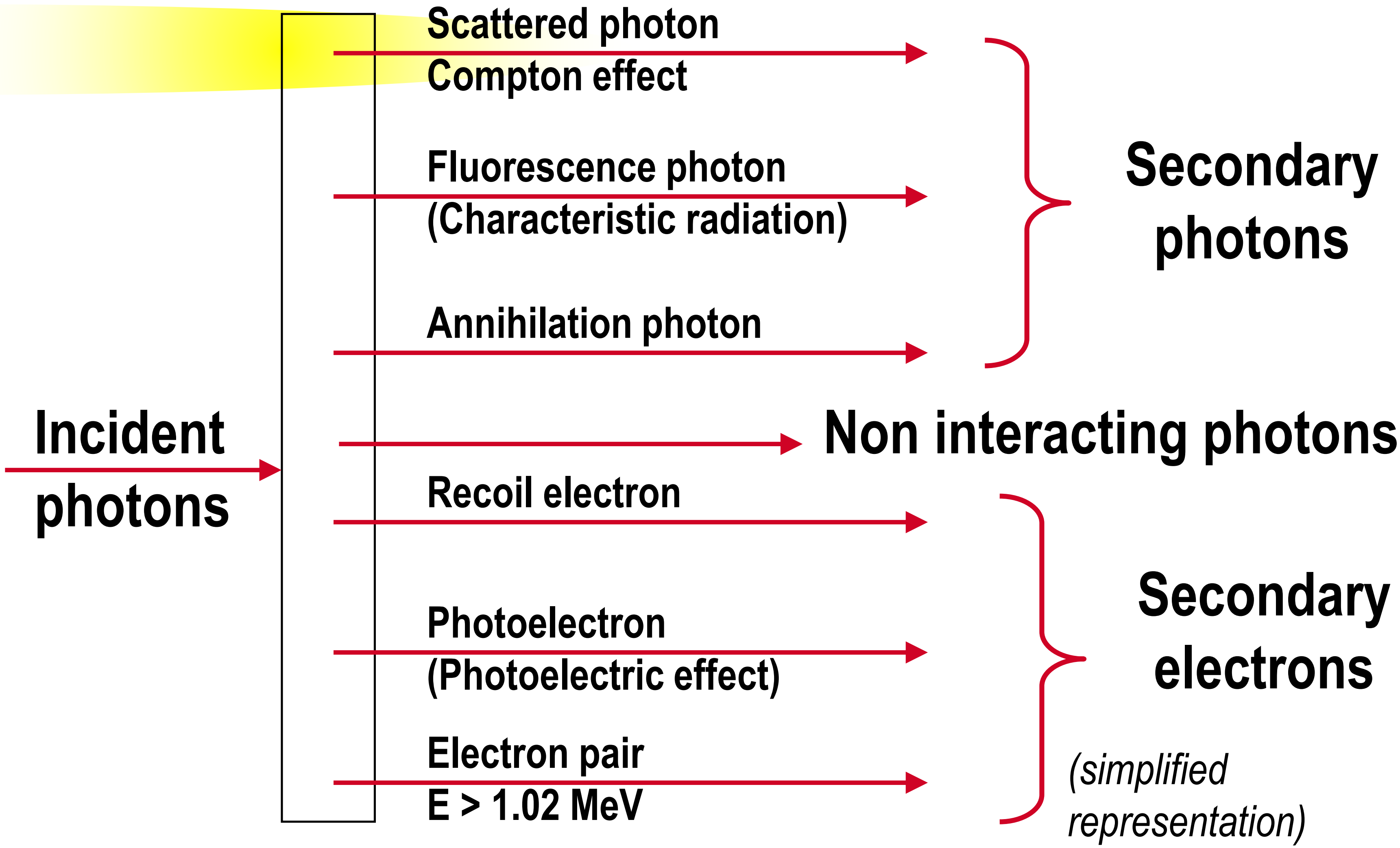
Linear Energy Transfer

- Biological effectiveness of ionizing radiation

- Linear Energy Transfer (LET): amount of energy transferred to the medium per unit of track length of the particle

- Unit : e.g. [keV.μm^{-1}]

Photon interactions with matter



How do we describe attenuation of X-rays by body?

Assumptions:

1) Matter is composed of discrete particles (i.e. electrons, nucleus)
2) Distance between particles >> particle size
3) X-ray photons are small particles
   Interact with body in binomial process
   Pass through body with probability p
   Interact with body with probability 1-p (Absorption or scatter)
4) No scatter photons for now (i.e. receive photons at original energy or not at all.

$$N \rightarrow | \leftarrow \Delta x \rightarrow | \rightarrow N - \Delta N$$

The number of interactions (removals) α number of x-ray photons and Δx

$$\Delta N = -\mu N \Delta x$$

μ = linear attenuation coefficient (units cm^{-1})

$\mu = f(Z, \varepsilon)$ Attenuation a function of atomic number Z and energy ε

Solving the differential equation: $dN = -\mu N dx$

$N_{in} \rightarrow | \leftarrow x \rightarrow | \rightarrow N_{out}$

μ

$$\int_{Nin}^{Nout} dN/N = -\mu \int_0^x dx$$

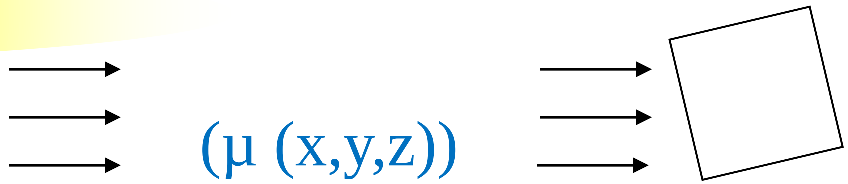
$$\ln (N_{out}/N_{in}) = -\mu x$$

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

If material attenuation varies in x, we can write attenuation as $\mu(x)$

$$N_{out} = N_{in}\, e^{-\int \mu(x)\, dx}$$

If I_o photons/cm^2



$(\mu\ (x,y,z))$

$I_d\ (x,y)$

Detector Plane

$$I_d\,(x,y) = I_0 \exp\left[\, -\int \mu(x,y,z)\, dz\right]$$

Assume: perfectly collimated beam (for now),
perfect detector
no loss of resolution

Actually recall that attenuation is also a function of energy ε, $\mu = \mu(x,y,z,\varepsilon)$

$$I_d(x,y) = \int I_0(\varepsilon) \exp[-\int \mu(x,y,z,\varepsilon)\, dz]\, d\varepsilon$$

Which Integrate over ε and depth.

For a single energy $I_0(\varepsilon) = I_0\, \delta(\varepsilon - \varepsilon_o) = I_0$

After analyzing a single energy, we can add the effects of other energies by superposition.

If homogeneous material, then $\mu(x,y,z,\varepsilon_0) = \mu_0$

$$I_d(x,y) = I_0\, e^{-\mu_0 \Delta z}$$

Attenuation of an heterogeneous beam

- Various energies $\Rightarrow$ No more exponential attenuation
- Progressive elimination of photons through the matter
- Lower energies preferentially
- This effect is used in the design of filters
- $\Rightarrow$ Beam hardening effect

Half Value Layer (HVL)

- HVL: thickness reducing beam intensity by 50%

- Definition holds strictly for monoenergetic beams
- Heterogeneous beam ↓ hardening effect
- $I/I_0 = 1/2 = \exp(-\mu\ HVL)$ $HVL = 0.693 / \mu$
- HVL depends on material and photon energy
- HVL characterizes *beam quality*
- ↓ modification of beam quality through filtration
- ↓ HVL (filtered beam) $\neq$ HVL (beam before filter)

(HVL) Half Value Layer :

- HVL اندازه گیری (معیار) غیر مستقیم انرژی فوتون یا کیفیت تشعشع می باشد.

- Homogeneity Coefficient:
- از آنجائیکه تشعشع بر مشترالانگ تک انرژی نیست ، مقدار تشعشع کاهش یافته در ضخامت های اولیه مثلاً اولین HVL سریعتر از لایه های دوم و سوم خواهد بود ولی تشعشع سخت تر می شود نسبت HVL اول به دوم ضریب یکنواختی نام دارد و پراکندگی انرژی تشعشع را نشان می دهد

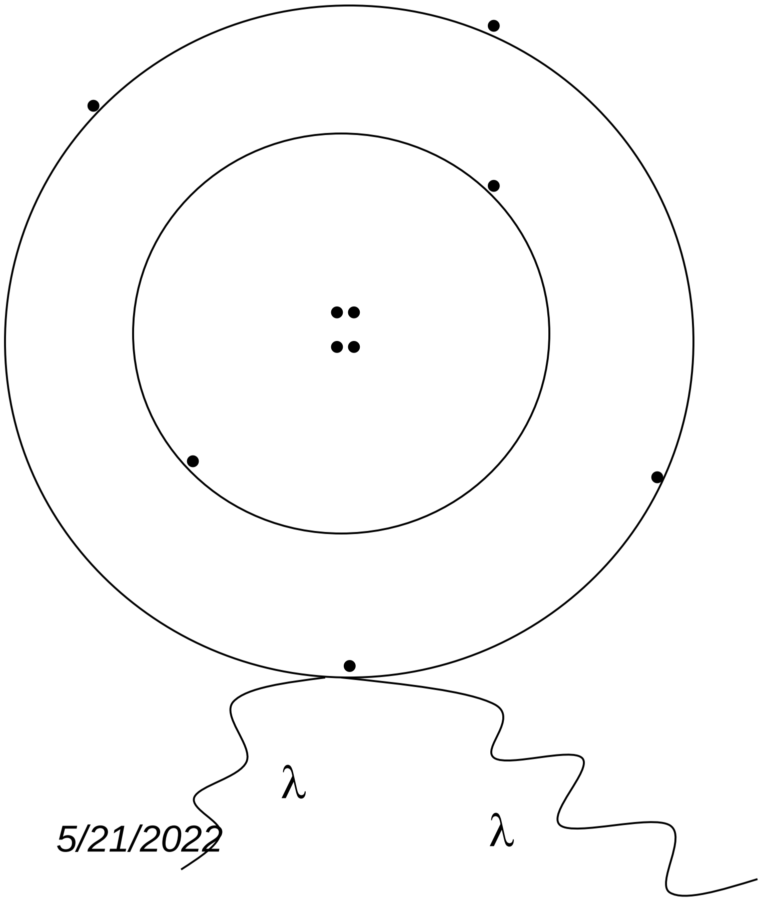
$$HC = HVL_1/HVL_2$$

X-ray interaction with matter

Coherent Scattering
Photoelectric Effect
Compton Scattering
Pair Production
Photodisintegration .

Physical Basis of Attenuation Coefficient

Coherent Scattering - Rayleigh



Coherent scattering varies over diagnostic energy range as:

$$\mu/p\ \alpha\ 1/\varepsilon^2$$

Photoelectric Effect

Longest photoelectron range 0.03 cm

Fluorescent radiation example:

Calcium 4 keV Too low to be of interest.
Quickly absorbed

Items introduced to the body:

Ba, Iodine have K-lines close to region of diagnostic interest.

