Interactive Visuals to Explore X-ray Spectrum and X-ray Attenuation

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Interactive applets have been developed to help Radiologic Technology students explore some of the key physics concepts behind diagnostic X-ray images. The first applet uses a simplified model for mass attenuation coefficients to allow students to explore the roles of material properties and X-ray energy in differential absorption which in turn to contrast features in diagnostic X-rays. The second applet uses a simplified model to describe bremsstrahlung and characteristic X-rays, allowing students to investigate the effect X-ray tube high voltage and filters on the X-ray spectrum. The validation of the qualitative features of the simplified models is also discussed. These applets were created using the Easy Java Simulations tool from the Open Source Physics project.

www.opensourcephysics.org Open Source Physics
www.um.es/fem/Ejs/ Easy Java Simulations

Student Concepts

X-ray Interaction with Matter and Image Contrast

- Compton Effect
  - interaction probability
    - independent of atomic number Z
    - inversely proportional to photon energy E
- Photoelectric Effect
  - interaction probability
    - proportional to Z^3
    - inversely proportional to E^3
- Both effects proportional to mass density

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Modeling X-ray Interaction with Matter

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

I = intensity

μ = linear attenuation coefficient

t = thickness of material

$\mu = \rho(\tau_m + \sigma_m)$

ρ = density

τ_m = photoelectric effect mass attenuation coefficient

$$\tau_m = \tau_{m0} \left(\frac{Z}{Z_0}\right)^3 \left(\frac{E_0}{E}\right)^3$$

does not account for energy constraints

absence of photoelectric "edges"

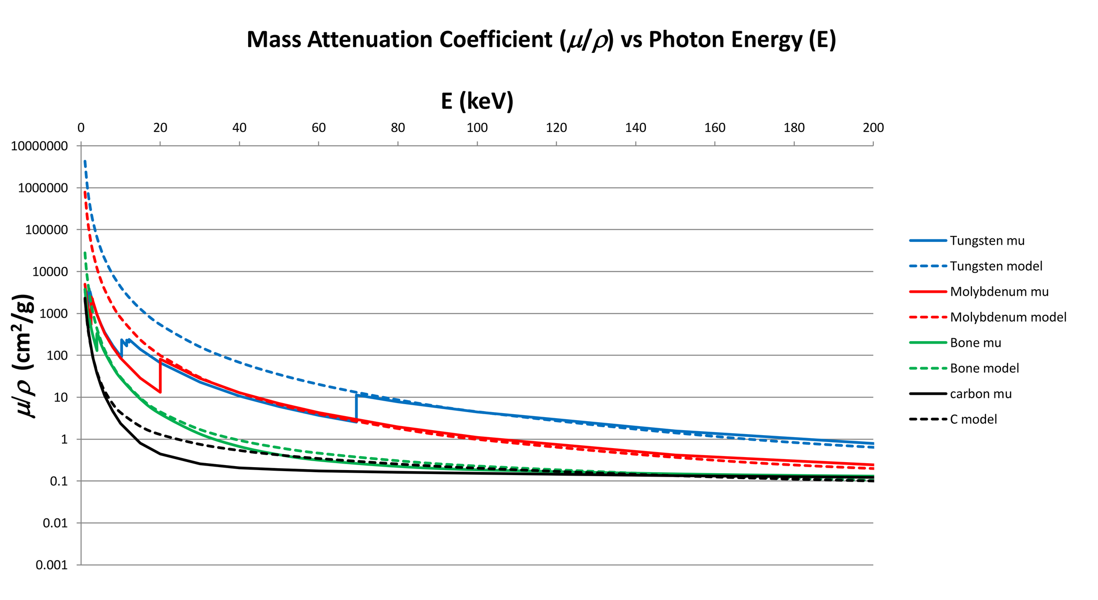
σ_m = Compton effect mass attenuation coefficient

$$\sigma_m = \sigma_{m0} \left(\frac{E_0}{E}\right)$$

simplistic model gives qualitative agreement

$Z_0 = 20 \quad \tau_{m0} = .085$

$E_0 = 100 \quad \sigma_{m0} = .2$



Experimental mass attenuation coefficients from NIST: http://www.nist.gov/pml/data/xraycoef/

