Introduction to Biomedical Imaging Systems
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Lecture - 31
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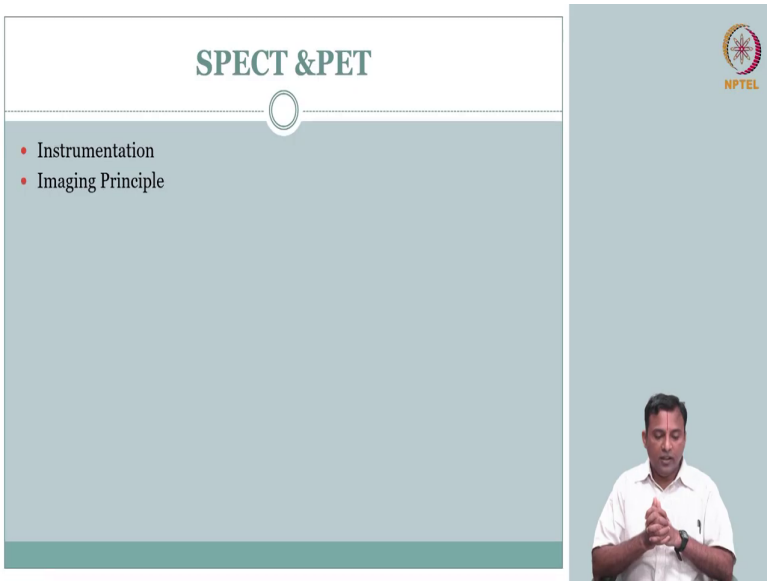

Ok. Welcome back to the next module. It is time we move on from planar scintigraphy to the other two nuclear medicine modalities which are SPECT and PET. So, as you would notice in if we have to draw an analogy to what we did in X-ray base modalities, we first did X- ray physics and then we covered X- ray projection radiography and then we talked about getting the tomography right slice. Similarly, we have done now gamma, gamma rays.

So, the physics of gamma rays and then, essentially the radioactivity aspect and then we covered the projection scintigraphy or planar scintigraphy very analogous to your projection

radiography. So, now, in that regard we will now move on to the modalities in nuclear medicine that has a tomographic reconstruction part.

So, in some sense why I wanted to elaborate on that before we jump in is conceptually is very similar to what we have done with X ray base. So, now, that we have covered planar scintigraphy the PET and SPECT what we will do is contextualize to this particular sitting otherwise, the concept of how do you do the tomographic reconstruction right is almost similar. We will use some variable changes, but otherwise it is similar to what we have covered already.

So, we have scintigraphy. Now, how do we: So, we know what signal is recorded the gamma rays how it is recorded in planar scintigraphy. So, we will start from there with a scope of seeing what is the acquisition. First, instrumentation for SPECT and PET and then, the imaging principle; imaging principle more specifically to do with your tomographic reconstruction ok.

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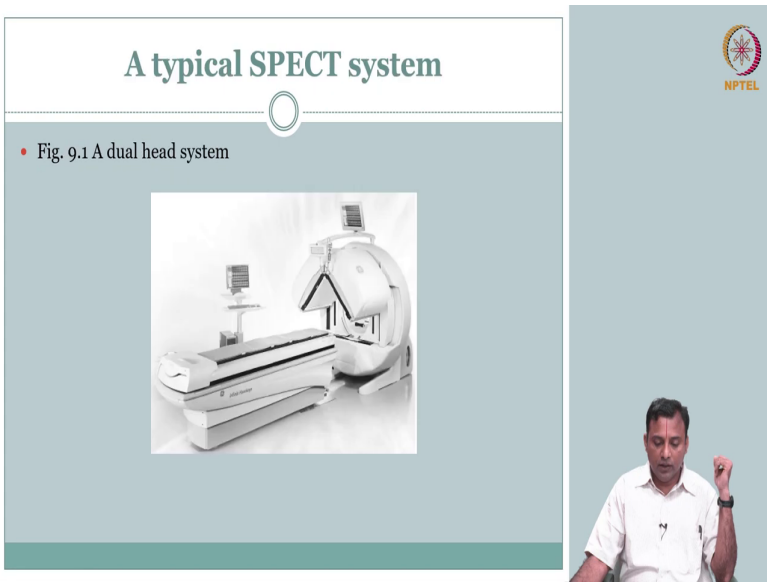

So, let us start with the instrumentation. As you will see this is a typical SPECT system, what you notice here is apart from the patient table right you notice this arm. In planar scintigraphy, we were talked about this anger camera right. So, which was you know flat and we saw this that was your planar scintigraphy. Here, what do you notice this is a dual head system.

So, this is one camera this is another camera. It has some angle. Of course, this is flexible you can make them 180 degrees right. So, this is attached to this arm and this can move around. So, you have a patient lying here, you can move around. So, the same principle of what did we do in tomography in X ray, we have to get data we got there in one line and then we moved from different thetas.

So, we ended up acquiring g of l comma theta if you will recall. We will connect back to that ok. So, here we start with scintigraphy planar scintigraphy concept. Only thing that we add on

to the instrumentation is this plane. Of course, here is an example of dual head system. You could extend the same one head one planar scintigraphy with the anger camera.

We can put it to a arm and that can rotate around right different directions you can get the planar scintigraphy data and then do the reconstruction. So, this is the difference. Of course, because of that because you have to do reconstruction there are some small detailing that needs to take place, but otherwise is very similar right.

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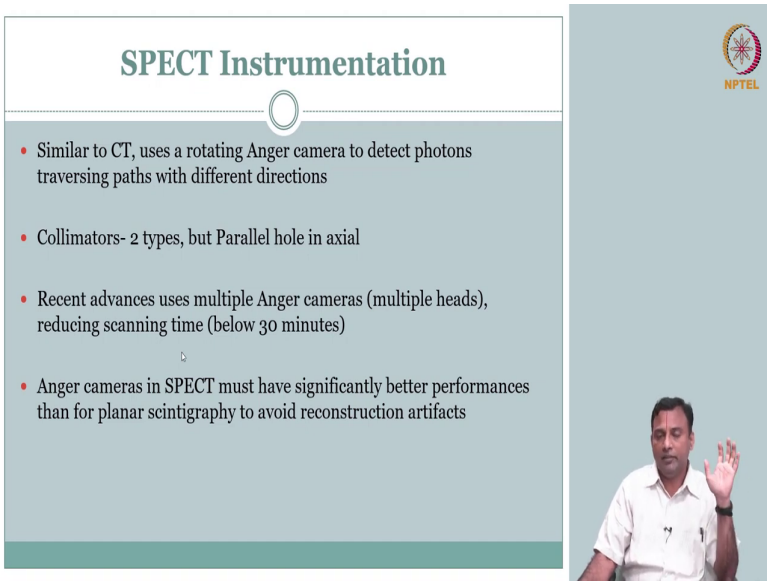

We did similar to CT. Here, you have a anger camera that is rotated and you get the photons gamma photons in this case right. We get it from different paths, because the radioactivity is sending in different directions, you move the anger camera get it from different locations and then we should be able to reconstruct it.

Here, because of the way it is done you have your collimators. Of course, we will think about this parallel hole collimator right, but you could also have your diverging right the other types that we talked about. So, you can think about having a fan beam in some sense. So, we will talk with parallel hole. So, that it is straightforward to what we covered in our X ray CT right at least the introduction material before we compensated it for fan beam ok.

So, we will do parallel hole. So, I showed you example of two heads. So, you could have more than two heads. Again, it is depends on. So, the radio activity per say unlike in your X ray projection radiography, the source you excite the source when you want. So, you move excite the source you move excite the source rotate excite the source whereas, here radioactivity is there inside the body you have prepared the patient. So, the radio activity is sent in different directions.

So, in some sense signal is coming on. It is how fast you can capture from different locations that is the key. So, you could have multiple heads meaning multiple planar anger camera at different angles and you could record. But you know typically in that sense you could think about having it full throughout the body, but usually what they found is there is a there is a trade off right.

So, it becomes very cumbersome very expensive to do all that. So, usually two head is reasonable, especially the configuration that I showed. You can make it flat 180 degree. So, you can do hole body scan with the same thing. So, there are essentially, it is brute force you know multiplication of the number of anger cameras. You can get fast recording right. At any particular camera, you are going to get the radioactivity based on how much time you are according that part does not change.

But simultaneously, you can record using multiple heads. So, that way your acquisition time; especially, if you want to do whole body and so on right. Your acquisition time can come significantly less, but our focus will not be on all those. Those are extension with brute force. We will be interested in saying how do we get one tomographic slice right one single photon emission computed tomography.

So, having said that the idea here is, because you are going to do the reconstruction, your camera here should be little more sensitive right. So, it has to be little more better performance than your planar scintigraphy, because you are using this as an estimate to you get a unknown right you are trying to get the source where it is radio activity is coming from. You are trying to locate the source where the radioactivity is coming from.

So, in some sense there are some minute details that had to be taken care, but we will not worry too much about that ok. We will worry about ok the camera collimator all that is fine tuned and therefore, how do we get this data what is this data how do we get the recon.

