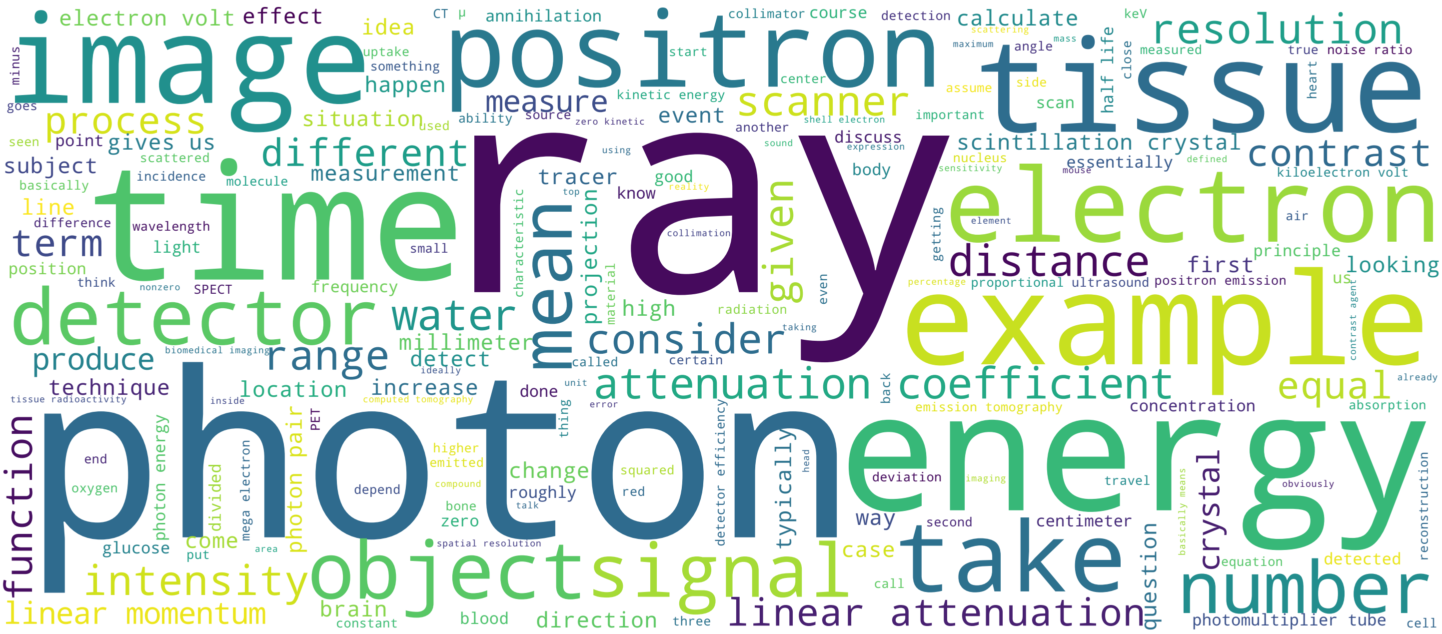
6.4 Resolution in PET imaging

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter

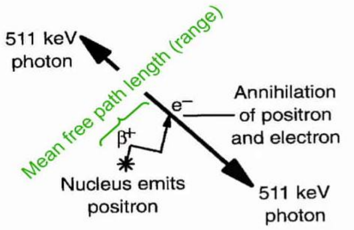


Search MOOC

Video

6-4. Why is Resolution never perfect ?

Annihilation Range and photon non-collinearity



Range: limits spatial resolution
(In air, β^+ range ~ several m)

Isotope	Half-life (min)	Max. Energy (MeV)	Range in H_2O (FWHM, mm)
^{18}F	110	0.6	1
^{11}C	21	1.0	1.2
^{15}O	2	1.7	1.5
^{13}N	10	1.2	1.4
^{68}Ga	68	1.9	1.7
^{82}Rb	1	3.2	1.7

Now, ideally, we would like to have a scanner that gives us an infinite spatial resolution in theory, and we would be happy with such a technique. However, this is not the case in PET, and the question here is, why can the resolution be never perfect? Well, let's look at the process here. We have the positron that's being emitted from the unstable parent nucleus. The positron diffuses, loses energy, and does the annihilation with an electron after a certain distance. And this distance here is called the mean free path length, or the positron range. And this range, there's nothing we can do about it. This range exists, it is there, it is nonzero, so the positron does not leave the nucleus and immediately annihilate with an electron; it takes some distance. Let's give us some idea in the air, if you have a positron emitter, the positron range is actually several meters, so it is quite long. But if you look now in water-- and here I've plotted on this table a number of isotopes. We'll start out with the most ubiquitously used, fluorine-18, with its characteristics. It has a half-life of roughly two hours. The kinetic energy of the positron is roughly 0.6 mega-electron volts, and the range of the positron in water is roughly a millimeter.

