Medical Image Analysis
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Lecture 05

Radionuclide Imaging

Hello and welcome back. So, in this video, we are going to look at Radionuclide imaging, sometimes also referred to as nuclear medicine. So, this will kind of officially conclude all the radiologic imaging systems that you generally would run into.

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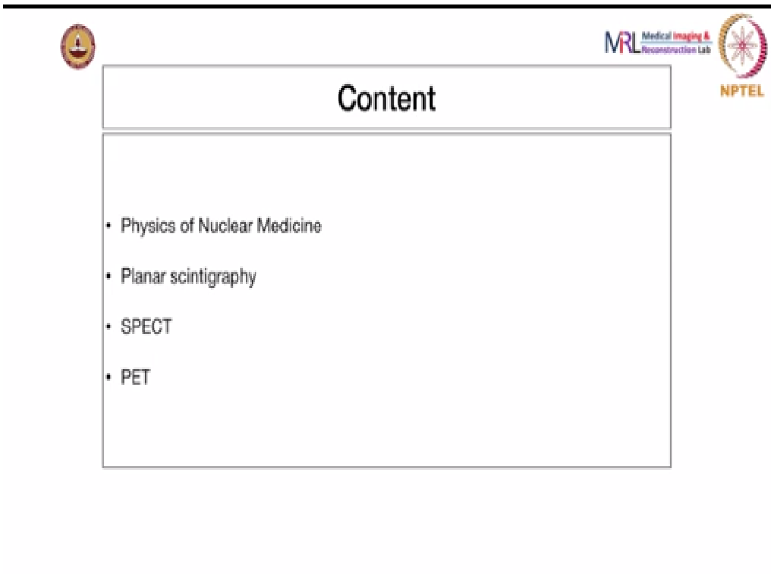

So, here is the overall content, we want to look at the physics of this particular modality. And briefly look at, planner scintigraphy, SPECT and PET, these are the three different imaging modalities which come under radionuclide imaging or nuclear medicine.

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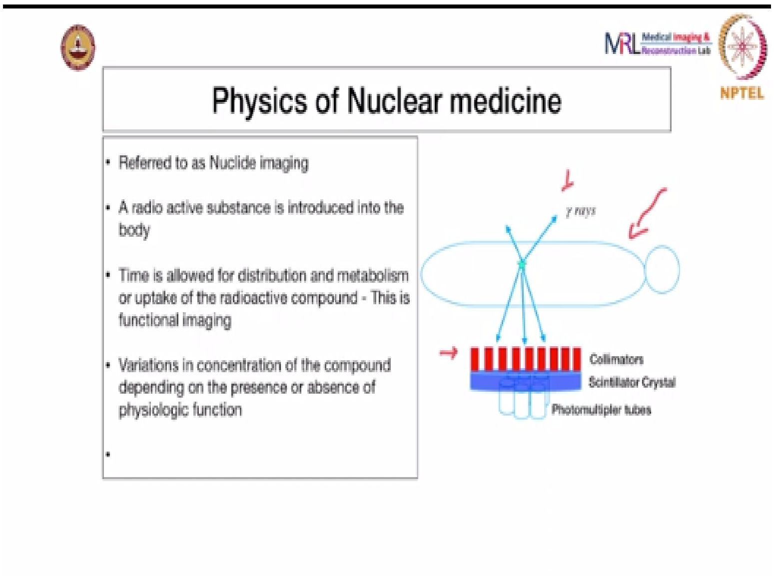

So, what is the physics of nuclear medicine? So, this set of imaging modalities that we are going to see, they are collectively referred to as nuclear imaging or radionuclide imaging. and which basically involves a radioactive substance being introduced into the body and then you allow for some time for the body to take up these substances.

So, this is why this particular imaging modality is referred to as a functional imaging modality because the tracer actually interacts with the biology, there is a biological interaction between the tracer and the body also the physiological interaction if you can call it. So, which means that more than the anatomy itself like previously we are looking at even with CT, MRI, or ultrasound, you are mostly concerned with the structure.

So, you look at anatomical structures, or there are different contrast mechanism, especially in MRI that we have seen. But in this case, it is mostly or this is functional imaging, basically, we are trying to do what is called physiological imaging. And how do we do that and we it is accomplished by looking at variations in concentrations of the radioactive tracer, and that then, the hypothesis is that the variation will indicate that something is wrong.

So, for instance, there is an isotope iodine that is used for imaging. Iodine is readily absorbed by the thyroid gland. So, any radioactively tagged, any radioisotope of iodine would normally go and get accommodated in the thyroid glands, which will give you an indication of how good those glands are working. So, this is the, one of the very simple examples of how you would do, you would use radiotracers as they are called for imaging purposes.

So, on the right the picture shows a typical imaging system. So, we have the, if you can call it, we have the patient here, and then we have injected the patient with the radiotracer or the radionuclide. And it has gone and accumulated somewhere in the body, and it emits most of the time. In fact, all the time, the preferred choice of imaging is gamma rays. So, the gamma rays are basically high energy X ray photons.

So, if you can think of it as similar to X ray high energy photons, and they are typically more energetic, since they have the same or similar energy. So, for instance, 140 KV is a typical energy. And outside the body, we have a bank of crystals, collimators and behind (with) there is a scintillator crystal. Scintillator crystal traps these high energy particles that are emitted and added and there is a canvas set into light which are detected by photomultiplier tubes or photo diodes.

Now, there is a big difference, I mean, between this and the other modalities that you have seen so far. It is just that, you see the source quote unquote, if you can call it that, it is actually inside the body, that is a big difference. So, if you look at all the other imaging systems, there is usually a deposition of energy either in the form of radio frequency or, in the case of MRI or an X ray source outside the body or an ultrasound basically sound source, ultra sound source.

