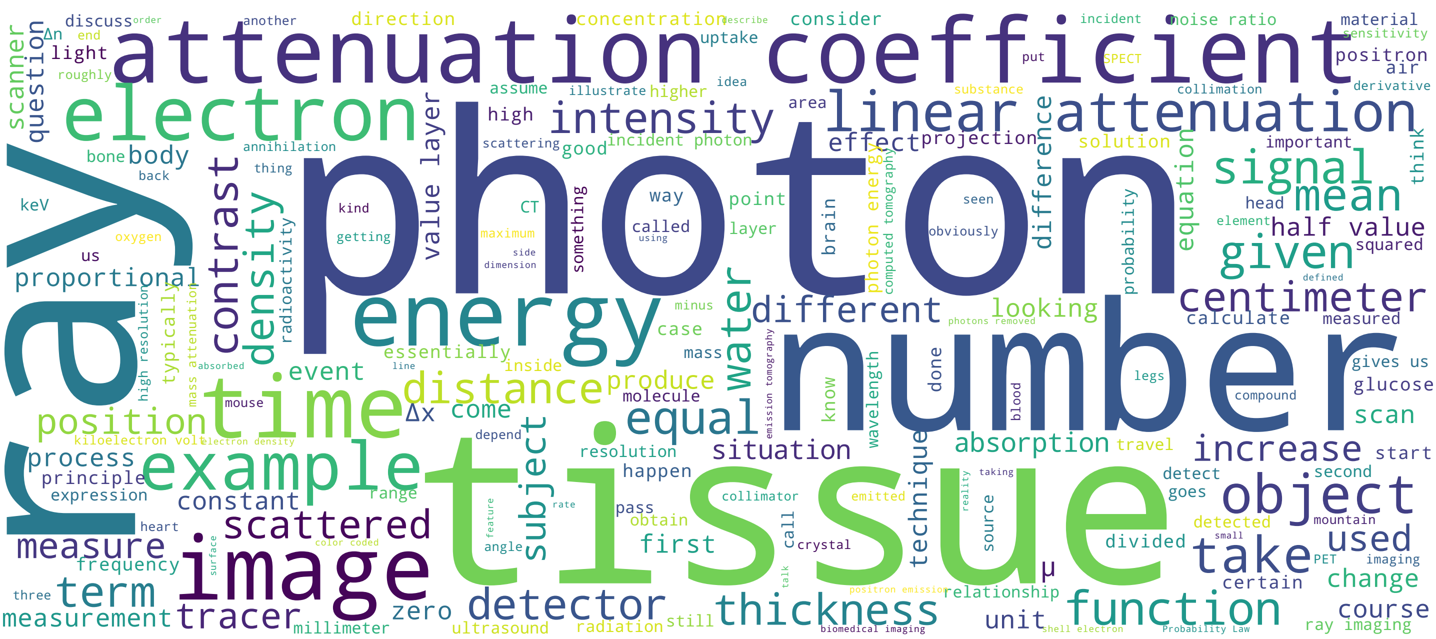
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