So, this is for your SPECT instrumentation. As you see there is nothing new here ok. You know the data that we get which is your anger camera you get the gamma rays detected. The anger camera we read in planar scintigraphy. So, from a instrumentation perspective, SPECT borrows heavily from your planar scintigraphy.

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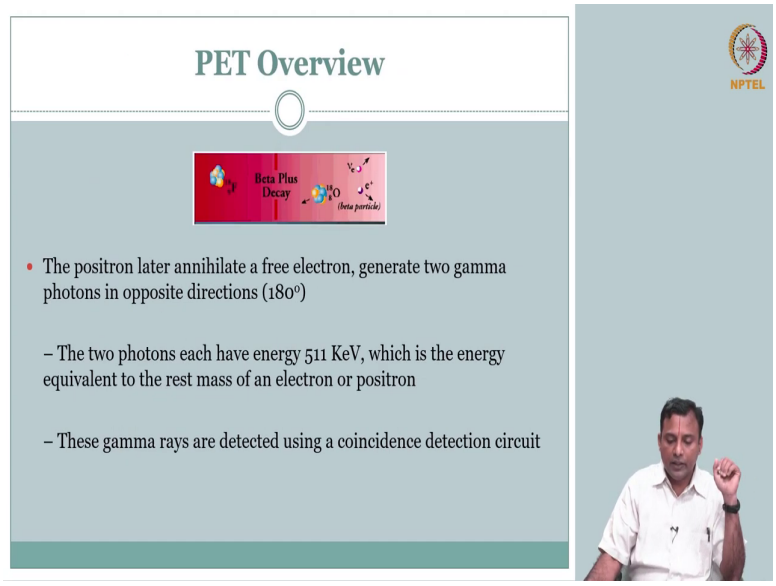

So, let us quickly look at PET also, that way we can get you to imaging equations we can make the differences ok. So, PET recall that here you have a positron, but in some sense, you are not really. So, we give the radioactivity and then there is this positron decay or a beta plus decay, but we are not really imaging the positron or we are not capturing the positron.

What happens is this positron annihilates when it moves it interacts with the free electron it annihilates there and therefore, you get this free two gamma photons. And the beauty about this is these two photons that are coming out, they are exactly opposite like 180 degrees in direction. So, they go in opposite directions and it also turns out to be you are talking about electron so, electron as a mass right and then a velocity. So, you can get an energy.

So, the rest mass right kinetic energy from that is half m naught v square. So, when you do that these photons that are coming also have you know the rest mass energy equivalent for an

electron, which is 511 kilo electron volt. So, the important detail in positron emission tomography is here also you get you are ending up detecting only the photons gamma photons; however, it has a specific energy which is 511 kilo volt.

And more importantly, there are. If one decay happens, you are going to record two photons at 511 kilo electron volts that are exactly in line that is exactly 180 degree in direction and that is a key information. So, you might think ok this is a gamma energy as well.

So, why cannot I just use whatever we did already single photon emission tomography instead of one camera I can probably have two anger cameras on two sides and then go about the same way. I mean say gamma photon. I know my gamma camera is there already. So, I could essentially do that along with that as long as we are able to right.

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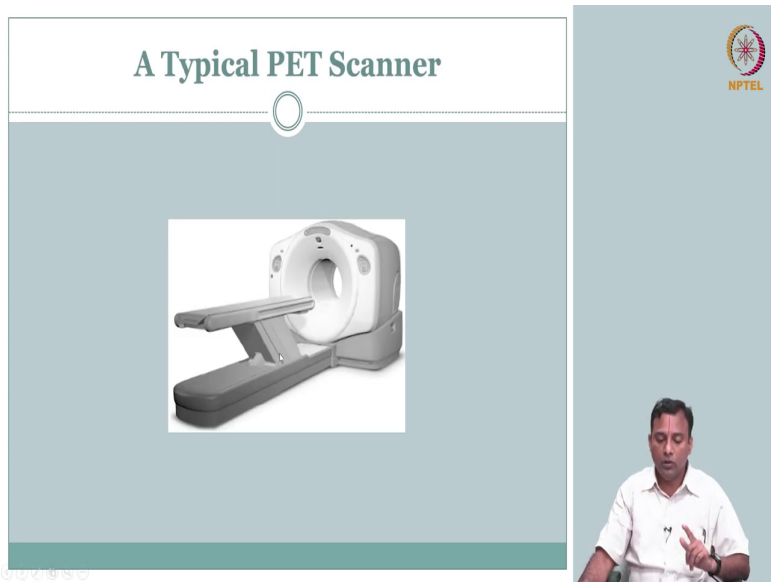

We can do that right you might imagine that. So, along with that if you can able to say when these two are hitting that is a information that we should probably use as well. So, a typical PET scanner looks something like this nothing much different. Everything is enclose its looks very similar to your say CT or an MRI. I mean at least the you have a bore right. You have a gantry and then the patient table can go in and come out.

So, very very similar, but what is inside apart from the detectors right we talked about there should be some way and mechanism to detect this 180 degree they come. So, they have a decay. They go in two different directions. So, if I catch photon in two different directions, is it simultaneous is it coming from the same activity; that judgment we should be able to do ok.

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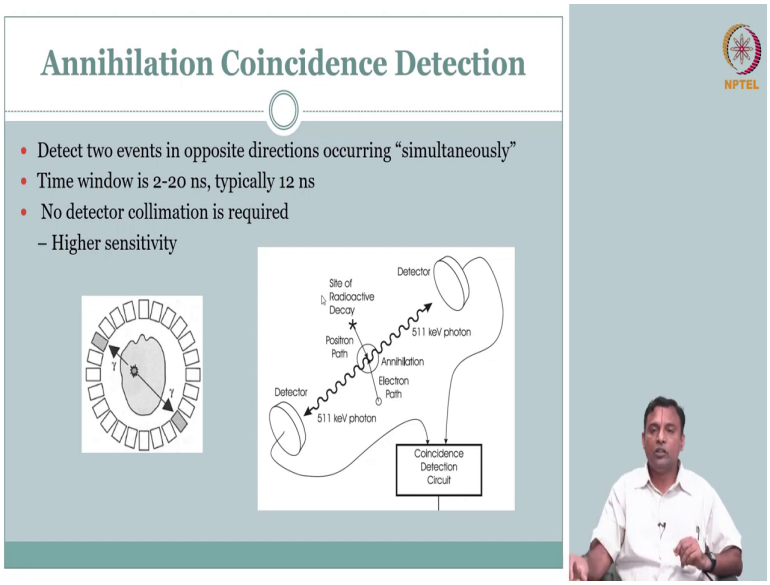

So, we talked about this we have. Apart from the detector and stuff, the important key feature here is the ability the positron itself gives rise to these two photons. So, the idea is from the

radioactive decay the positron comes out, but then it annihilates with then electron and you get two photons of 511 kilo electron volts.

So, if you are able to detect these two and you have a very good timer circuit when these two are getting hit right, then I may be able to say whether they are near simultaneous. If they are near simultaneous along the line that is joining the detector is where this activity has happened right. So, it is coincidence detection circuit. So, this is a very integral part an important part of your PET instrumentation.

And this is very important, because we are going to use this information to our advantage. And that information is if I get a activity, can I get another activity about the same time on the detector that is exactly 180 degree other side. If I can get that, then I know that activity has happened in the line right connecting through to the two detectors that much I can say ok.

So, you see the advantage here, the advantage unlike your SPECT when you use the you know anger camera, there you have to have you do not know the source. It can come at any angle.

So, essentially you had to have a collimator whereas, here. And therefore, what happened, because you have collimator, you also reduce the number of photons that are captured right, because your collimator is taking some and it is reducing in the spirit of reducing the Compton scattering. It also reduces signal right.

Whereas here, I do not have to worry about that. I can I do not need to have a collimator. I will let all the photons come and hit get detected. So, I can increase the sensitivity. After I detect it, as long as I can go back and say which one which two photons right hit simultaneously. If I can have a threshold, then I can say in timing. I can say these two are near simultaneous and therefore, they correspond to the same activity along the line.

So, in that sense I do not need to worry about my Compton scattering. So, I can remove the collimators right. So, detect two events in opposite direction occurring simultaneously. Of course, the simultaneous is what is simultaneous within some tolerance ok.

So, you can have an activity here. So, you have a detector. So, if you detect. So, you will have activities detected right. So, if you can go to the circuit and that is able to tell when these two happened right and if it so happens that it is within some shot, because simultaneous means it is not exactly the same there should be some tolerance right, because it is on different location slightly.

So, simultaneously is measured in terms of this tolerance in the window so, 2 to 20 nanoseconds. If you detect a event in this detector and you also detect an event in this detector right and they are within the small time window, then I will say probably the activity is happened along the line connecting these two.

So, now, because of this, I do not need to worry about my collimator. This circuit is going to help me get as much signal in the within the photons that are detected. What are the true photons that we want to worry about right that is made sure based on this window threshold ok and therefore, your sensitivity increases way better. Also, notice one another difference even here probably you could see.

So, you expect that there need not be collimator. So, if I am to use the same argument of SPECT you know planar scintigraphy, essentially when we came to SPECT, the same angle camera can be rotated. Now, instead of having only one rotate if I can have two of them and then rotate that maybe, I can you know detect simultaneously and then do the coins.