So, all these are outside the body and then it travels through and then we sense it outside again. So, in this case, the source of radiation, the source of radiation, that is whatever we are sensing actually comes from inside, but we have injected it, and then the idea is to localize and measure it. So, this is the typical setup for all radionuclide imaging including scintigraphy, planar scintigraphy, SPECT or PET.

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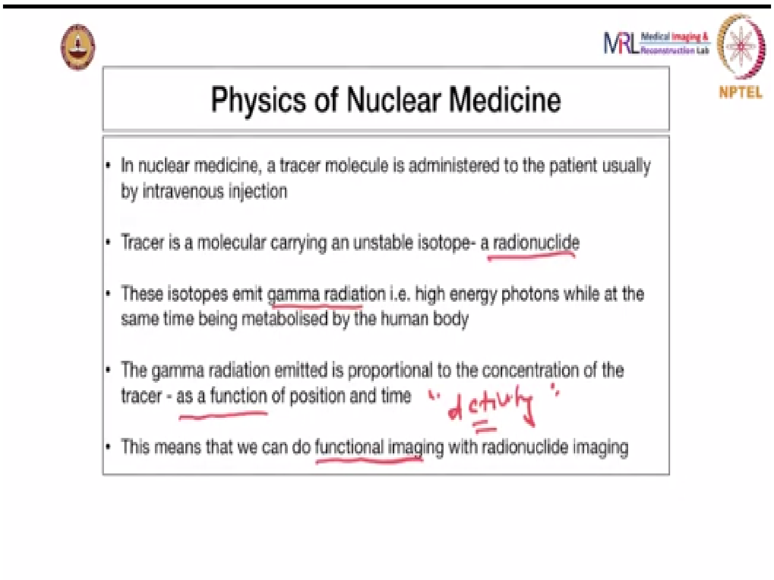

So, just to summarize again, in nuclear medicine a tracer molecule, we call it a tracer molecule or radiotracer is administered to the patient by intravenous injection that is typical. And what is this tracer? It is basically a molecule carrying an unstable isotope, it is basically a radionuclide. And typically, these isotopes emit gamma radiation that is high energy photons, while at the same time being metabolized by the human body, that is what I meant.

There is a physiologic imaging happening here rather than just the anatomical imaging. The gamma radiation emitted turns out to be proportional to the concentration of the tracer. And which can be then the emitted radiation is recorded. And based on the emitted mean photon count, we can estimate the concentration of the activity. So, we are not exactly doing the absolute concentration, but something known as the activity concentration.

So, it is not just the concentration of the substance itself, but rather something known as the activity concentration is what is measured. So, activity concentration is measured. So, this we can actually show using simple mathematics but just to give you an example. So, for instance, when you are doing X ray imaging, basically, let us say sorry, CT, what you are measuring is the underlying quantity you are measuring is the linear attenuation coefficient.

The attenuation coefficient is what you are trying to measure, when you and that the attenuation coefficient typically turns out to be proportional to the or depends on the atomic number density of the element. So, in this case, what we are measuring even though we will be counting the gamma radiation, the number of photons in the gamma radiation, the mean photon count is recorded typically, using that what is being projected as a main proton count is something known as the activity concentration, which in turn gives an indication of the actual concentration of the radiotracer at that particular tissue location.

So, we (will) mentioned we will measure this as a both as a function of position and time. So, this entire system, all the systems that we have seen, like I said before is known as functional imaging rather than anatomical imaging.

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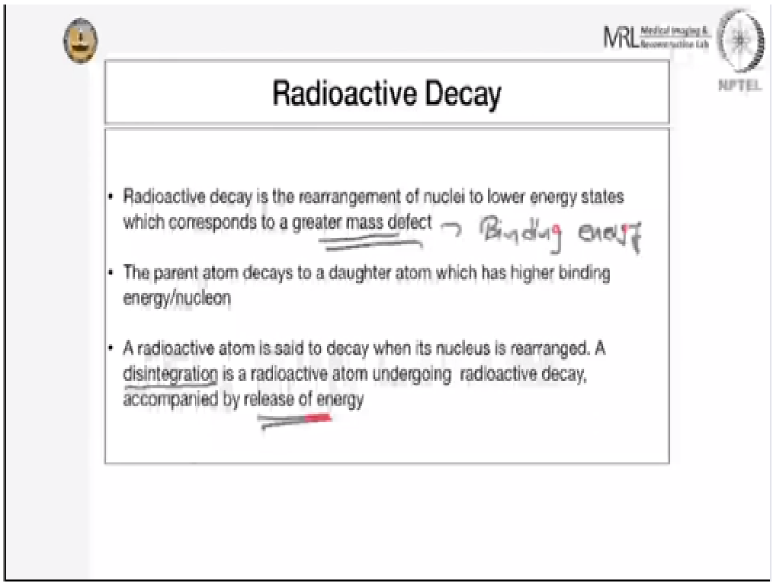

So, just a primer on radioactive decay and so, radioactive decay is the rearrangement of nuclei to a lower energy state. So, there are some nuclear which are inherently unstable. And these nuclei tend to go to lower energy states, again this and this lower energy states corresponds to greater mass defect, this again comes from the physics of radioactive decay. So, basically the sum of the, so the parts tend to be less than the individual sums.

So, if you look at the, if you calculate the mass of the protons and neutrons of an atom and then you actually measure the nucleus of the atoms that weight tensors will then be a difference, so, that difference is known as Mass defect. And so, usually we are trying to lower energy states which have greater Mass defects. So, but we do not have to worry about this right now, just to understand the root of the instability of these radioactive nuclear or radioactive atoms.