3.1 Basis of contrast for x-ray imaging

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



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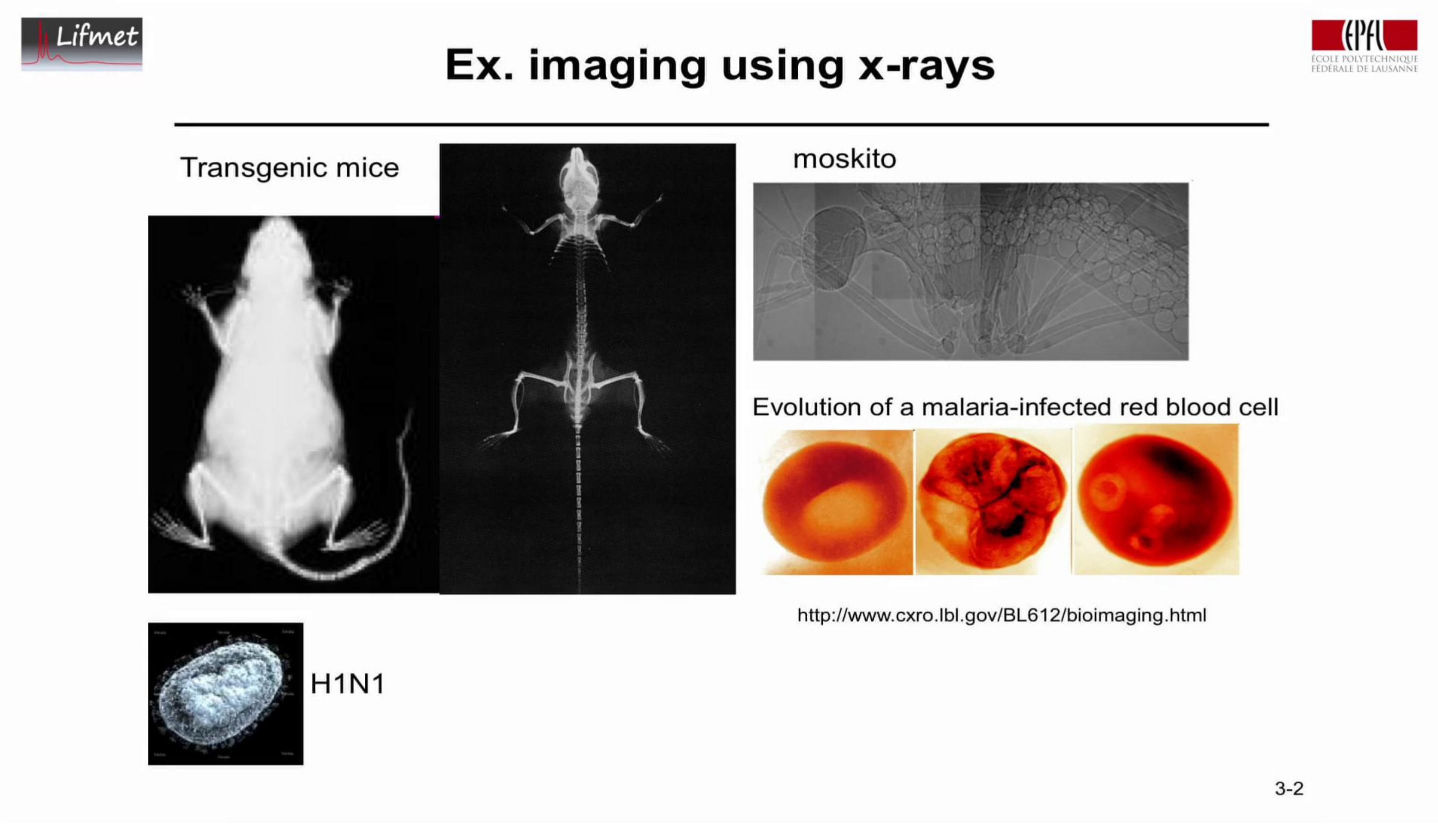
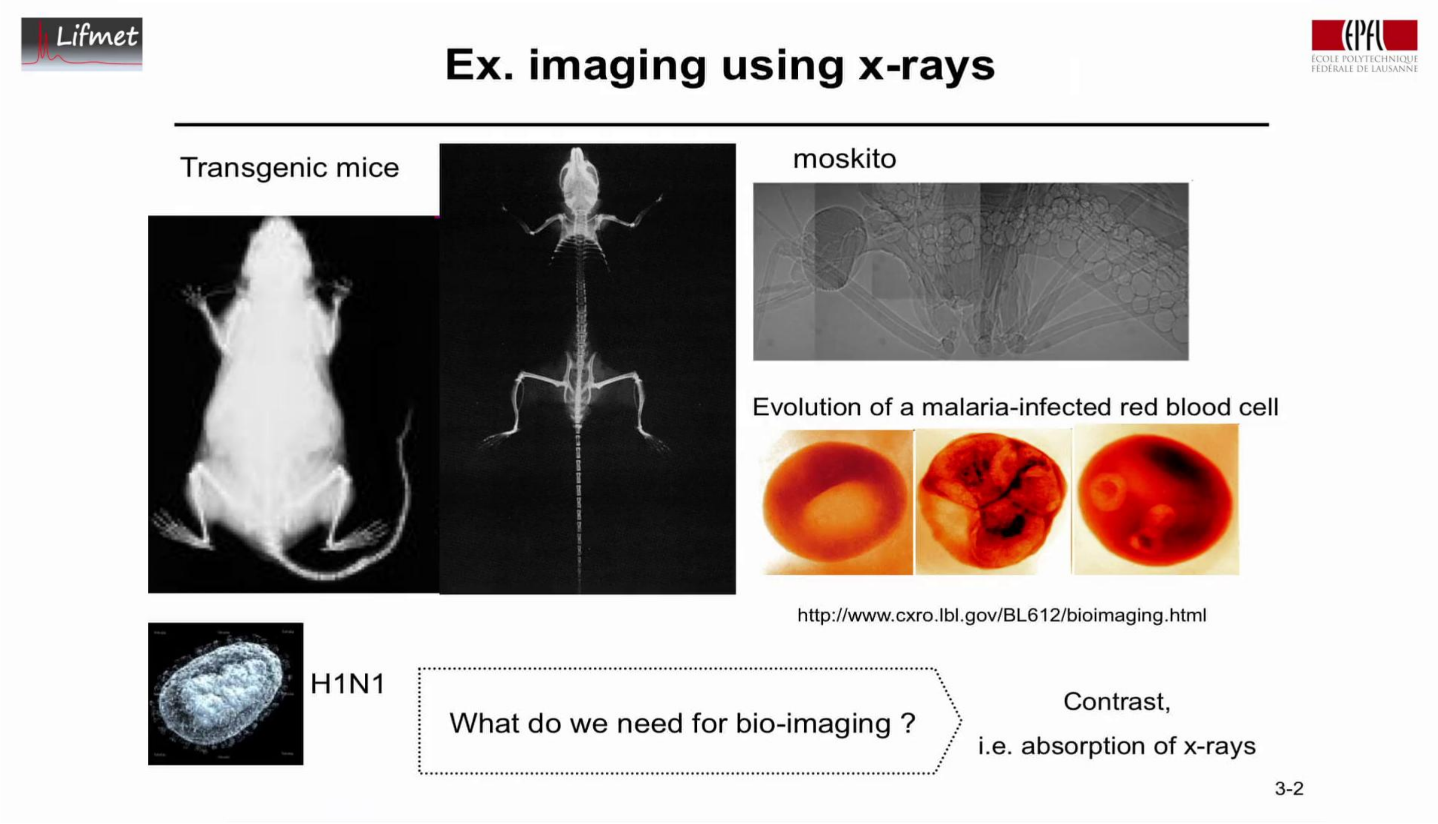