Model overestimates attenuation below photoelectric edges, but provides qualitative agreement with data

Modeling X-ray Spectrum*

Bremsstrahlung

$I(E) \propto Z(T - E)$

T = electron's kinetic energy

Characteristic X-Rays (K-shell)

$I_K \propto (T - E_K)^{1.65}$

E_K =K shell binding energy

Intrinsic Filtering: energy dependent attenuation of X-rays

electrons penetrate anode

attenuation by X-ray tube components

modeled as:

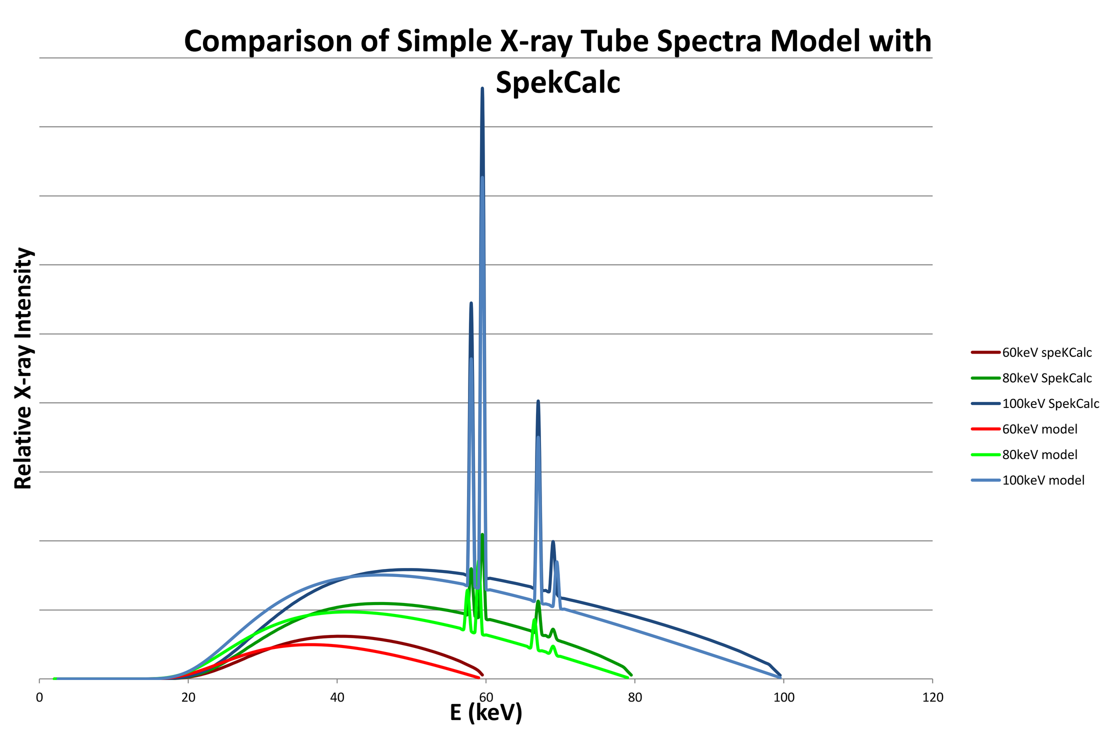
$$Z = 29, \rho t = .1\ g/cm^2$$

Additional Filtration

filtration by design for diagnostic X-ray imaging

beam "hardening" + attenuation

*Following simplified models from discussion in "Semiempirical model for generating tungsten target x-ray spectra" Douglas M. Tucker, Gary T. Barnes, and Dev P. Chakraborty, Med. Phys. 18, 211 (1991)



"SpekCalc: a program to calculate photon spectra from tungsten anode x-ray tubes" G Poludniowski et al 2009 Phys. Med. Biol. 54 N433

Differential Absorption App

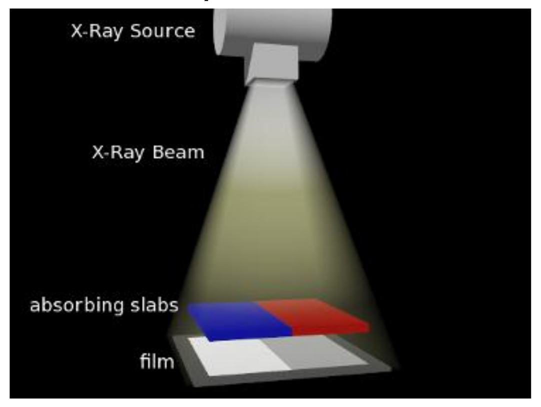
Introduction: Differential Absorption and Diagnostic X-Rays

X-ray images are created when X-rays from a source penetrate an object and then expose a film. The difference in how different materials absorb the X-rays in the beam produces the contrast that generates the detail of the image.