So, from a logic point of view that is fine alright that is what it is doing, but then there are key differences here. What are the key differences? The key one of the thing is your you want to do this so, that is fine you can modify that instrumentation, but then you do not have collimation. So, if I have to use the same instrumentation for SPECT right, then I have to take the collimator for one study put the collimator for another study; that is one thing and then.

So, then one inconvenience, but then that is the inconvenience, but then there the gamma can be any energy that is coming right. Even though you have the tracer, it has a energy that you are looking at it is coming. Still there is this Compton scattered one that comes at lower energy right. So, we saw about that z pulse and how we try to reduce that.

Here, you are very specific you are looking at 511 kilo electron volt that is coming right. You are not really a worried about the radio tracer per say right, you are looking at only one energy. So, maybe the detection part instead of using the same anger camera specification and the material where you had to have a host of different energies you know it has to be good so that it can cover different radio traces.

Here, I do not have to do that. I do not have to compromise on that. I know there is only one energy that is going to come which is 511 kilo electron volt. So, I do not need to really use the same say we talked about sodium iodide right with thallium. We do not really need to use you know a generic one that can be ready for different radio tracers.

I can actually get something very fine tuned for efficient for your 511 kilo electron volt. And therefore, what happens is the detector here, is slightly different, instead of using just the anger camera with one crystal which is of that the head that you saw right. So, big here, we could we could do little better, because of the known requirement.

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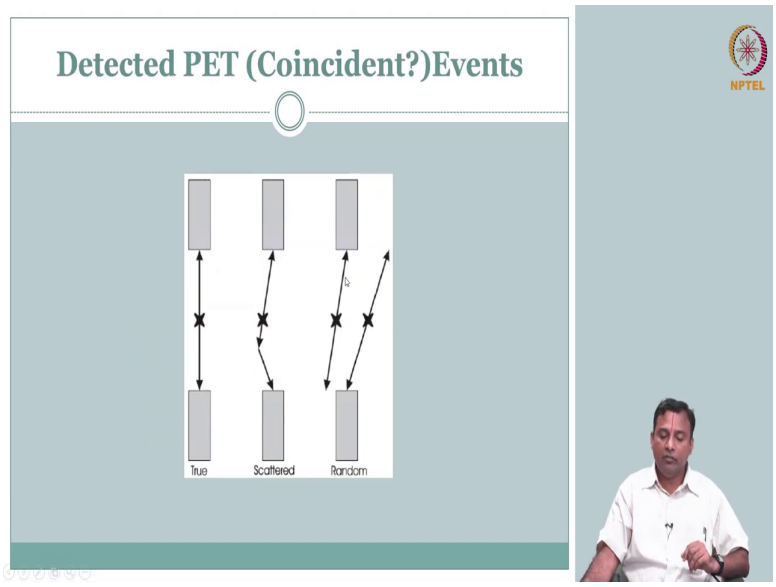

So, what we have identified is you have this coincident circuit. So, I need to be able to do this localization coincidence. So, there are three types of signals that you can get or activities that you can detect, but you are going to way only those activities which are true. What do I mean by true? I should have a another photon detected within that short time interval along the detector that is on the opposite side, only if this happens, then I that is a true.

You could always have. Here also, there could be some noise like for example, it could be due to scattered right. So, it is going there scattered it is coming here that is a possibility or this is actually going there some other activity is giving here. So, from your timing circuit so, this is kind of random.

So, from a timing circuit there could be random right. You are picking some other activity this is getting some other activity within the time interval that you have. We cannot do much

about that, but what you can do is these things you can avoid. So, if you have a scattered if it is scattered the energy is reduced.

So, at least the scattering that is happening within the crystal after it comes to the crystal right. We can reduce. So, when will that crystal you know how does this happen. So, we ok from the body is one story the other part that we saw when we covered anger camera is your crystal the thickness right you want the efficiency to improve. So, if you increase the thickness what is going to happen, you are going to have Compton scattering from the crystal right before it goes into the photo multiplier tube and get amplified.

So, at least that we should be able to reduce. How can we reduce that? Maybe, we can go for a thinner crystal, but if you go for a thinner crystal maybe it is not you know catching the gamma photon right. So, since we have coincidence circuit that is a blessing, but how can we reduce this probability. Maybe, we can go for a better crystal property that is very efficient at this particular 511 kilo electron volt.

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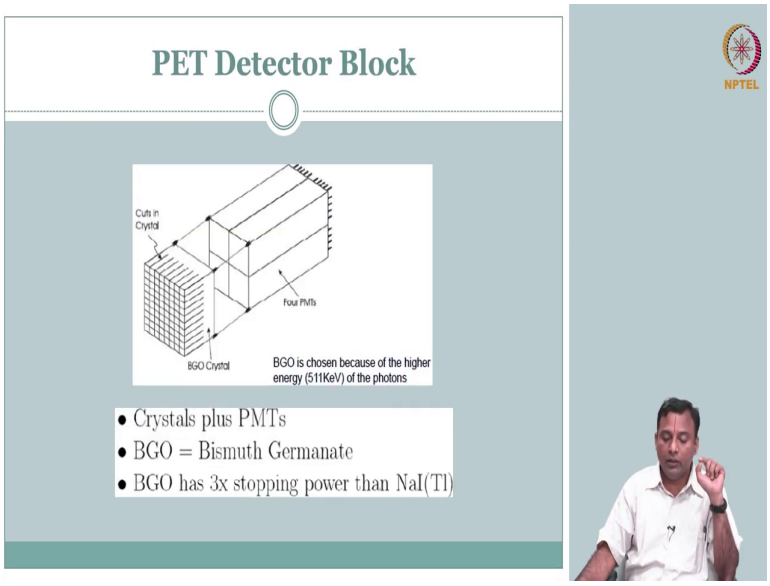

And therefore, here right here the crystal material is usually Bismuth Germanate right. So, here you notice it is very tuned for 511 kilo electron volt compare to your say sodium iodide right. Compare to sodium iodide, this has three times stopping power; that means, it can be thin one third right. So, it has its advantages you see. So, the idea here is principle is same I how we did for SPECT same gamma principle gamma ray detector.

But then, here it is fine-tuned only for 511 kilo electron volt that is an advantage that we can do. And that way the idea is if I want two crystals right if I want them to maybe intuitively, we might think why do not we have a small detector and many of them then maybe we can better localize, but then the challenge is the smaller we saw about the pixel signaled noise ratio right in nuclear medicine that will become a problem.

So, in order to avoid that what PET does is, it does take the advantage of both. So, it has one block. So, you have only one right you have only. You have a big detector constructed based on several blocks and each block you have these four photo multiplier tube. This is one block that is shown here ok.

So, this block is basically your crystal plus your photo multiplier tube. So, this is like your previous one this is like your previous one you have a crystal and then back of it you have your photo multiplier tube. And then we will use this idea of x comma y remember z pulse x comma y so that we can get our x comma y localized centre of mass calculation z pulse right.

So, you could use that your advantage and therefore, this is a nice combination you want to have single crystal, but at the same time you want to have better resolution. And therefore, here material is different and the configuration of your detector is also slightly different.

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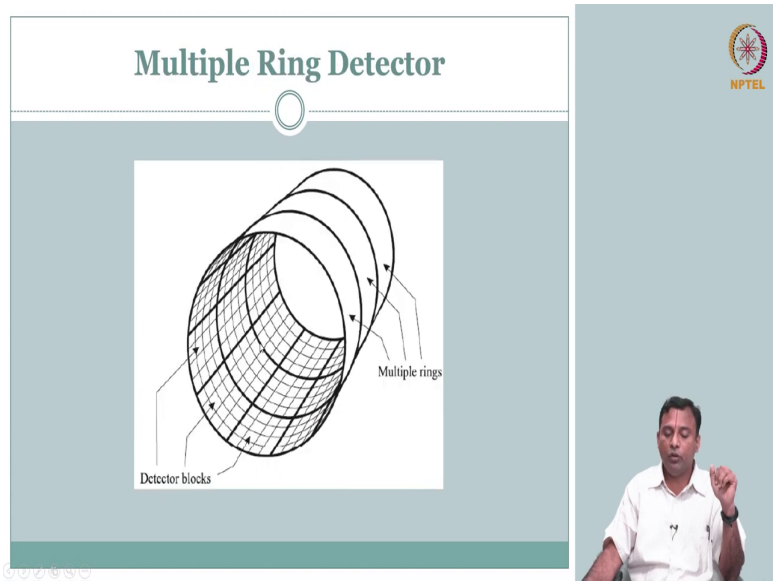

So, here we go for ring right ring detector, because you want to simultaneously detect you do not want to have some rotation and waste time. So, you want to have your ring detector, but in the ring detector if you have each of these crystals right in some sense cut and arranged like this that becomes complicated and you might lose your signal to noise ratio. So, what they have done is they have used a block.

So, this one block is one crystal; that one crystal has four in example shown we have four photo multiplier tube. And therefore, what is nice is you could be able to still localize within that crystal. So, you can get your good signal to noise ratio and better resolution, because you are able to correct for your x comma y and you have several blocks.