So, typically, the parent atom, the atom that decays is called the parent atom, it decays to a daughter atom, which has a higher idle binding energy per nucleon. So, the Mass defect translates to something called binding energy and so this binding energy is the higher upper nucleon if we are in the daughter for the daughter atom, so that is basically a transition to a much so called lower energy state or a stable state.

So again, these are the terms that go into describing radioactivity. Radioactive atom is set to decay when the nucleus is rearranged. So, if you have done rearrangement of the nucleus in terms of its atomic number, or mass number, then it is called radioactive decay. And there is also a terminology use which is usually you will see it is called disintegrations.

Disintegration is basically a radioactive atom undergoing radioactive decay. And usually this radioactive decay is accompanied by some release of energy, which is of course, what happens in some cases like the release of energy is in the form of gamma radiation which we measure.

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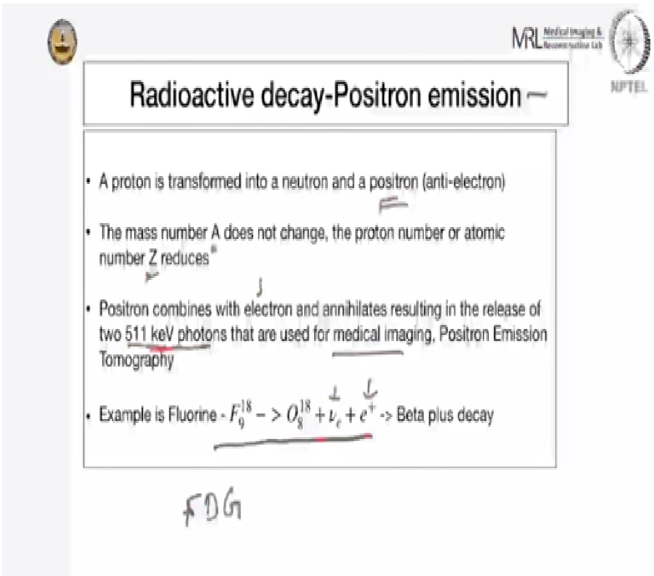

So, there are two several types of radioactive decay. So, we will look at two which are commonly used in nuclear medicine or in radionuclide imaging. So, the, one of the modes of radioactive decay is through Positron emission. So, in this case, what happens in the atom is that a proton transmutes into a neutron and positron. Positron is nothing but the antiparticle of an electron, say mass of the electron opposite charge. The mass number A does not change.

So, A typically refers to a mass number and Z refers to the atomic number. Since the proton is transformed, the proton number reduces. These positrons combined with electrons. So, when these are emitted, they combine with the nearest free electron, and they anile it and they add ends up in the release of two 511 keV photons. And this actually is used for medical imaging.

So, this is what is used in Positron Emission Tomography, because whatever you inject the radiotracer you inject into the body for positron PET imaging, it actually emits positrons which then combined with nearest electron and then release these two 512 keV photons which are detected. So, this is one radioactive emission route which is used in positron emission.

So, for instance, one of the examples of positron emission is fluorine disintegrating into oxygen, this is called electron neutrino and the positron here. So, it is called a beta plus decay, this just for sake of illustration. So, there are a lot of radioactive compounds or radiotracer, which emit positrons, handoff of all found favour in for instance, in PET.

So, one of them that you will come across often, that is used as the fluorine radioactive fluorine, and it is used as fluorodeoxyglucose. So, what happens is that they will replace the oxygen in glucose with fluorine, and then inject into the body. So, what happens is, typically, the hypothesis is that tumours have higher metabolism, so they will uptake this fluorodeoxyglucose.

So, they will uptake the glucose much more than regular tissue. So, a lot of the FDG that you inject will end up in the tumour tissue, but remember that the fluorine is radioactive, this is reactive, this is the radioisotope fluorine, it limits positrons. And then you will be able to measure whether a particular tissue mass is actually a tumour or not based on the accumulation of this radioactivity there. There is just a nutshell as a general principle of how you would do Positron Emission Tomography.

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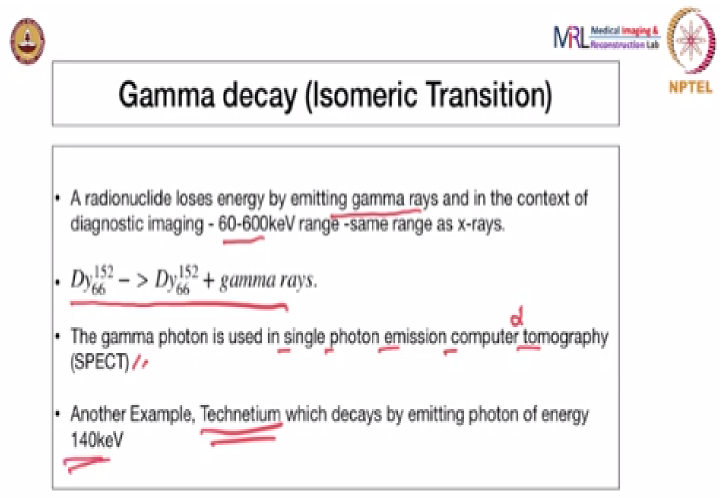

The other means of radioactive decay is gamma decay, also referred to as an isomeric transition. So, the radionuclide is inherently unstable, but it has no transmutation; it just goes into a lower energy state by emitting gamma rays. And in the context of diagnostic imaging, about 100 to 600 keV, the same rate, so, gamma ray is nothing but high energy, high energy photons, X rays are also energy photons, except that they have just correspond to different energy ranges.