For today, I would like to start with a few examples to show you what kind of images one can obtain with x-ray imaging. Let's start with the first image, and this is a transgenic mouse; a fairly general x-ray image. We can see here absorption throughout the body and we can also discern the legs of the mouse. However, if one selects only the areas that have high absorbance of x-rays, then we can see a very nice, a very high resolution skeleton here of this transgenic mouse with the features. There's the tail, the legs, the rib cage, at very high resolution. Insects are also a good target for x-ray imaging; there's excellent contrast with the air, even though there's not much mass. Here you can see a mosquito. Here is the head, the antennas, and the legs. Now, mosquitoes transmit a disease, and that is malaria. And we have here the blood cell image with x-rays, color coded, pseudo color coded. A normal red blood cell as it goes through different stages of the transfection with malaria, with the malaria parasite. With x-rays, one can even go to cellular resolution. Here is the H1N1 virus. We see this is a single cell organism, we can see inside the structure, and we can see even at the surface, the surface antennas with which the virus propagates itself.

Notes

Summary

0m 04s

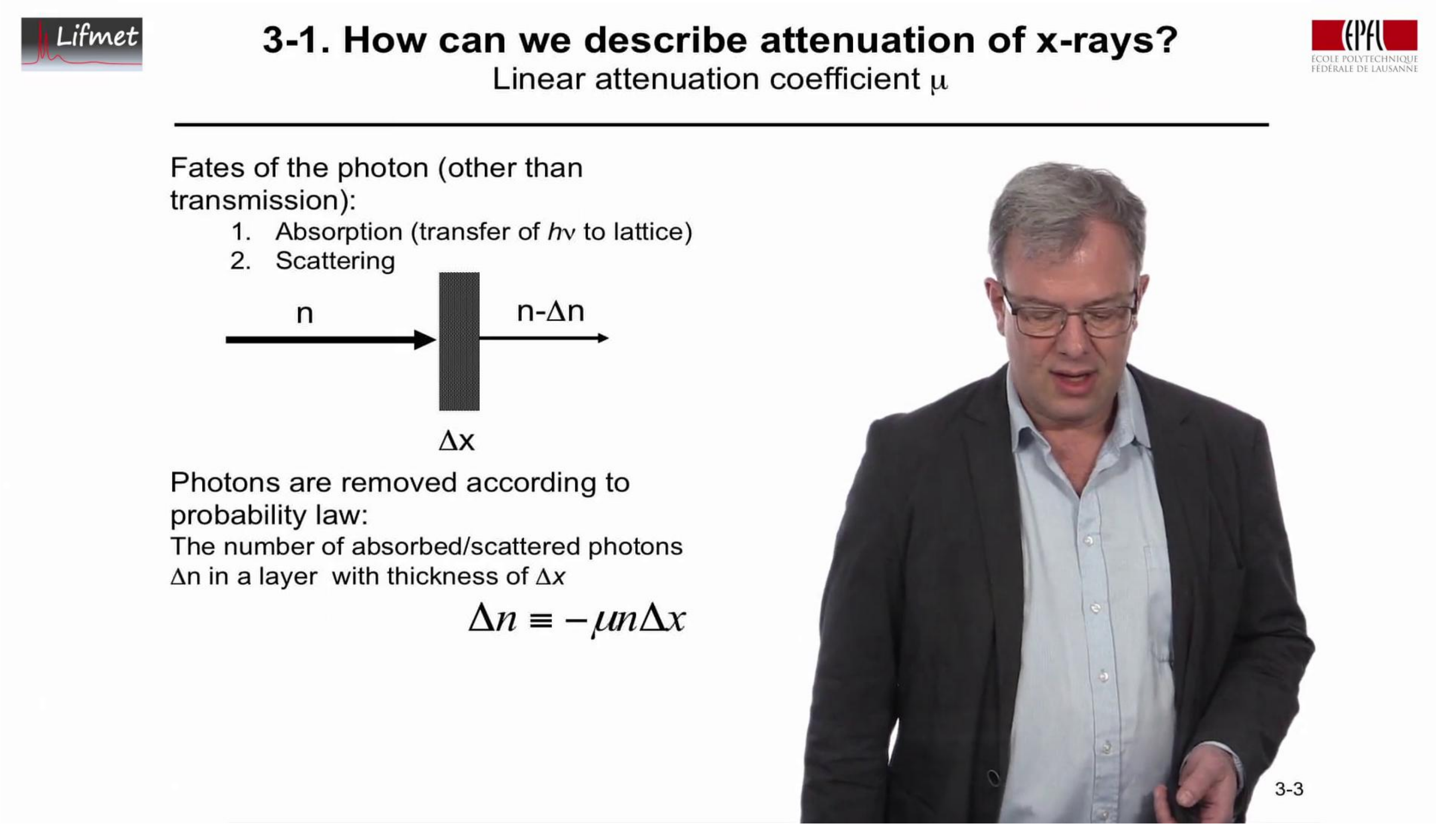


Now, what do we need for bio imaging? What is essential for bio imaging? Here, it is contrast. Now, how do we generate contrast with x-rays? Remember with x-rays-- we discussed last time the generation of x-rays-- we bombard our living being or object with x-rays. And so, what we need for generating contrast is absorption of x-rays. It's the absorption that generates the contrast. If we don't have absorption, we'll get the original intensity, and we will know nothing about our object. So clearly, absorption is key here, and this is the mechanism, the primary mechanism that produces contrast for x-ray imaging. And this will be the subject of today's lecture, of this week's lecture sets, what mechanisms produce absorption of [contrast] of x-rays.

