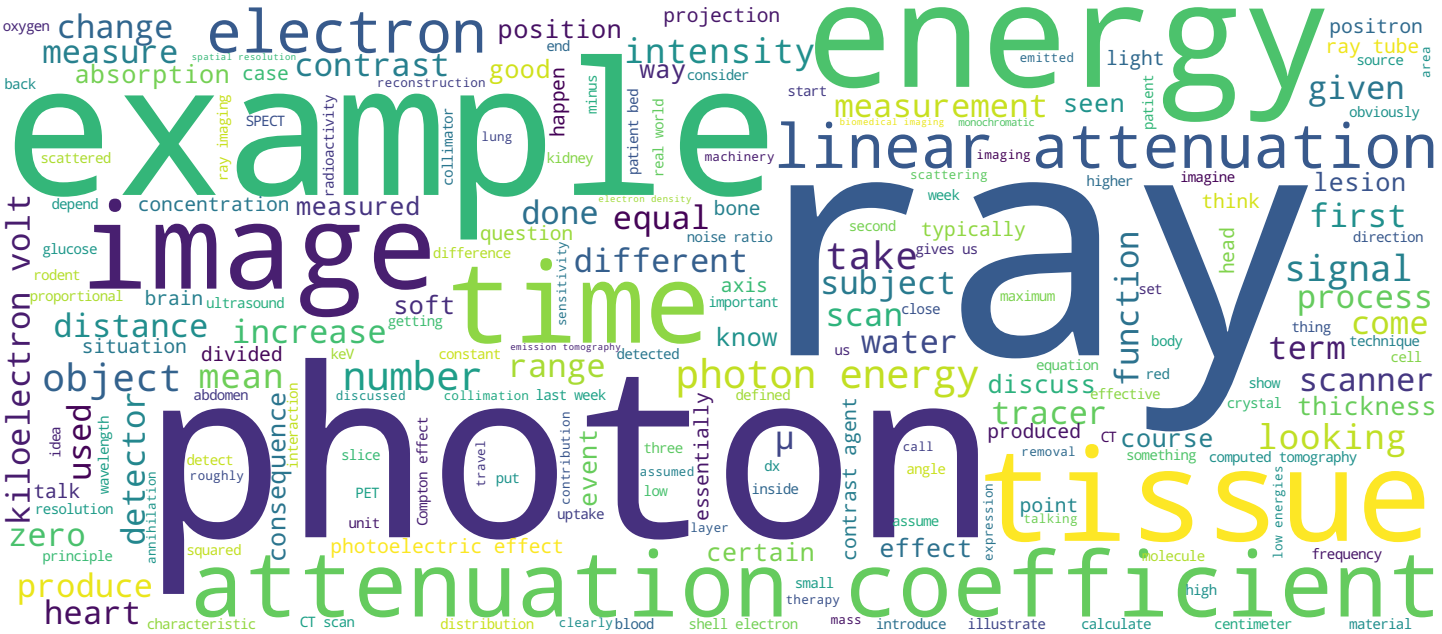
4.1 Absorption & x-ray spectrum

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter

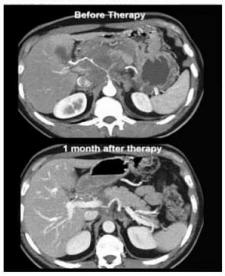


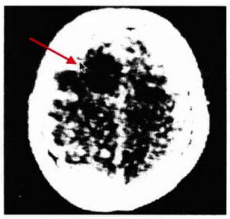
Search MOOC

Video

Computed Tomography
invented 1971

Primitive pancreatic lesion
(neoplastic)





