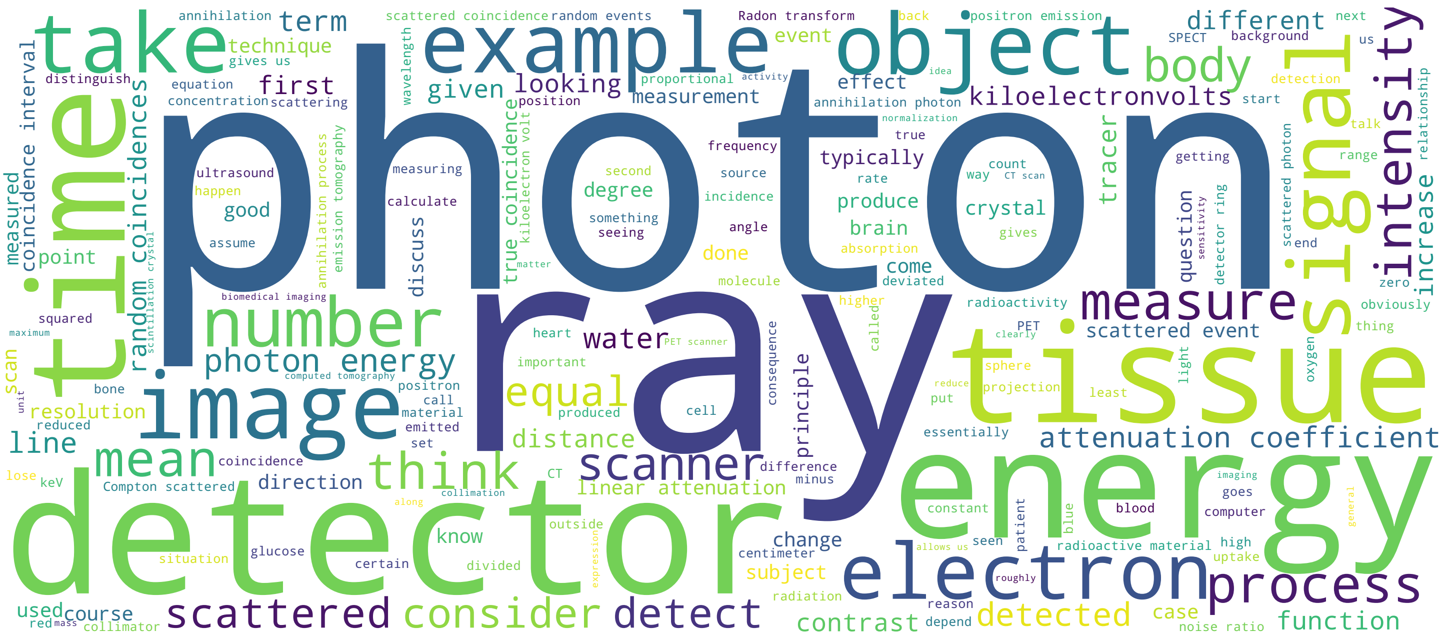
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

6.2 Types of coincidences measured with PET

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



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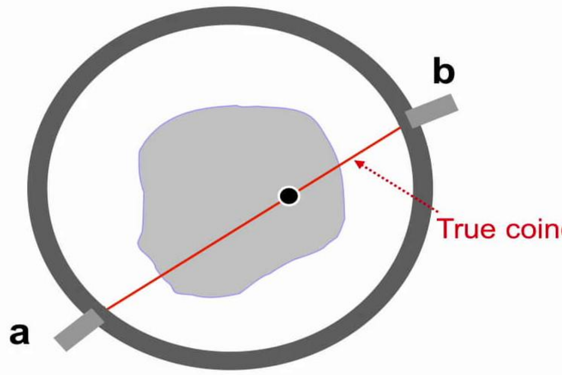
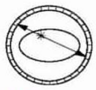
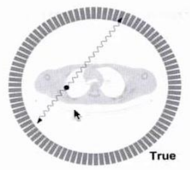
6-2. What is really measured with PET ?







6-8

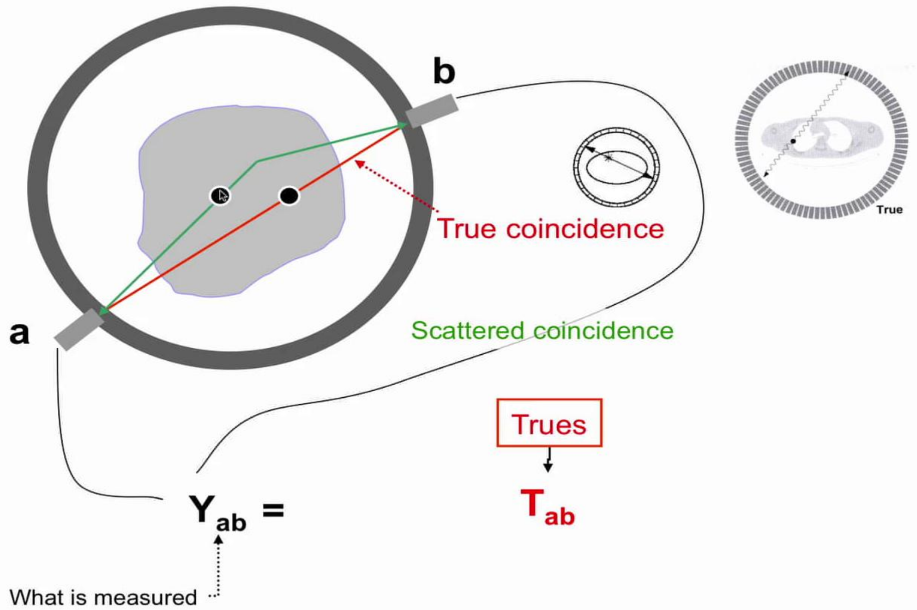
In this section we'll discuss the measurements that are being done by PET. I first want to start by looking at the detection process in general, so we'll have an object here. This almost looks like a face here. It's just an object. You could think of this as the nose. We'll put here on the detector ring, we'll have a *detector a* and a *detector b* here. These are just two arbitrary detectors that I've chosen out of the whole ring. The rest, I haven't drawn here, so we have detector *a* and detector *b* Now, we have an annihilation of a positron and an electron that is indicated here at this location and now we'll look at the true coincidence. True coincidence is we have the two photons that are being sent off in opposite directions and detected simultaneously in detector *a* and *b*. Here's the schematic presentation with the scheme, an oval. Here's the process, the annihilation. These are the two photons going in each direction, and these two crystals will detect the X-ray, or if you prefer, with an image of an object, of a subject in here, the heart, the lung. We have here the annihilation process for the "trues". We have the X-rays going in opposite directions.