Notes

Summary

1m 46s

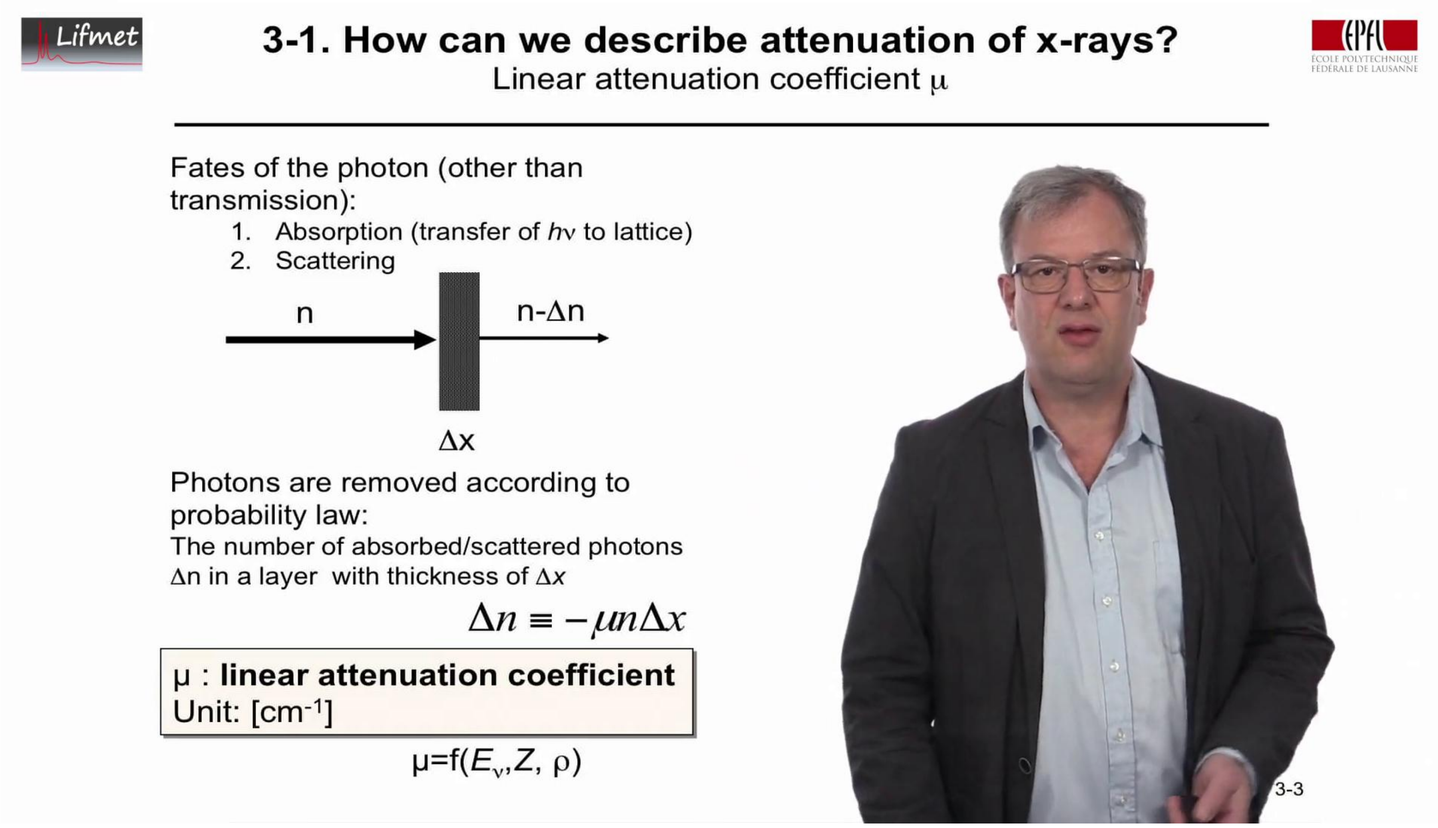


So how can we describe the attenuation of x-rays? We'll just go with an empirical demonstration here. Aside from that the photon might just pass through our object, what are other fates that the photon can have? It can be absorbed. It would transfer its energy to the lattice, to the tissue, or it can be scattered. And if it is scattered, by means that we will discuss next week, we will not be detecting a scattered photon. Let's take a situation here where we have a tissue layer of thickness Δx here, we have n photons incident. n can be for example a 1000, 10,000, some number here. They pass through this layer of tissue of thickness Δx, and after, we have n - Δn photons that continue the trajectory. Now, the photons are removed according to Probability Law. If we look at the number of photons that are being absorbed or scattered in a layer of thickness Δx, we'll call this number Δn. And this is given by this empirical law that the number of photons, Δn -- it's negative because they're being removed-- it's proportional to the number of incident photons, that's the Probability Law.