So, this is one element, which is the example which undergoes a decay by just emitting gamma rays. So, this particular kind of isotope which emits gamma rays is mostly used in something called the Single Photon Emission Computed Tomography. But typically expected SPECT S-single, P-photon, E-emission, C-computed, T-tomography. So, it is usually the acronym SPECT.

So, this kind of imaging systems, gamma ray emission are used. So, each of them will have a slightly specialized hardware. So, we will look at them briefly when we, when you get there. So, for instance, as SPECT imaging, technetium is often used, this is used widely, for instance, even for bone imaging, as well as cardiac imaging. So, most of the imaging that is done with SPECT this involves technetium. And technetium decays by emitting gamma ray photons, and the emission energy is about 140 keV.

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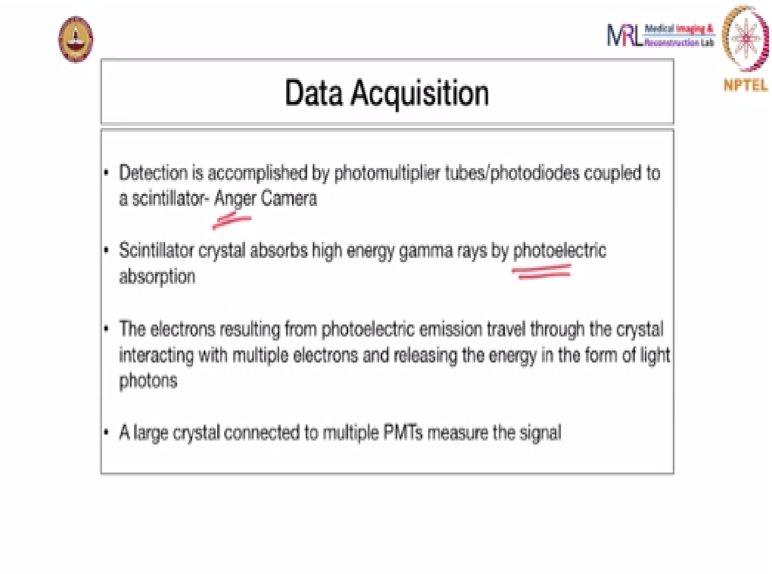

So, how do you acquire data for radionuclide imaging? So, just to summarize what we have seen so far, this involves basically injecting radiotracer into the body, the hypothesis is that radiotracer will go and accumulate, preferably in certain regions corresponding to the pathology. And so that is why it is called functional imaging.

And you, what you have to do is, but then, of course, remember it is radiotracer, because it is in actually, when you say radiotracers, it also means that it is in very small quantity, you cannot inject a lot of radioactivity in a person, you will of course, cause damage.

So, you have very, very small amount of radio tracer is injected and they accumulate and you measure the emitted gamma rays for instance, if a SPECT or high energy photons in our 212 keV photons in case of PET or inferences or gamma rays in the case of planar scintigraphy we will see that.

In all three cases, users just try to measure the number of photons which are exiting the body due to the emitted radiation. So, this detection of the emitted gamma rays is accomplished using something called the anger camera or we also call it the gamma camera. The anger camera is the name of the person who invented it. anger is the name of the person.

So, the basically consists of a collimated up front we saw in that picture of the illustration a few slides ago, and, and behind the collimator is a very large crystal scintillation crystal which will convert this high energy incident gamma rays into visible light.

And the visible light output is basically measured by an array of photoelectric photomultiplier tubes of photo diodes. So, it is typical, for instance, what we will see is known as planner scintigraphy or even for SPECT is a large crystal very fairly large crystal connected to multiple photomultiplier tubes. So, how does the scintillator convert to light?

So, this is basically through photoelectric absorption, so the scintillator absorbs the higher energy gamma rays, optical absorption. The electrons resulting from the photoelectric absorption travel through the crystal and in their interactions with multiple electrons, they release energy in the form of light photons.

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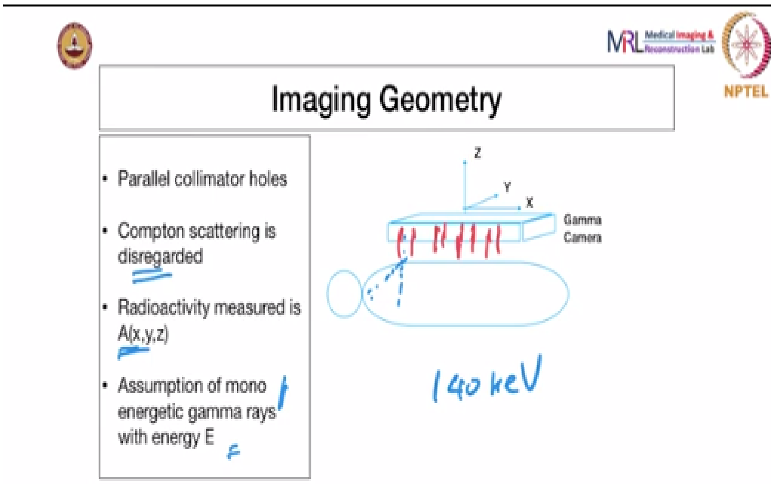