Notes

Summary

0m 04s

6-2. What is really measured with PET ?



6-8

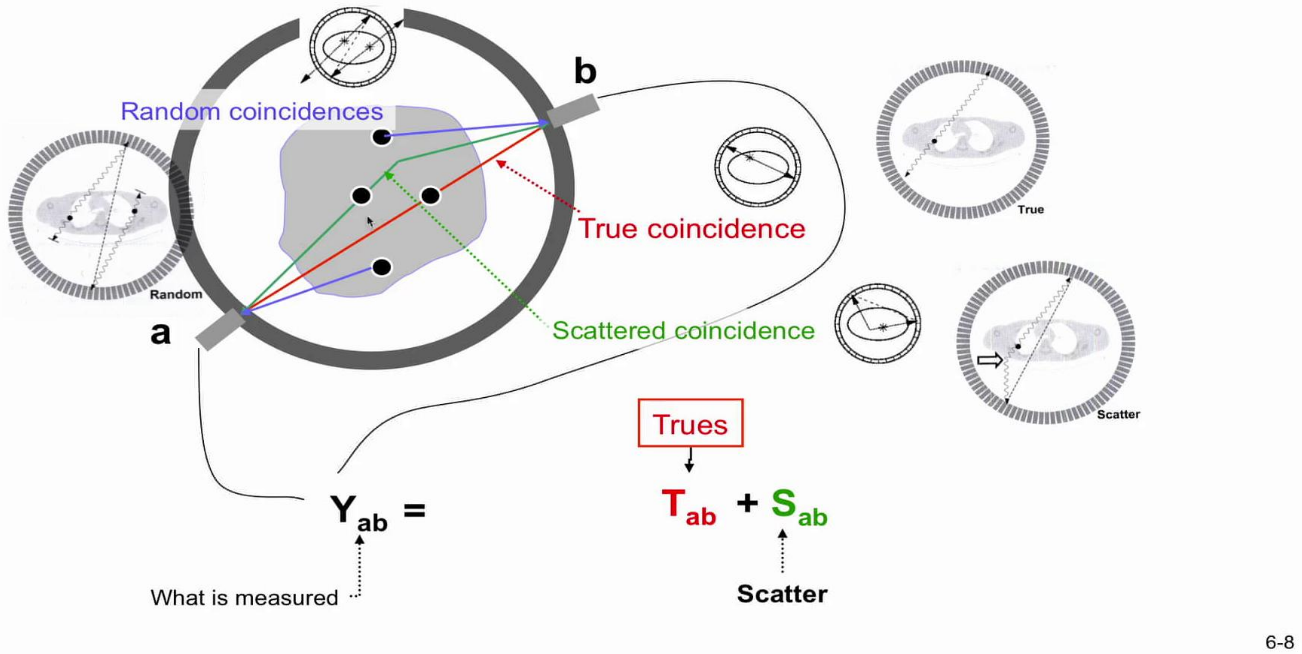
This is what we've outlined. This is the process of what we want to measure, so we have a certain number of true counts, that is, simultaneous events that we measure. We'll call this the "trues": Big *T* for "true coincidence" and AB, true coincidence between detector *a* and detector *b*. What we are actually measuring out of detector pair *a* and *b* is the mesurement *Yab* Again, *a* and *b* designate the two detectors *a* and *b*. Here, their position is not really important, but we have them here so this is what is measured. If you look at what is now shown here, we have a lot of empty spaces around the *trues*. In an ideal world, this would be equal to this, but there are quite a few things to consider. The next what we consider is a scattered coincidence. What we mean by scattered coincidence is we have an annihilation process. Now it's here, and at least one of the photons is being Compton scattered in the tissue so it's being deviated by a certain angle, and in this case the electron-positron emission annihilation happens here, but the scattering of this photon here is such that it arrives still in detector *b*.

Notes

Summary

1m 27s

6-2. What is really measured with PET ?



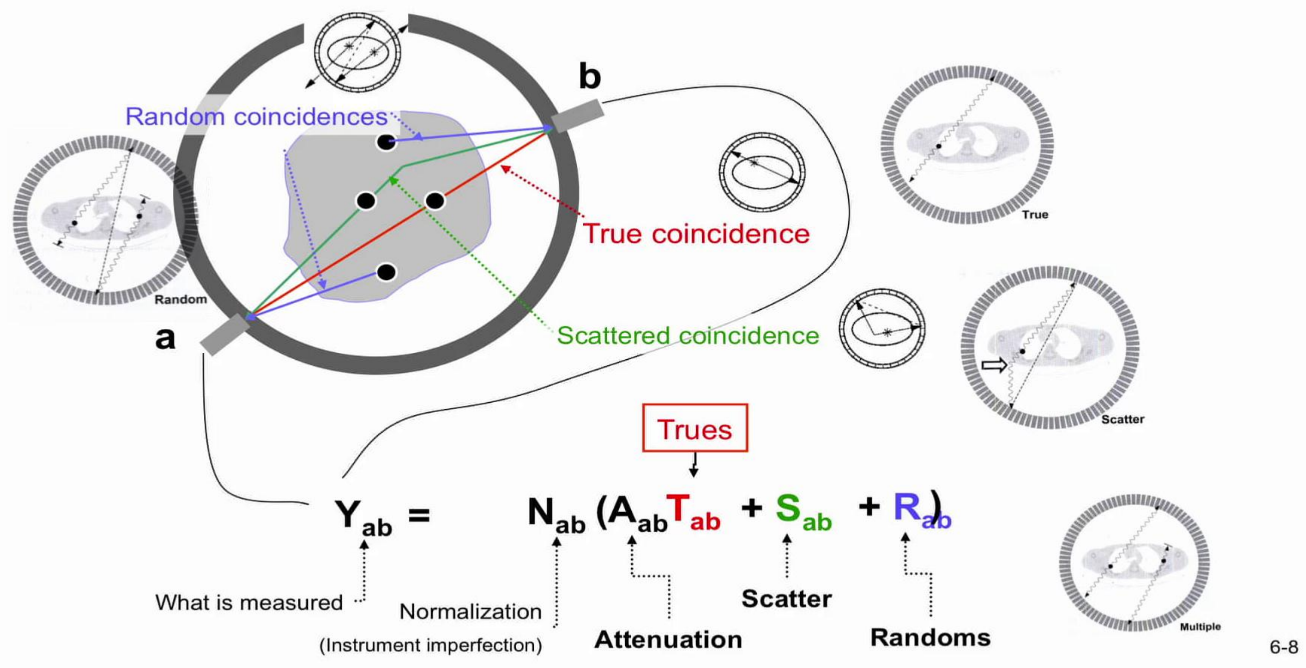
This detector cannot distinguish so we have scattered coincidences. Here's, schematically, another graphic. Here's the annihilation. At least one of the photons is Compton scattered, and this gives us a line of incidence that goes here or here with the object, subject in place. We have Compton scattering of one of the X-rays, and these two detectors here are responding simultaneously. So what we have is in addition to the true coincidences, we have scattered coincidences. Then we have random coincidences, and random coincidences are coincidences where we have simultaneously two positron electron annihilation processes. Of these four photons that are being produced, we are losing two. Whether we lose them in the body or whether we lose them in the detector, for some reason we are losing two of the photons. What happens now is we have two events here, this one and this one. One of the annihilation photons is not being detected for this process, and one of the annihilation photons in this process does not happen to be detected. So for some reason we have had the photon go into this detector and the photon go in this detector. So the scanner will also think these are a coincidence.