So, this arrangement provides multiple benefits for the reason that we talked that is one thing and then you notice in some sense that way you could see this ring right you could visualize

exaggerate visualize several slices right. I could get several slices so in fact, in one configuration if you really want only one slice right when you go one slice not to affect the next slice. You could actually have something in between like that can shield inter detector ok along these annular ok.

So, you have this idea that you have benefits of both; one single crystal block, but then you also have several different blocks; so that you could write several different blocks that will allow you to get more you can do 3-D volumetric or you can do planes that are stacked next to each other right you could do any of that ok. So, this is a unique configuration compared to the other two modes that we have seen in nuclear medicine.

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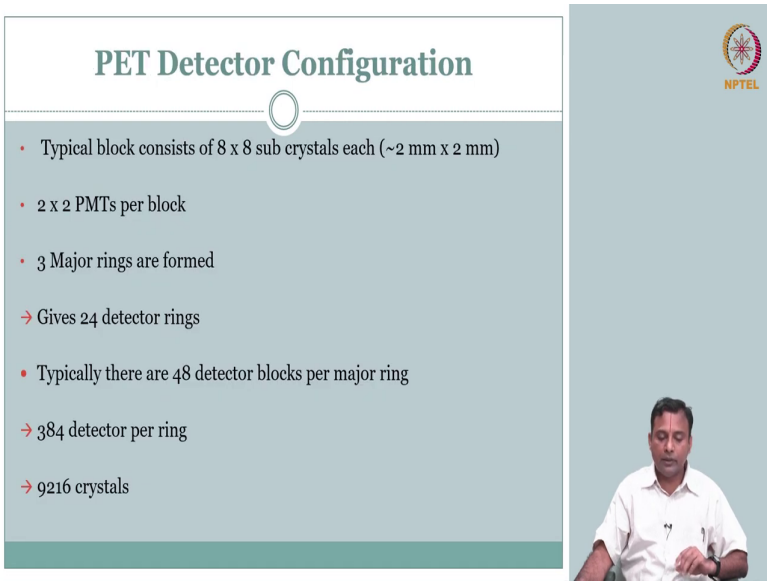

Therefore, typical numbers right. So, you have something like this. You have 8 sub crystals so, your each crystal is about 2 mm cross 2 mm, but then we are talking about several blocks

each block has 2 cross 2 photo multiplier tube. So, what we saw is 3 major rings are formed right that is based on the block, but if you look at the you know each one has 8.

So; that means, you can look at each block has 8. So, you can look at it as 24 detector rings ok. So, you typically there are 48 detector blocks per major ring so, along the circumference ok. So, this is involved intricate. So, the instrumentation is little more complex than your other two, but then here you can do a better job. You have versatility, timing right. So, you have lot of 384 detectors per ring and so many crystals.

So, now, otherwise the instrumentation the concept of what each one does is very similar to what we covered already in the planar scintigraphy ok. So, there is nothing more to the instrumentation part of it. So, once we are through with instrumentation. Now, we are ready. So, we know something happens the activity happens it comes and hits the detector. So, I can collect right on the detector. So, now, what do we need to do? First is recall our imaging equations and then do the reconstruction ok.

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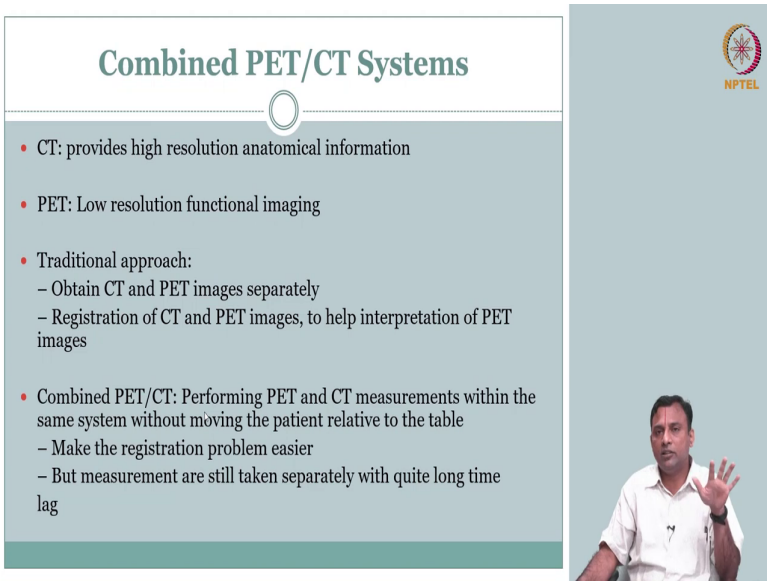

So, let us before we jump into that the just the while we are at instrumentation, it is also fairly common to have. Nowadays, you have what is called as PET CT remember PET is a functional imaging system whereas, CT as we saw is a good for structural imaging. And therefore, they found it to be very useful the they as in the clinical practitioners have found it to be very useful when you have both of them well registered.

So that you see the anatomy and the activity there; that gives them lot more insight into the problem that they are trying to clinical problem that they are trying to you know understand. So, there are PET CT instrumentations. First guess would be ok I have the patient get your CT, then do your PET and then we can register these two that is how that is the traditional approach ok; however, there are now systems which are integrated where you have combined

PET CT where you have both right so that the patient does not move from one location to another location.

So, the advantage of this is of course, you can make the registration problem very easy. This is very important, because especially when you are going to do some you know study where you want to see how the heart is behaving right there the heart is there you motion. So, you want to do it fast. So, it is prudent that you have it in the same location; that way it might be easier to do the registration.

Of course, you can do the reconstruction later. After you acquire the data, you could still go back where you can have some gating like we discussed. So, we could always do the reconstruction later, but at least acquisition can be done simultaneously or at the by the same location you do not have to move the patient to different instruments ok. So, with respect to instrumentation this is what it is. Now, let us get to our imaging.

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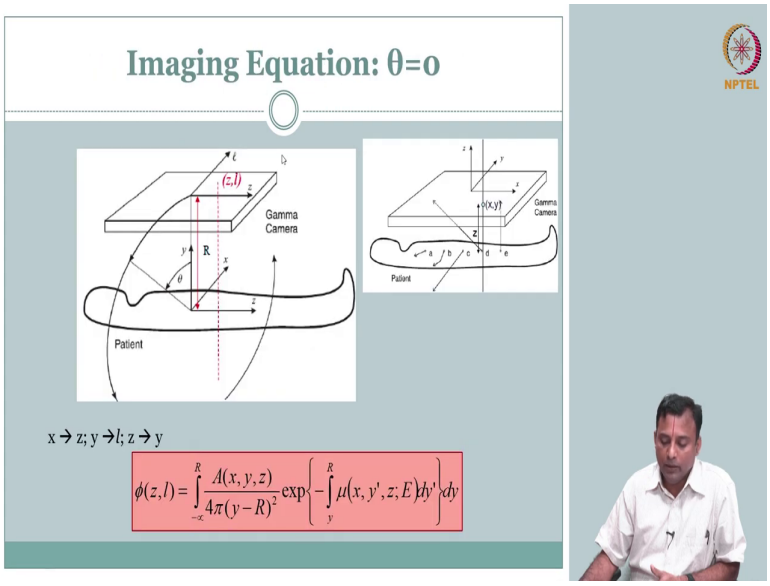

So, given this instrumentation you have detected. So, where is the patient? Here, is the patient. What do we want to see? We want to see tomography. So, axial slices is what traditionally right we are looking at so; that means, I have to first get my coordinate system correct. You will notice that in CT as well we did this coordinate system. So, it will be fruitful for us to make sure the coordinate here corresponds to the way we set it up for CT.

So, you have a iso centre where the patient is and then you have l comma theta was your data format if you recall from your CT X ray CT. So, here we would like to have a similar set up so, that we could quickly use the reconstruction algorithm that we already have. So, here is a setup. So, this is the camera is going to move around the patient. So, these are going to be your coordinate. So, you have your R distance from the centre of the patient to the detector right that is your capital R.

And you have this l z, z is going from head to tail. So, your you notice our imaging equation that we did for when we begin our gamma rays right. This is what it was we said the detector is here the gamma rays could come anywhere and notice here we were drawing this with respect to the detector system.

So, this was your y this was your x this was your z so, when we did this material from a detector point of view what is detected in the imaging the physics part in nuclear medicine. We wrote imaging equation in this coordinate system whereas, it will be proved.

And now, that we want to actually, because there the image was this plane right. There the image was your x y that is why we wrote it like that, but here what is going to be your image, your image is going to be through the patient it is a slice. In CT if you recall our image was till x comma y.

So, we would like to go back to have analogy with the CT and therefore, we would like the image the slice to be x comma y, whereas, if you take the slice here, it would not be x comma y right. It will be z y comma z. So, it will become inconvenient right we will get lost. So, what we will do is upfront. We will change the variables right coordinate system so, that we can get consistent with our reconstruction formulas that we did.

So, we will now write it in terms of this coordinate system the ISO centre and what we need to do then is from here what we had the imaging equation to what we want. So, that we can recon in x comma y we look at this and say this y is l right this x is your z ok and your z is your this direction right y.