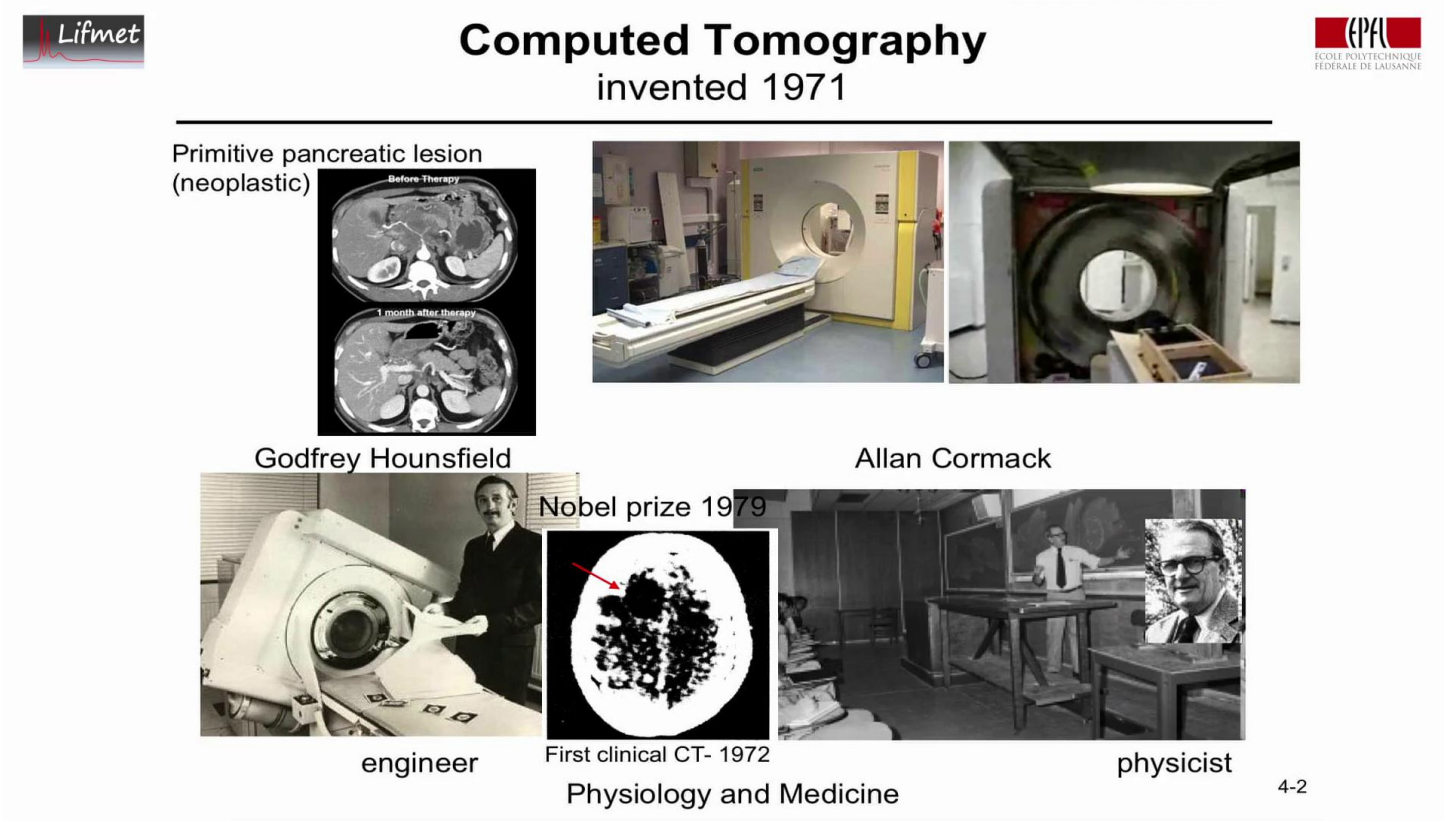
First clinical CT- 1972

Last week, we talked about how x-rays-- the mechanism by which the x-rays are being absorbed in the tissue when we have established that absorption of x-rays is the major contrast in x-ray imaging. So, this week, we're going to talk about how we generate images from this absorption data in the real world. We'll first talk about some complications that arise in the real world, and then we'll talk about the reconstruction algorithm that is needed in the second half of this week's lectures. But first, I'd want to start out with the underlying technique, showing some examples-- this is computed tomography that we're talking about. It was invented in the early '70s. And what we're looking at here is an example of the use of computed tomography-- we have a CT scan here of the abdomen. We see a lesion here, before therapy and after therapy-- how the lesion has disappeared. Now, here's an example of a CT-- early one, 1972-- and you can appreciate the difference in quality of the images compared to contemporary CT with this early one. One has to really put an arrow to highlight the lesion here-- this is a cranial CT, that of a head, and the lesion-- it's really not apparent what generated that lesion.

Notes

Summary

0m 04s

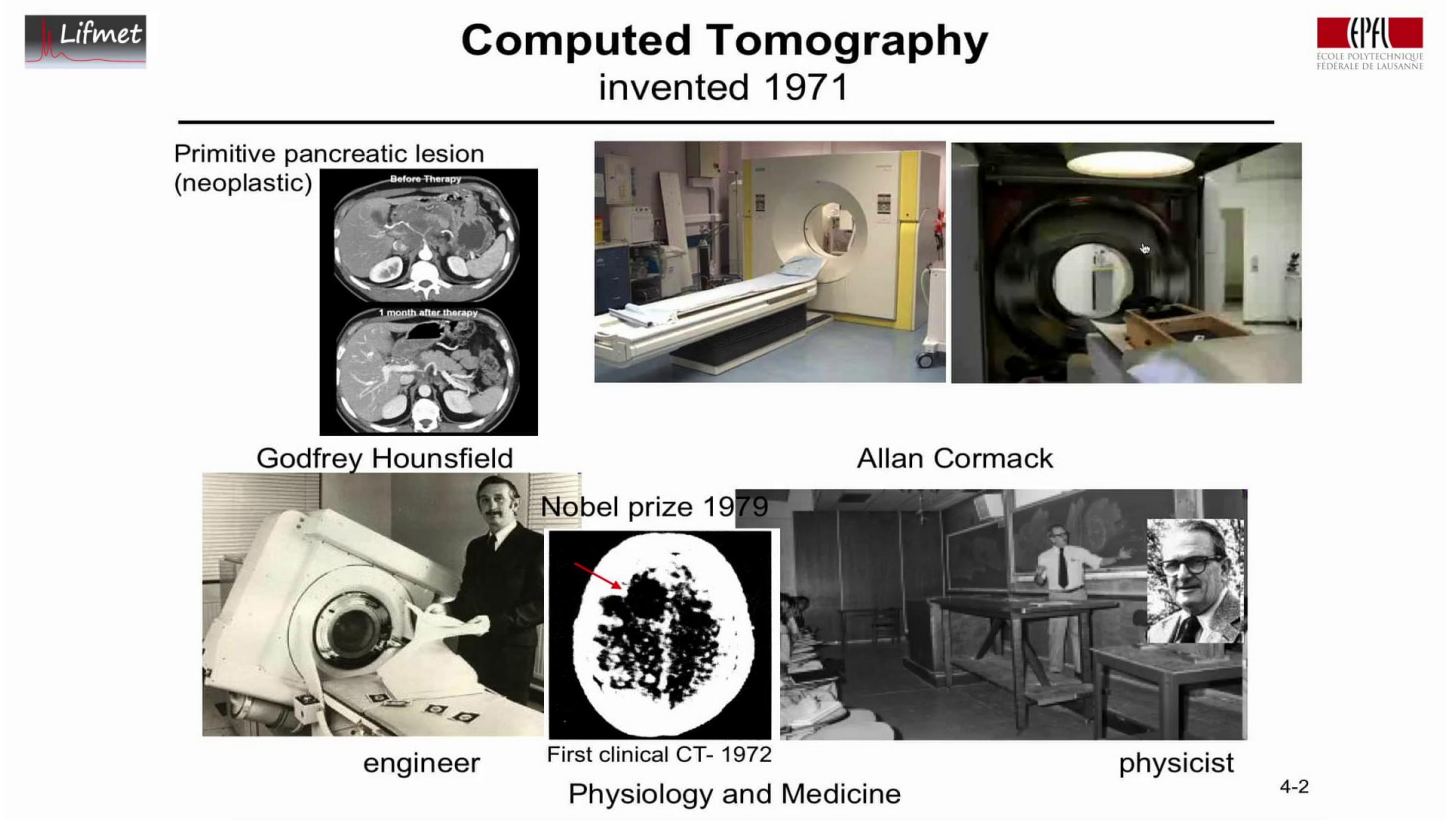


CT was developed by Godfrey Hounsfield-- he developed the mathematical algorithm, an engineer, and Allan Cormack, a physicist, he is shown here-- and they received the Nobel Prize for physiology and medicine. This is what a CT scanner looks like-- I wanted to show it to you so that we have an idea what we are talking about. This is the scanner-- is in this enclosure, here-- this is the patient bed-- you would lie on this patient bed, it would be lifted, and then entered into this hole here where the scanning is taking place. Here would be the head, the head would be inserted in here. And of course, we don't want to show to the patients all the technical insides, so, there's a nice cover covering up the machinery that's behind it. And now, we're looking here in this video-- we're looking actually at what's in the machinery. As you can see, there's something turning inside-- what we're looking at here is the inside-- that is this cover here is lifted, you see the cover is up here, and now you see this turning, and quite an amazing noise as the machinery, the scanner is being turned for producing the scan.