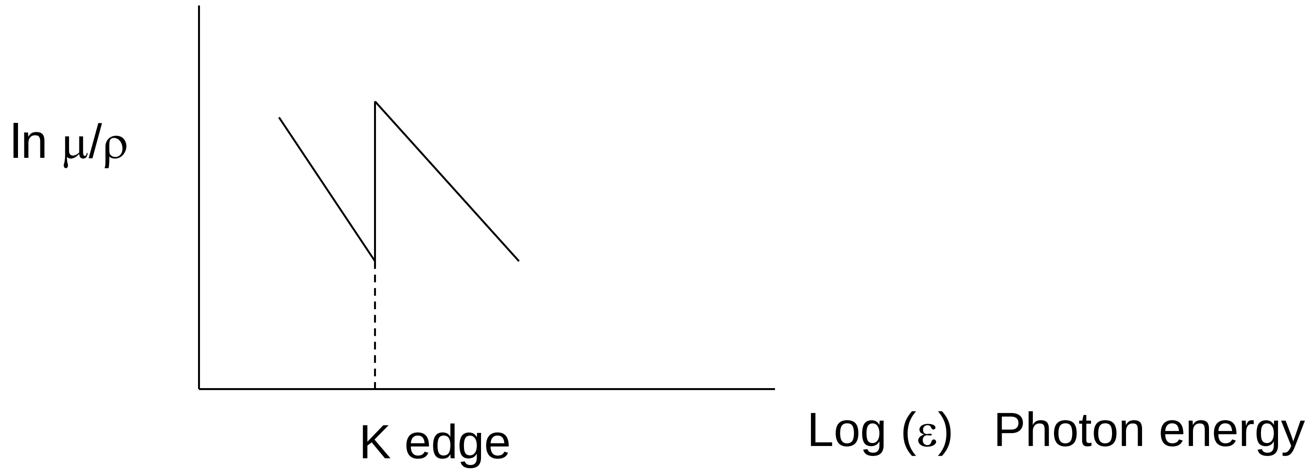
Photoelectric effect

- Incident photon with energy $h\nu$
- Absorption: ≈ all photon energy absorbed by a tightly bound orbital electron
  - ➔ ejection of electron from the atom
- Kinetic energy of ejected electron : $E_e = h\nu - E_B$
- Condition : $h\nu > E_B$ (electron binding energy)
- Recoil of the residual atom
- Attenuation (or interaction) coefficient
  - ➔ photoelectric absorption coefficient

$$\frac{z^3}{E^3} = \frac{z^3}{(hf)^3}$$

We can use K-edge to dramatically increase absorption in areas where material is injected, ingested, etc.

Photoelectric linear attenuation varies by $Z^{3\text{-}4}/\ \varepsilon^{3}$



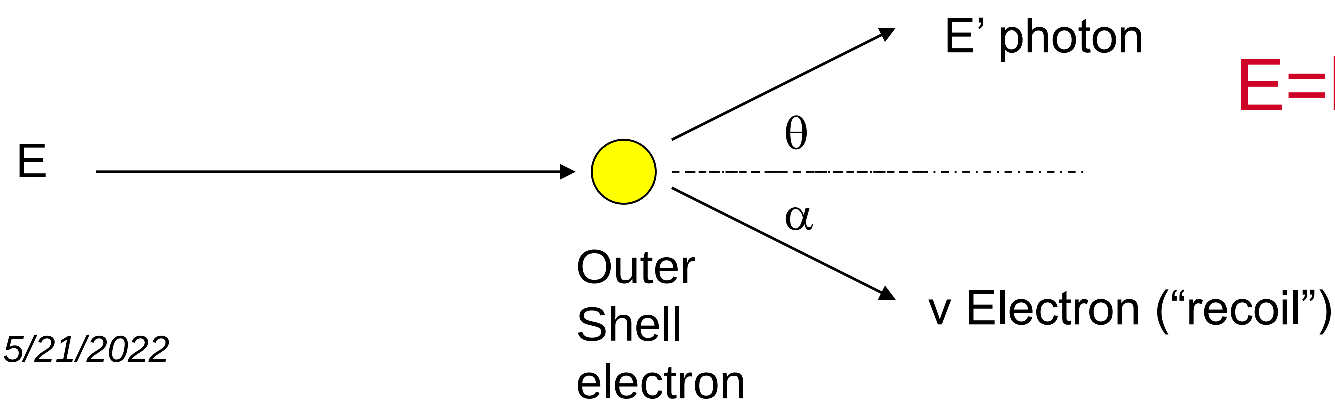
Compton Scatter

- Interaction of photons and electrons produce scattered photons of reduced energy.
- The probability of interaction decreases as hν increases
- Compton effect is proportional to the electron density in the medium

When will this be a problem?

Is reduced energy a problem?

Is change in direction a problem?



$$E = h\nu = E' + E_e$$

Satisfy Conservation of Energy and Momentum

1) $E = E' + (m - m_0)c^2$ (m-m$_o$ = electron mass : relativistic effects)

$$m = m_0 / \sqrt{1 - (v/c)^2}$$

Conservation of Momentum:

2) $$\frac{E}{c} = \frac{E'}{c}\cos(\theta) + mv\cos(\alpha)$$

3) $$0 = \frac{E'}{c}\sin\theta - mv\sin\alpha$$

Energy of recoil or Compton electron

$$\Delta E = E - E'$$

can be rewritten as

$$E' = \frac{E}{1 + \frac{\Delta\lambda}{\lambda}}$$

h = 6.63 x 10^{-34} Jsec

eV = 1.62 x 10^{-19} J

m_o = 9.31 x 10^{-31} kg

$\Delta\lambda = h/m_o c\,(1 - \cos\theta) = 0.0241\ A^0\,(1 - \cos\theta)$

$\Delta\lambda$ at $\theta = \pi$ = 0.048 Angstroms

Energy of Compton photon

$$h\nu' = \frac{h\nu}{1 + (1 - \cos\theta)\frac{h\nu}{m_0 c^2}}$$

Greatest effect $\Delta\lambda/ \lambda$ occurs at high energy

At 50 kev, x-ray wavelength is .2 Angstroms

Low energy ⌫ small change in energy

High energy ⌫higher change in energy

Mass attenuation coefficient (μ/ρ) $\propto$ electron mass density

Unfortunately, almost all elements have electron mass density $\approx 3 \times 10^{23}$ electrons/gram

Hydrogen (exception) $\approx 6.0 \times 10^{23}$ electrons/gram

μ/ρ for Compton scattering is Z independent

Compton Linear Attenuation Coefficient $\mu \propto$ p

Avg atomic number for Bone ~ 20

Avg atomic number for body 7 or 8

Rayleigh, Compton, Photoelectric are independent sources of attenuation

$t = I/I_0 = e^{-\mu l} = \exp[-(u_R + u_p + u_c)l]$

$\mu(\varepsilon) \approx \rho N_g \{ f(\varepsilon) + C_R (Z^2/\varepsilon^{1.9}) + C_p (Z^{3.8}/\varepsilon^{3.2})\}$

Compton Rayleigh Photoelectric

N_g electrons/gram (electron mass density)

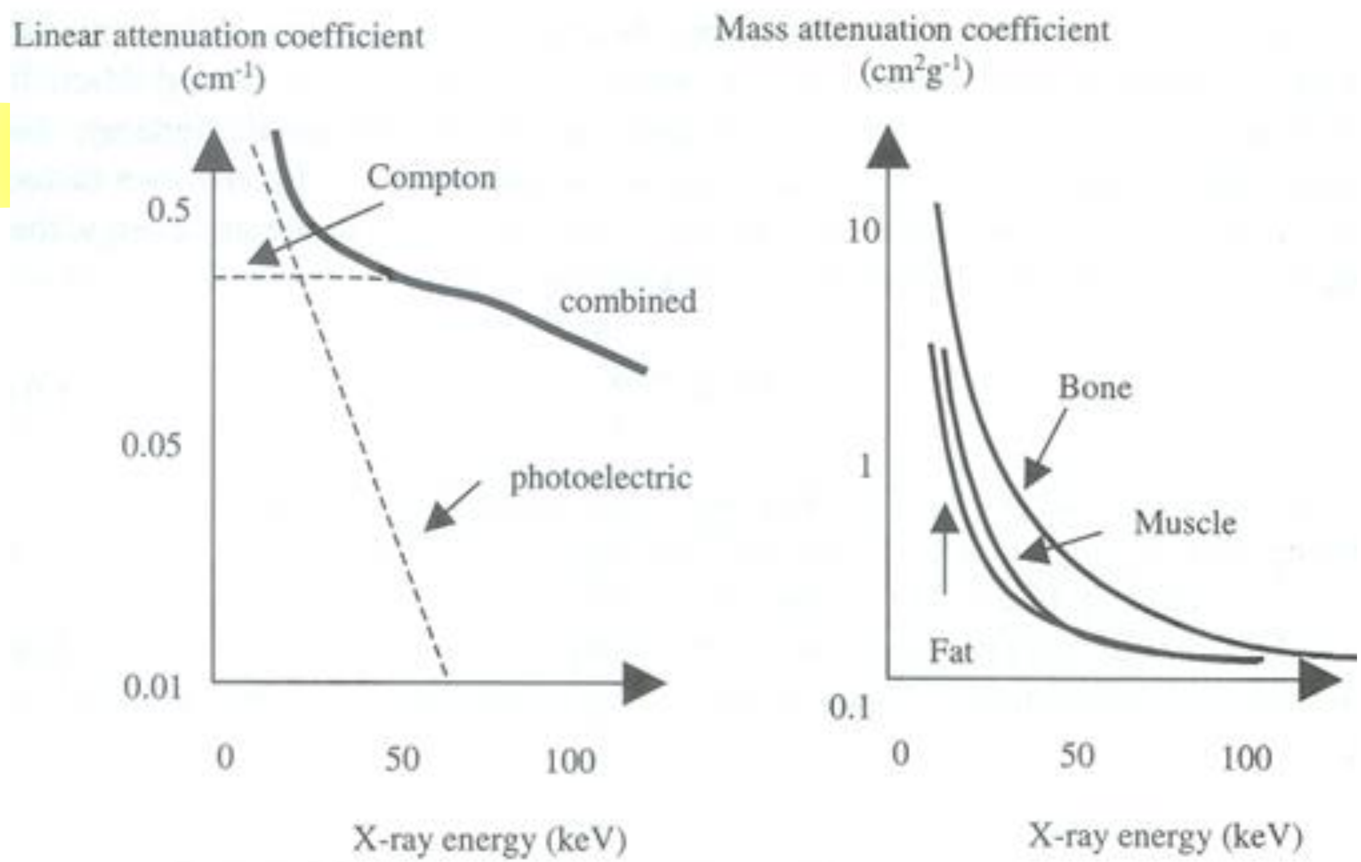
So ρN_g is electrons/cm^3

$N_g = N_A (Z/A) \approx N_A/2$ (all but H) A = atomic mass

$f(\varepsilon) = 0.597 \times 10^{-24} \exp[-0.0028(\varepsilon - 30)]$

for 50 keV to 200 keV ε in keV

Attenuation Mechanisms



Curve on left shows how photoelectric effects dominates at lower energies and how Compton effect dominates at higher energies. Curve on right shows that mass attenuation coefficient varies little over 100 kev. Ideally, we would image at lower energies to create contrast.