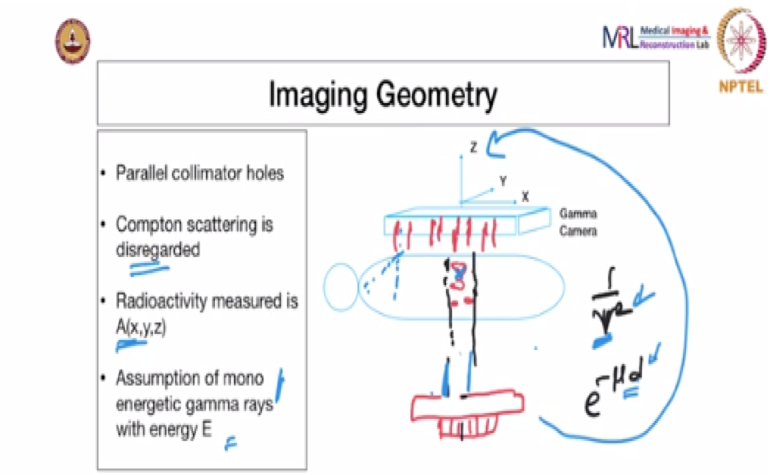

So, the imaging geometry is shown here. We will have parallel collimatory holes, so I have not shown the collimated recall here, you can see that something like this, a bunch of, lead shielding kind of, array which sticks out of the detector, out of the scintillator. It is much longer here, you can think of it like that. So, the collimator holes make sure that the gamma rays that are hitting the scintillator come from a specific direction.

So, you cannot have, for instance, if you, you cannot have something from here hitting it, you will be stopped by the collimator. So, everything is only in a straight line, it is. So, you are making sure that the measurements that you are getting come from a specific region of the tissue and not from everywhere in the body, let us say you have no collimator, there is a lot of scattering of the emitted radiation also possible so you will not be able to localize.

So, the collimators are helped to help localize and the other aspect is compton scattering can be disregarded. This is again from an energy point of view. Because the emitted gamma rays are 140 keV let us say for instance, 140 keV. The Compton scattered once they tend to be slightly lower energy. So, there are ways of disregarding those signals. So, Compton scattering is done away with.

What is measured is the (raid) a activity, activity concentration, which is also denoted by A not to be confused with the atomic mass number A. And of course, we also assume that the gamma rays are more energetic, which is true mostly. And what happens in the case of planar scintigraphy is you will get a picture just like X ray projection, we will see that in the next few slides we had here.

So, I will just one second, let me just whip this out. So, I am going to draw it on the other side so that it is easy. So, if you have a collimator here, so you have a bunch of let us say, I am going to draw with a slightlys different color, get a bunch of radioactive compounds here, they may have different concentrations, may be the same concentration, it does not matter. So, the signal you will be getting, so the scintillator is here and then you have a bunch of, let us say, the photodiodes are here, or the photomultiplier tubes are here.

So, the signal you will get, this restricted for particular, this collimator is restricted to this, let us say this, this projection on the body, but this is depth. So, you can be sure that whatever measure, signal that you are measuring here, the number of which is basically the number of proportional to the number of gamma rays that hit this particular dot spot in the scintillator, they are all restricted to this very small cylinder of tissue inside the body.

But then, depth resolution is kind of difficult to do and there is one more problem, there are two types of attenuation that happens. So, for X Rays, there is only a linear attenuation, but here, there is also an 1 over r square attenuation because radiation is emitted in all directions. So, it is not like radiation is preferably emitted along the direction along the, towards the detector. So $1/r^2$ there is a 1 over r square fall off in the flux of the radiation.

Also there is an attenuation, the $e^{-\mu}$, the depth. So, those two are always happening when you do this radionuclide imaging. The other aspect is seeing X ray for instance, if you can see that two projections acquired 180 degrees apart are the same, because the path travelled by the X rays will be the same, however this is not true. So, if you have, let us say, a radioactive compound somewhere here.

If you measure using a camera on one side of the patient, the activity that you measure will be slightly different from the activity that if you measure it from the other side, that is basically take a measurement from here, from this side. Let me draw it properly from this side, and then let us say you rotate the camera around the patient and you take a measurement there.

So, because there are two sets of attenuation side, one is dev 1 each one of them dependent and 1 or r square is basically dependent on the distance to the camera. So, this depth dependence it comes from this d is inside that issue, this is distance to the camera. So, if you rotate the camera, both of them change.

So, there is a depth dependent attenuation and distance to the camera attenuation, both of them have to work when you do this gamma, gamma ray imaging, or radionuclide imaging. So, but having said that, having said that, so we just for planar scintigraphy, the detector is translated across the body of the patient.

And at each point you record the amount of gamma ray photons being measured. And in turn, they can be related directly to the activity concentration or the number of disintegrations per second if you can think of what happens inside the tissue at every location. So, this is planar scintigraphy.

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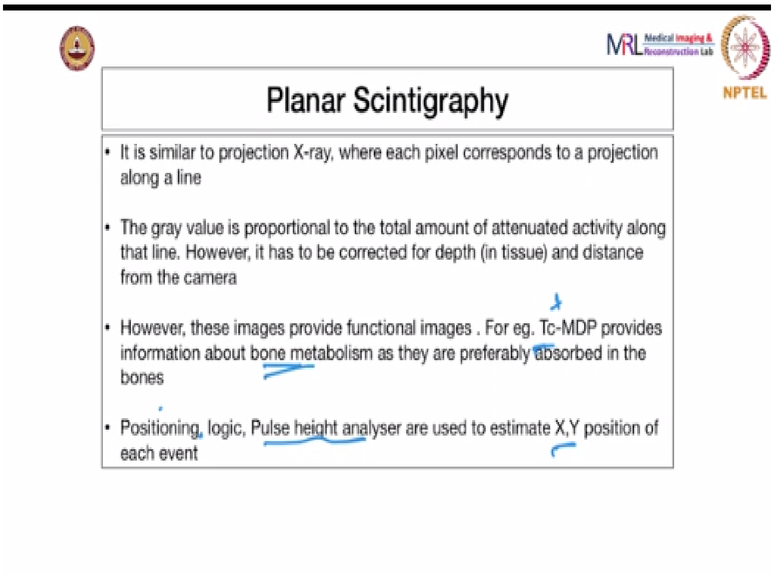

So, parallel scintigraphy, it is a much more simple form of a nuclear medicine imaging or nucleate imaging, it is very similar to projection X Ray so, where each pixel corresponds to a projection along a line. So, the gray value which is measured by the photomultiplier tubes is proportional to the amount of attenuated activity along that line. But it has to be corrected for depth and distance from the camera. I will explain this slightly more.