Notes

Summary

1m 31s



So, this is obviously what we don't want the patient neither to hear nor to see-- this would be intimidating and people would have much more trouble complying with the requirements of the scan. In the lectures of this week, we will discuss the reason behind why this machine is turning, how this is used for generating images.

Notes

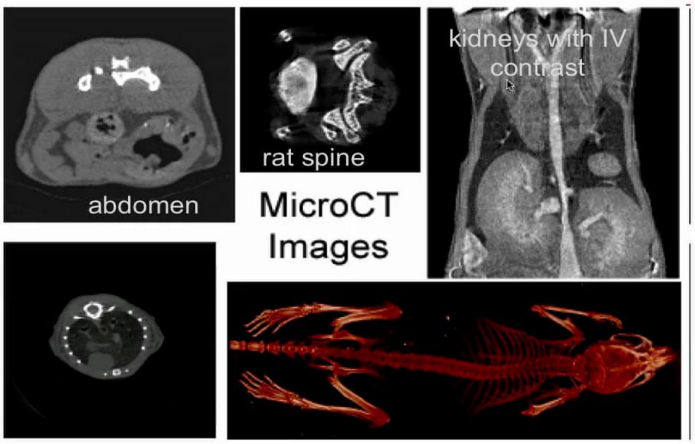
Summary

2m 49s

CT of animal models

transgenic mice and cancer models

micro-CT scanner



microCT (~50 µm spatial resolution)

4-3

CT is not only used for human patients. It's also used in research for animal models. Here, I wanted to give you some examples. We'll first talk about the scanner itself. You can see this is how the scan-- here's the enclosure of the scanner. Here's the person, here's the opening-- this volunteer, here, would be on the patient bed, here, and inserted into the scanner. Clearly, the opening here is not adequate for the subject--for the rodent-- so the scanner has been adapted for the smaller geometry-- we're taking advantage of having a closer proximity of the detectors to the subject. Now, here are some MicroCT examples, some images. And MicroCT means really, CT with high spatial resolution-- we're talking, typically, here, of 50 microns spatial resolution-- in-plane resolution. The first image is of the abdomen. We can see here the abdomen, we see some lesions here, we have the heart here, and some other organs. This is a MicroCT of the rat's spine. We see the spinal cord here, and the disks surrounding it. This is an example of kidneys with IV contrast. We have the CT scan, and then we can see the vessels very bright-- they have contrast agents in them-- that's what we have discussed last week.

Notes

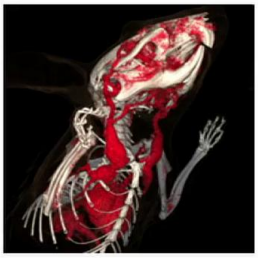
Summary

3m 11s

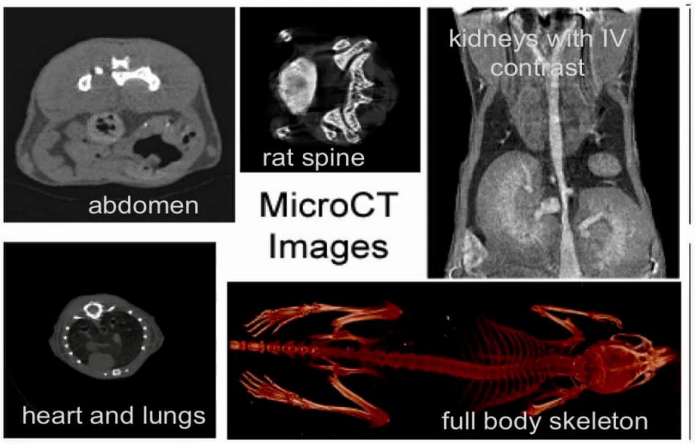
CT of animal models

transgenic mice and cancer models

micro-CT scanner



Mouse: blood vessels (red)



microCT (~50 µm spatial resolution)