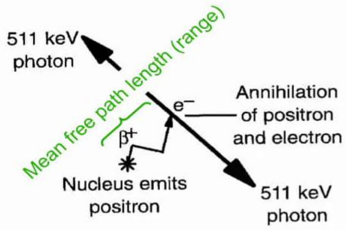
Notes

Summary

0m 04s

6-4. Why is Resolution never perfect ?

Annihilation Range and photon non-collinearity



Range: limits spatial resolution

(In air, β^+ range ~ several m)

Isotope	Half-life (min)	Max. Energy (MeV)	Range in H_2O (FWHM, mm)
^{18}F	110	0.6	1
^{11}C	21	1.0	1.2
^{15}O	2	1.7	1.5
^{13}N	10	1.2	1.4
^{68}Ga	68	1.9	1.7
^{82}Rb	1	3.2	1.7

That's the full-width, half-maximum-- so, half of the positrons will travel further than one millimeter. If we look at C11, the half-life is around 20 minutes, the energy is higher, it's one mega-electron volt, and the range of the positron emitted from the C11 nucleus is a bit higher than that of the fluorine. Oxygen-15, also a widely used tracer, has a surprisingly short half-life of two minutes. Positron energy of nearly two mega-electron volts, and here, the range of the positron in water is 1.5 millimeters. Then we have nitrogen-13; 10 minutes half-life. Gallium-68 which can produce a half-life of 70 minutes, and Rubidium, of one minute. Voltages between 1.2 and 3 mega-electron volts, and, again, the range of the positron in water is around 1.5 millimeters. So, these distances, we cannot manipulate them, we cannot improve them, they are there, they are a given, and... We have to deal with this imprecision. This basically means that even if we're able to determine precisely the location of a positron and electron annihilation, this does, by one millimeter distance roughly, *not* represent the location of the parent nucleus. So, here are the most frequently used isotopes: fluorine-18, C11 and oxygen-15.

Notes

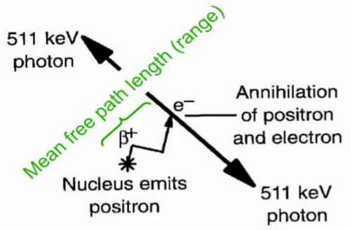
Summary

1m 31s

Lifmet

6-4. Why is Resolution never perfect ?

Annihilation Range and photon non-collinearity



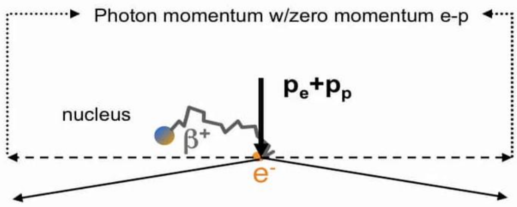
Range: limits spatial resolution
(In air, β^+ range ~ several m)

Isotope	Half-life (min)	Max. Energy (MeV)	Range in H_2O (FWHM, mm)
^{18}F	110	0.6	1
^{11}C	21	1.0	1.2
^{15}O	2	1.7	1.5
^{13}N	10	1.2	1.4
^{68}Ga	68	1.9	1.7
^{82}Rb	1	3.2	1.7