Photoelectric vs. Compton Effect

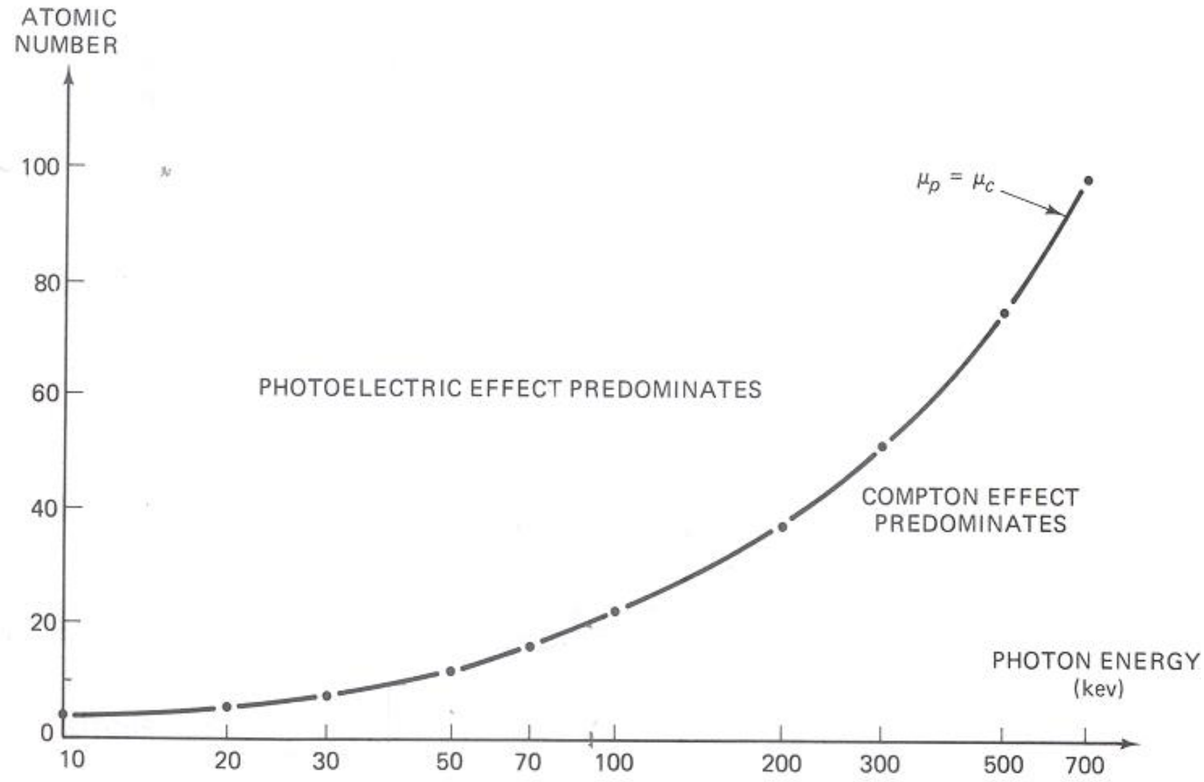
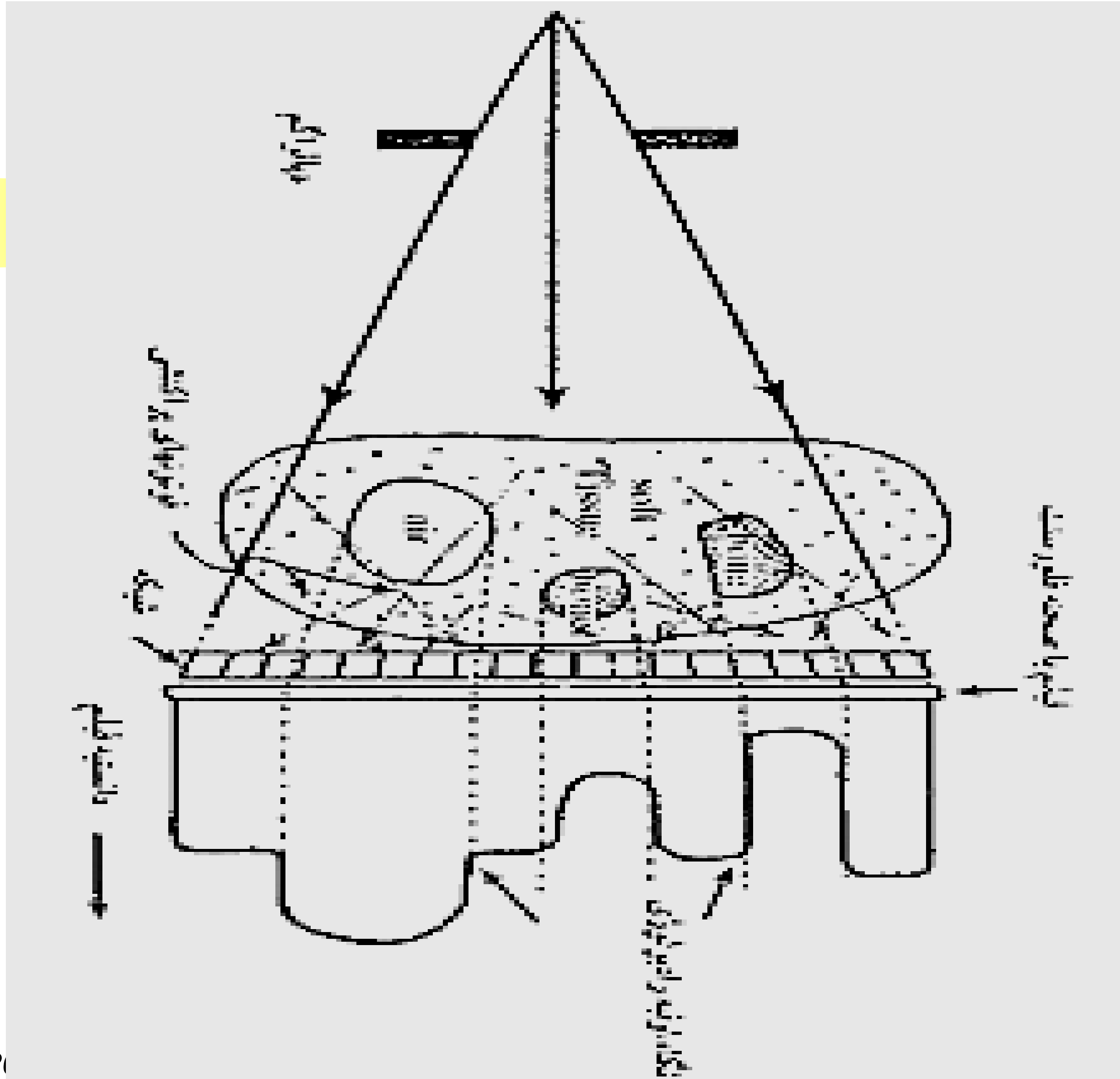


FIG. 3.6 Relative importance of the two major types of x-ray interaction. The line shows the values of *Z* and photon energy *hν* for which the photoelectric and Compton effects are equal.

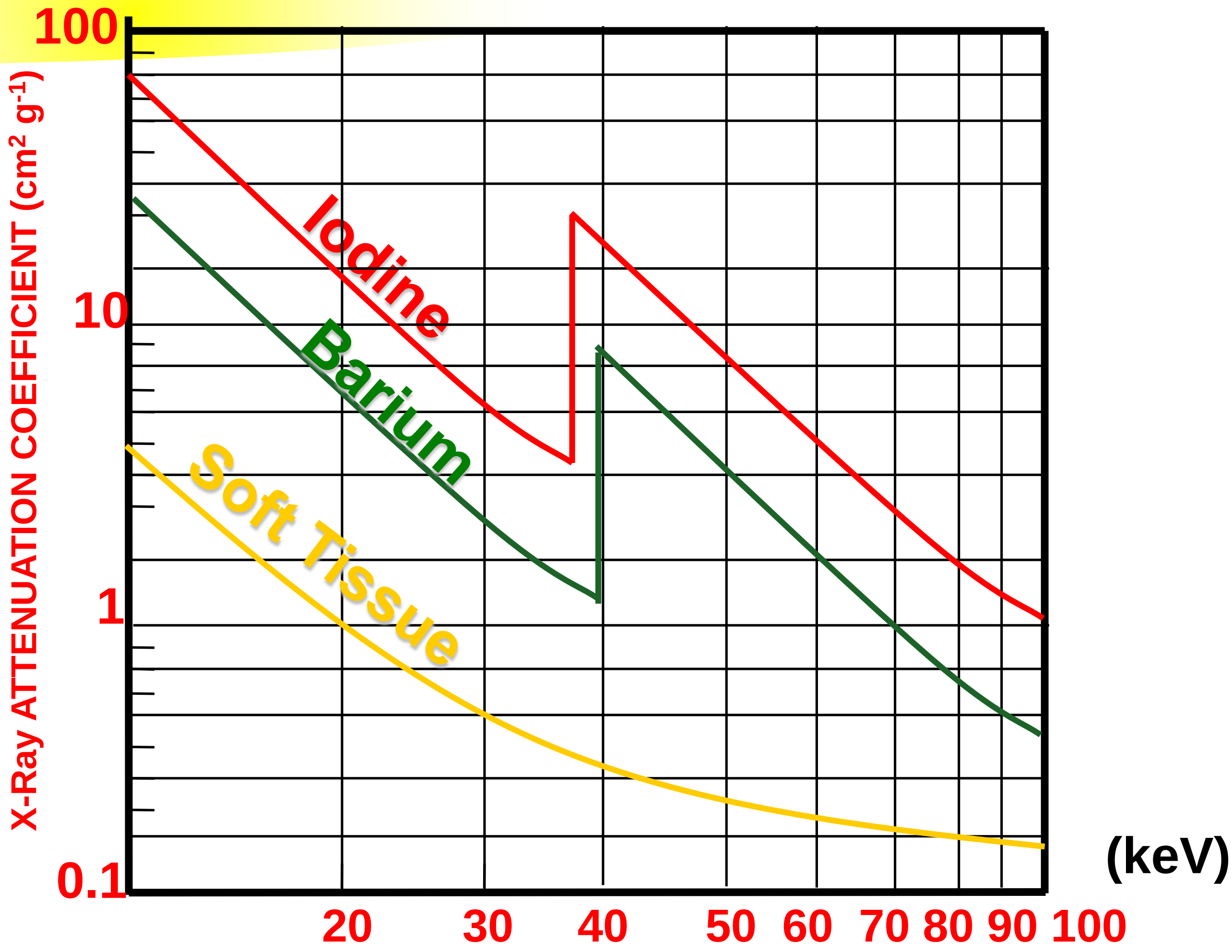
The curve above shows that the Compton effect dominates at higher energy values as a function of atomic number.