So, we recognize this make the substitution x to z y to l. So, we have this imaging equation go back to our nuclear medicine imaging equation that we did in the physics part module. So, we had the equation already. All I am doing now is recognizing this coordinate system for your data acquisition. We are going to change the variables so as to be consistent with our CT x comma y, because here also our recon is going to be image is going to be x comma y.

So, it better represent the axial slice ok. So, this is the variation if you do that the same equation, I have just changed the variables. So, with this equation we got before. So, phi of z comma l is you have this A of x comma y comma z is your radio activity. Again, here we have not really changed much the radioactivity we have left it as A of x comma y comma z patient coordinate.

So, we will not you know we will not worry too much about it right now it is a 3-dimensional right. We leave it at 3-dimensional. So, we do not change the variables here. It is only the director that we have changed it in respect to this coordinate. And then you have your decay term right, because it is coming the radioactivity is coming from within the body it is crossing through the body.

So, body to the detector could have some attenuation ok. So, this is our equation just doing this substitution. So, what we need to do now is our objective is eventually to get transmission slices right, tomographic slices that means, A of x comma y comma z. I am not really interested the each different slice is different.

I want one SPECT image or PET image I mean is one slice. So, I just need to worry about x comma y. So, A of x comma y is what I want. I can locate at different z I can be at head or I can be foot that is fine ok. So, we will not have to worry about this variable z. We can make this plane which is what we will be interested ok. Imaging is what we have we are not interested in volumetric. We will do only slice imaging here ok.

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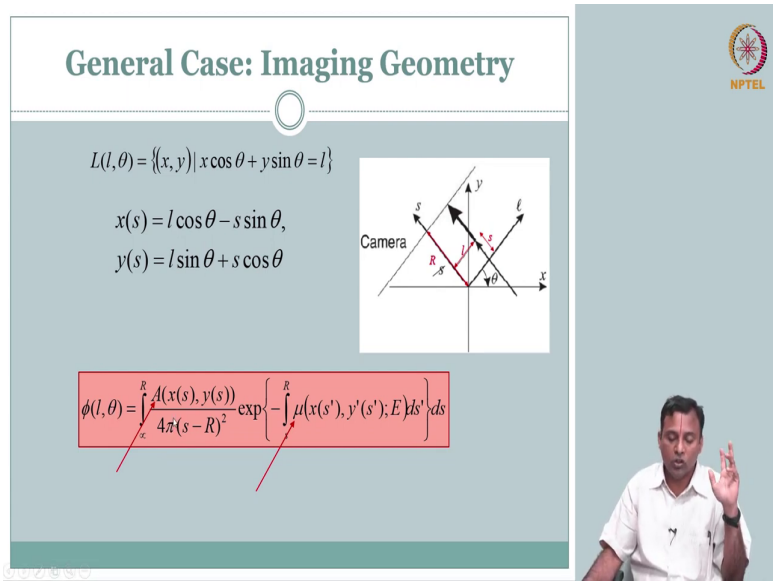

So, what we need to do is with this right with this case that we have. We should start to write our imaging equation. How do we do initially we know of looking at the system your L can be written in this parametric form right this is we covered this even when we did it the CT.

So, but then here what you notice is we want to vary. So, we could write it in terms of s. See what do we have right now is theta equal to 0 just to go back a little bit. So, we have your theta equal to 0, right. We have it, but when you. So, in that regards if you look at it, your what you are getting in the detector is integration through your y direction right, but if I take theta at some other angle it need not be right if you take at 90 degree.

Then you are integrating along the x axis clear. So, that is a subtle difference, but important difference here because unlike your CT where the source and detector moved around the patient. Here, the source is within the body only the detector is moving right. So, your line of

line integral if it at 0, it is going through your y direction whereas, if you go move around, it may go through some other direction so, this is not right.

So, we would like to write it such that we account for that. So, how do we do that? You have your l comma theta right. So, instead of writing that we will say we can write it in terms of s right in terms of s and therefore, you notice from here we could do this transformation.

So, at any particular theta we can start to write right this is your camera, so, this is your location. So, you are moving. So, which element that is along l correct. So, there is this l parallel lines how are they separated right. So, this is your l and at whatever angle your detector is located right. So, this is your theta. So, you can write it in terms of s right. So, x of s. So, this is another parametric form where you write it in terms of l and s ok.

What is this advantage? Now, we are not you know how it is moving around right. So, you do not want to write it in terms of y and x, because theta is changing you want to account for that. So, if you do that then we could substitute right in phi of l comma theta you could substitute these variations. All of this is substitution of your change of variables right within the limits.

So, you have your A of x s comma y s. So, we have dropped E z. As discussed, we will talk about only one cross section right. So, we have dropped z for that reason. Now, this is our imaging A of x of s comma y of s and exponential is coming through that ok. So, what do you have ok fantastic. I have this is my data that I am recording of this what is your known, what is your unknown this.

I can get rest of it I can you know R and all is fine, but the problem is I am I have to go after this guy this is what we want to find. We want to find the radioactivity along the line or along the slice, but what do you have? You also have another variable which is your mu.

See the whole of X ray projection radiography we talked X ray CT we were only going after this guy. So, we had this equation. We are going after only one unknown. Now, you have two

unknowns. I am actually interested in going after radioactivity I am not really interested in this. Now, I am interested in this, but this is also an unknown.

So, this is very tricky. How do you solve the problem right? Well, I need to have some additional information. If I can have additional information about this maybe, I can solve for this ok. So, you have two unknowns. Not only that the problem is there is also this depth dependent right you have R is this direction right R s is along the R. So, where it is located so, that there is a inverse square law that is effecting as well.

So, there are two problems here; one is I have mu which is an unknown and I have some factor here which is dependent on the which could contribute to the inverse square. I have a problem. I want this guy. How do I simplify the problem? If I have additional information to simplify the problem, then perhaps it is it will become tractable. Where is that information? Well, I mean you know it is easy to question, but when I am here what will I do ok?

What do I know before this? Well, ok I am starting out what is the easiest way. If I do not really know this mu, what can I say? Well, I am not worried about mu I do not know. So, I will pretend there is no mu ok. I will pretend there is no mu there is no body there is no distance attenuation that I will not worry.

I will just make my reconstruction based on what I activity that I detected is just based on the activity that is happening not accounting for the attenuation that it would have gone through. That is one ignore the mu is one solution. You will be surprised that is the that is the most commonly used approach.

Because given what it is still is reasonable that you are getting some information that you did not get otherwise right with the nuclear medicine functional imaging. So, they were actually able to live with this doing that approximation or simplification whatever you want to call it ok. Of course, if there is any other way that we can get our mu, then maybe I have my mu and therefore, the only unknown is going to be this. So, I can collect this from different l comma theta and do our regular CT ok

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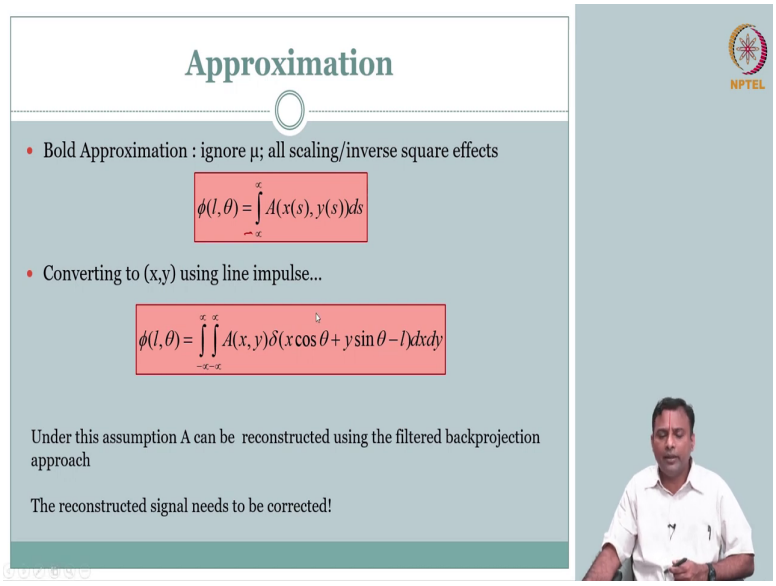

So, let us just look into first bold approximation. What is the bold ignore mu ok ignore mu and all these scaling inverse square law do not worry about that. See, you are not really going for any quantitative number, you are going for the high radioactivity, less radioactivity you know that is good enough that is the first level information that you are getting.

So, really you know these are details which are complicated, but it turns out this bold approximation still is very powerful and this is very useful; that is they are able to get a recon that is reasonable to do clinical diagnosis. So, if you do that what do you get, phi of l comma theta is minus infinity to infinity A of x s y of s ds.

How does this look? essentially, it is saying I am just integrating from minus infinity to infinity right along this object a of along this line A of x s comma y s of ds along this line.

What is your phi of l comma theta? So, this is what does this it is a line integral right. So, the along this line is projected onto this point.

Have not we seen this before right? You have seen this before this is your can be seen as your radon transform right. Only thing is we use g of l comma theta right that is what we used maybe you know, but otherwise, we already see there is nothing fancy about this. Now, we have radon projection I need to right I have a collection of I of l comma theta I need to get my A of x comma y right. So, how do I get my A of x come y?