Notes

Summary

2m 49s

6-2. What is really measured with PET ?

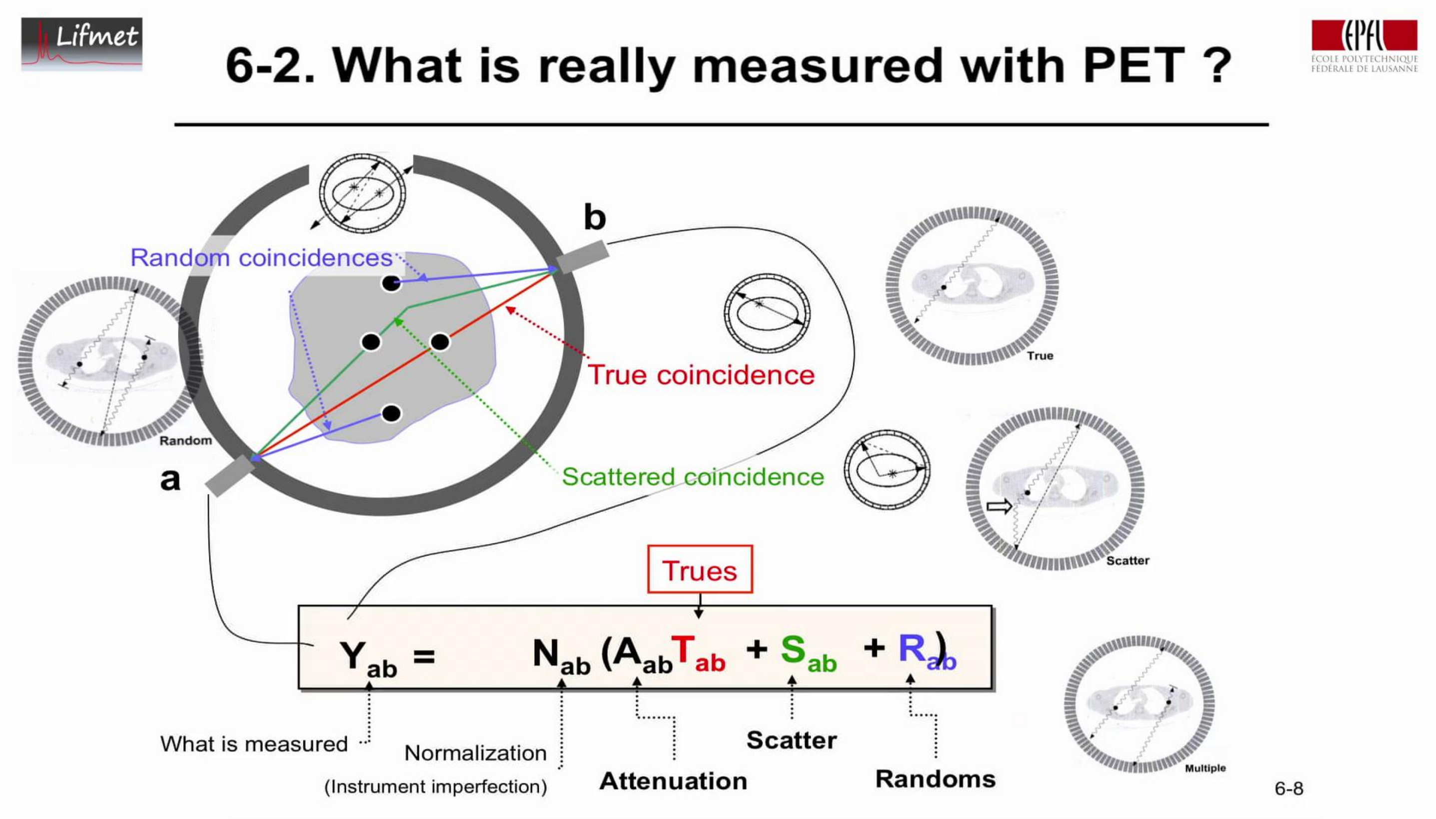


Here's the illustration schematically. We have one photon lost, this one and this one, and here with the depiction of the body; two events simultaneously, and two of the photons are by whatever process, doesn't matter what the process is. They are lost and we detect only from each of the annihilation processes one of the photons, but they are happening simultaneously. We have, this is what it's called, the *randoms* as well. Then we have to consider multiple events. There the computer can say "I've seen three events simultaneously. There's something not right. I can discard them." For the trues we have to consider the attenuation so we have to take into account attenuation. Remember, the X-rays travel in general through the body, so not all the X-rays will be arriving at the detector, and we have to consider the attenuation to back-calculate the specific activity in the tissue. Finally, we have in this process-- we have a normalization here. Once we have all these events that are being detected, we also have the normalization to consider. The normalization is essentially a process that takes into account scanner imperfection. We won't talk about it in this course.