Ideally, we would like to use lower energies to use the higher contrast available with The photoelectric effect. Higher energies are needed however as the body gets thicker.

x-Ray Image Formation and Radiation Contrast



X-ray absorption characteristics of iodine, barium and body soft tissue



Contribution of Energy to attenuation of X-rays in bone

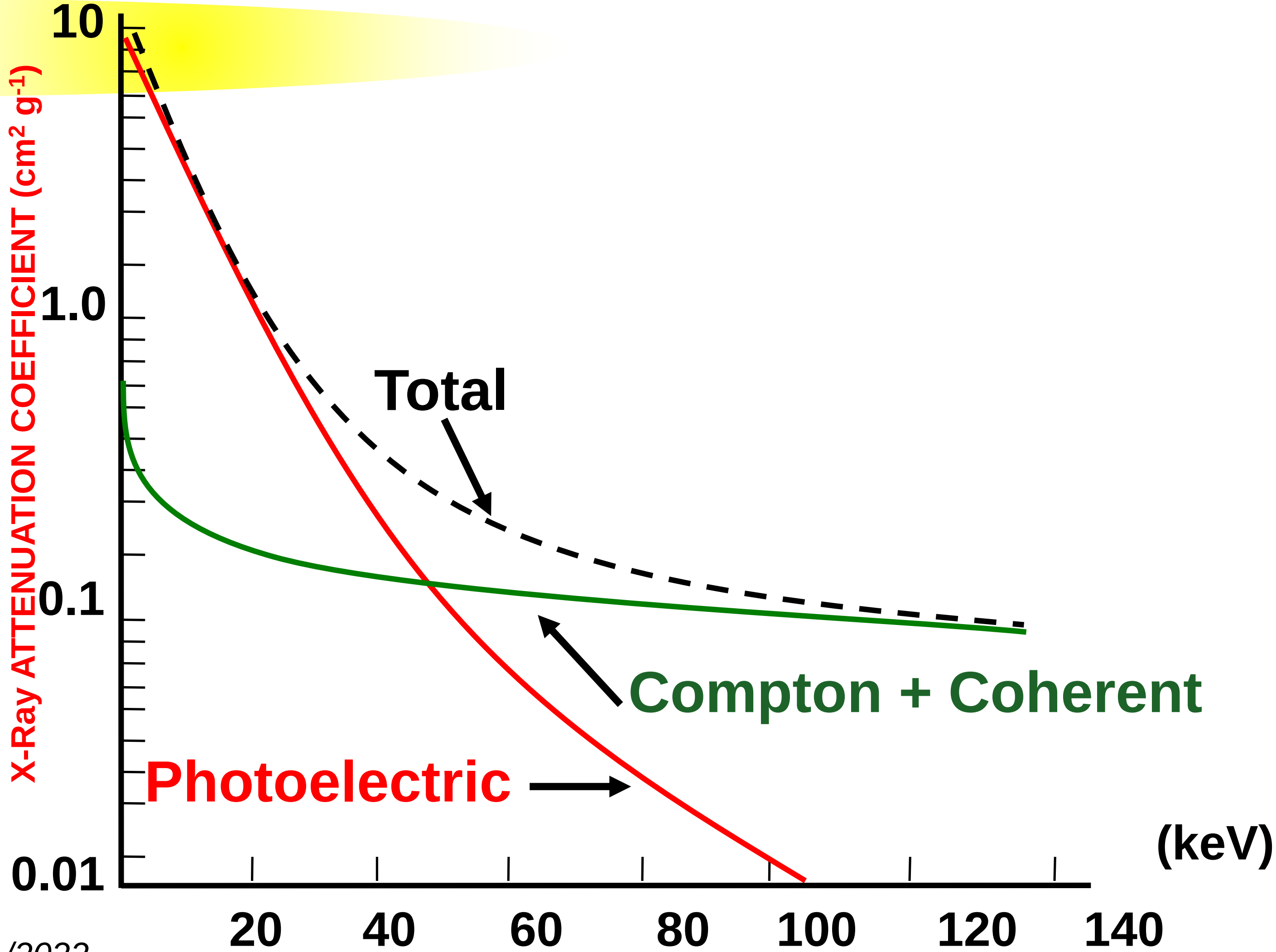


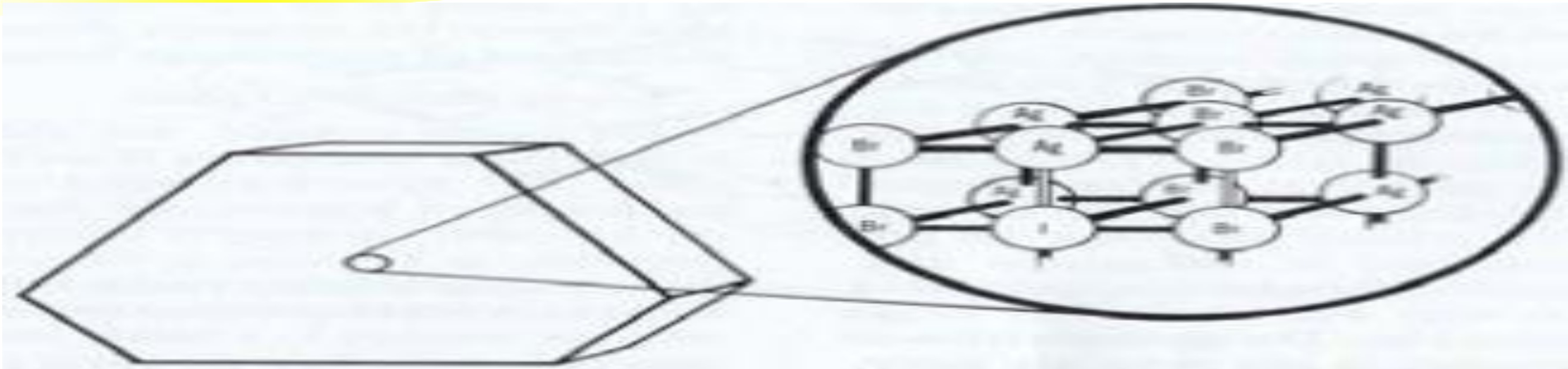
Image formation (Film)

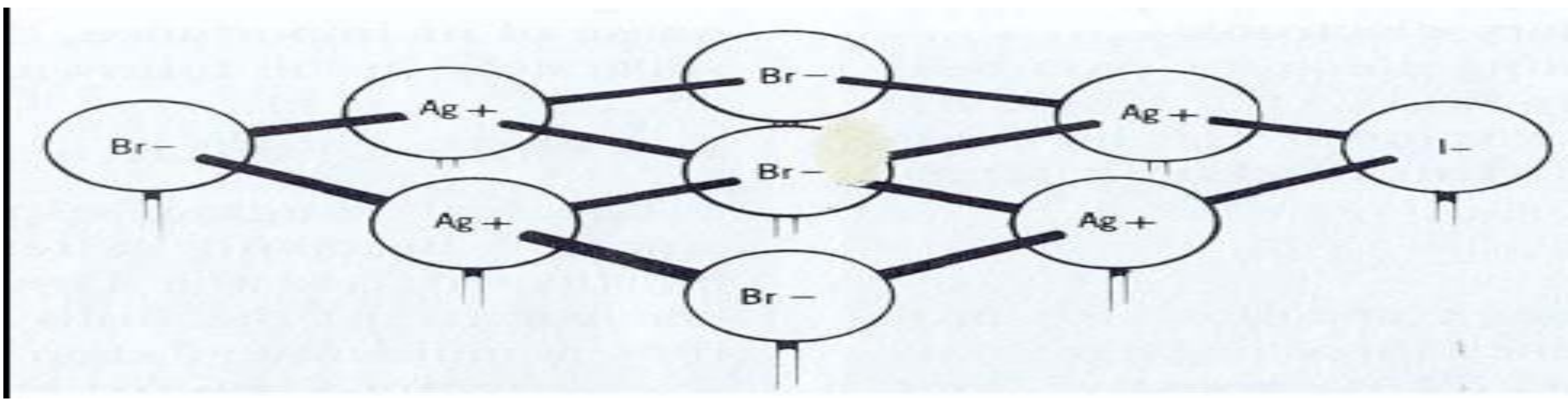
- X-ray photons converted to light photons Image before processing
  - Photoelectric Effect (**intensifying screen**)

- **Film is made to be especially sensitive to the effects of light from an intensifying screen. When these screens, on either side of the film in a cassette, are exposed to x-rays, they emit light which in turn exposes the film.**

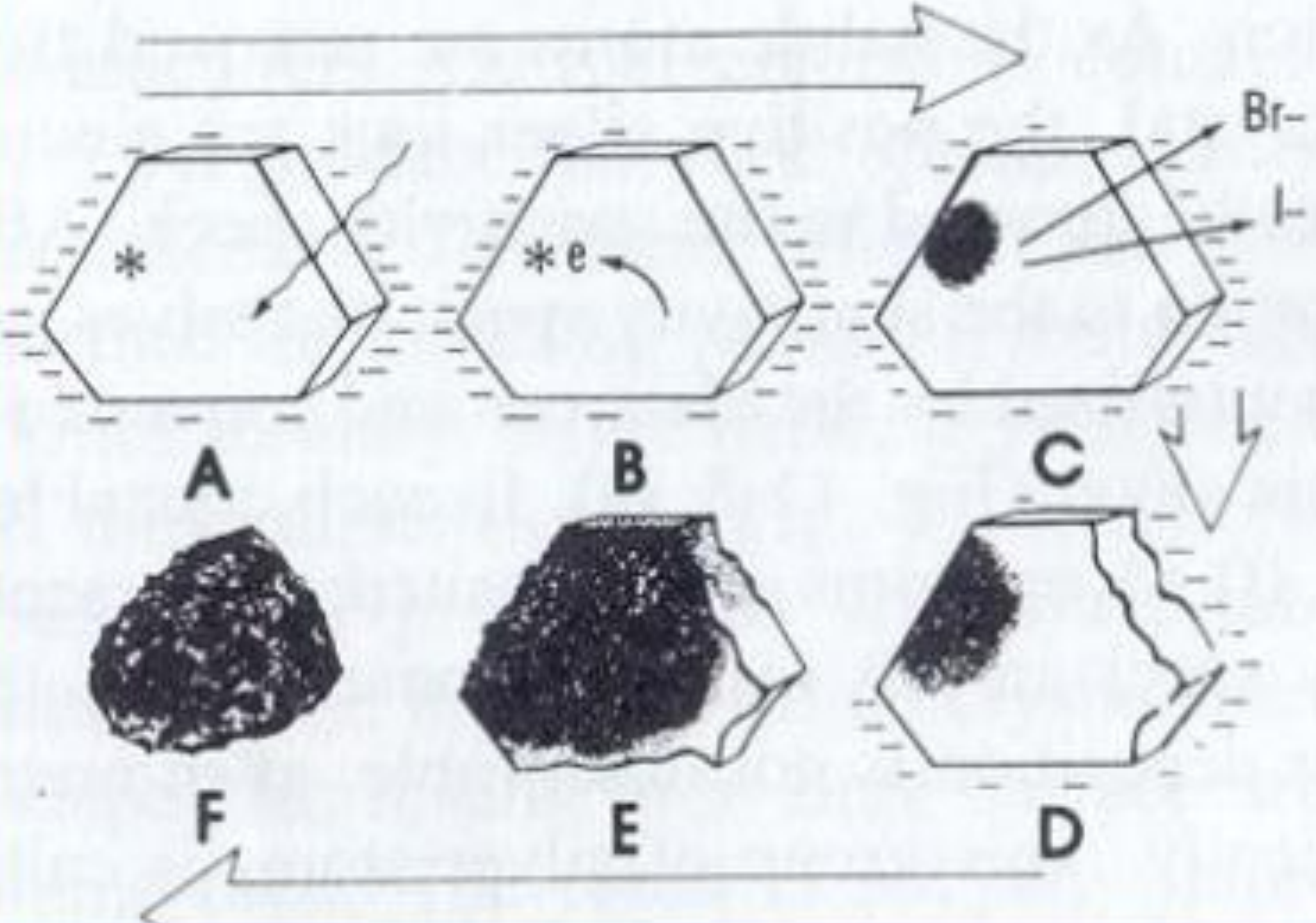
- Latent image Made visible by chemical processing