Collinearity: Assumed for Reconstruction

Background: At time of annihilation, e-p pair has non-zero kinetic energy

→ conservation of momentum



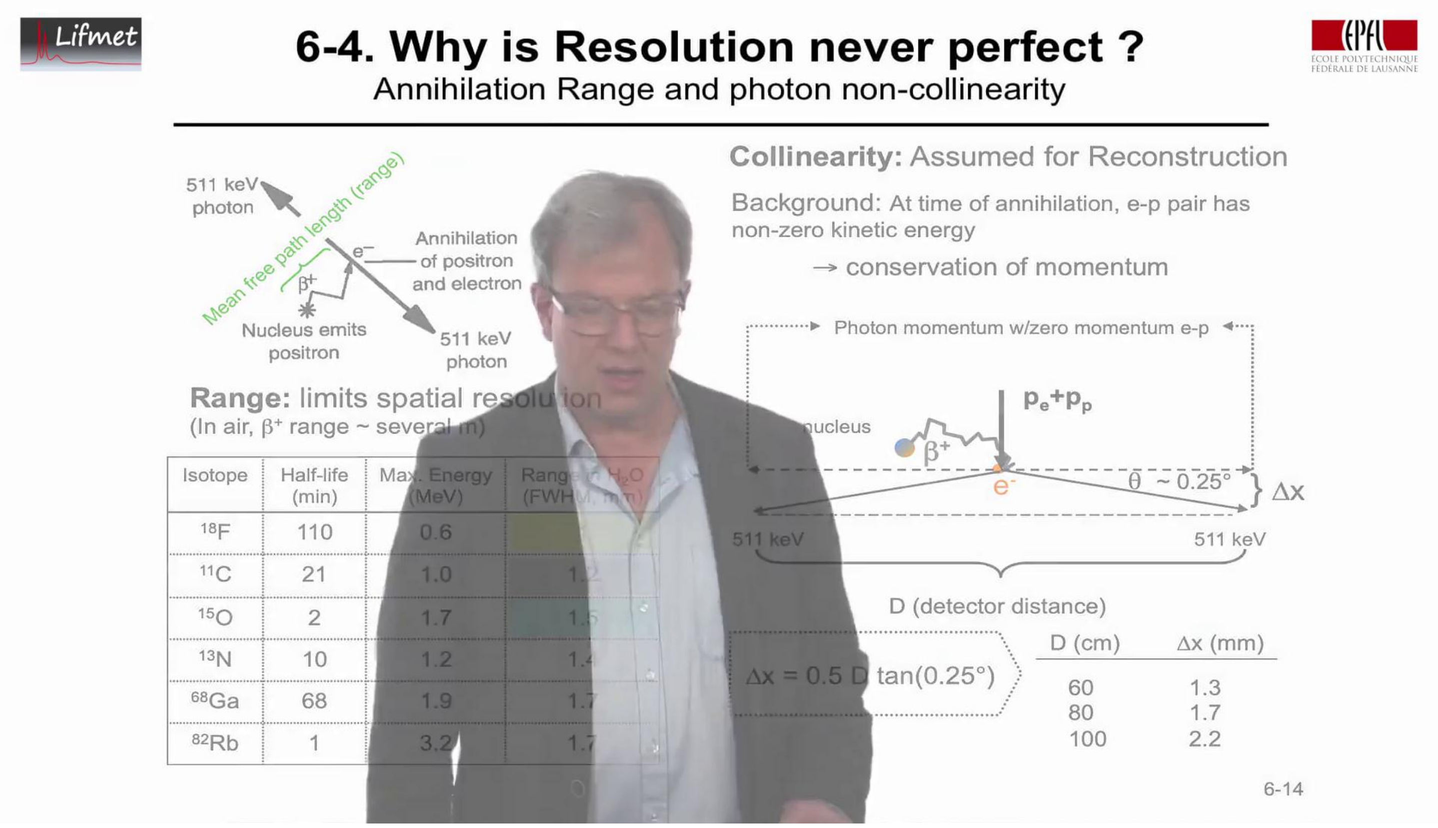
6-14

Now, there is another effect, and that is we have assumed collinearity of the photon pair for the reconstruction. So, the background of this is that we have assumed that at the time of annihilation, the electron-positron pair has zero kinetic energy. Now, in reality, they will not have zero kinetic energy, and we have conservation of momentum to consider. So, let's have the nucleus here. We have the positron. It finds the electron, annihilates, and goes up in perfect 180 degrees. This is the situation where the positron and the electron together have zero kinetic energy. In this case, the two photons will be perfectly 180 degrees apart, and we have zero momentum of, also, the photon pair. Now, let's consider a situation where the positron and the electron have nonzero linear momentum. So, the positron and the electron, their linear momentum is nonzero, that's indicated by the arrow here, so this is a resulting linear momentum. Now, the process of annihilation conserves linear momentum, so the photons, the two photons, should have nonzero linear momentum. To achieve this, we have to imply that the two photons are not emitted 180 degrees apart, but are deviated by a small angle from this collinearity.