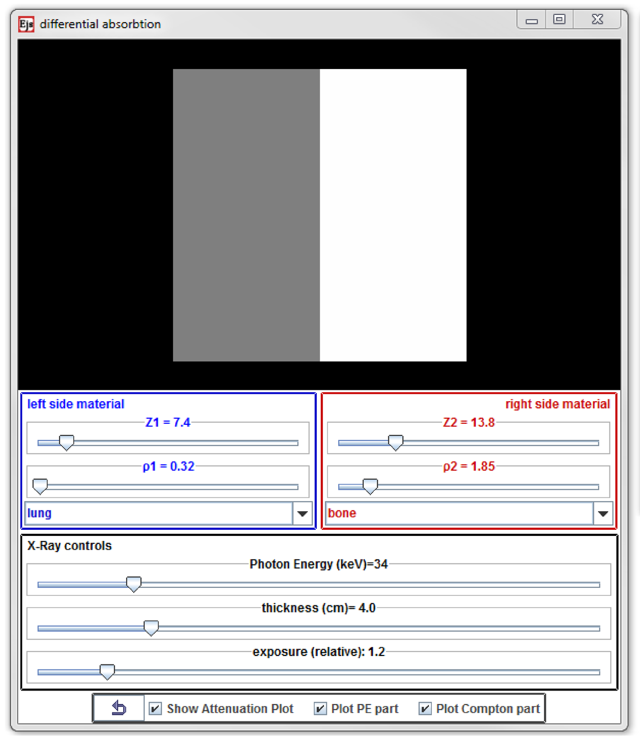
For a typical medical diagnostic image, the X-ray interaction with matter is primarily through the Photoelectric effect and Compton scattering.

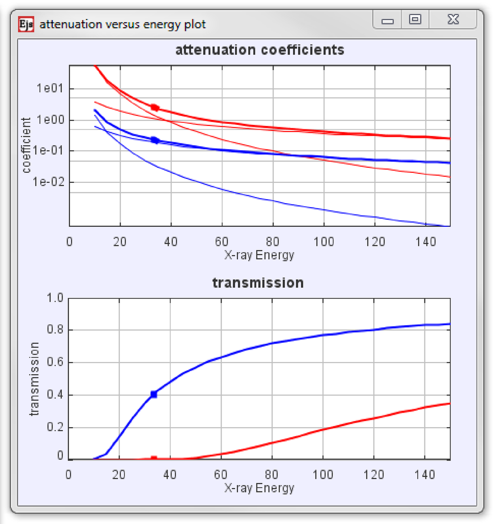
The strength of these two mechanisms depends upon the energy of the X-ray photons, the atomic number of the material as well as the density of the material.

This simulation provides a qualitative exploration of the difference of how X-rays interact with varying material properties and how this difference can produce contrast in the x-ray image.



The App:





Discussion Questions:

Experiment with different material settings. You can change the atomic number and the density of the two slabs separately. You can also change the thickness of the slides, but they will always have the same thickness. You can also control the photon energy[1] and exposure (think of this as setting mAs). Mixtures of materials (such as bone, soft tissue and other materials) use an averaging process to determine an effective atomic number.

- How does increasing the atomic number (Z) affect the attenuation coefficient graph?
- How does increasing the atomic number affect the transmission graph?
- How does increasing the density (ρ) affect the attenuation coefficient graph?
- How does increasing the density affect the transmission graph?

Changing the photon energy just changes the energy for the simulated exposure, and is indicated by the markers on the graph.

- Verify that changing the photon energy does not change the graphs.
- Does changing the photon energy change the simulated film?

The exposure control is essentially an uncalibrated version of mAs for the radiation technologist.