Silver Halide Crystal





95% of crystal is silver bromide


Br-
I-
*
*e
A
B
C
D
E
F

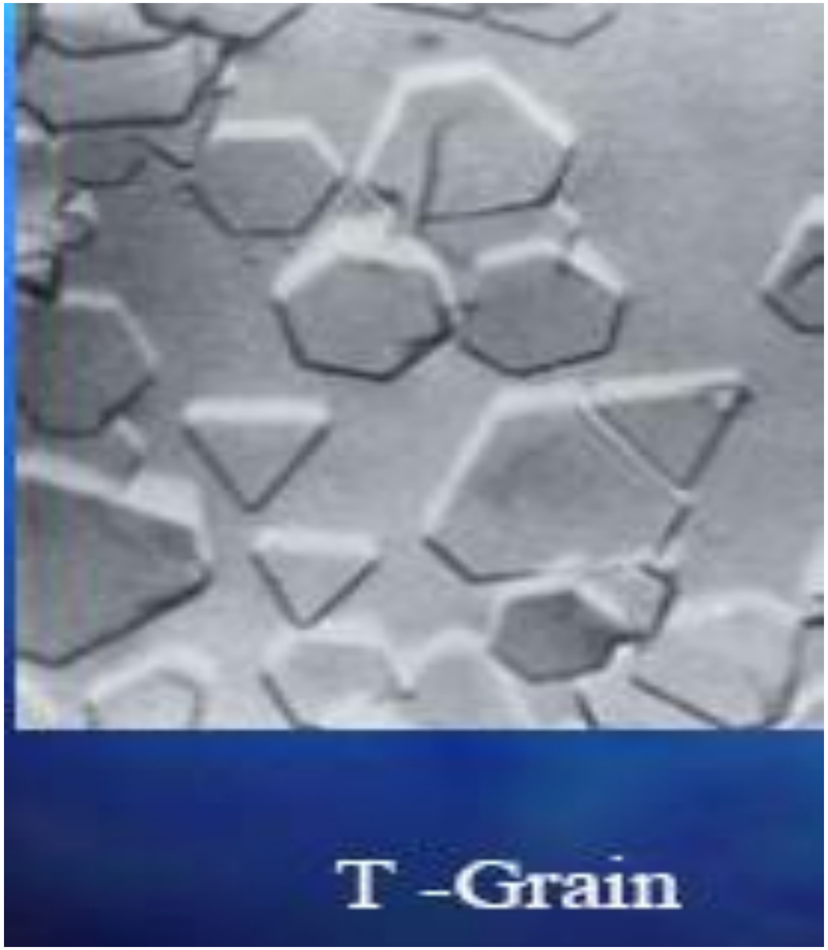
Silver Halide Crystals

- There are two types of silver halide crystals.

  - Tabular (flat) crystals
    - The crystals are placed in the emulsion so that the flat surface (top view below) is parallel with the surface of the film.

  - Globular (rounded) crystals are used in D-speed (Ultraspeed) film;
    - these crystals are like small pebbles.

Shape of silver halide crystals



Intensifying screen structure

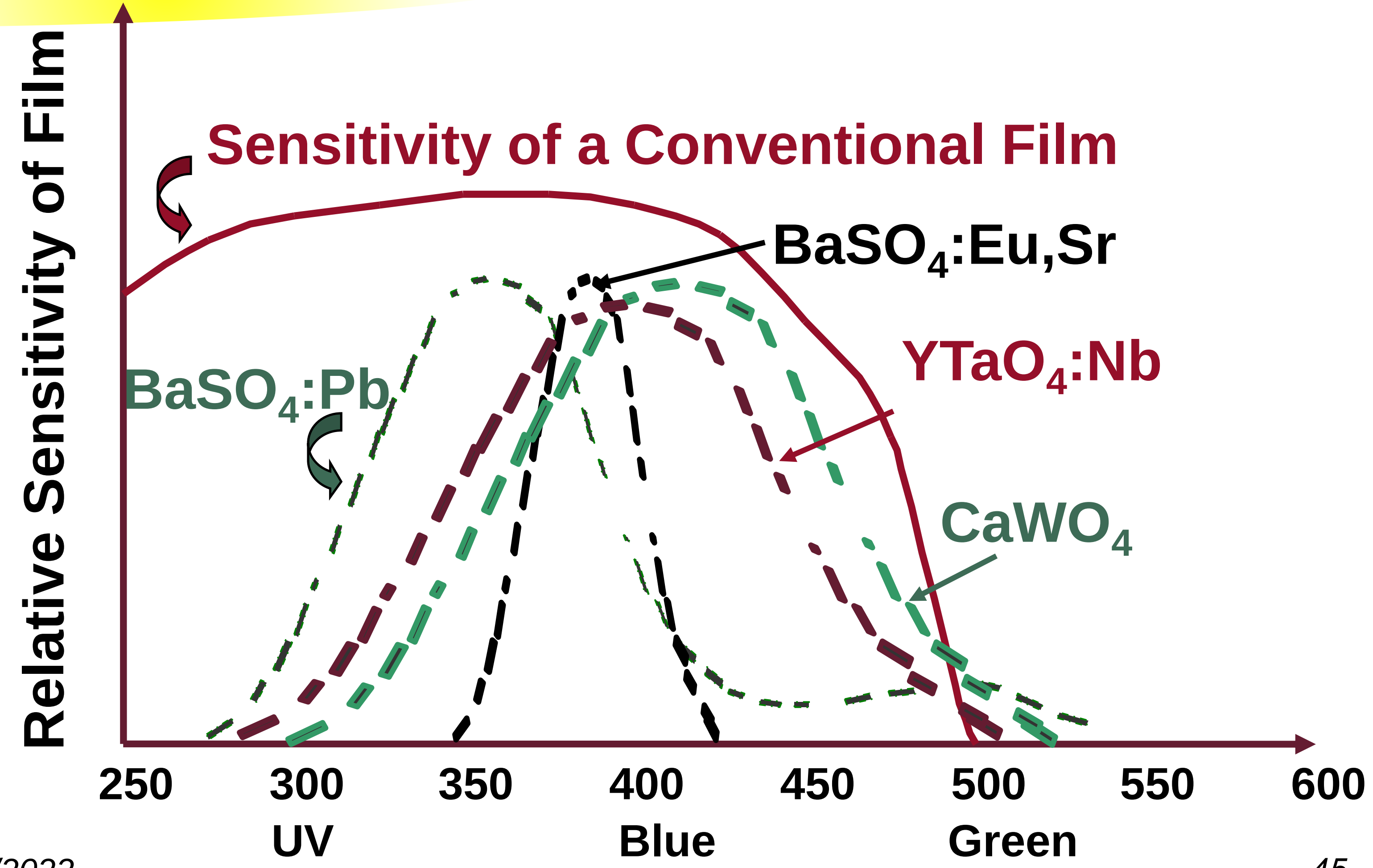
- **The fluorescent layer** (luminophor crystals) should :
  - be able to absorb the maximum quantity of X-rays
  - match its fluorescence with the film sensitivity (color of emitted light)

- **Type of material :**
  - Calcium Tungstate ($CaWO_4$) (till 1972)
  - Rare earth (since 1970) (LaOBr:Tm) (Gd_2O_2S:Tb) $\Rightarrow$ more sensitive and effective than ($CaWO_4$)

Intensifying screen characteristics

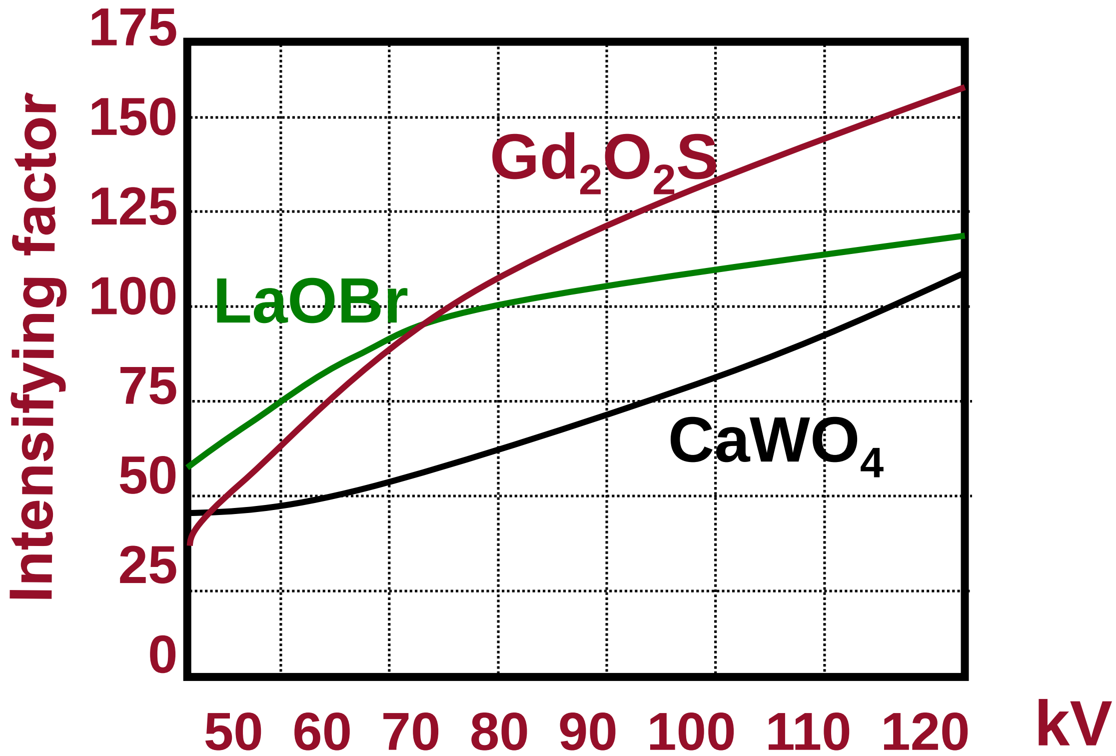
- **IF** (Intensifying Factor): ratio of exposures giving the same film optical density, with and without screen
  - 50 < **IF** < 150 (depending on screen material and X-ray beam energy)
- **QDE** (Quantum Detection Efficiency): fraction of photons absorbed by the screen
  - 40% for $CaWO_4$ < **QDE** < 75% for rare earth (depending on crystal material, thickness of fluorescent layer and X-ray spectrum)
- η (Rendering coefficient): ratio of light energy emitted to X-ray energy absorbed (%)
  - 3% for $CaWO_4 < \eta <$ 20% for rare earth
- **C** (Detection Coefficient): ratio of energy captured and used by the film to energy emitted by the crystal (%)
  - **C** is maximum for screens emitting in UV color wave length ≈ 90%

Intensifying screen characteristics



Intensifying screen characteristics

Intensifying factor: ratio of exposures giving the same film optical density, with and without screen



Intensifying Screen Speed

- The speed of the screen depends on crystal size and the thickness of the phosphor layer (larger crystals and thicker layer increase speed). Image quality decreases as the screen speed increases. The three speeds are:
- Fast (Rapid): requires the least exposure but the images are less sharp
- Medium (Par): medium speed, medium sharpness
- Detail (Slow): produces the sharpest images but requires the most exposure

Screen film combination

- **Sensitivity** (screen film): The quotient K_0/K_a, where K_0 = 1 mGy and K_a is the air kerma free-in-air for **the net density** D = 1.0, measured in the film plane
- **Screen film system**: A particular intensifying screen used with a particular type of film
- **Sensitivity class**: Defined range of sensitivity values of a screen film system
- **Single** emulsion film: One coated film used with one intensifying screen
- **Double** emulsion film: A double coated film used with a couple of intensifying screens
- **Screen film contact ➔ ➔ ➔ ➔ Quantum mottle**

Screen film combination performance

- **Spatial Resolution**: capability of a screen film combination to display a limited number of line pairs per mm. It can be assessed by the Hüttner resolution pattern.

- **Modulation Transfer Function** (MTF): description of how sinusoidal fluctuations in X-ray transmission through the screen film combination are reproduced in the image

- **Noise spectrum**: component of noise due to intensifying system (screen film)
  - Quantum noise, Screen noise, Granularity

Screen film combination performance

- Identification of screen by type and format
  - type mismatch (use of different types of screens) FOR THE SAME FORMAT **is not ADVISABLE**
- Screen film contact
  - loss of spatial resolution
  - blurred image
- Cleanliness
- Inter cassette sensitivity

Image quality

Image quality: the **subjective** judgment by the clinician of the overall appearance of a radiograph.