First, is we can you know convert this to our x comma y using line samples you have it in s. In that plane, you want to go it in terms of x comma y you can use line impulse right. So, this is again the s to x comma y we have done this before as well ok. So, you can write this phi of l comma theta is A x y you have used the delta function to pick it that is along that line that is what was written here, right.

So, this is nothing if you look at this. This is nothing more than very similar to your g of l comma theta and here you had mu or f of x comma y if you really go back to the start of the CT this is your f of x comma y the ground truth object that you want to go after. This is your estimate of your projection g of l comma theta. So, given g of l comma theta measured g of l comma theta, you want to calculate an estimate for f of x comma y here it is A of x comma y right. After this there is no nothing is very similar to what you did before.

Subtle difference is of course, there are some scaling factors and then there your g of x comma y was logarithmic right you had i by i naught lan of. So, we had that g of x comma y had to be converted to that logarithm. Whereas here you do not have that, but apart from that, this is essentially what you collected this is what you want to get tomography.

So, you can end up reconstructing using whatever filtered back projection approach that we covered earlier ok. So, this is actually turns out to be very powerful and useful. Of course, if you say no, no I want to correct this, because this is I had a mu right this is disregarding the mu, can I do any better.

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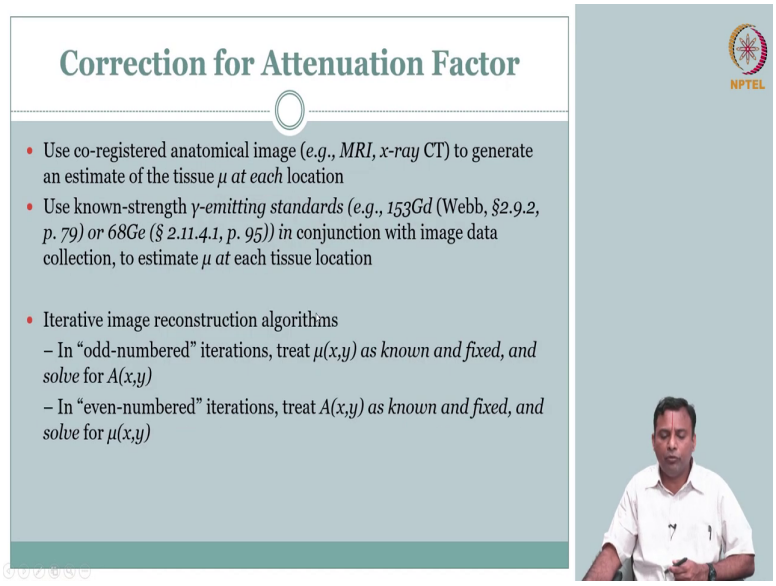

Yes, you can do better. There are few ways you can correct for that. One of the ways is you get a corresponding image from your x ray CT or MRI right. So, you can get an estimate for mu. So, if you get an estimate for mu, then you can get that you know roughly for each location. If you get that, you can use that information.

Or another way to do it is ok I will have some calibration way right use known strength gamma emitting standard and then collect the imaging data ok. So, I will have a known strength. The radioactivity is not inside the body. I will have a known strength and then some tissue and then your detector, then I know my known strength I know the path. I can get average mu ok.

So, I can do that that is one way of doing it. So, you have to get the information from somewhere else ok. It is a different experiment that you will have to do. Another approach is

iterative image reconstruction which is currently gaining much popularity, because all these computational advances right. So, we will guess make a initial guess right.

In one iteration, I will treat mu of x comma y as a known. So, I will have some guess start for my mu ok and then try to get my A, but I am not happy. So, once I get my A of x y then it next iteration, I will treat A of x y as a known and try to solve for mu of x y. Likewise, you iteratively do this until some optimization you say ok this is a threshold and which you stop iterating.

Because this is probably you know the A of x y estimate is close to your ground truth A of x y based on some error criteria ok. So, or your cost functions so, this is a popular way to do it, but like I said these are new majority. You can still get away with they getaway actually with disregarding mu ok.

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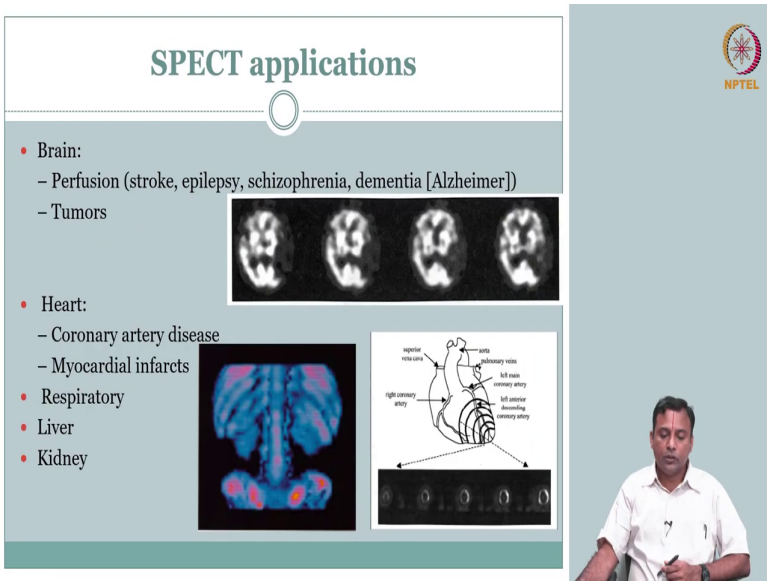

So, there are several application for SPECT brain. Again, brain is a active organ where me we always talk about cardio, but then brain is very important opportunity, because CT remember CT was it is in the skull. You have to go through the skull that why CT got popularity projection radiography especially for brain soft tissue ok. For brain was a challenge, because your skull would take all the pixels.

So, CT was very powerful to start to see inside the brain, but that is structural. So, we want to see the activity as well. So, brain is a very important functional aspect imaging for the brain is a important application tumors right. And the rest of it is usual suspects your heart, respiratory, liver, kidney right you could do all of this. So, this is quite popular.

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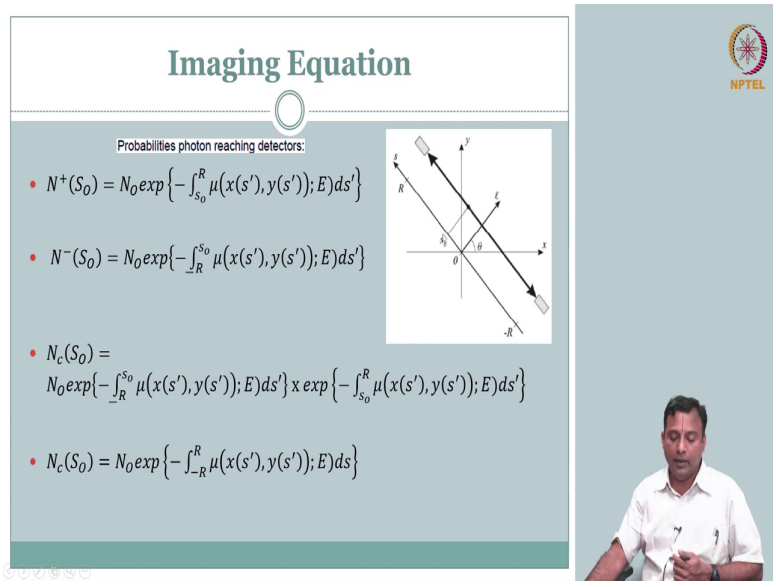

But more popular is your PET ok. We will see why PET. What is the imaging equation for pet? So, we know similar projection energy you get the data similar right the detector that part

is not much different. What is different here is the arrangement. So, we need to be make sure that we write our equations corresponding to the acquisition geometry for PET.

So, here for example, what you are doing you have your coincident detector. So, this is what we are interested we are interested in the line that is going here. So, how do we write this line in terms of l theta. So, along this line there is a radio activity that is happening. This radioactivity is happening.

So, you have this N number of photons right the gamma photon coming hitting here gamma photon going hitting here ok. So, before we jump in, let us see it is a probabilistic thing right. You get the your decay gives your positron, positron catches an electron and gives photon in two directions right 180 degrees apart, but it can be any direction.

So, it is a; so, number of photons that you detect is going to be having some probability right. So, what is the probability that the photon is going to hit the plus here plus direction right. So, probability a photon reaching the detectors right, because first is what is the probability that is going to hit this detector. We can get that we can get that as you have this radioactivity right N 0 is the one that is coming out.

This N 0 has to go through this tissue with attenuation mu. So, it is starting with s naught it is going till R right upper limit. Whatever loss is there is your mu of along that line for that particular energy clear. So, this is something that we knew from before nothing fancy. So, this has to happen right. So, this has to happen.

What should happen then what is the probability that it is hitting on the other side very similar N minus of S naught is similar thing only thing notice that your limits are slightly different. So, here we are writing instead of S naught R we have written it from R to S naught ok.

It does not really matter. This is along the line. So, the gradient takes care of it. So, if you can write it as minus R, then it will work out to be very similar. So, essentially what you are

getting hit here, what you are detecting here, has come through this line integral what you are getting here is come through this line integral ok that is what these two are same.