- Does increasing or decreasing exposure affect any of the graphs?
- Does increasing or decreasing exposure affect the simulated film the way a similar increase in mAs would affect a real X-Ray image?

Use the preselected material properties for lung tissue for the left slab of material and soft tissue for the right slab of material. Make sure to set the other parameters to their defaults (Photon Energy = 50 keV, thickness = 1.0 cm, exposure = 1.0). The attenuation coefficient curve (in blue) for lung tissue is less than that for soft tissue (in red) at all X-ray photon energies. This means that the photons are more likely to interact with the material if they pass through soft tissue than if they were to pass through lung tissue.

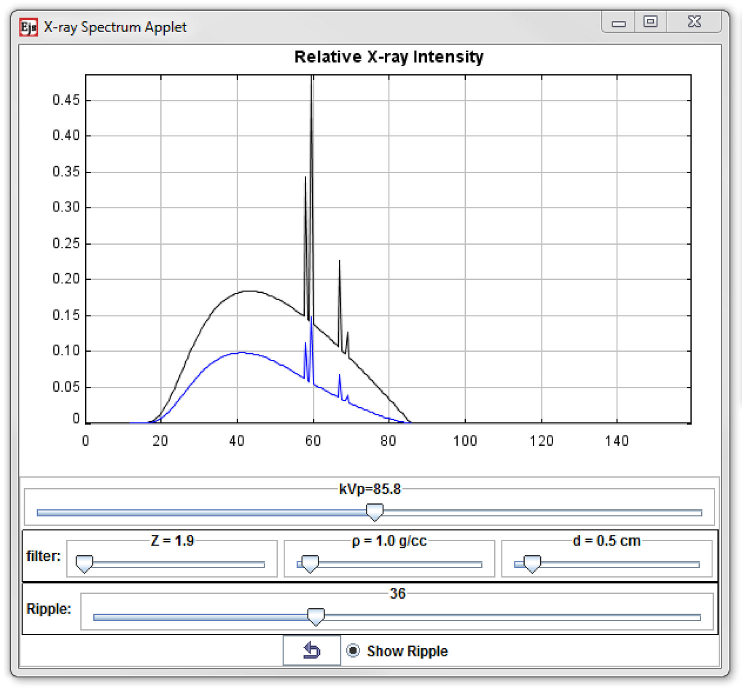
- Which material will the X-Ray photons be more likely to pass through? Do the respective transmission curves show what you expect? Explain.
- With these two materials, vary the Photon Energy but leave the thickness set to 1 cm and the exposure set to 1. Is there an energy or range of energies that give a "best" contrast between the two sides in the simulated X-Ray film? Is there some feature of the transmission graphs that could explain this "best" contrast?
- Set the thickness to 10 cm. Can you predict what range of Photon Energy would give better contrast?
- Reset the thickness to 1 cm, and now select the left side material as bone and the right side material as Barium. Using the transmission graphs, make a prediction for a range of energies which will penetrate each slab.

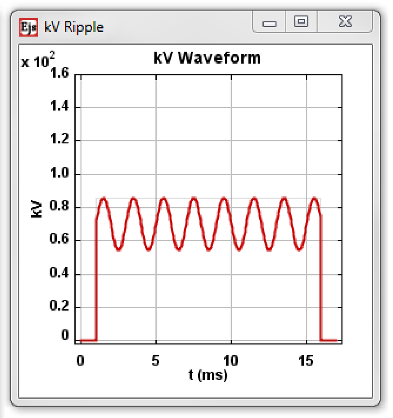
1 Remember that real diagnostic X-Ray machines produce photons at a variety of efferent energies. The amount of photons at a particular energy is called the X-Ray spectrum and will depend upon kVp, tube current and the xray target material (usually Tungsten).

X-ray Spectrum App

Introduction:

There are a variety of factors that affect the spectrum of X-rays produced in a diagnostic imaging unit. This applet shows the effect of varying the high voltage (kVp), added filtration and ripple in the high voltage supply to the X-ray tube.





Discussion Questions:

The total X-ray energy is the area under the spectrum curve. What effect does changing kVp have on the total energy of the X-ray beam?