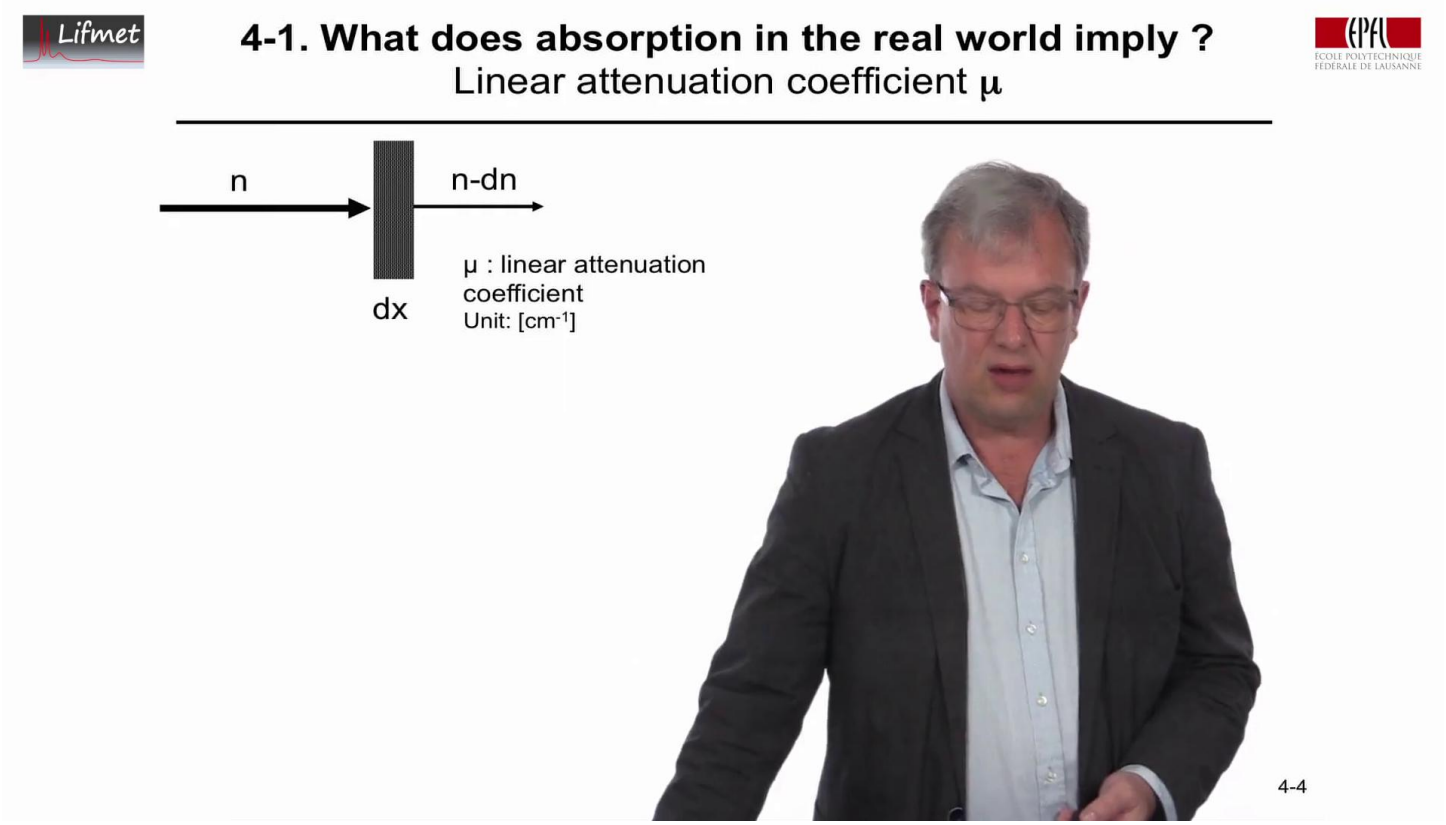
4-3

We can see the contrast enhances the kidneys. So, this is intravenous contrast that highlights the blood flow in the kidneys. This example, here, is of the heart and lungs. We have the lungs here in dark, obviously, they have low CT numbers. We have the heart here, here's the spine, and these white dots-- can you guess what they are? They are the rib cage of this rodent. And if we select the display to select the highest absorption, we are obviously going to look for high electron density, that is, for calcium. This is the bone--and so this is a very nice, high resolution image of the full body skeleton of a rodent in this example. The use of intravenous contrast agents can be used to depict blood vessels. The change in contrast can be extracted from the images. It's color coded in this image in red, so we see the vasculature. And this is superimposed on a image that's been thresholded for the skeleton. So, we see the skeleton of the animal and the vasculature where the contrast agent has been going into. So, this is a way to illustrate the architecture of the blood vessels in the animal, superimposed on normal anatomy, so we can recognize where they are.