Notes

Summary

4m 15s

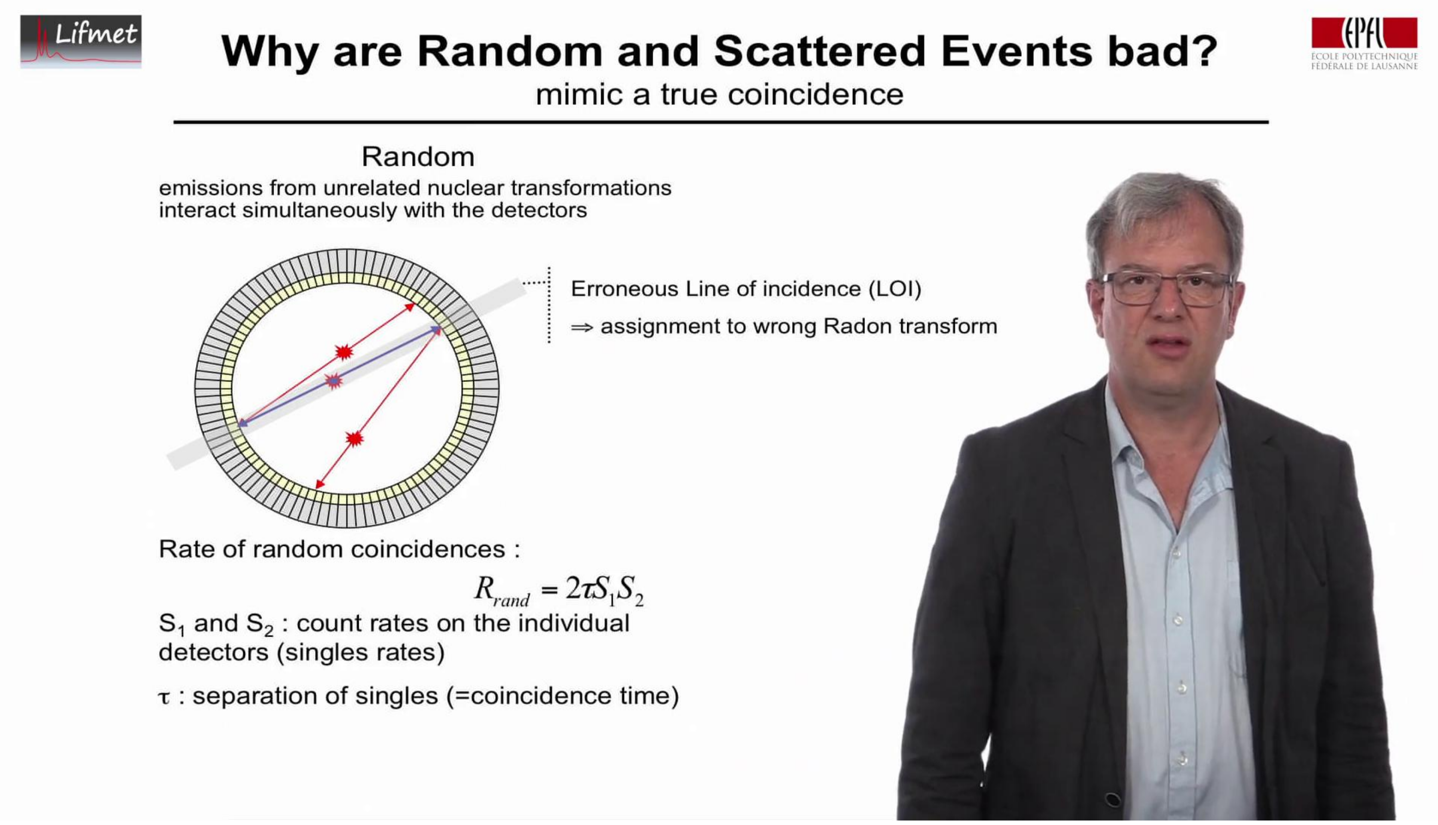


We'll just assume that this has been done, and we are detecting the intensities uniformly across the entire detector ring. But if you think of it, there's some differences in the electronics, in the manufacturing of the scintillation crystal, so it makes perfect sense that we don't have the same ability to detect the annihilation photons between all the pairs. To summarize, what we are measuring is: the true coincidences, scattered coincidences, and random coincidences, and we have to take into account attenuation as well.