Characteristic X-rays cannot be created unless the kinetic energy of the cathode electrons can overcome the binding energy of the K shell electrons of the target atoms. Estimate this binding energy (in keV) by noting the accelerating potential at which the characteristic X-rays first appear. Does it make sense that this threshold energy is greater than the energies of the characteristic X-rays? (explain)

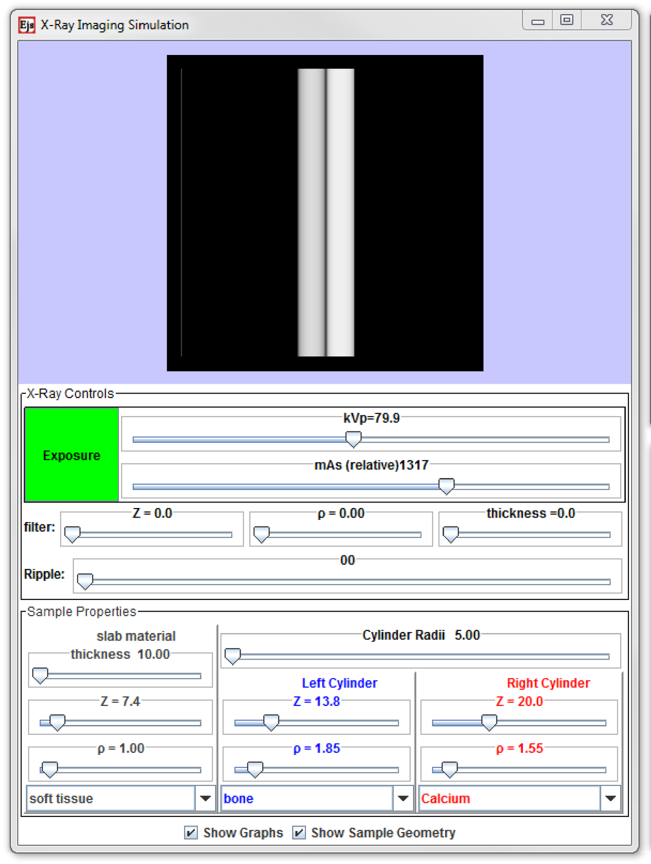
With kVp set at 12o kV, add filtration by setting the following characteristics of the filter material: atomic number (Z) =1, density (ρ in g/cm³) = 1 and thickness (t in cm) to 1.

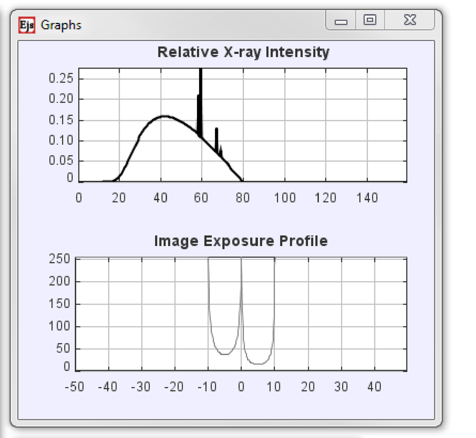
- What happened to the overall intensity of the beam? (i.e. the area under the curve).
- Were all energy X-rays equally affected? Which part of the X-ray spectrum was affected the most?
- What happens to the total intensity of the filtered beam and the spectrum when Z is increased?
- What happens when the density is increased? Is this the same effect as increasing Z?
- What happens when the thickness is increased?

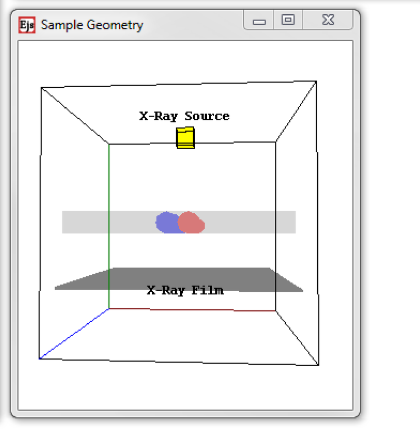
Remove the filters by setting all filter parameters to zero. What happens to the total intensity when ripple is increased? Which part(s) of the xray spectrum are affected the most? Does having ripple in the high voltage produce the same type of effect as filtration? (explain)

X-ray Imaging App

A Summary/Review of Basic Imaging Physics







All X-ray Applet materials available in

http://phys23p.sl.psu.edu/RadSc