Notes

Summary

4m 42s

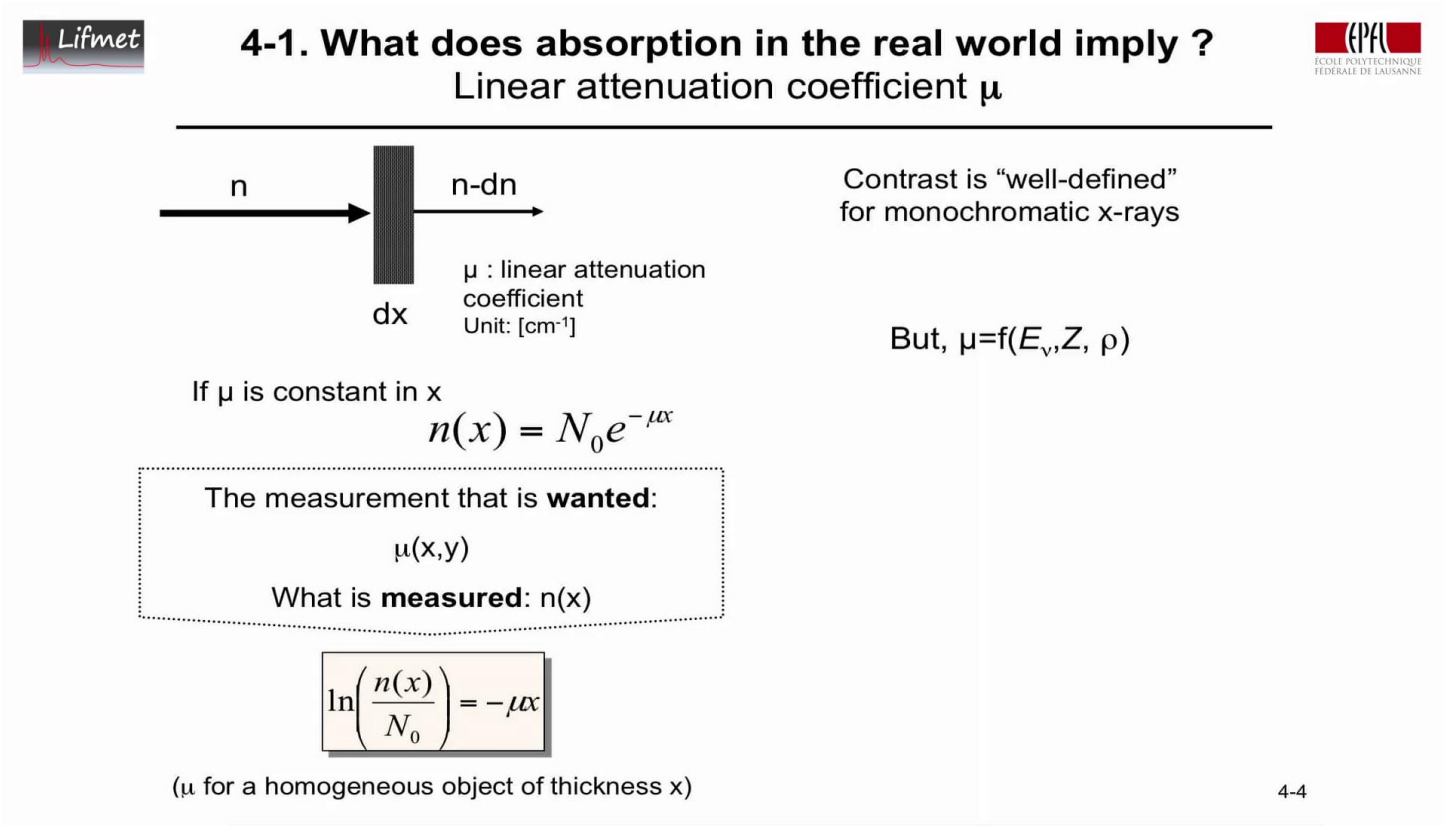


Before we go to the reconstruction of the images, I want to discuss what the absorption that we've discussed last week-- what that means in the real world. We're going to mainly be talking about the linear attenuation coefficient μ, here. Let's go back. And we'll assume here, we have a tissue of thickness dx-- this is a very small thickness-- you can imagine it's a micron, nanometer, something like that. Just very, very small. We then have a number of photons, n, that come to this slice, and then we have a number of photons n - dn, that pass through the slice. So, dn photons here, in this example, are being absorbed by this tissue layer of thickness dx. We've had talked last week about the linear attenuation coefficient, which has units of one over centimeter. And if we assumed that over the thickness of dx, here, which is a good and fair assumption, we have seen that the number of photons at the position x is given by the number of photons impacting the layer N_0 times e to the - μ x.

Notes

Summary

6m 05s

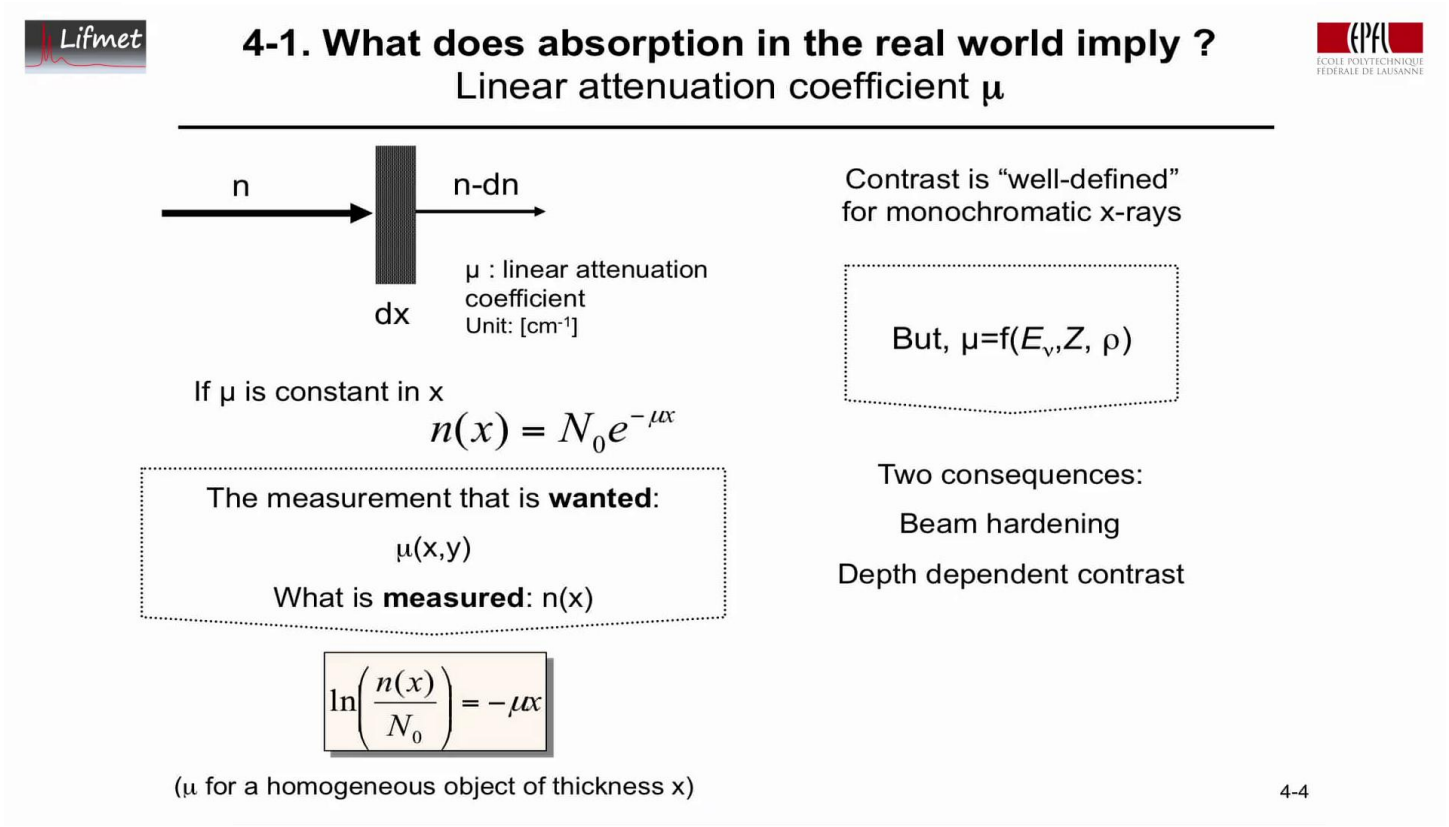


Now, if *dx* is very small, we can always assume that μ is constant in *x*. The measurements so that we want-- for which we want to reconstruct, is a two-dimensional image of the linear attenuation coefficient, so I'll write it here as the function μ of *x* and *y*. But what is actually measured is the number of photons that arrive in the detector. So, how is the link between those two measurements-- let's look at that. Well, it's actually a simple logarithm-- so the logarithm of the measured photons divided by the photons impacting the layer that is equal to - μ *x*. And since we know *x*, we can, in this simple example, we can infer the linear attenuation coefficient. This, here, is the example, for a homogeneous object with thickness *x*, here. So, we have assumed here that this is *x*, for this example. Now, contrast is well defined for monochromatic x-rays. We have the linear attenuation coefficient for a certain photon energy in kiloelectron volts-- that is a well defined parameter-- and so, we get a very well defined contrast. But, we have seen that the linear attenuation coefficient depends on the photon energy, it depends on the atomic number, and it depends on the electron density.