Notes

Summary

3m 12s



So, we have the two 510 kilo-electron volt photons. They are not perfectly opposed to each other, because their net linear momentum is nonzero. So, this will now give us a line of incidence that's different. We will detect the photon at a different place than where the positron-electron annihilation has happened. This angle is very small. It's 0.25 degrees, roughly, so we can estimate from that the error in location. So, we'll take the distance Δx here, we'll say we have a detector distance between the two detectors of D, and so we can calculate with this. We can calculate the deviation of where we detect the photon pair relative to the true location, is 0.5 D, times tangent of 0.25 degrees. So, what does this mean? We'll plot here, just as a function of D, the position error we have if the two detectors are 60 centimeter apart, then with a 0.25 degree angle, we have an error of one millimeter-- 80 centimeters, it's nearly two millimeters, and 100 centimeters, it's a bit above two millimeters. This gives you an idea of the location error. Now, we're assuming collinearity of the photons, so they're opposed to each other, outside.

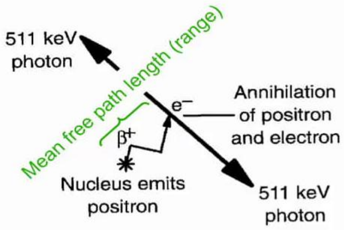
Notes

Summary

4m 46s

6-4. Why is Resolution never perfect ?

Annihilation Range and photon non-collinearity



Range: limits spatial resolution

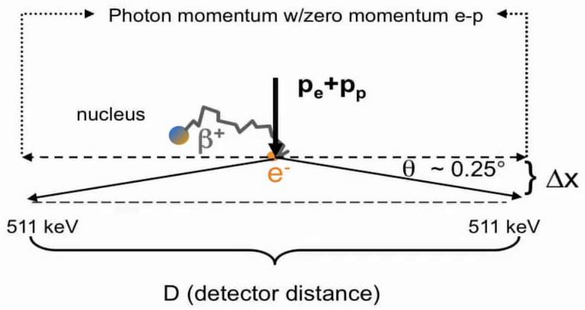
(In air, β^+ range ~ several m)

Isotope	Half-life (min)	Max. Energy (MeV)	Range in H_2O (FWHM, mm)
^{18}F	110	0.6	1
^{11}C	21	1.0	1.2
^{15}O	2	1.7	1.5
^{13}N	10	1.2	1.4
^{68}Ga	68	1.9	1.7
^{82}Rb	1	3.2	1.7