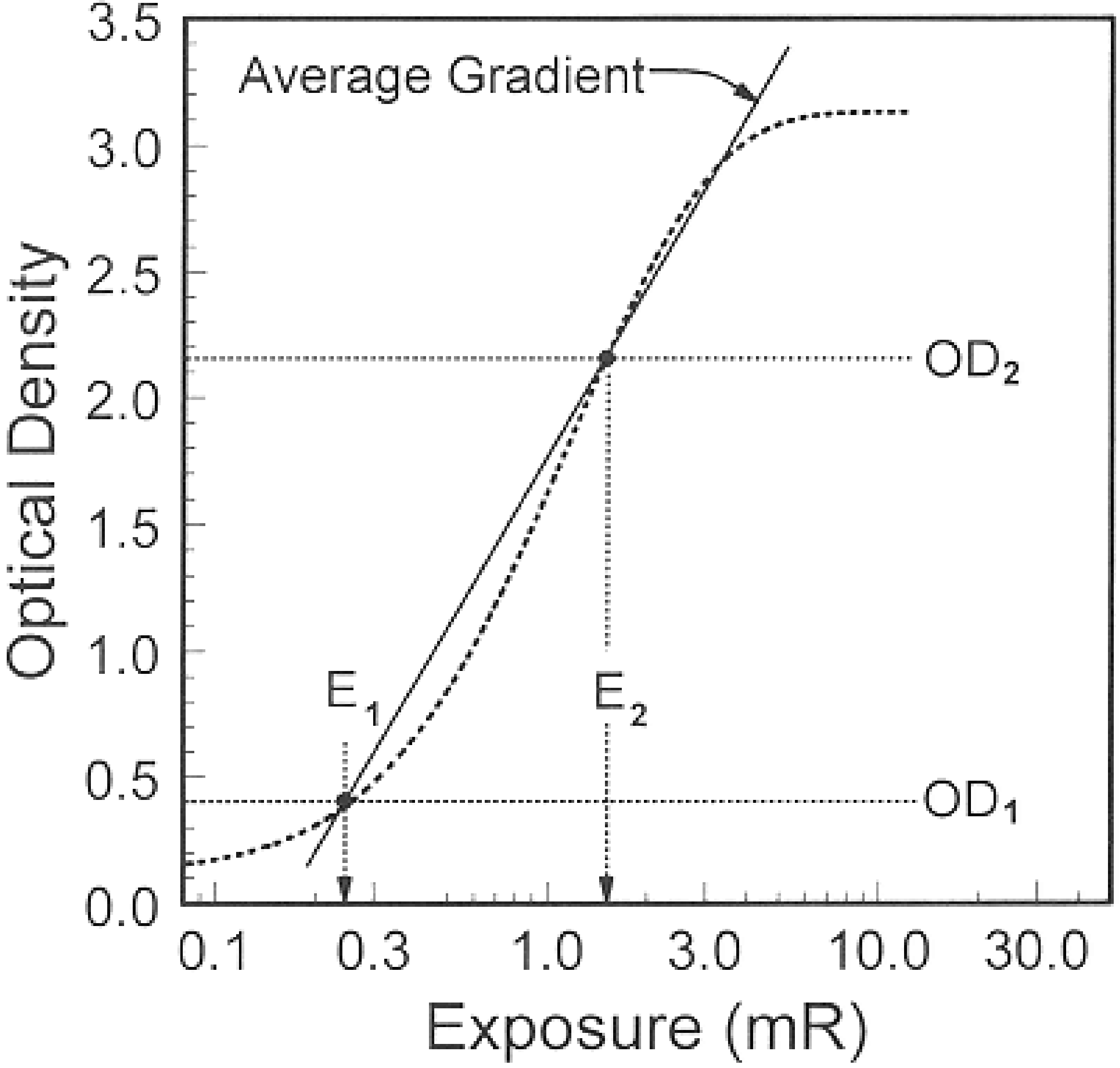
- **Density**,
- **Contrast**,
- **Latitude**,
- **Sharpness**,
- and **resolution**,

Image quality-Optical density

- X-ray film is a negative recorder – increased light (or x-ray) exposure causes the developed film to become darker
- Degree of darkness is quantified by the OD, measured with a densitometer
- Transmittance and OD defined as:

$$T = \frac{I}{I_0}$$

$$\mathrm{OD} = -\log_{10}(T) = \log_{10}\left(\frac{1}{T}\right) = \log_{10}\left(\frac{I_0}{I}\right)$$


Average Gradient
Optical Density
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
OD2
OD1
E1
E2
0.1
0.3
1.0
3.0
10.0
30.0
Exposure (mR)

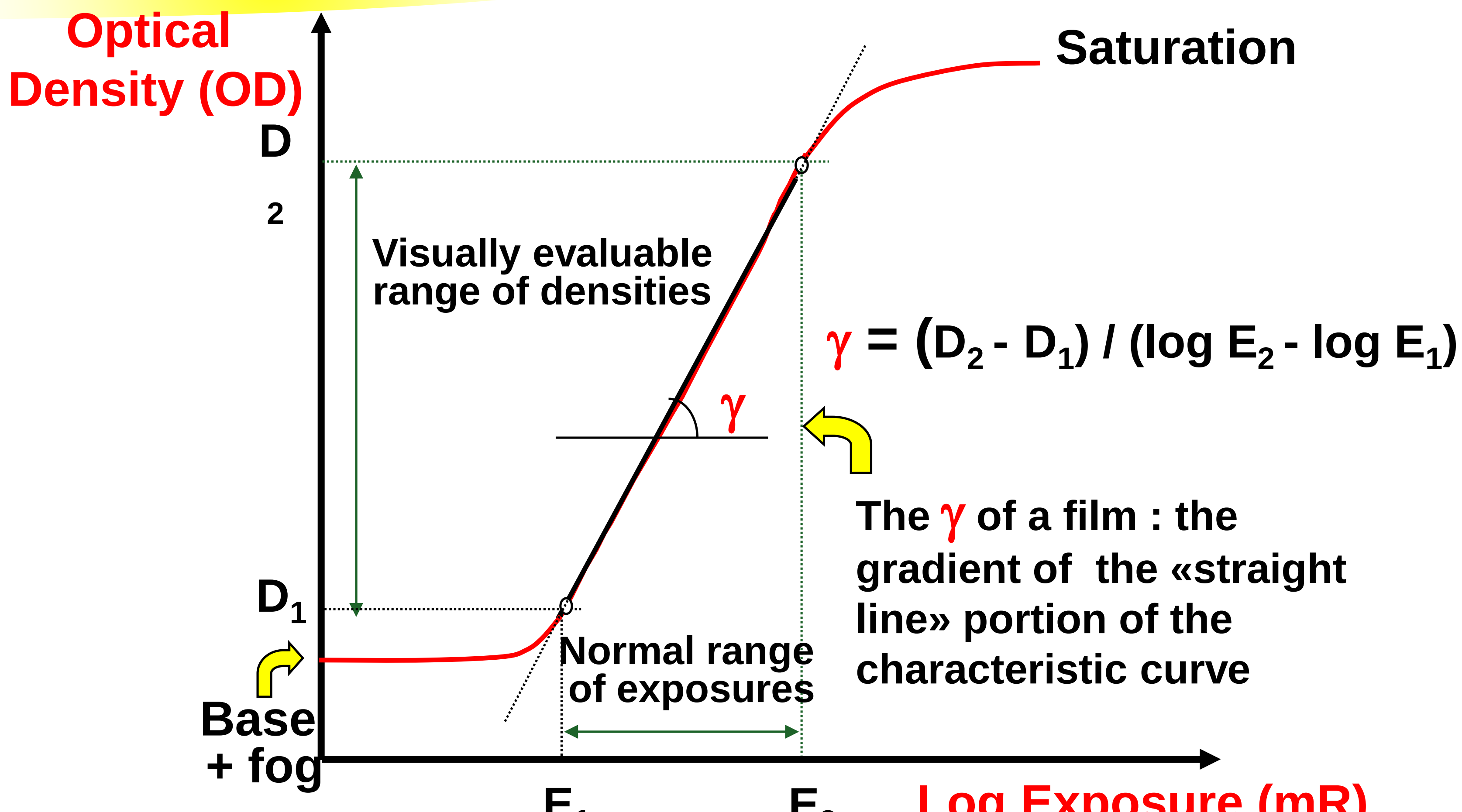
Average gradient

- OD1 = 0.25 + base + fog
- OD2 = 2.0 + base + fog

$$\text{Average gradient} = \frac{OD_2 - OD_1}{\log_{10}(E_2) - \log_{10}(E_1)}$$

- Average gradients for radiographic film range from 2.5 to 3.5

Characteristic curve of a radiographic film



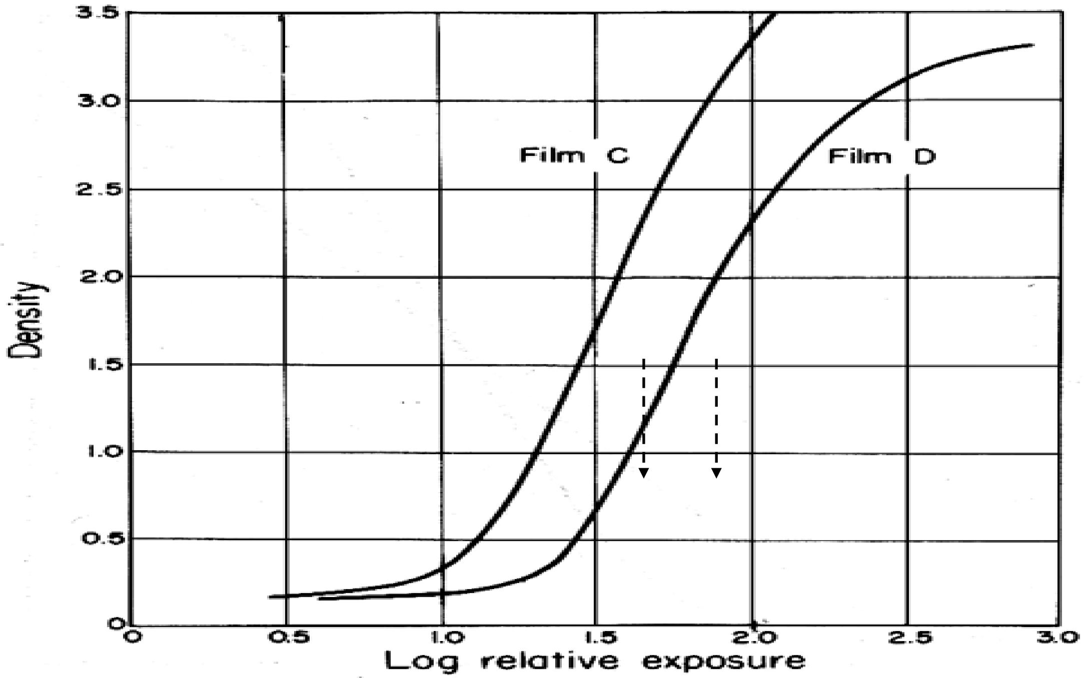
Film sensitometry parameters

- **Base + fog**: The OD of a film due to its base density plus any action of the developer on the radiographically unexposed emulsion
- **Sensitivity (speed):** The reciprocal of the exposure value needed to achieve a film net OD of 1.0
- **Gamma (contrast):** The gradient of the straight line portion of the characteristic curve
- **Latitude**: Steepness of a characteristic curve, determining the range of exposures that can be transformed into a visually evaluable range of OD

FILM FOG!!!!