Notes

Summary

7m 17s



This has some consequences in real life. And one of the consequences is beam hardening, and the other one is depth dependent contrast. And this you can imagine in the following way. When the photons arrive at the tissue, they have a certain spectrum of energy, and this spectrum of energy has different absorption, so, the linear attenuation coefficient depends on the energy of the photon in μ. And so, we have a higher absorption, typically, at the lower energies-- so that means that the [inaudible] being removed and the energy of the photons that pass deeper into tissue, the average energy, increases, and that's what's called beam hardening. And that is because the μ is dependent on the photon energy, we are getting a depth dependent contrast.

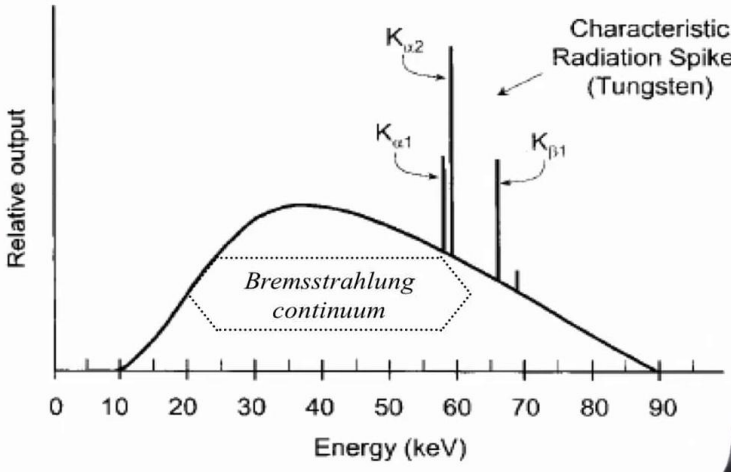
Notes

Summary

8m 43s

What does the Energy Spectrum of an x-ray tube really look like ?

filtered Bremsstrahlung and characteristic emission



So, let's look at this in the real world. And we will first focus on the energy spectrum of an x-ray tube-- what this really looks like. So, this is the relative output on the *y* axis-- on the *x* axis, we have the photon energy in kiloelectron volts, and we have the distribution of the density of the photons for a given energy window plotted here. What we have first, is the bremsstrahlung continuum. Remember, we had talked two weeks ago how x-rays are being generated-- they are generated, primarily, by bremsstrahlung, and we cannot predict exactly what the energy-- the precise energy is, so, there is a continuum-- a distribution of photon energies that are given. We have also characteristic x-rays-- that is, when we remove an inner shell electron-- so called radiation spikes, or characteristic x-rays, or fluorescent x-rays-- and this is the interaction with orbital electrons-- and here we have the K_α_1, α_2, and the K_β lines, here, for tungsten.

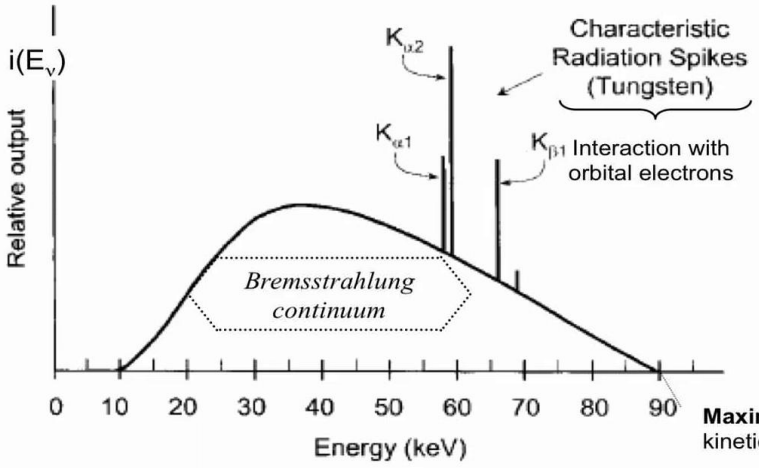
Notes

Summary

9m 39s

What does the Energy Spectrum of an x-ray tube really look like ?

filtered Bremsstrahlung and characteristic emission



$$I_0 = \int_0^{\infty} i(E_v)dE_v$$

i(E$_v$): complex function

Maximal x-ray energy is = kinetic energy of e$^-$ (eV$_{cathode}$)

4-5

What we do know, there is one fundamental constant that is fixed, and that is the maximum photon energy-- this photon energy, here, in this example, is 90 kiloelectron volts-- it is given by the voltage applied on the x-ray tube across the anode and cathode, in this case, it was 90 kiloelectron volts-- so, this is a fundamental limit-- it is defined by the operator, we can set it in the scanner, but this is the maximum that we have. We cannot have a photon energy that's higher than that. Comes simply from the fact that this photon energy is, when an electron impacts the anode target, loses all its energy at once into a single photon. So, what we have is the total intensity-- that is total number of photons that are being produced-- is the integral of this function, here, from zero to infinity, of the relative output, here, that's the intensity as a function of the energy integrated over the energy. This is a complex function-- we don't really have a good mathematical or physical model to model it, so what we are looking at is to characterize it in a simpler way. And the way this is done is to define a effective photon energy-- E effective.