Collinearity: Assumed for Reconstruction

Background: At time of annihilation, e-p pair has non-zero kinetic energy

→ conservation of momentum



$\Delta x = 0.5\ D \tan(0.25°)$

D (cm)	Δx (mm)
60	1.3
80	1.7
100	2.2

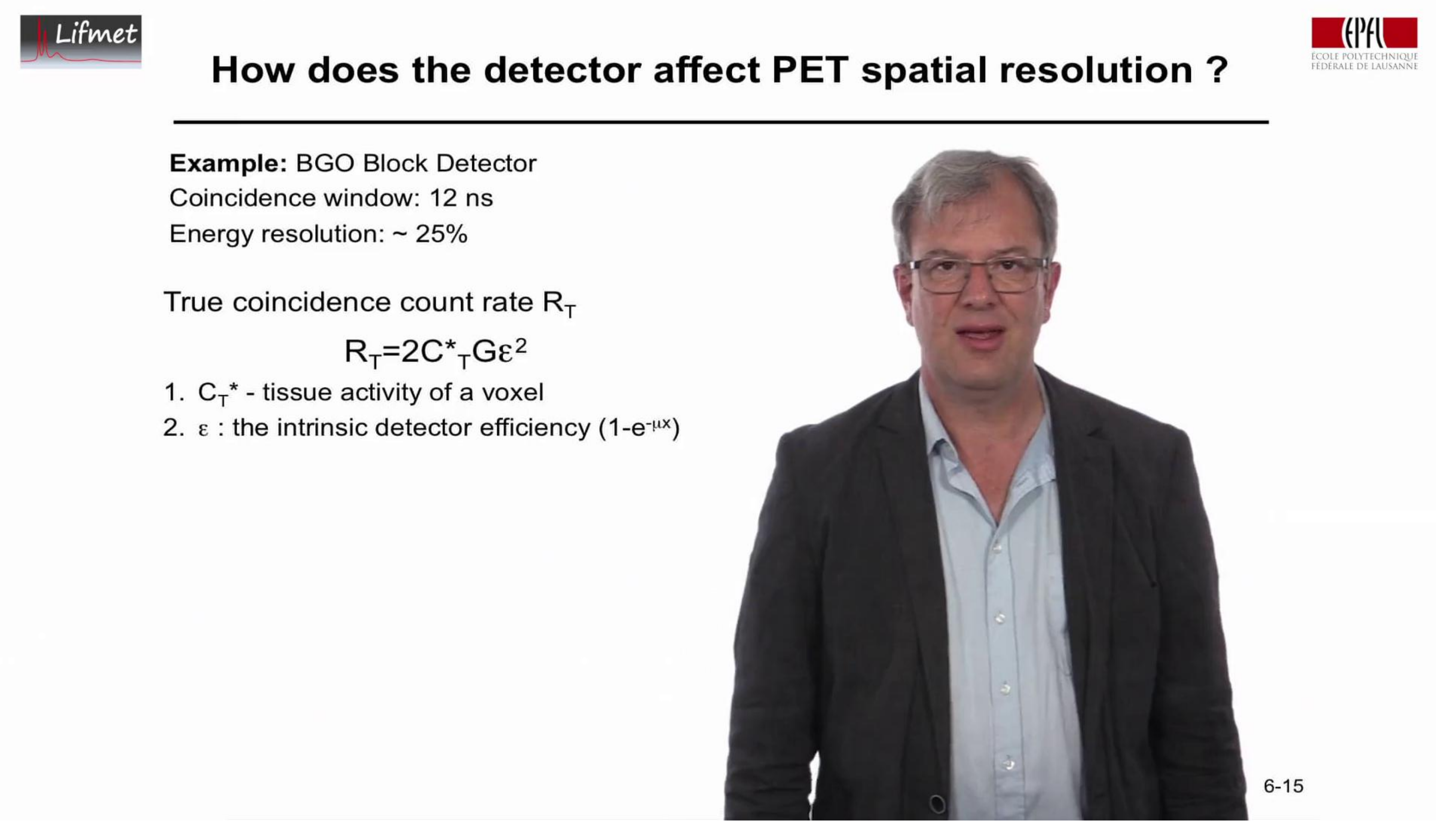
6-14

If they are not, then we have deviations, from 60 centimeters to one meter, of roughly 1.5 millimeters. So, this deviation can happen in all directions, so this basically just means that we have a blurring of the representation of the position-- of where the electron and the positron annihilated. This adds on top of the range of the positron. *We already have here the range of the positron.* That gives us an uncertainty, and then, if we have a large detector distance, we have also an uncertainty in determining the location of where the positron and electron annihilated.