- Unintended uniform optical density on a radiograph because of x-rays, light, or chemical contamination that reduces contrast & affects density

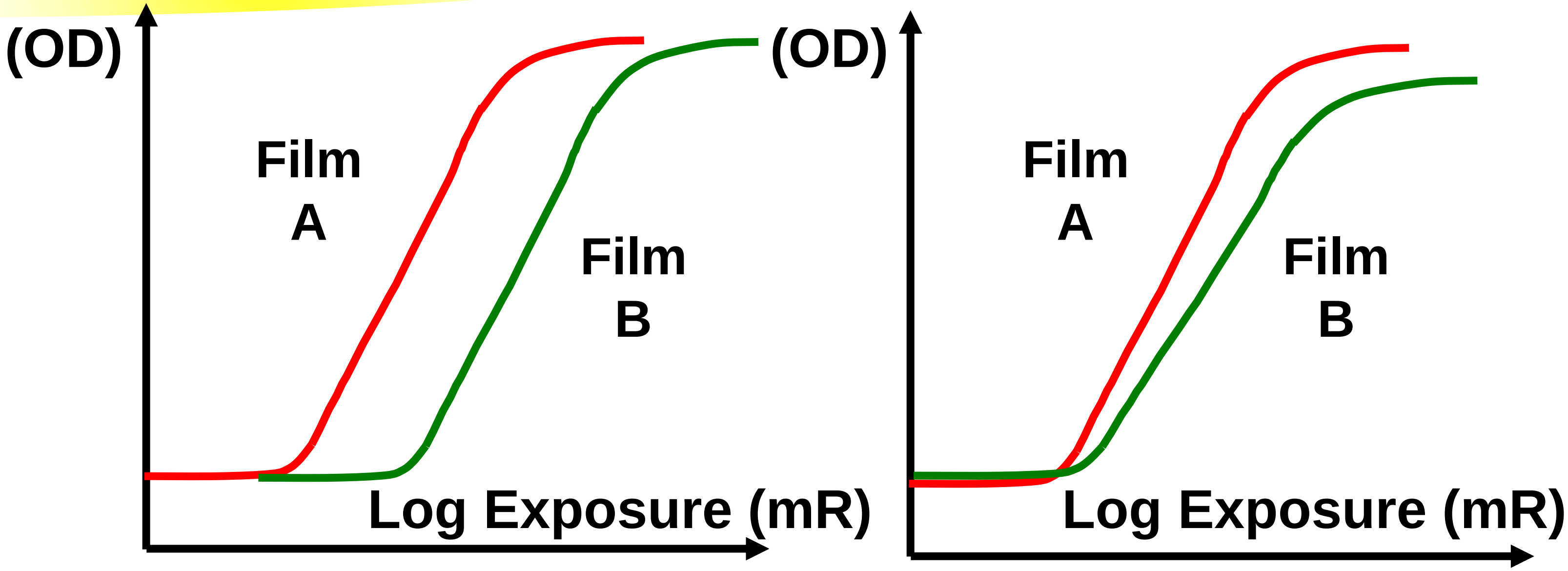
Film/Screen "Speed"



The amount of radiation required to produce an image of standard density. Film speed is controlled largely by the size of the silver halide grains.

- Film/screen "speed"
  - speed = 100/E where E is exposure in mR to produce an optical density of 1.0
  - position on exposure axis dependent on "speed"
  - higher "speed" number translates to lower patient exposure

Comparison of characteristic curves



Film A is faster than Film B

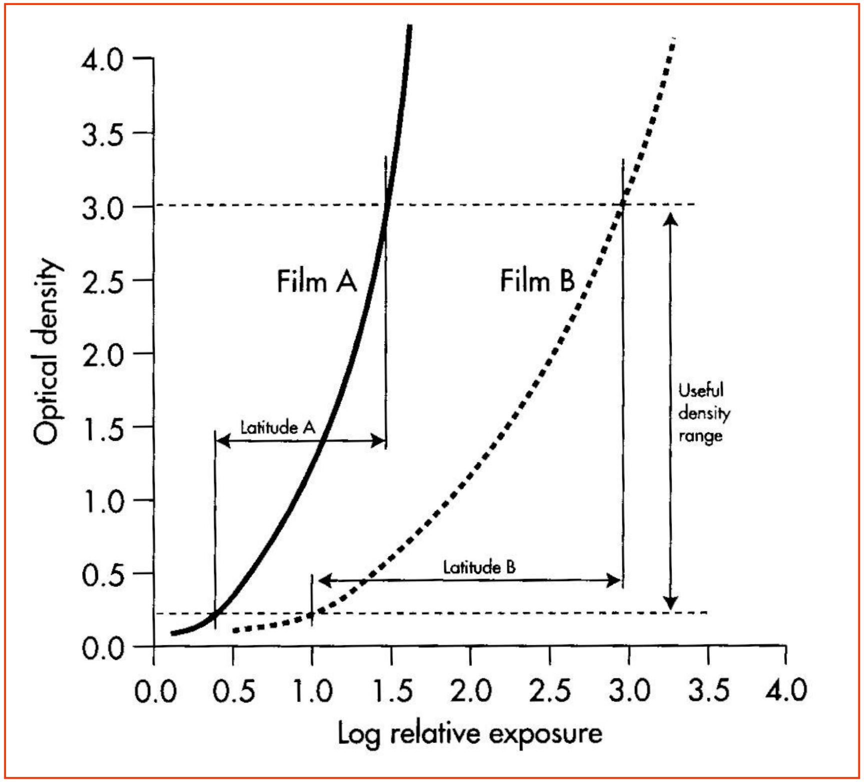
Film A and B have the same contrast

Film A and B have the same sensibility but different contrast

Film latitude

The range of exposures that can be recorded as distinguishable densities on the film.

Films with wide latitude have lower contrast.

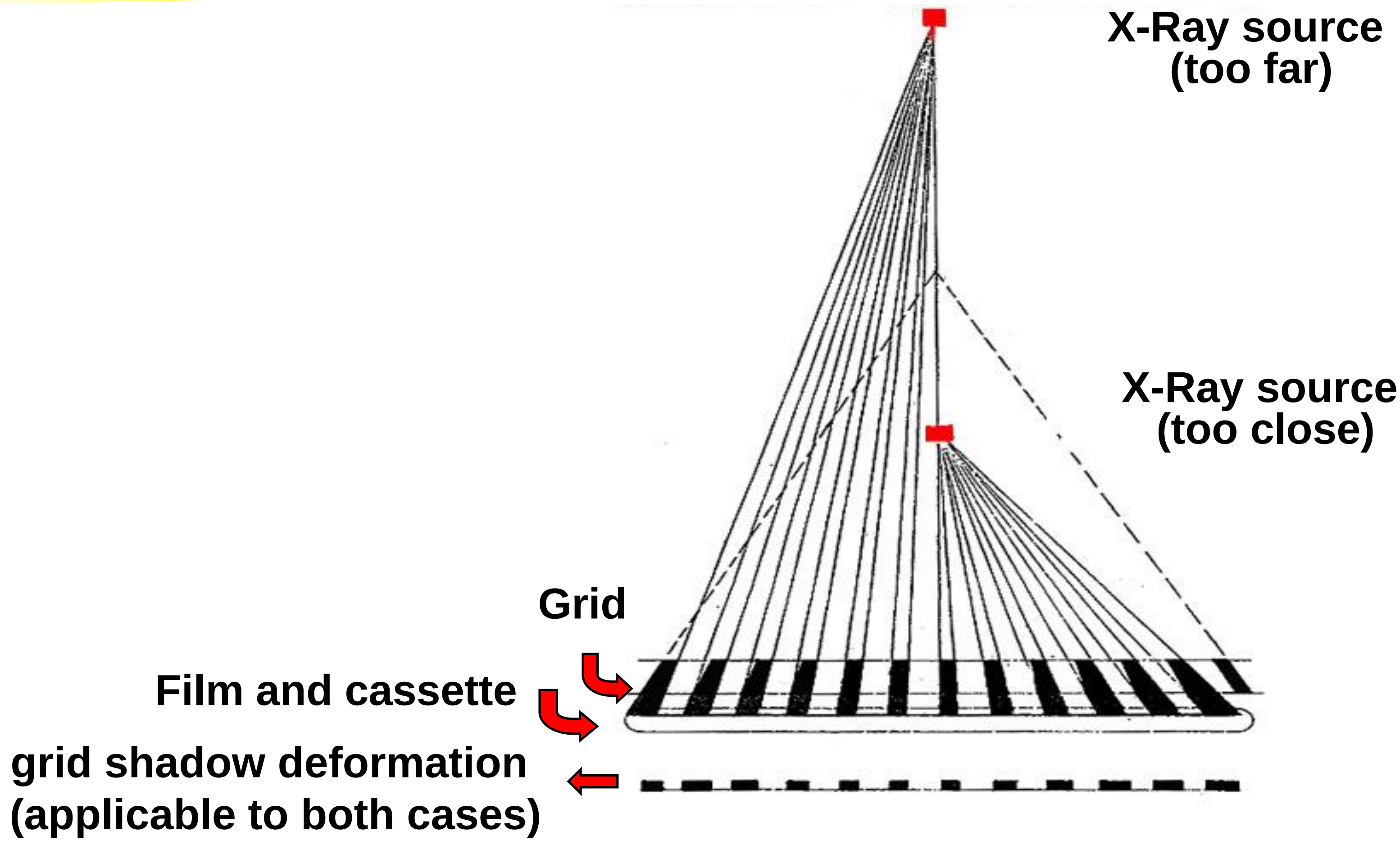


Radiographic noise

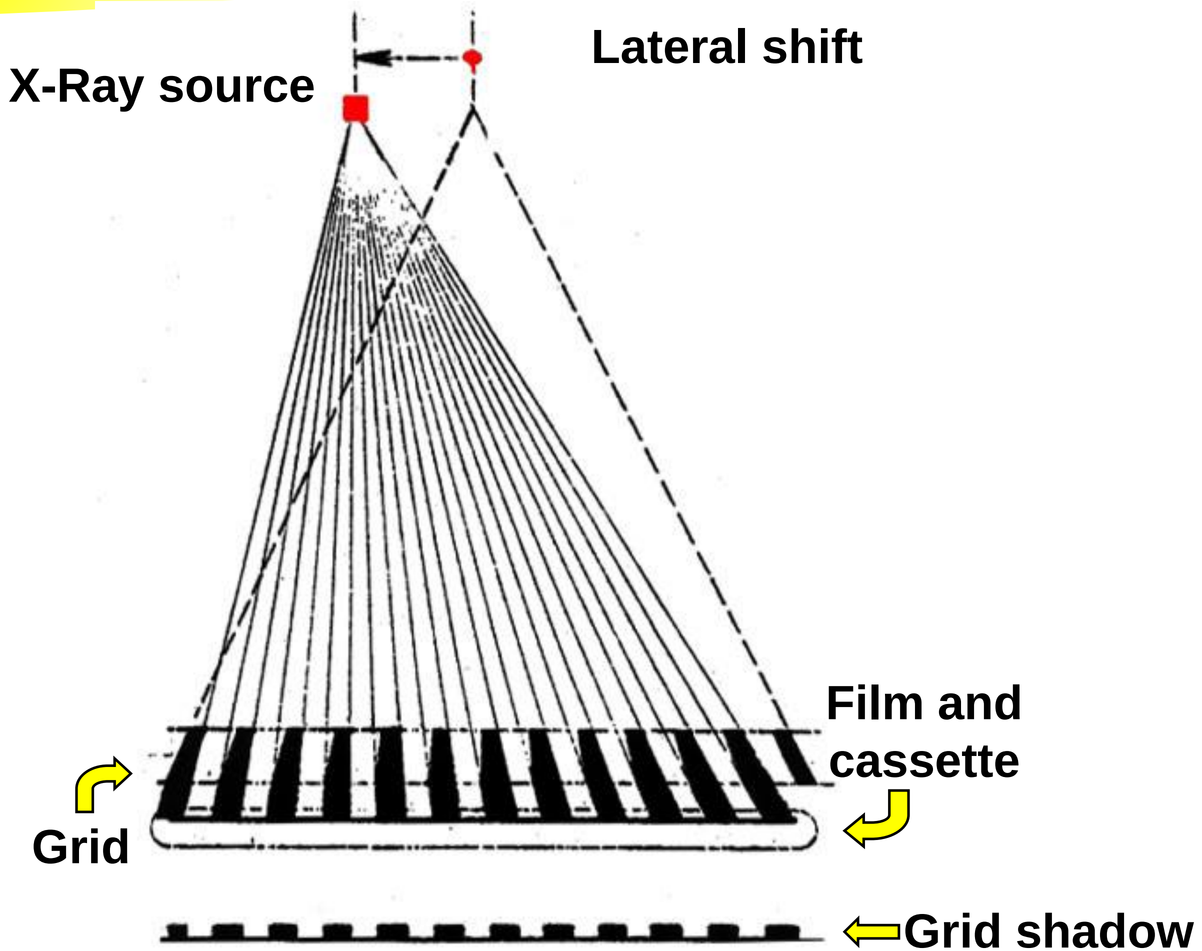
Radiographic mottle – uneven density resulting from the physical structure of the film.