Notes

Summary

2m 47s



So, if you have a 1000 photons, we remove 10%, we have 100 photons removed, We have 10,000 photons, with 10% removal, we will have a 1000 photons removed. The probability that they're being removed is proportional to the thickness of the layer that also makes sense-- the probability that a photon is either absorbed or scattered would increase as the number of the thickness of the tissue increases. That's the *Δx* here in this expression. And then we have a proportionality constant, this *μ* here which is an empirical constant that reflects the makeup of the tissue. And this μ is called the linear attenuation coefficient. It has units 1 of a centimeter, at which they are typically displayed. And it's called the linear attenuation coefficient; linear is because of this equation here, that the probability law stipulates that the number of photons removed is proportional to number of incident photons and thickness of the tissue layer. Now in reality, and this will be the subject of today's lectures is that this linear attenuation coefficient is a function of the energy of the photon in μ. It's a function of the atomic number, *Z*, and it's a function of the electron density, *ρ*.

Notes

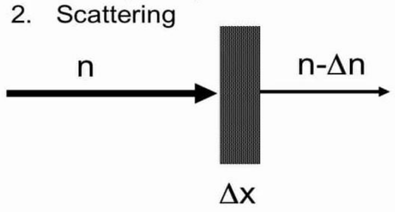
Summary

4m 16s

3-1. How can we describe attenuation of x-rays?
Linear attenuation coefficient μ

Fates of the photon (other than transmission):

1. Absorption (transfer of $h\nu$ to lattice)
2. Scattering



Photons are removed according to probability law:

The number of absorbed/scattered photons Δn in a layer with thickness of Δx

$$\Delta n \equiv -\mu n \Delta x$$

μ : linear attenuation coefficient
Unit: [cm^{-1}]

$\mu = f(E_\nu, Z, \rho)$

Consider situation where $\Delta x \rightarrow 0$, and n=f(x)

$$dn(x) = -\mu n(x) dx$$

$$\frac{dn(x)}{dx} = -\mu n(x)$$

Solution ?

$$\boxed{n(x) = N_0 e^{-\mu x}}$$

3-3

So now we will pretend that we take this situation here, and we'll pretend that this *Δx*, we can assume it's a centimeter, we'll let it go to very small values, that's a millimeter, then a micrometer, then a nanometer. It'll now make it very thin, so we'll mathematically we'll let *Δx* go to 0, and we'll have the number of photons that are being observed as a function of distance x, as they pass through the tissue. So if we do that, then we can replace the difference in photons. This equation here with infinitesimal equations. *Δn* will go to 0, so it will be *dn infinitesimal*, Δx will go to 0, so it will be replaced by the term *dx*, and we will obtain now the differential equation that the derivative of the number of photons as a function of position is equals to -*μ* times the number of photons at that position. That's a first order... that's a differential equation. We know the solution, the derivative of a function equals to the function times the constant, and the solution is therefore simply given by the exponent law. So, the number of photons after having passed through a tissue at position x, is equal to the incident photons and zero, that's the number of photons that arrived from the outside on our object, time *e* to the - *μ x*.

Notes

Summary

5m 40s

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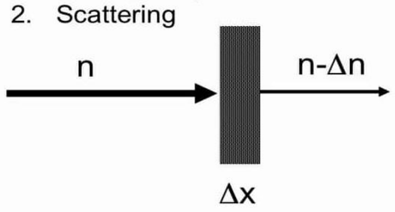

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$$\frac{dn(x)}{dx} = -\mu n(x)$$

Solution ?

$$\boxed{n(x) = N_0 e^{-\mu x}}$$

(provided μ is constant in x)

Definition

Half value layer (HVL) $\equiv$ The thickness of a material allowing to pass one half of photons:

$n(x_{HVL}) = N_0/2$

$$N_0/2 = N_0 e^{-\mu(\mathrm{HVL})}$$

$$\mathrm{HVL} = 0.693/\mu$$

3-3

In this solution, we have assumed that the linear attenuation coefficient is a function of position to get this simple solution. This is a simplification but this illustrates how we get from the linear law to an exponential law of photon density. Now, the linear attenuation coefficient, as I mentioned here, is given in 1 of a centimeters, and that's the unit that's not very intuitive. And so we use very often the half-value layer to describe the attenuation of a tissue. And the half-value layer is essentially defined as the thickness of material that passes one half of the photons. So at the number of photons at *x* equals to the half-value layer of thickness, x(HVL), is equal to the incident photons and zero divided by two. Half of the photons go through, and we can verify that by plugging this into the above equation. Here, we plug this in, this relationship here, we find this relationship and the solution of that is at the half value layer that is the x(HVL) layer here, is equals to *0.7 / μ*. This didn't still say much to it, but since μ is in one over centimetes, the unit of the half value layer is in centimeters and this much more intuitive to grasp the ability of a material to absorb x-rays or of a tissue.