Notes

Summary

5m 35s

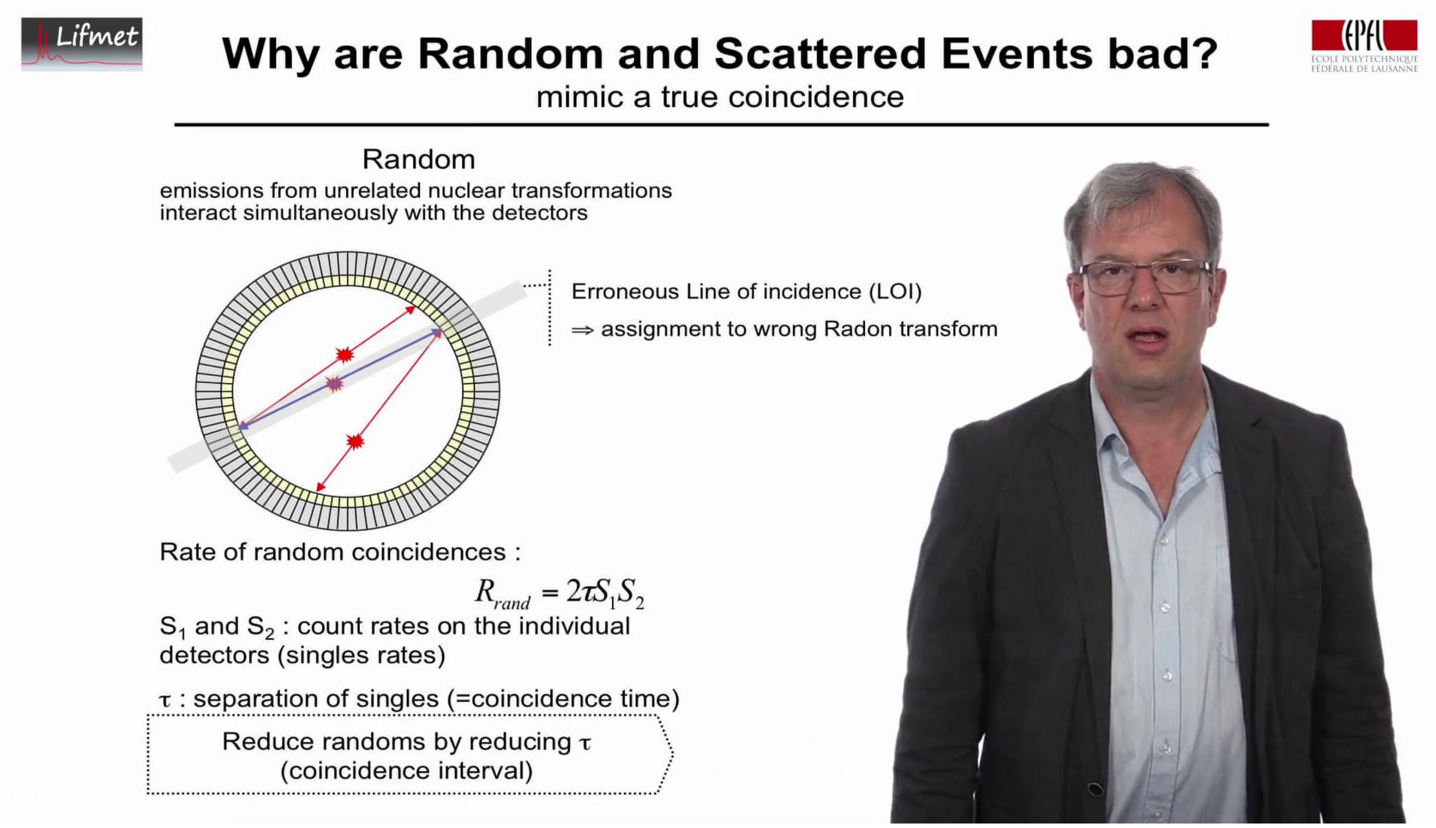


So I just previously introduced all the coincidences that we can detect, and now we'll discuss two of the coincidences that we really don't want to measure and how we can mitigate their effects. Let's first look at the random coincidences. We have two nuclear transformations that have nothing to do with each other. They are not in the same place and they are interacting; they're being detected at the same time. If we look at only this photon arriving at a detector and only this photon arriving at the detector, then what our scanner will think, "we've got a detection here and a detection here, so somewhere along this line has been an annihilation of a positron," whereas, in reality, we had two annihilations happening at different places. The scanner will actually think that there is a line of incidence that is in the gray shaded area here in this direction, but this is erroneous so this gives a wrong Radon transform and provides image distortions. Fortunately, we can estimate the rate of random coincidences. This is given by two times the coincidence interval times the singles count in the detector pairs, detector one and two here, so these are the individual counts.

Notes

Summary

6m 18s



You basically measure the counts in each of the detectors, you multiply that by two times the coincidence interval, and this gives you the rate of random coincidences, and with that, you can estimate whether the rate of random coincidences is important or not compared to the trues. This also implies a simple way to reduce the number of random coincidences and this is by reducing the coincidence interval, so if the material allows it, we will use an as short as possible coincidence interval compatible with the detector material. Imagine you have a coincidence interval of one second, you'll count a lot of random events, but if your coincidence interval is a few nanoseconds, you're going to count much less. Another consequence that arises here is that since the rate of randoms increases with the singles count rate squared, we have a upper limit of this SNR; the Signal to Noise Ratio of the scanner will not improve as we increase the dosage to the patient. At some point it will be overtaken by the random coincidences. So, we can minimize the number of random events that are being detected by reducing the coincidence interval. This, however, does not work for scattered events.

Notes

Summary

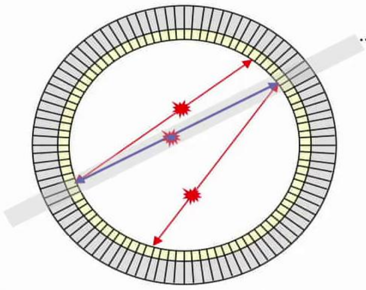
7m 37s

Why are Random and Scattered Events bad?

mimic a true coincidence

Random

emissions from unrelated nuclear transformations interact simultaneously with the detectors

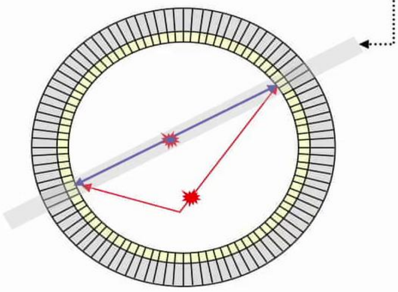


Erroneous Line of incidence (LOI)

⇒ assignment to wrong Radon transform

Scatter

At least one annihilation photon is (Compton) scattered



Rate of random coincidences :

$$R_{rand} = 2\tau S_1 S_2$$

S_1 and S_2 : count rates on the individual detectors (singles rates)

τ : separation of singles (=coincidence time)

Reduce randoms by reducing τ (coincidence interval)

Does not work for scattered events (why?)