Notes

Summary

6m 19s

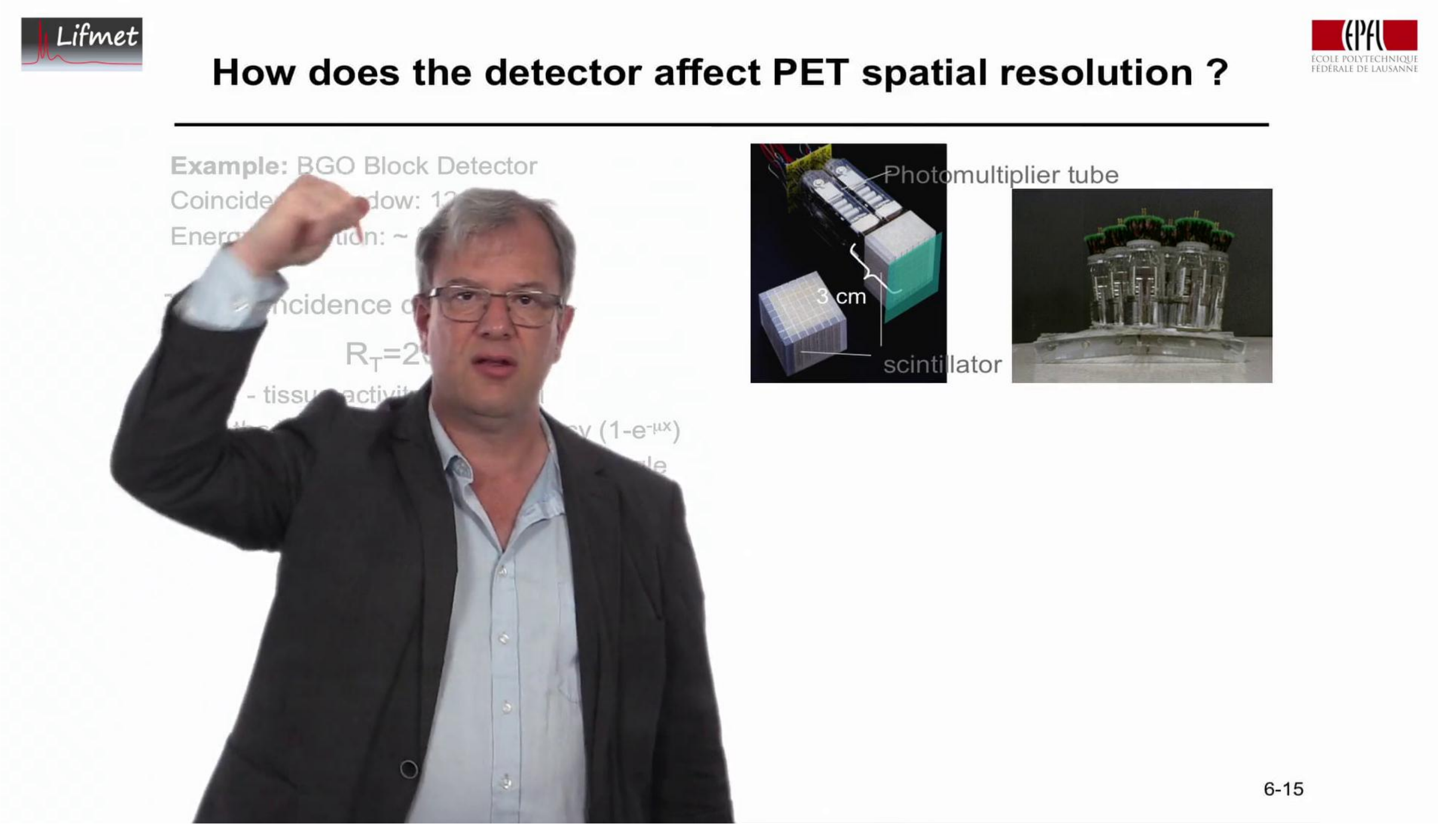


Now, we have said that the detection of x-rays for positron emission tomography, the methodology that's used-- that is, scintillation followed by amplification by photomultiplier tubes, is the same as for SPECT. And as you might remember, the photomultiplier tubes have a certain dimension. The scintillation crystal has to have a certain thickness, and this is the question: how does the choice of the detector affect the spatial resolution of the positron emission tomography scan? So, let's take as an example a BGO block detector. I'm bringing here this example to also put some numbers on the characteristics. The coincidence window that you can choose with a BGO block detector is on the order of 10 nanoseconds. The energy resolution is roughly 25%, so this is to give you some specific numbers. Now, we will look at the true incidence count rate-- we'll call that R true, R_T for true-- is given by two times the tissue radioactivity, times the factor... C_T * is the tissue activity of a voxel. We have ε is the intrinsic detector efficiency. It actually represents the ability of the scintillation crystal to stop the x-ray, the 510 kilo-electron volt photon, and to simplify it, it basically means here the ability to stop them.