But the, but the important aspect here unlike your SPECT is see this S naught is arbitrary location right you do not know. You know along this line of along this line the activity has happened right, but the good thing about PET is, because of this coincidence what you know is this is along this line that is one good news.

The other good news is if I am to take this activity whatever I detect is something real right that is the object of that is the activity of interest then it has to be coincident. And therefore, what is the probability that you will have this and this probability of this is this one probability of detecting here is this one.

So, probability of this and this is going to be multiply this into that ok. So, this has to happen and this has to happen. So, quickly you notice. Even though it looks big the advantage is you have exponential into exponential you can sum the what is there inside the exponential right E power x into E power y is E power x plus y. So, if you do that what do you see? Essentially, these are same x of s is the line, but your limits have changed from R to S naught to S naught to R.

What does that mean? I have minus R to; S naught to minus R there is a minus R actually ok you can combine that you get the full path minus R to plus R ok. So, N c coincidental is nothing, but N naught the activity that happened there and exponential of loss over that path minus R to plus R.

So, now, you see the advantage. At least maybe you do not see it yet, but you can recognize already that this has this is a big deal. This is simplifying our problem little bit. All this multiplication that coincident criteria helped us get this limits which is from minus R to R.

So, in some sense what you are recording is total loss along the line here. We will see if you are not able to spot the advantage of this, we will see it in one more slide ok. So, this what we are. So, what is our real objective. Our real objective is not just N naught. This is the

probability with which you are going to get the activity detected. Our interest is you know detector is measuring this radioactivity.

So, you are catching these activity over time; that is your integrating say whatever the source is giving out this activity this photons you are catching those photons over time right that is your detectors job. So, we can write our imaging equation instead of N is the probability of getting hit, our actual data is integral of this right you are catching all the photons over time right.

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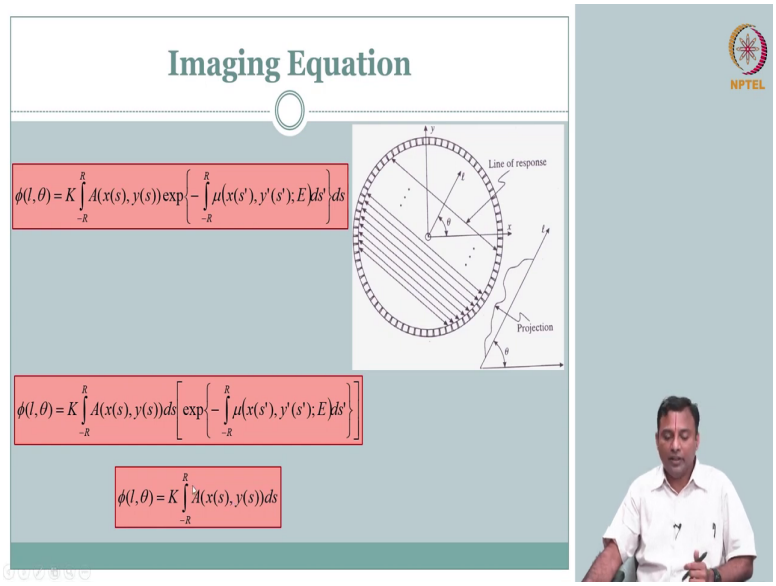

So, what you have is configuration like this right. You have your l theta and in particular theta. So, your these are the lines this minus R to R this is what we are catching right. So, in this configuration. So, what do we write our imaging equation phi of l comma theta right phi of l comma theta is nothing but, all the scaling factors, effect of geometry, effect of this that;

you can put here, detector efficiency you know all of that you can put here the some constant right.

But more importantly you notice you are integrating from minus R to R of A of x s y s right. Instead of N, I have expanded the two integral of this guy. Along with N we had the probability of detection right. So, there you had to exponential within minus R to R. So, now notice even though this looks two integral and this looks little complicated in SPECT also, we saw similar and we said this is an unknown this is an unknown.

So, we had a problem. So, similar problem we also have here, but one subtle thing that we could which is better here is your integral minus R limits minus R to R right. So, what we can do is this is not dependent on where the s is. See that is the beauty. This is not dependent on where the s is it is not the variable with s right.

So, wherever the radio activity that is does not matter wherever this mu, it is the integral through the mu right integral along the line from minus R to R that is important. So, we can separate this term right. So, you have a phi of l comma theta K of this ds only your radio activity term A of x comma y ds that is the thing this one is just the along the line of the whole object. So, what this why this is advantageous is, you actually do not have to know the two parts which part is more closer to one detector right that you do not really need to know.

All I am interested is in total attenuation along that line. If that I that much I know, I am good ok. So, you do not really need to know where along the line see remember. So, I could use the projection data I do not really need to know my mu along the line right, because this is full minus R to R.

So, I just need to know the projection of the mu that much I know. If I can get that problem is solved. Unlike your SPECT where you have to have you should also know the location of your mu. How the mu is distributed along the line x comma y you should know. Only then you can start one part the other part right.

Of course, here that is not the problem. So, what we can do is same thing we will pretend that your attenuation if you ignore for a minute right if you ignore, because it is not a variable here. So, it you in it is a factor. So, we will ignore that for a minute. If we ignore it, you just get phi of this guy you know this already convert this into x l theta right this s we. Similar thing that we did for SPECT just coordinates parametric form you get your phi ok.

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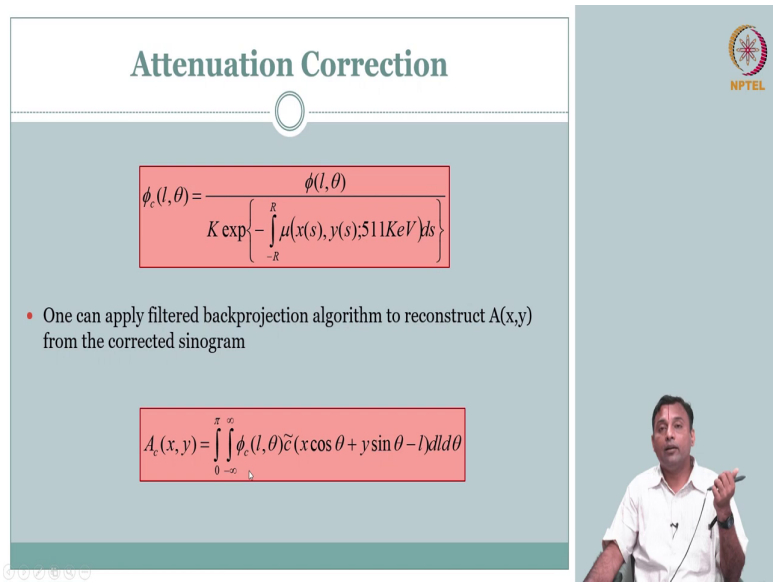

So, there is no big deal about this. So, you can do correction for attenuation here more elegantly than before. How do I say that? All I need is the projection. So, I can get that variable right. So, I can get my corrected phi as your phi and this term the K into exponential I know it is exactly at 511 kilo electron volt. So, I can do this I can get it. I am interested only in the projection.

So, what we can do is have a source outside along the line, get the detector or done or you can use your you know PET CT right we talked about PET CT is a very common thing. So, from CT you already have for the same registered patient right you have your CT image.

So, if you have your CT, you can always get your mu and get this integral. So, you can calculate this no big deal ok. So, after you get this, it is just the question of applying your filtered back projection. Very similar to what we have done before ok. So, you can write your corrected A of x commas. This is your tomographic image right of your radioactivity in x comma y plane right.

You get this corrected projection values. Nothing it is your typical filtered convolution back projection ok. So, filtered back projection convolution back projection is what is shown. You can use the same algorithm like before. So, only thing is how do you arrange the data correctly to use the same algorithm that you probably would implement right; that is the key here. Otherwise, really the details of the algorithm reconstruction is very similar or you understood the CT X ray CT it is a; it is a careful extension of that ok.

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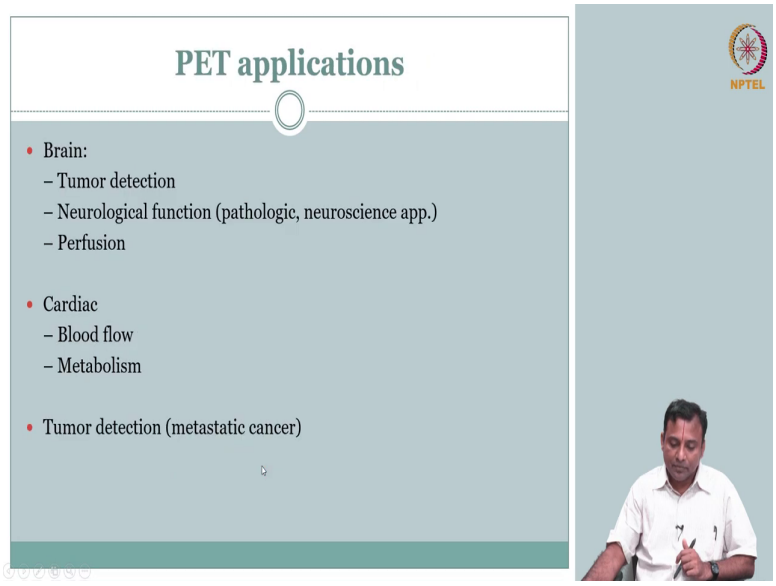

Likewise, PET has multiple applications not I mean same brain you have neurological neuroscience application lot of science questions on understanding of brain you kind of use PET right cardiac, tumor deduction, right.