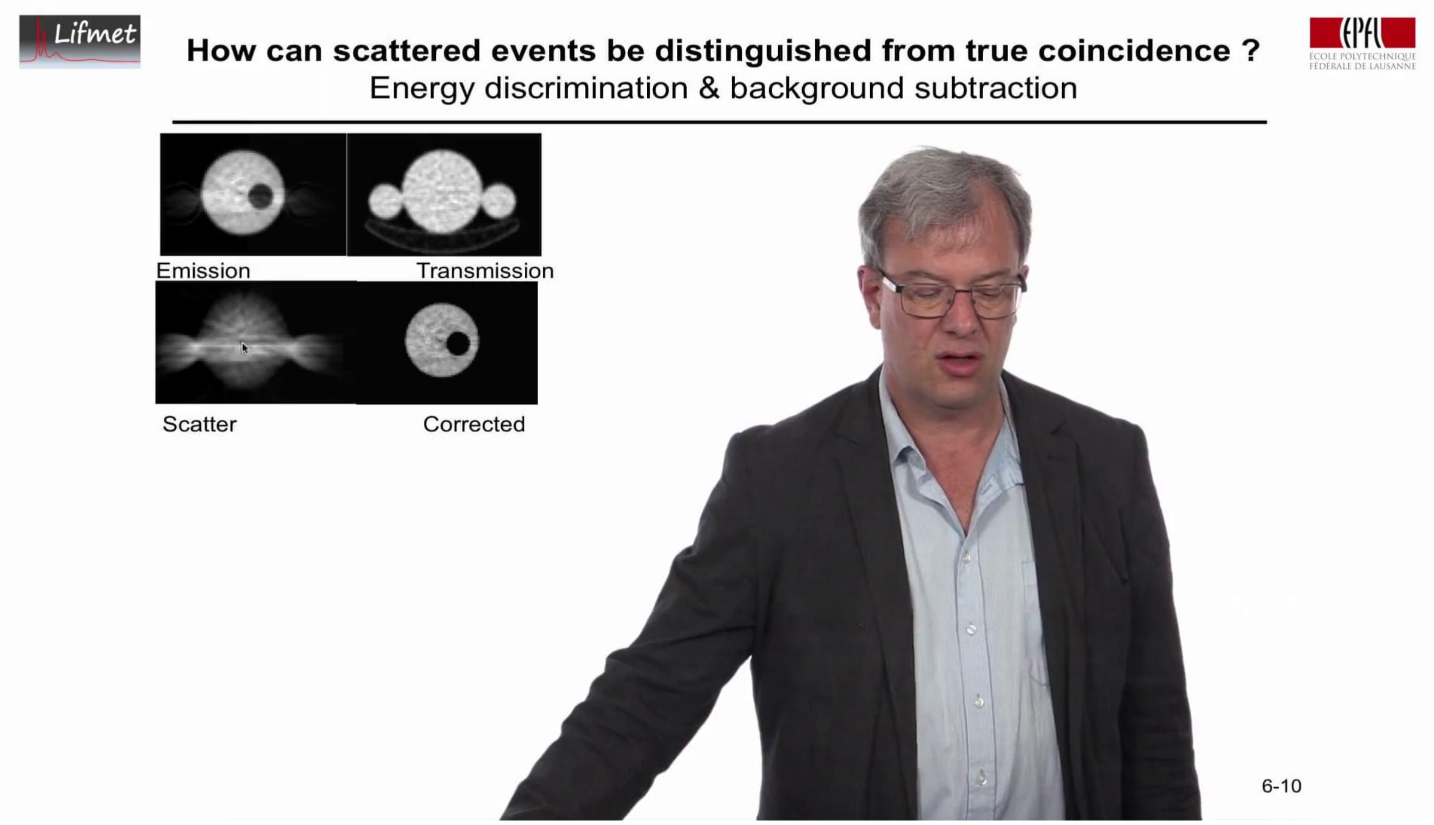
6-9

Why would that be so? Well, scattered events happen, essentially, instantaneously, so we have at least one of the annihilation photons is Compton scattered, so here's the detector ring and here we have the annihilation process, and now one of the photons has been Compton scattered. This happens instantaneously, so we would still detect scattered events simultaneously, one here, one here, so this scanner will think that somewhere along this line has been the annihilation, so the line of incidence that it will assign here for this particular situation drawn here is along this line, and this is, of course, quite distant from the true location of the positron and electron annihilation which happened here in this case down here. So with random events, to reduce the coincidence time, this allows us to minimize the number of random counts, but with the scattered events, we can't do that.

Notes

Summary

9m 11s



So the question is, how can we distinguish scattered events from a true coincidence? We look here at an image that has been recorded with a PET scanner. It is actually of a sphere filled with radioactive material. You can think of it as fluorodeoxyglucose. The sphere and a small sphere placed inside that does not contain radioactive material. This is what has been measured with the PET scanner. If we take the same setup and put it into a CT scanner, this is what we see. We see, actually, one sphere with water. This sphere also contains water, but non-radioactive, and two spheres here on the outside with water but not radioactive material. So this is where we have, if you will, tissue. If we look at what is the scattered coincidences and then the corrected image, we have the scattered events are being imaged here and if we correct this image for the scattered events, we get the true depiction. And you can see here there is clearly a misrepresentation of the activity into these objects because some of the X-rays can pass through here and be deviated, and so the scanner will think that the radioactivity is in here where we have, in this case, material where the X-rays can be scattered.

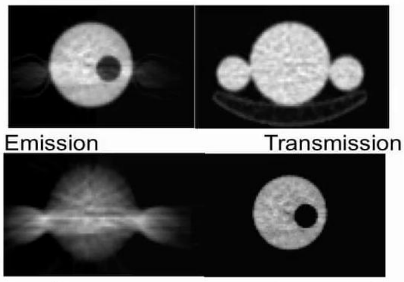
Notes

Summary

10m 20s

How can scattered events be distinguished from true coincidence ?

Energy discrimination & background subtraction



Most scattering is by Compton

$$E_f = \frac{m_e c^2}{2 - \cos\theta}$$

theta/Ei	511	(keV)
20	482	
45	395	
90	256	
110	218	
180	170	

6-10

This image plus this image gives this image, and we can see here that the scattering happens also in tissues, assigns the wrong Radon transform to tissues which are not containing radioactive material. Most scattering at 510 kiloelectronvolts, which is the energy of positron emission tomography, happens by Compton. If you look at the Compton formula, here is the general formula. We have a relationship between the original photon energy and the final photon energy, if that photon is being scattered by an angle of θ. Now, we know the energy of the photon. The energy of the photon, *Ei*, that's been emitted by the annihilation process, that energy is equal to *me c squared* so I'll just put in here *me c squared* and here as well, and I simplify the equation, and this gives me the equation of the energy of the photon after the scattering process. So it's the rest energy of the electron divided by *two minus cosine* θ. Let's look at the θ here on the left column in degrees and here we have the emitted energy of the photon, that's 510 kiloelectronvolts, so if our photon is deviated by 20 degrees then the energy is reduced by 30 kiloelectronvolts.