Notes

Summary

7m 02s

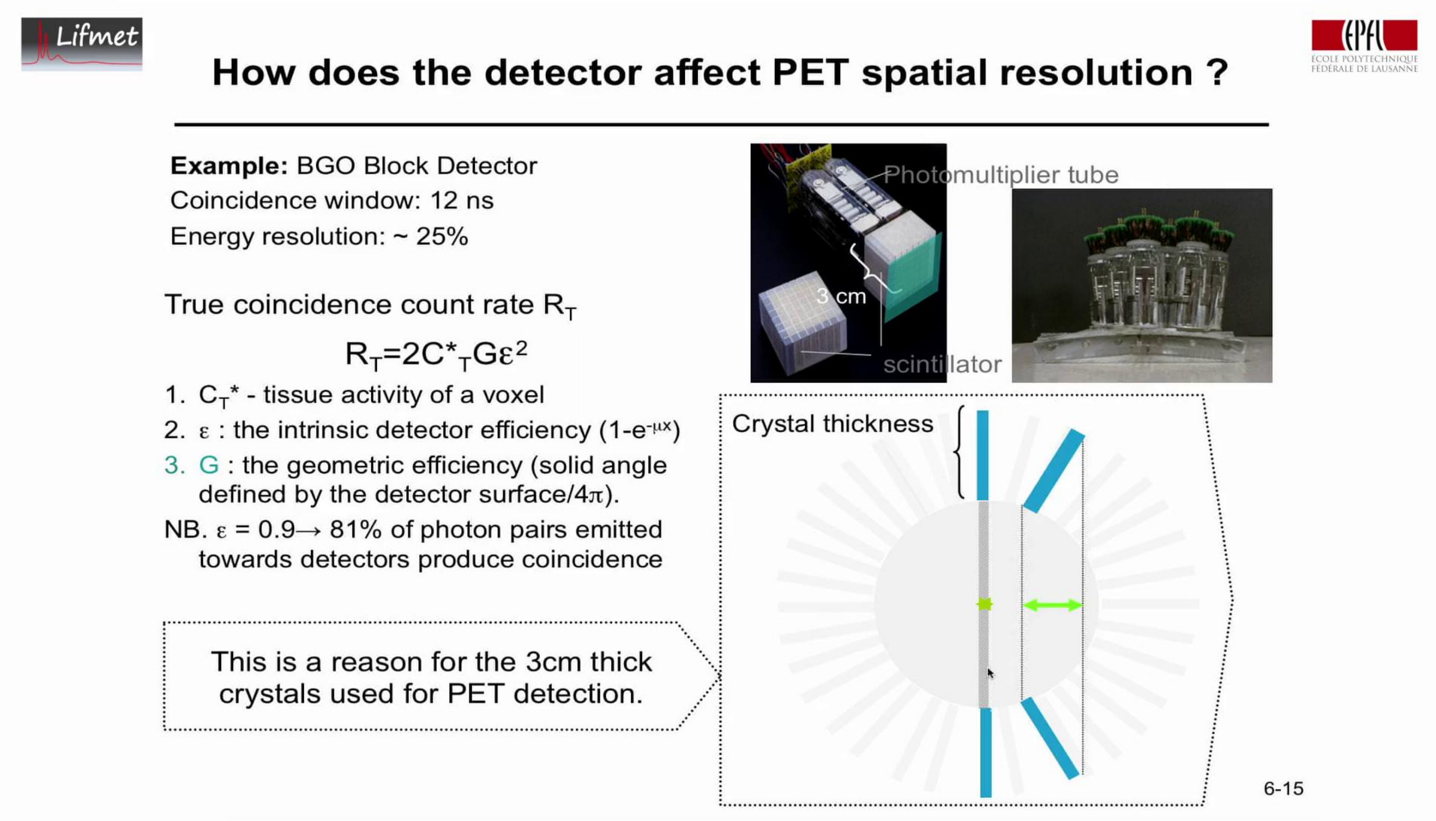


So, it's given by *1 - e* to the *- μ x*. The *μ*, the linear attenuation coefficient here, is that of the scintillation crystal. So, ideally, we would have a fairly thick crystal--x being high-- linear attenuation coefficient being high, in this case the efficiency would be close to one. So, here's an example of a scintillation crystal, and the photomultiplier tubes on top. We'll look here at a more modern detector. We have the photomultiplier tubes here, here's the electronics, here's the scintillation crystal, and the scintillation crystal has a certain thickness here. We have to consider also the geometric efficiency-- that is, what percentage of the solid angle do we see by the detector? So, the detector surface here, in green, divided by *4 π*, the radius squared, this gives us the percentage of all the counts, all the x-rays, that we can detect. Think of it this way, all the x-ray pairs going all directions, we have a detector up here. This detector will only see a small percentage of the entire spherical surface at its location, and these are the maximum counts that you can have, it's geometric efficiency.