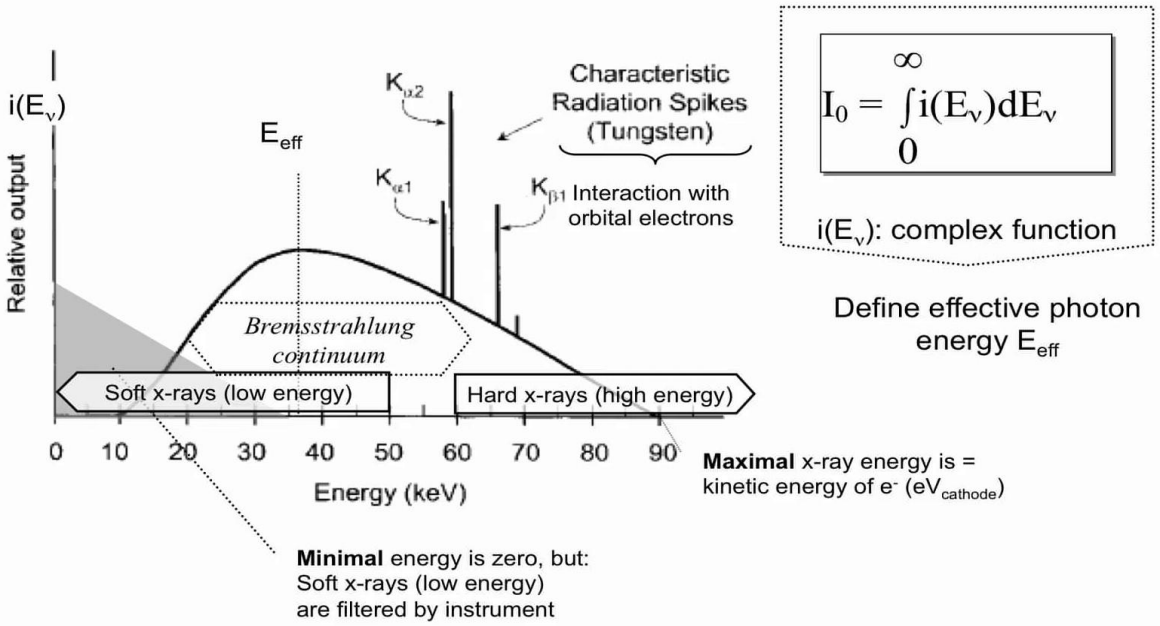
Notes

Summary

10m 50s

What does the Energy Spectrum of an x-ray tube really look like ?

filtered Bremsstrahlung and characteristic emission



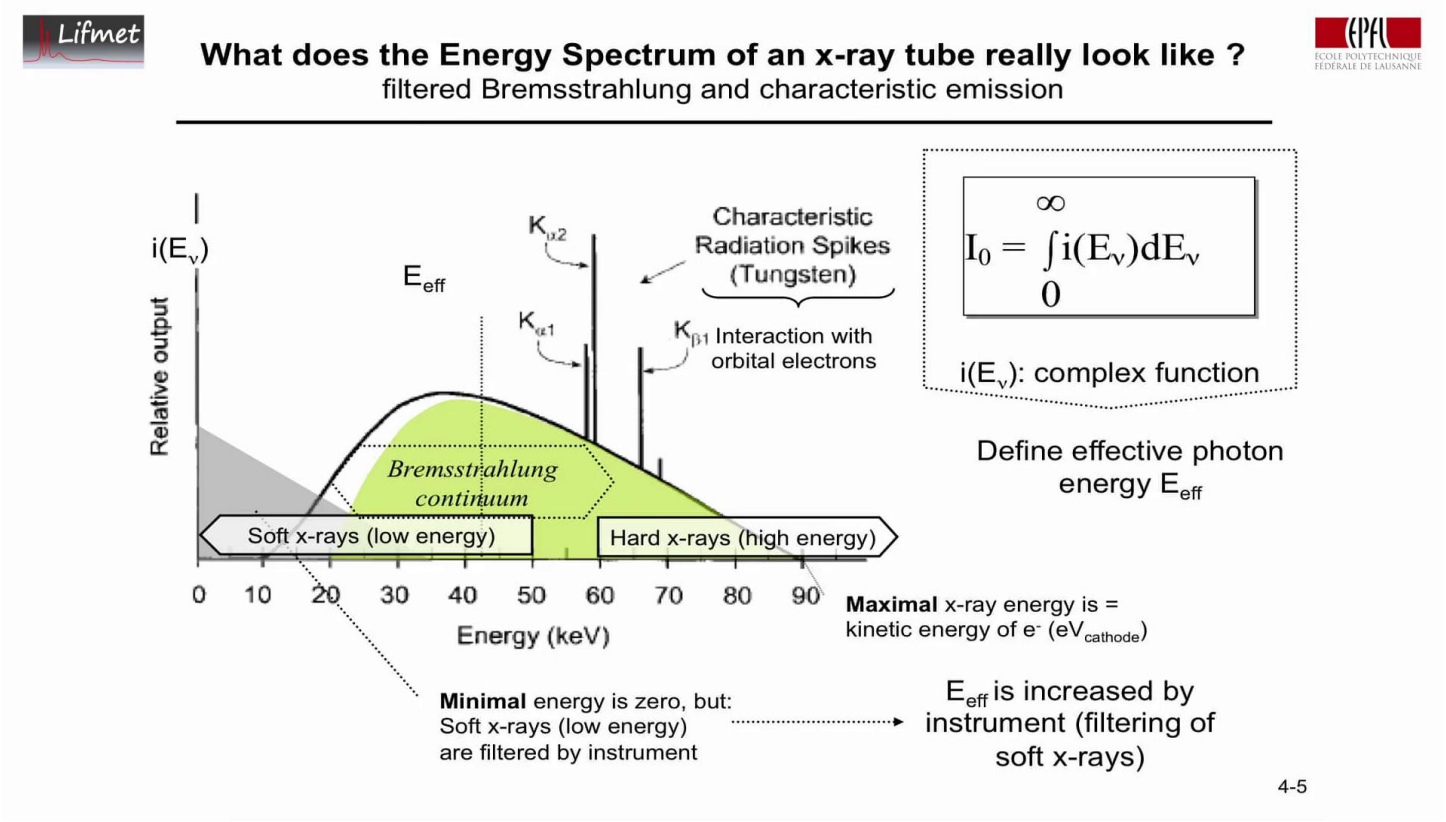
4-5

It kind of corresponds to the medium or median energy of the photons that are seen by the subject. So, the effective energy, in this example, would possibly be something like this, from the x-rays that are leaving the x-ray tube. Now, here's a term that I need to introduce-- that I'd like to introduce, that is the term of soft x-rays. They are soft, because they have low energy. They are called soft, because they don't penetrate very deep into the tissue. And, in contrast, we have the hard x-rays-- they are high energy, they are more penetrating, that's why they are called hard x-rays. Now, if we think about the process of bremsstrahlung, the minimal energy of a photon that is produced is close to zero. So, in theory, it's possible to produce very soft x-rays within x-ray tubes. But that's not what we see here in this graph. We see the energy drop off here to zero at around 10 keV. What we do have is a filtering of the instrument-- remember, the x-rays are produced in vacuum-- in an x-ray tube-- we have a glass there where the x-rays are being allowed to pass towards the subject. And that glass filters the very soft x-rays, and nothing goes through.