Notes

Summary

7m 12s

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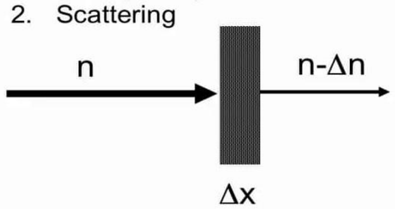

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$$\mathrm{HVL} = 0.693/\mu$$

Typical HVL values: several cm for tissues, 1-2 cm for aluminum, 0.3 cm for lead

3-3

What are typical half-value layers here? Are they given typically for tissues at several centimeters? It depends ont he x-ray that's being used. For aluminum, it's on the order of 1 to 2 centimeters, and 3 millimeters for lead, or 0.3 centimeters here.

Notes

Summary

8m 43s

What are typical attenuation coefficients ?

Material	Density (g/cm^3)	Electrons per Mass (e/g) $\times 10^{23}$	Electron Density (e/cm^3) $\times 10^{23}$	μ @ 50 keV (cm^{-1})
Hydrogen	0.000084	5.97	0.0005	0.000028
Water vapor	0.000598	3.34	0.002	0.000128
Air	0.00129	3.006	0.0038	0.000290
Fat	0.91	3.34	3.04	0.193
Ice	0.917	3.34	3.06	0.196
Water	1	3.34	3.34	0.214
Compact bone	1.85	3.192	5.91	0.573

μ/ρ (water) = μ/ρ (ice)

3-4

So let's look at the question, "What are typical attenuation coefficients?" So we'll look at the linear attenuation coefficient for different materials; hydrogen, water vapor, we have air, fat, ice water, and compact bone. Here's the density of the tissue given in *g / cm*. Here's the density of the electrons given, the electrons per mass, and then we have the electron density per volume--is given here, and this is the linear attenuation coefficient. And we can see a close correspondence between the linear attenuation coefficient and the density of the electrons in the tissue. I think that's remarkable. If we look at the density of water and the linear attenuation coefficient, we divide the linear attenuation coefficent by the density of water, be it ice or in liquid form, then we find that this is the same. There's a 10% difference in the linear attenuation coefficent in water and ice, and there is a 10% difference in density between ice and water. This means that for water, whether it's in liquid or in solid form, once we normal per mass, then we get the same constant, so we get a universal constant for that particular compound.

Notes

Summary

9m 03s

What are typical attenuation coefficients ?

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μ/ρ (water) = μ/ρ (ice)

Definition

Mass attenuation coefficient μ/ρ

Unit : [cm^2/g]

(constant for all forms of the same chemical substance, e.g. water)

Why do we need more sunscreen in the mountains ?

3-4

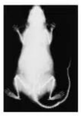
And therefore it is useful to define the mass attenuation coefficient which is μ / ρ, it has the unit of cm^2/g, and this would then give us a value that is constant for all forms of the kind of substance, in this case, for example water. So the mass attenuation coefficient is defined as the linear attenuation coefficient divided by the density of the compound. And this also an explanation why we need more sunscreen in the mountains. If we go up in the mountains, the air is thinner. Because it is thinner, it has a lower linear attenuation coefficient, it is still the same air. So the mass attenuation coefficient would be the same, or given that the density is lower, up in the mountains we have more-- less attenuation by the air. Of course, we're also higher up so the ultraviolet from the sun that arrives still has some distance to travel.

Notes

Summary

10m 25s

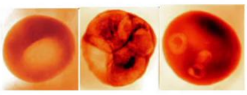
Credits



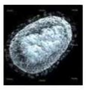
Mouse x-ray
http://veterinaryscienceclub.weebly.com/about-our-club.html

Mouse Skeletons (Creative Commons)
http://skeletonpictures.org/p/76/mouse-skeletons/picture-76

Moskito
Unidentifiable source (internet)



C. Magowan, W. Meyer-Ilse and J.Brown, LBNL
http://www.cxro.lbl.gov/BL612/bioimaging.html



Dr. Ricardo Musto
http://galenoenlinea.blogspot.ch/p/temas-de-medicina-general.html

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“The Essential Physics of Medical Imaging”
Table 3-1, from Jerrold T. Bushberg, J. Anthony Seibert, Edwin M. Leidholt, John M. Boone

Notes

Summary

11m 30s