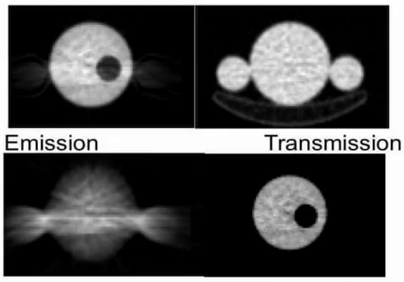
Notes

Summary

11m 49s

How can scattered events be distinguished from true coincidence ?

Energy discrimination & background subtraction

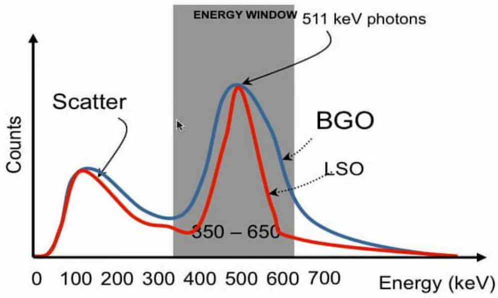


Most scattering is by Compton

$$E_f = \frac{m_e c^2}{2 - \cos\theta}$$

theta/Ei	511	(keV)
20	482	
45	395	
90	256	
110	218	
180	170	

Measure E_f → identify severely scattered photons



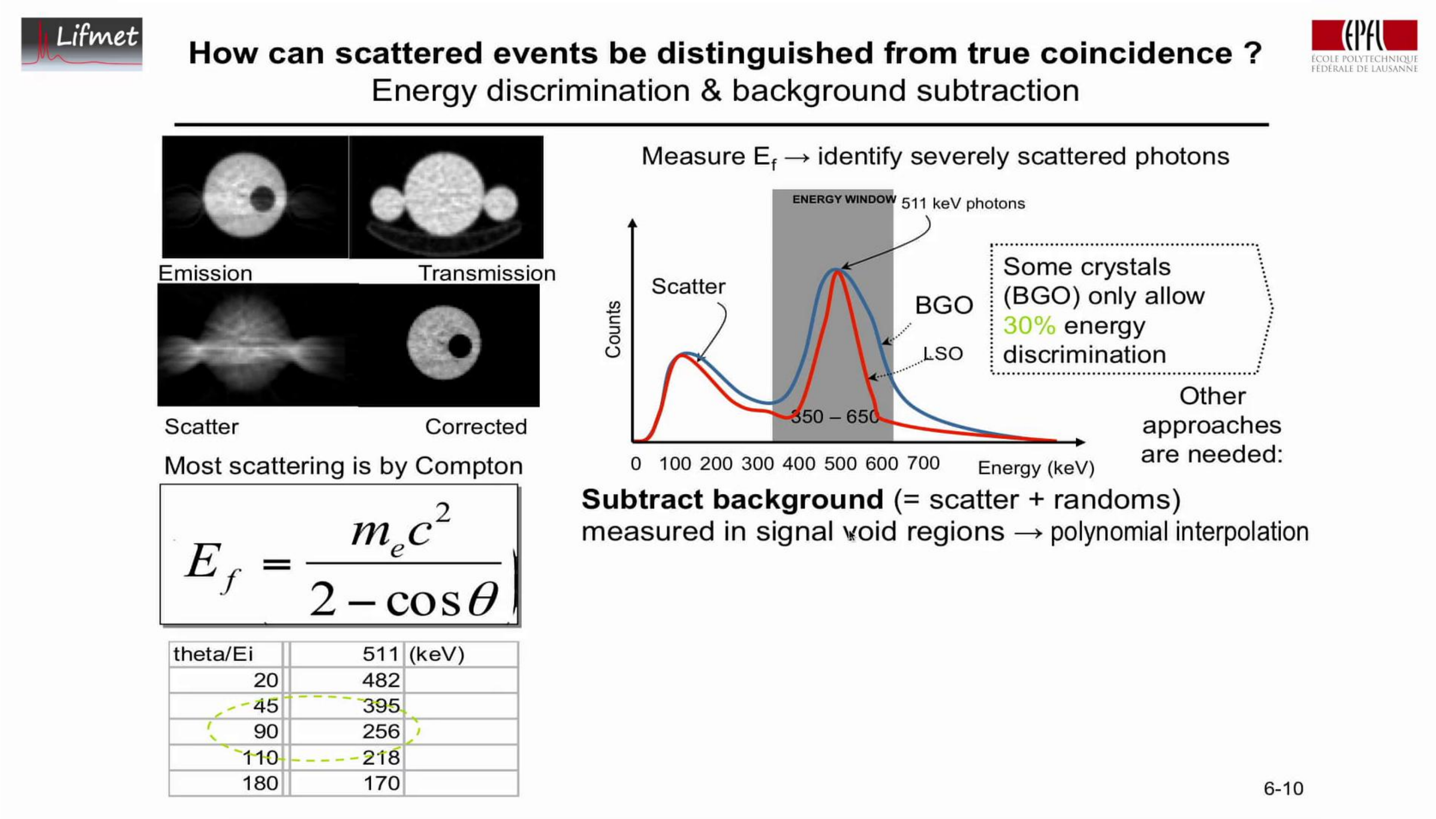
6-10

If it is scattered by 45 degrees, it is reduced by 115 kiloelectronvolts. So, what's the principle that we need to do now? The principle is we measured the energy of the photons that we detect and if the photon that we detect does not have the energy corresponding to 510 kiloelectronvolts, then we will conclude this photon has been scattered and we will not count the event. Let's look at what we are seeing. We have on the vertical axis the counts, on the horizontal axis, the energy in kiloelectronvolts. This is the so-called LSO crystal. We have the photo peak here, and the Compton backscatter. In this crystal, we could set the energy window for 425 to 650 kiloelectronvolts and here the peak is the 510, the annihilation photons that we detect. Anything else that we are seeing is our photons that are being scattered that we can discard. Now, let's look at a different crystal here in blue. That's the BGO crystal. We've already mentioned that material. This crystal is not as good in discriminating energy. Its primary photo peak is broader, so the energy window here is now from 350 to 650 kiloelectronvolts. It's a broader window that is being detected so the discrimination of energies is not as good.