However, these are functional images. So, for X ray, it is very difficult to discern anatomy because you have multiple tissue types along the path of the X ray and they attenuate them differently, but you will not be able to separate them. But in the case of, even planner scintigraphy, even though it is similar to X ray projections, it measures the activity concentration, so you do get functional information for instance.

So, for instance, technetium imaging provides information about bone metabolism because technetium MDP this particular isotope is absorbed in the bones preferably. So, what do we have to do so this basically, this imaging chain consists of a positioning logic, positioning logic. Basically positioning logic is for figuring out where in the scintillator, the particular gamma ray hit, because it is one single scintillator. There is a pulse height analyser to reject the scattered radiation. And these together are used to put together, they will use to estimate the X ray portion of each event.

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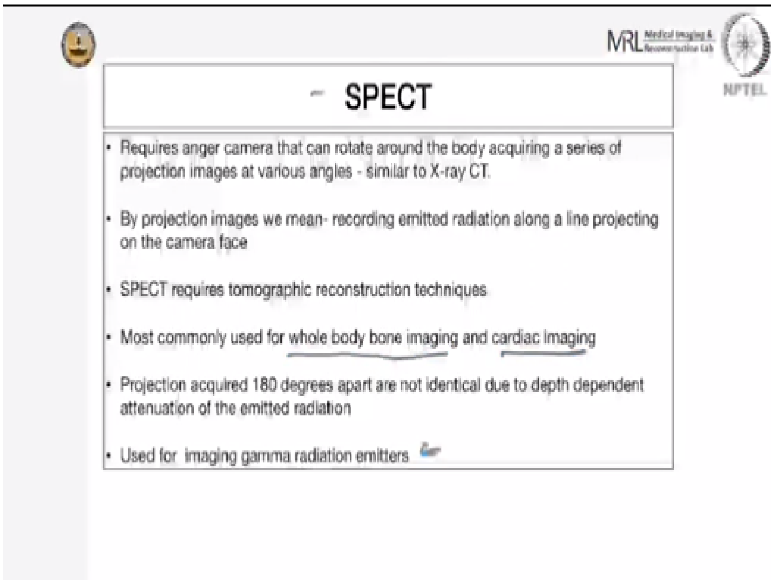

The other one that we talked about, which is closer to x-ray imaging, or the reconstruction is closer to x-ray imaging is SPECT, it is called Single Photon Emission Computed Tomography. So, what this requires as the name implies, it requires a reconstruction. So, planner scintigraphy does not require reconstruction, you just translate the camera or the patient at every location. So, it is a fairly large area, so you will be able to get the entire body as you translate over the patient and you will get a projection of the underlying activity onto the camera.

Here, we want to reconstruct so we will be a computed Tomography thing, so we have to reconstruct, so the request the camera camera that can rotate around the body, this is very similar to what you saw CT acquiring a series of projection images at various angles. That is what I said is very similar to CT. By projection images, we mean here recording emitted gamma radiation at different angles.

And it is usually recorded recording emitted radiation along the line projecting other camera face, that is what we showed you in the previous illustration. So, you always saw recording along the straight like a cylinder which is basically projected from the face of the detector. And SPECT requires tomographic imaging techniques and it typically and most of the SPECT imaging (come) falls under all body bone imaging and cardiac imaging.

Once again here the problem is projections acquired 180 degrees apart are not the same because as I said, there are two effects; one is dept dependent attenuation of the emitted radiation also distance to camera will vary. And this of course, typically used for gamma ray gamma radiation emitters. So, here SPECT once again it is very similar to CT in a sense that you have a bunch, you rotate the camera and you measure the radioactivity along the line projecting onto the camera or just camera face basically, if you can think of the collimators as like a cylinder.

So, all in that whatever is confined in the straight cylinder is what you typically image. So, you do that at every angle. And then you can also again once again model the underlying activity as some kind of a line integral. And you should be able to do this reconstruction very similar to back projection.

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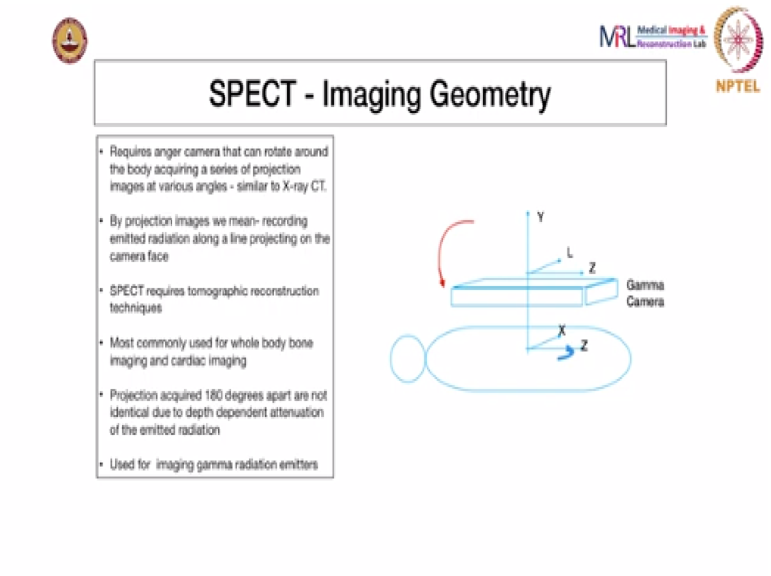