Notes

Summary

8m 38s



So, to give you an idea, if you look at the intrinsic detector efficiency, if we have the detector efficiency of this detector here, let's say, is 90%, since we are detecting a photon pair, we have to also consider the detector efficiency on the other side. So, if each detector has an efficiency of 90%, then we have 81% of the photon pairs that are emitted towards the detectors, that produce coincidence. And so, this is a reason why we cannot use infinitely thin crystals. We have to use them fairly thick, and a typical dimension here is three centimeters. So, if we look now at our detector ring, here, see, crystal thickness, we will now look at the detector ring, and we are considering these two detectors here, just opposite of each other. This is the line of incidence that's defined by the two crystals, and if we have an annihilation event here, then we will attribute all the events here on this line of incidence. This is the good situation, we have good resolution, with the detector width here, the position measured here and here that defines the line of incidence. Now, let's consider two detectors a little bit offset, that are not just opposite each other.

Notes

Summary

10m 01s

How does the detector affect PET spatial resolution ?

Example: BGO Block Detector
Coincidence window: 12 ns
Energy resolution: ~ 25%

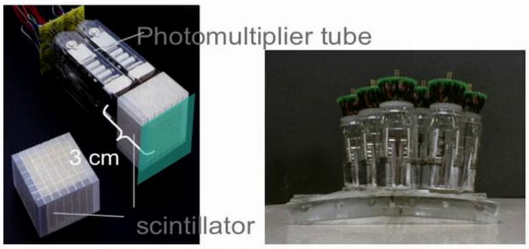
True coincidence count rate R_T

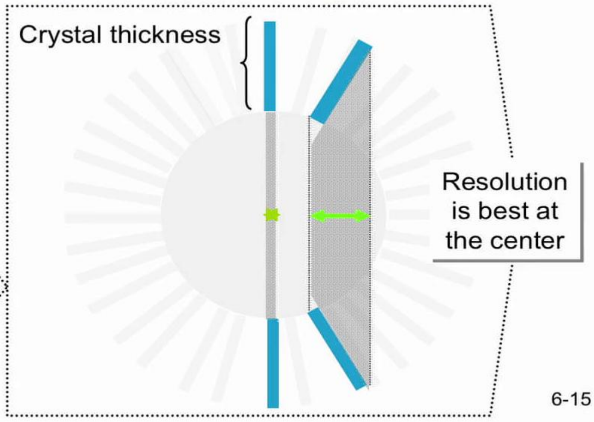
$$R_T = 2C^*_T G \varepsilon^2$$

1. C_T^* - tissue activity of a voxel
2. ε : the intrinsic detector efficiency ($1-e^{-\mu x}$)
3. G : the geometric efficiency (solid angle defined by the detector surface/4π).

NB. ε = 0.9→ 81% of photon pairs emitted towards detectors produce coincidence

This is a reason for the 3cm thick crystals used for PET detection.





6-15

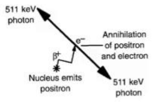
We have an event detected in this crystal, and we have an event detected in this crystal. So, what does this mean now? Basically, it means we can have detected an event anywhere in this shaded area. This will create-- any even that is in here, or any event that's detected here in this crystal or this crystal, could have had the annihilation between an electron and a positron anywhere in this gray area. So, as you can see now, as we are getting away from the center of the scanner, the resolution is poorer, because of this geometrical consideration. So, the take-home message here is, of a standard PET scanner with this technology, the resolution is best at the center of the scanner.

Notes

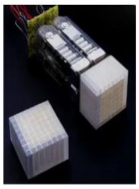
Summary

11m 24s

Credits



“The Essential Physics of Medical Imaging”
Fig. 22-14, from Jerrold T. Bushberg, J. Anthony Seibert, Edwin M. Leidholt, John M. Boone



Siemens-CTI ECAT 951 PET scanner
http://www.siemens.com/

Continus detector design
http://equipment.xqhospital.com.cn:8050/uploadfile/2012/3/7/20120307041838.pdf

Notes

Summary

12m 14s