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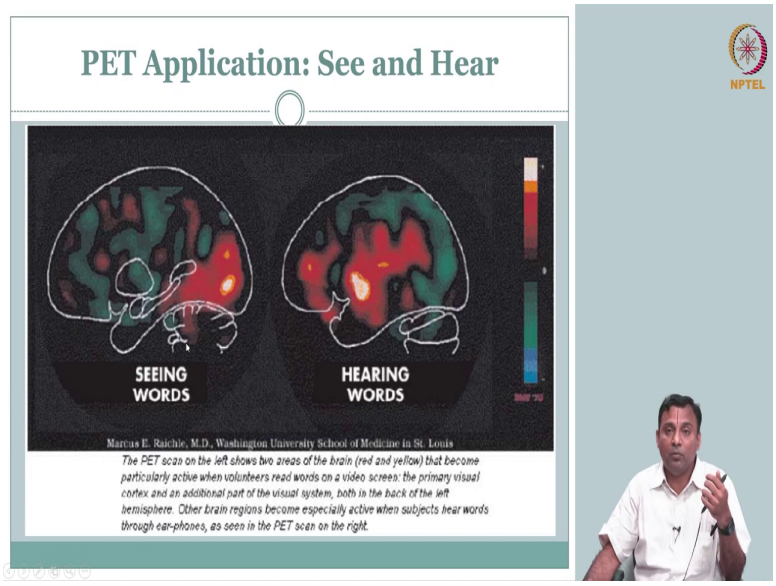

So, several interesting things just to reiterate that it is a functional imaging here what. So, here is an experiment image from an experiment where when a I mean a participant is shown right. So, he is reading from the text. So, when he is reading from the text your visual cortex right you are looking at it. So, your brain that controls your vision part that gets excited activated ok.

So, lot of activity happens here, associated with reading and therefore, this is lighted up. Whereas, the same thing if the same content if they are ask to hear through a earphone right they are not seeing, but they are hearing a different part of the brain is getting active. So, all these I mean this is a cool image right. So, it is borrowed from here, but the idea is you can you know functional imaging we said.

What are the insights that we can get here? You can give radioactivity we can see where high metabolic activity happens right. So, here when I am reading a different part of the brain is active, when I am listening a different part of the brain is active. I can actually see where it is ok.

So, these are very powerful very beautiful modalities from a functional imaging perspective. So, you do not see the brain details that much right, but then you can combine it with your CT and then you can have a brain CT fused with your PET. You could get both the information right ok.

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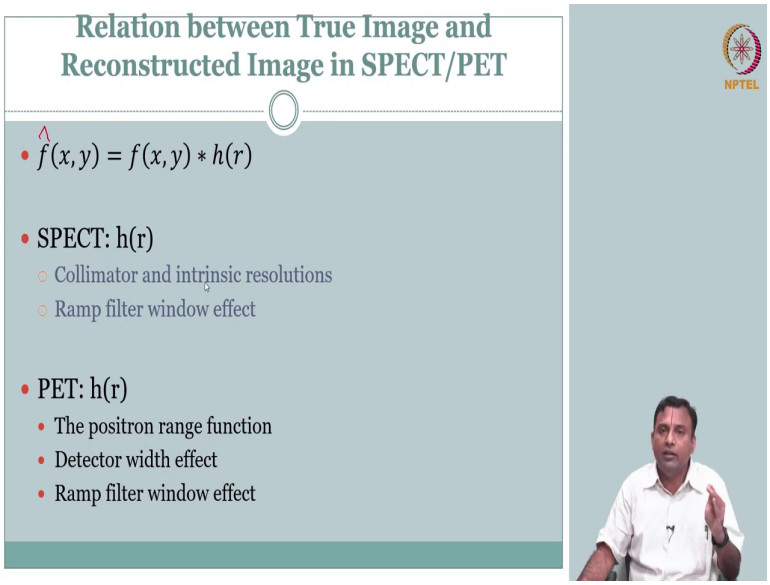

So, coming to the last part which is the image quality aspect we will not a spend too much time on this, because lot of image quality aspects that we saw already is direct carry forward. The only thing is here we talked about you know your collimator and then your detector part

that is the see acquisition is different right compared your planar scintigraphy you have multiple acquisitions and you are doing recon.

So, only where so, we can actually formulate this as your ideal image or there should be a hat here this is an estimate right estimate is your ideal image convolved with your h r. What is this h r? In case of SPECT, you have to include the response from your collimator and intrinsic resolution we covered this right.

Collimator and intrinsic resolution apart from that, there is this filtering coefficient filtered back projection that effect ok. So, that will come into effect. And in your PET, the positron range function that is a new thing that came. So, how your detection thresholds right timing window coincide that is the only part that is new.

So, that threshold could have an effect on the noise and so and also your resolution for that matter. So, your positron range detector width. Notice we kind of we do not have one big detector, we have a blocks that we have done. So, detector width effect of course, here also for ramp filter window effect will come ok.

So, nothing really apart from this is very similar to what we covered in our planar scintigraphy image quality; same thing carries forward here ok. So, I think with respect to nuclear medicine right. At the introduction level we have covered what we wanted to cover.

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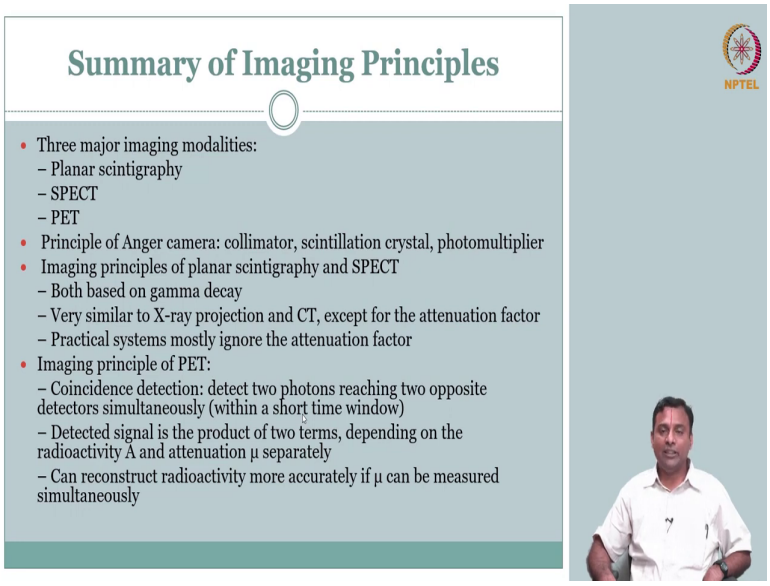

To summarize, we covered three major modalities within nuclear medicine. What are they; planner scintigraphy, SPECT, and PET ok all this we covered. What all we covered first we talked about the most important aspect that is new here is your anger camera, which had your collimator, scintillation crystal and then photo multiplier tube ok we.

Apart from that we talked about the imaging principle in planar scintigraphy and SPECT the recall right. We talked about how do we use your x comma y z pulse that is an important concept when we talk about anger camera ok apart from that. So, we talked about the imaging principle here. And then essentially, we argued here it is both gamma decay that is what we are interested.

So, for most part the T right SPECT the T is very similar to your X-ray projection that we did and X-ray reconstruction X-ray CT that we did. We could ignore the attenuation factor which

is routinely done right in most practical system attenuation factor is ignored, but we also see is see that it is an active area where you could do corrections ok. Likewise, in PET the important aspect principle of PET is here also you have gamma, but then the gamma is you have a positron.

It says positron emission tomography, but then it is you are not catching the positron directly. This positron annihilates and give a gamma at 511 kilo electron volt. So, you are catching the gamma ray at 511 kilo electron volt. When I say that catching you are catching two of them which are coincident that is an important aspect that is different here, coincident detection.

So, you have a threshold to say what is simultaneous and that will allow you from differentiating that activity that you think is legitimately from the decay that is along the line connecting the directors or is it some random photon. So, once you have that, you get here you can differentiate or you can segregate your A radioactivity terms and your mu terms that way you could correct here as well ok the.

So, simultaneously you can correct your A. So, you can get your corrected PET for corrected for your mu distribution ok you can get that from say for example, PET CT that we talked about ok. So, I think this provides a reasonable introduction material or nuclear medicine and how what is the physics, what is the instrumentation, what is the image reconstruction and what is the image quality as you would notice if you covered the first part right.

The recon in X-ray and physics in X-ray from there to nuclear medicine. We highlighted only the key differentiating aspects. Otherwise, this line of thinking about talking about physics capturing the instrumentation to engineer that physics for an application right, then your imaging equation and then your image quality is very very similar ok. Let us stop here. Now, we will move out of the radiation and get into non-radiation, non-ionizing radiation based imaging modalities.

Thank you.