The SPECT, I once again SPECT imaging geometry we will see here with this requires an anger camera that can rotate. So, here it is illustrated, the angle camera being rotated around the body acquiring a series of connections. So, if we cut this, there is a typical camer. It is in 2-D. It is like a, it is like a flat panel if you can call it that. It is a big crystal with a bunch of photodiodes behind the crystal. So, you will rotate it.

So, this is the Z axis, Z axis is always along the body of the patient, patient is laying down and you would rotate it along the z axis and at every point you would collect a series of projections very, very similar to the projections that you acquire using the for X rays of using an x ray CT detector. So, very similar to that so you will acquire a bunch of predictions here. And after that you have the similar algorithms for reconstruction so, you will have cross sections of radioactivity concentrations being reconstructed.

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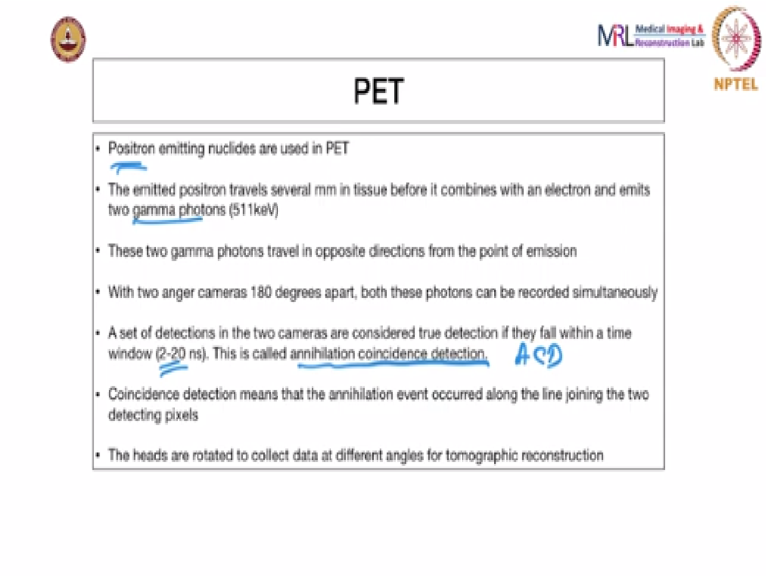

PET is another radionuclide imaging modality and positron emission emitters are used in PET, we saw that. So, what happens in positron emission is that the deposit emitted positron combines with an electron, so say it travels maybe a couple of millimeters in tissue before it is annihilated by an electron and that annihilation results in the emission of two gamma photons, 511 keV and these gamma photons travel in opposite directions from the point of emission.

So, we two anger cameras which are 180 degrees apart both these photons can be measured simultaneously and can be recorded simultaneously. So, how do you know it is simultaneous? So, we have a small window. So, a set of detections you consider to be simultaneous if they fall within that time window of 2 to 20 nanoseconds. So, and this is referred to as annihilation coincidence detection, usually ACD is the acronym.

So, the coincidence detection means that the annihilation event occurred along the line joining the two detecting pixels. And the red again is similar to speck and two X Ray CT, the heads are rotated to collect annihilation data at different angles. And once again, there is a tomographic reconstruction formulation. So, you get cross sections of the radiotracer activity concentration.

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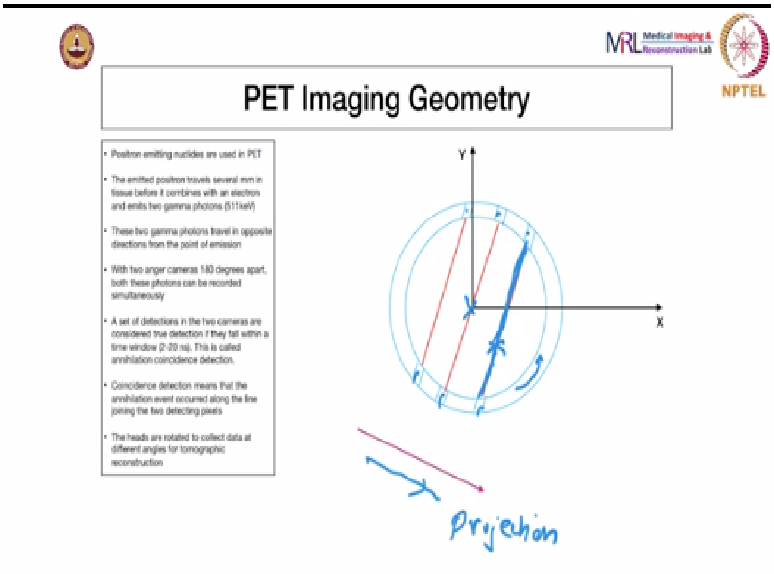

So, for instance, here is the PET imaging geometry. So, you will have a bunch of, you can think of this as the akin to a projection, this is a prediction, this is the axis along with you have the prediction. So, you have a bunch of detectors, parallel detectors 180 degrees apart, each of them detecting coincidence events along this line. They will detect coincidences reductions along this line, and of course, this so, that means that, you can actually form a so called cinnogram from these production measurements.