Radiographic artifact – defects caused by errors in film handling

Grid focusing error (virtual increasing of grid shadow)



Grid out of center
(virtual deformation of grid shadow)



Grid performance parameters

- **Grid ratio**
  - Ratio of the height of the strips to the width of the gaps at the central line
- **Contrast improvement ratio**
  - Ratio of the transmission of primary radiation to the transmission of total radiation
- **Grid exposure factor**
  - Ratio of total radiation without the anti-scatter grid to that with the anti-scatter grid placed in the beam for a similar density
- **Strip number**
  - The number of attenuating lamella per cm
- **Grid focusing distance**
  - Distance between the front of a focused grid and the line formed by the converging planes

Radiographic Contrast

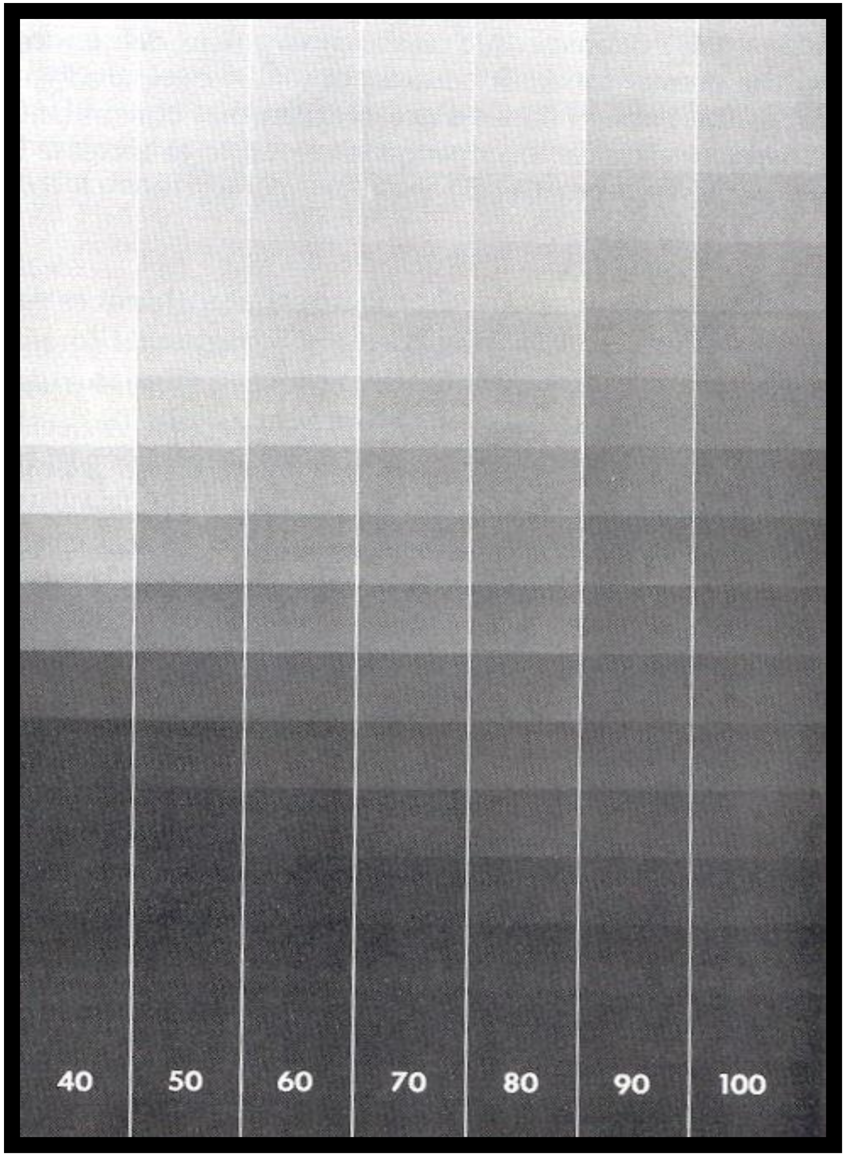
- Radiographic Contrast Depends On:
- 1. Subject Contrast
- 2. Film Contrast
- 3. Scatter
- 4. Fog

Subject Contrast

- **Subject** thickness, density, and atomic number

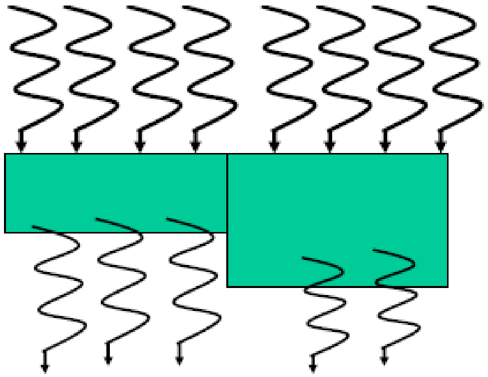
- **Beam energy** and intensity
  increased energy-
  decreased contrast

- **Exposure** (time or mA): if the film is excessively light or dark, contrast is diminished.

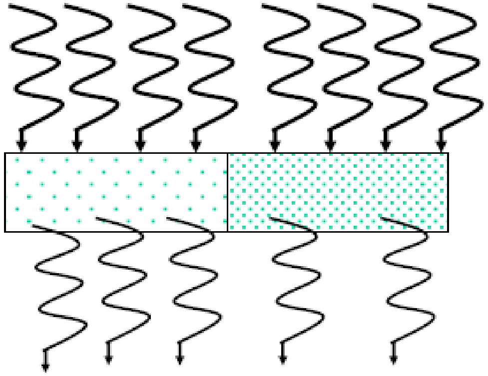


Subject Contrast- cont…

- Subject Contrast Depends On:
  - i. Thickness Differences



  - ii.Density Differences



Subject Contrast- cont

- iii. Atomic Number
  - Photoelectric interactions accentuate
    - subject contrast because:
    - PEE " Z3

Tissue	Effective Z	Z^3
Bone	14.0	2774
Fat	6.0	216

کنتراست

- کنتراست رابطه بین دو اکسپوز، شدت تشعشع و یا نور را نشان می دهد و تمایز و تشخیص دو بافت مجاور و حد فاصل آنها را امکان پذیر می سازد.

$$C_r = \ln\left(I_1/I_0 \right)$$

- وقتی شدت تشعشع X، وارد بدن انسان می شود سه حالت اتفاق می افتد:

- ۱– انرژی بطور مستقیم از بدن عبور کرده و بدون جذب از وسط ساختار بافت ها می گذرد.
- ۲– انرژی بطور کامل جذب شده و بدلیل جذب فتوالکتریک هیچ انرژی عبور نمی کند.
- ۳– بخشی از انرژی جذب شده و بقیه بصورت Scatter پراکنده می شوند. این حالت سوم بیشترین نفع را برای کنتراست بافت نرم تصویر دارد.

جـهت محـاسبه کنتراست، اگر توموری به ضخامت Δx و ضریب جذب μ در روی بافتی به ضخامت x و ضریب جذب μ داشته باشیم. کنتراست حاصل از تومور:

$$I_1 = I_0 \exp(-\mu x)$$

$$I_2 = I_0 \exp -\mu(x + \Delta x) \qquad \Rightarrow C_r = \ln(I_2/I_1) = -\Delta\mu x$$

۱- کنتراست منفی است یعنی اضافه کردن بافت تومور باعث کاهش تشعشع خروجی می شود.

۲- کنتراست بستگی به ضریب جذب خطی (μ) مواد دارد.

۳- کنتراست فقط بستگی به ضخامت تومور دارد نه ضخامت بیمار یا بقیه بافت، البته این فقط زمانی صحیح است که تشعشع فقط اولیه باشد و اسکتر نداشته باشد.

- ٤- برای فضای خالی (Cavity) به ضخامت Δx کنتراست:
- $Cr = +\mu \Delta x$
- ٥- در صورتی که ضریب جذب بافت تومور (که در روی بافت دیگر قرار گرفته) $\mu 2$ باشد در نتیجه:

$$C_r = -\mu_2 \Delta x$$

- ٦- برای اضـــافه کردن تومور یا مــــواد با ضریب جـــذب در داخــــــل بافت با ضریب جـــذب $\mu 1$:

$$Cr = -| \mu_2 - \mu_1 | \Delta x$$

فاکتورهائی که در کنتراست مؤثر هستند :

- ۱– ضریب جذب خطی استخوان بیشتر از بافت نرم است. بنابراین کنتراست جزئیات داخل استخوان بهتر از کنتراست جزئیات داخل بافت نرم است.
-
- ۲– کنتراست هر دو استخوان و بافت نرم با افزایش انرژی بالا کاهش می یابد (بدلیل رابطه لگاریتمی کنتراست).
-
- ۳– اختلاف ضریب جذب بین استخوان و بافت نرم با افزایش انرژی، کاهش می یابد (کنتراست بین آندو کاهش می یابد).
-
- ٤– وقتی کنتراست بالا بین بافتهـــــای نرم نیاز است از مواد کنتراست زا مثل باریم، تزریق هوا و تزریق ید استفاده می شود.

تشعشع اسکتر

۵- اسکتر بصورت تشعشع یکنواخت سرتاسر فیلم را اثر می گـذارد و کنتراست را کاهش می دهد در حضور اسکتر فرمول کنتراست:

$$C'_r = \frac{Cr}{1+s} = \frac{-\mu \Delta x}{1+s}$$

- باید :
- ۱- اندازه میدان تا حد امکان کاهش یابد (با استفاده از دیافراگم)
- ۲- ضخامت بیمار تا حد امکان مثلاً توسط کمپرسور کاهش یابد.
- ۳- gap یا فضای هوا بین بیمار و فیلم قرار گیرد (بدلیل کاهش تشعشع های زاویه دار)
- ٤- kvp تا حد ممکن و ضروری کاهش یابد.
- ۵- از وسیله ای که تشعشعات زاویه دار را جذب میکند مثل گرید (بوکی) استفاده شود.