Notes

Summary

13m 14s

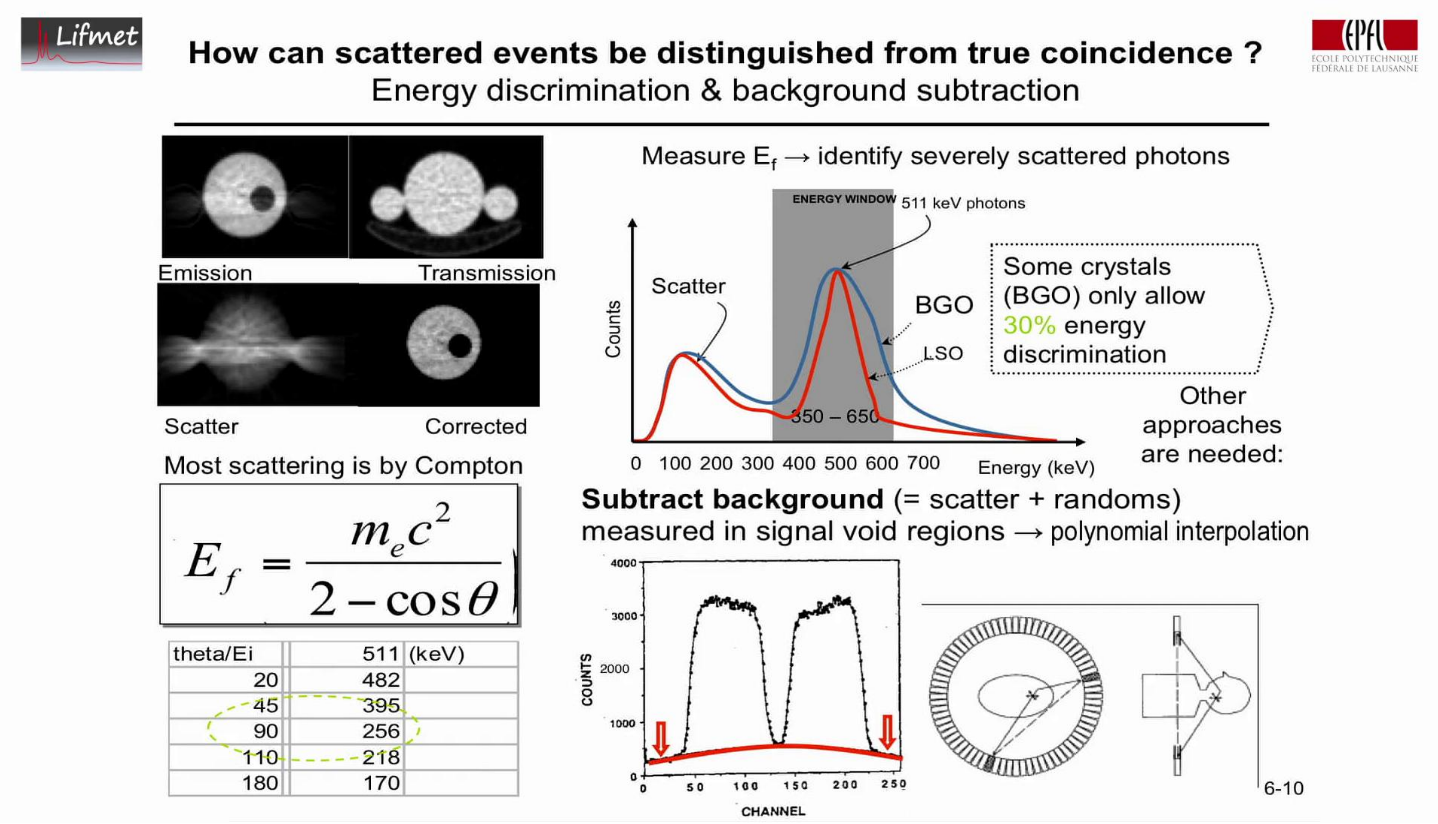


The consequence is, we have to consider when we measure the photon energy that we don't have a Δ distribution, a sharp definition of the photon energy where we can detect. We have a certain imprecision in the energy discrimination, and so, if we look at the example of BGO, we only have 30 percent energy discrimination here. If you look at something that we want to be sure that we can distinguish, let's say here we have roughly half of the photon energy, 256 kiloelectronvolts, then this means we are detecting photons that are scattered by 90 degrees or higher. The elimination of scattered photons, photon pairs, where one photon has been scattered, works well for severely scattered photons here, typically at least 60 to 90 degrees or higher, being scattered by such an angle. Therefore, in order to have a better elimination of the scattered photons, one needs other approaches. One approach is to subtract the background signal. This basically means we measure the signal in-- we look at the background in regions where we know that there is no signal. Usually one has a good idea, especially if one has simultaneously a CT scan and then interpolates the signal in those regions with a polynomial, and subtracts out that background.

Notes

Summary

14m 52s



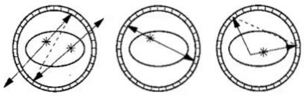
To give you an idea why we have signal in the background, here is an event that's happening in the body. It's being Compton scattered, and this will attribute a line of incidences outside the body, so it will have intensity that is outside the body. Here, if we're doing a cardiac scan, here are our two detectors, we could have radioactivity in the brain that is severely scattered, that is scattered and arises here in the detector and that would not be good detection. What we're looking at here now is a cut through an image, something like this. We have, obviously, two vials or two objects here which are positron emitting. We have the intensity going high here, but we can also see where there is no signal. Where there is no object there should be no signal, but we have not no signal here. We have some signal here. This is the background due to randoms and scattered. It also takes into account random counts, and all that is then needed is to take a polynomial interpolation of this background and then the signal here, this red line, would be subtracted from the image intensity and that allows us to eliminate the background signal due to scatter and random events.

Notes

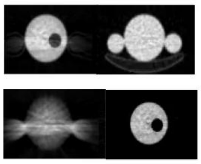
Summary

16m 22s

Credits



"The Essential Physics of Medical Imaging"
Fig. 22-15, from Jerrold T. Bushberg, J. Anthony Seibert, Edwin M. Leidholt, John M. Boone



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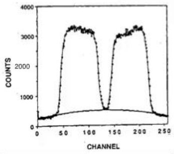

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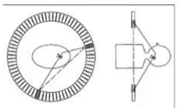

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Notes

Summary

17m 37s