So, how do you say its production, because any, let us say, some, the 511 keV photons are emitted from this location. So, you will have one detection here and another detection there. But if you see, you will see that this actually travels a certain distance in tissue, this actually travels slightly different distance tissue, and both of them are attenuated according to the exponential attenuation formulation we had for X ray photons. So, it is the same formulation.

And once again, you can cast the problem as is in the form of transform and try to reconstruct, very similar to that, I mean, I am just giving you a kind of a very toy version of this formulation of reconstruction problem. So, the productions are acquired in this way, which is basically you have detectors 180 degrees apart, which detect coincidence events, and then you are rotating along this axis.

So, you will have a gantry onto which these detectors are set, and then you rotate the gantry, and you acquire a bunch of images. Of course, the patient is along the Z axis, the axis of rotation, which is basically if you can think of it as going into the plane of the screen, the patient bed.

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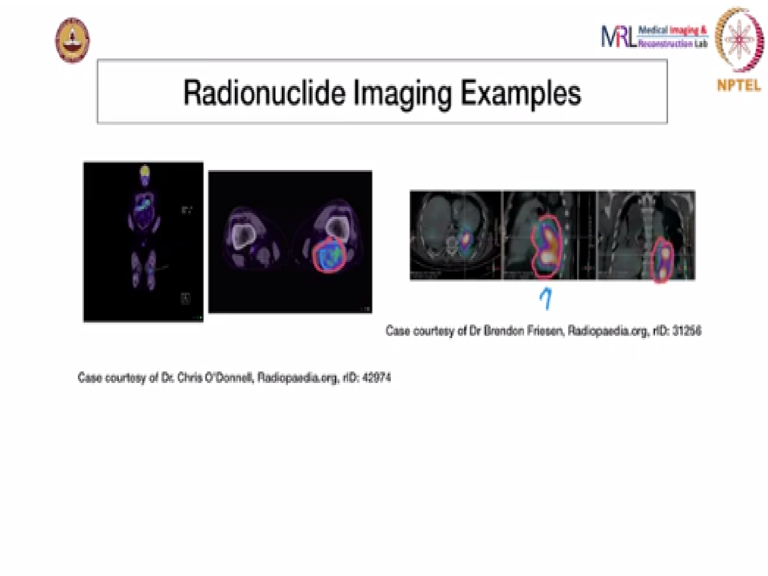

So, here are some examples of radiant nuclear imaging, if you have not seen these already, so for instance, on the left is the accumulation of, in this case, it says Positron Emission Tomography imaging, I believe and this one is SPECT. On the right is SPECT imaging, in this here is a compilation of radioactivity in the bone, which you have seen right there.

I am not going to do any diagnosis, but I am just telling you what the images look like, once again, these images, the images from the SPECT have been superimposed on anatomical image, I think in this case CT image. Similarly, the images from SPECT have been superimposed on a CT image here. So, this is basically the images from the SPECT system, this was an abnormality in the heart.

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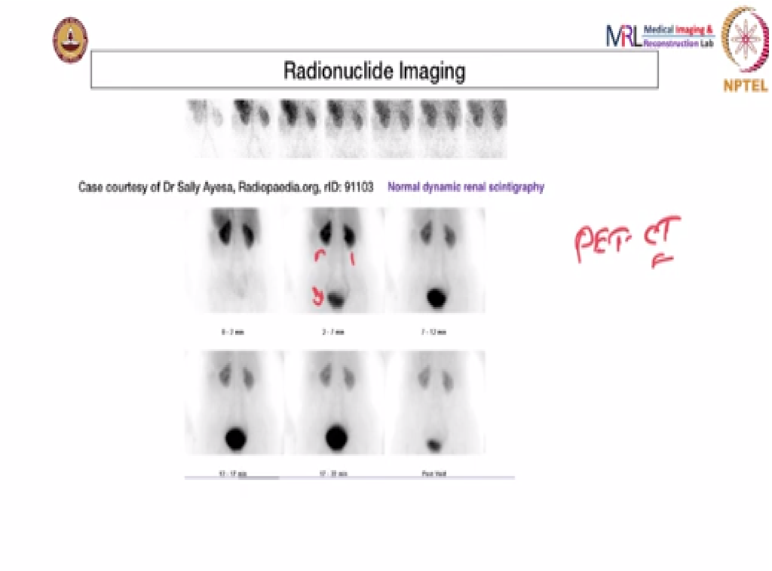

And similarly, the scintigraphy here, this is dynamic renal scintigraphy. From here you can measure how much each kidney over time if you measure this, the read activity in the kidney, you can figure out how much each kidney is contributing to the bladder output. So, these are the kidneys and this is the bladder that stretches we can measure, so this is how you see that there is no basically no anatomy here. It is just a bunch of blobs which indicate the presence of the radiotracer.

So, the previous images will also look the same except that they have been superimposed on top of a structural information. So, typically there are these PET CT scanners so called now we have I think PET MRI also. So, the PET scanner is used for imaging for the functional imaging, which is done after the injection of radioactivity and the CT scanner will be used for getting this far structure information.

So, they superimpose or fuse both of these reconstructed images, and that is what you will be able to see. So, without that information it will be very difficult to interpret, but an experienced radiologist, nuclear medicine radiologists will be able to interpret these images. So, where we conclude our review of the common diagnostic imaging or radiological imaging systems.

And this idea is to just give you a flavour of the kinds of systems available and the kinds of images you will run into if you actually do for instance, a career in medical image analysis or even diagnostic radiology for instance, with a bunch of images you have to understand what these images are so kind of adds to your domain knowledge. Thank you.