Notes

Summary

12m 12s



So, we're having this instrument filtering, here, from the glass, for example, that removes photons-- and one consequence of that is that the effective energy is actually shifted to higher energies. So, the overall x-ray spectrum, or the x-rays that impact the patient are becoming harder. So, this increase in effective energy is filtering of soft x-rays is done by the instrument, and this removal will lead to an x-ray spectrum that's shifted to higher energies, and therefore, harder x-rays.

Notes

Summary

13m 35s

What is the consequence of energy-dependent absorption ?

Beam Hardening - Effective energy depends on depth

A similar consequence arises in tissue:

Ideal:

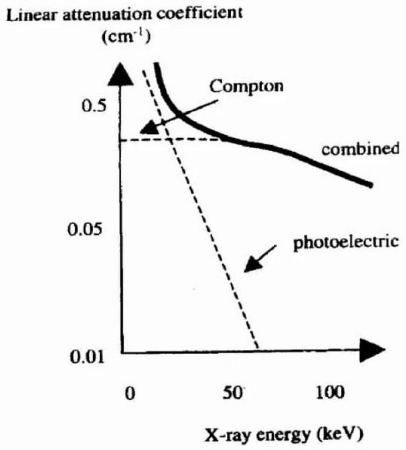
Monochromatic x-rays
($E_v(\lambda) = \delta(\lambda_0)$)

Reality:

Polychromatic, multienergetic i(E_v)

Absorption is not uniform with E_v

- Contrast changes with large objects and depth
- Excessive radiation dose to superficial tissue



4-6

So, what is the consequence of energy dependent absorption? So, we have a similar consequence to what we just discussed with the instrument in the tissue. Let's look at the linear attenuation coefficient, here. We have the x-ray energy from zero to a hundred kiloelectron volts on the x-axis. And we have a logarithmic scale of the linear attenuation coefficient on the y-axis. In the ranges that we are concerned for x-ray imaging, for CT imaging, we're dealing only with a photoelectric effect and the Compton effect. Now, as we can see, at low energies, we have a stronger dominance of the photoelectric effect-- so the linear attenuation coefficient increases quite substantially at low energies. Now, what does this mean for the real world? Let's look what we would have, ideally-- ideally, we would have monochromatic x-rays. The monochromatic x-rays-- we would be at this position-- we would have a uniform absorption of the x-ray; the photon energy does not change. But in reality, we have polychromatic multi-energetic x-rays. So, the consequence is that we have-- the absorption is not uniform-- with photon energy. Here, clearly, the linear attenuation coefficient is not uniform, so it changes.

Notes

Summary

14m 17s

What is the consequence of energy-dependent absorption ?

Beam Hardening - Effective energy depends on depth

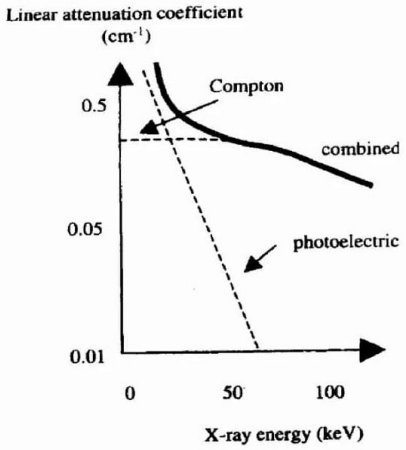
A similar consequence arises in tissue:

Ideal:

Monochromatic x-rays
($E_v(\lambda) = \delta(\lambda_0)$)

Reality:

Polychromatic, multienergetic i(E_v)



Absorption is not uniform with E_v

- Contrast changes with large objects and depth
- Excessive radiation dose to superficial tissue

"Solution": Reduce i(E_v) for soft x-rays

(e.g. 3mm Al eliminates 90% of 20keV photons)

4-6

The contrast, therefore, changes with large objects and with depth. Another consequence is we have excessive radiation dose to superficial tissue. So, let's talk about first consequence: contrast changes with large objects. We have, as the x-rays impact-- let's say we have a distribution of x-ray energies over this range-- we have, first, a removal of the intensity at the low photon energy-- so, we have a contribution of the photoelectric effect to the contrast mechanism. As the x-ray beam traverses the tissue, these photons are preferentially removed, and so we have an increase in contribution of Compton effect to the absorption of x-rays. So, we have a shift from photoelectric effect to Compton effect. Obviously, if you imagine that this is skin here, then we are looking, here, at a removal of the photons, primarily in the superficial tissues, skin, fat, and so on, and therefore, a higher radiation dose to these tissues. How can we mitigate this effect? So, the solution is actually to reduce the photon intensity for soft x-rays, that is, for low energies, in this range here-- we'd like to have not too much energy here, and this can be, for example, done with inserting a 3 millimeter aluminum plate, which eliminates 90% of the 20 keV photons.

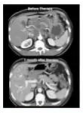
Notes

Summary

15m 46s

Credits


Creative Commons Pictures
https://fr.wikipedia.org/wiki/Allan_McLeod_Cormack
https://en.wikipedia.org/wiki/Preclinical_imaging

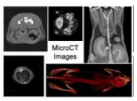


Michele Anzidei, M.D., Univeristy of Rome "La Sapienza"
http://www.radrounds.com/photo/fibrous-dysplasia-head-ct/next?context=user

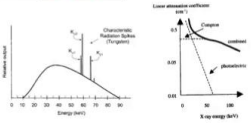
North Seattle University
http://facweb.northseattle.edu/mallen/AMA100+PPTMP3/AHM%20244%20PowerPoint.ppt

Computed tomography (CT) - scanner with open gantry
https://youtu.be/qUk8__QV_c4


The Telegraph, London



Samsung Medical Center Instrumentation for Small Animal Molecular Imaging



"The Essential Physics of Medical Imaging"
Fig. 5-5, from Jerrold T. Bushberg, J. Anthony Seibert, Edwin M. Leidholt, John M. Boone

Notes

Summary

17m 20s