Introduction to Biomedical Imaging Systems
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Lecture - 21
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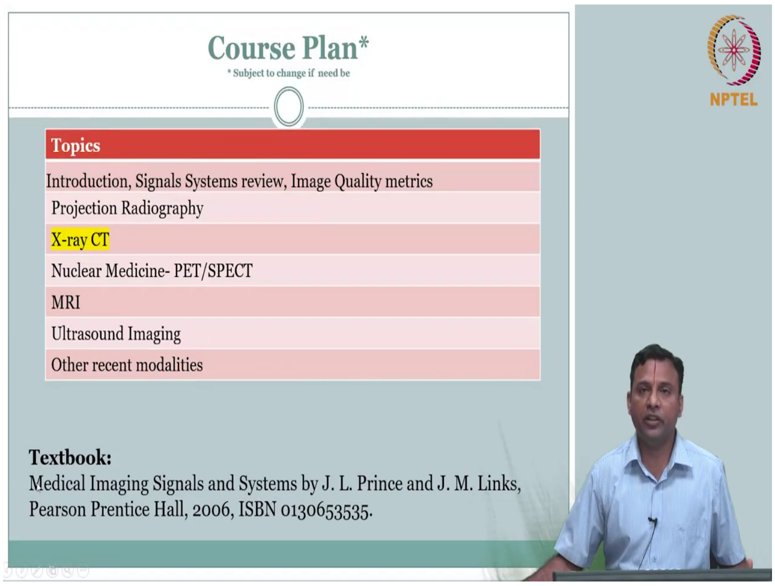

In this lecture, in this module, in fact, we will focus on CT X-ray based computed tomography. So, I would recommend you actually go through the introduction signals and systems review, image quality metrics and more importantly when we started project in the previous module of projection radiography, the physics right was covered that is namely your X-ray generation and how X-ray photons interact with the tissue and the fundamental attenuation law all those things that constitutes the physics of the modality right was covered in projection radiography.

So, when we cover X-ray computed tomography, I would assume you would have already gone through the previous lectures in the previous two topics therefore, we will proposition and start with only the instrumentation and then image formation and image quality. The physics of the modality I would recommend that you read in the previous module ok of projection radiography. So, without much further delay here, let us again most of the content I will be following the order in the text listed here, clear.

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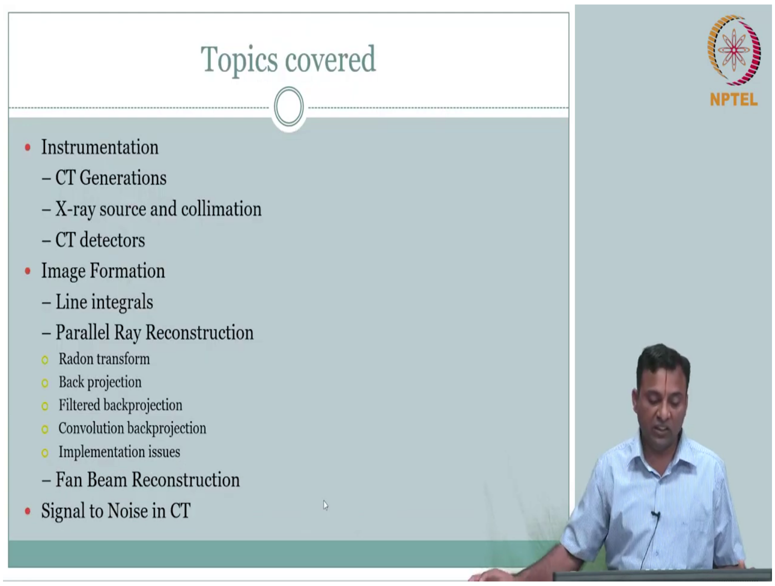

So, what are we going to cover? Physics I said you should have read it from the previous module. So, we are going to focus on instrumentation and then on image formation. I guess this is a very important module when people talk about CT, this is an important module and we will talk about X-ray CT however, you will notice that the T part the tomography the CT part the computed tomography part will be used in the other nuclear medicine right that we will be discussing as a separate module.

So, this is a very important topic and actually also very interesting topic. So, I would recommend that you kind of pay attention when your fresh try to go through these lectures and more importantly as I keep repeating all this is a you know separate module well established text books are there, maybe several vivid you know descriptions, simulations, cartoons, sketch animations of all this might be there.

However, there is no substitute to actually you go reading from where somewhere and also try to get the intuition. So, I will try to help along the way showing some examples, showing some demo or at least how you may want to think at least the way I think about it that I you know I would like to share, but there is no substitute to you actually going and taking a text book and reading from that ok. You have to have your own imagination of all of the topics that we are going to cover ok. So, we will get on with it first is your instrumentation right.

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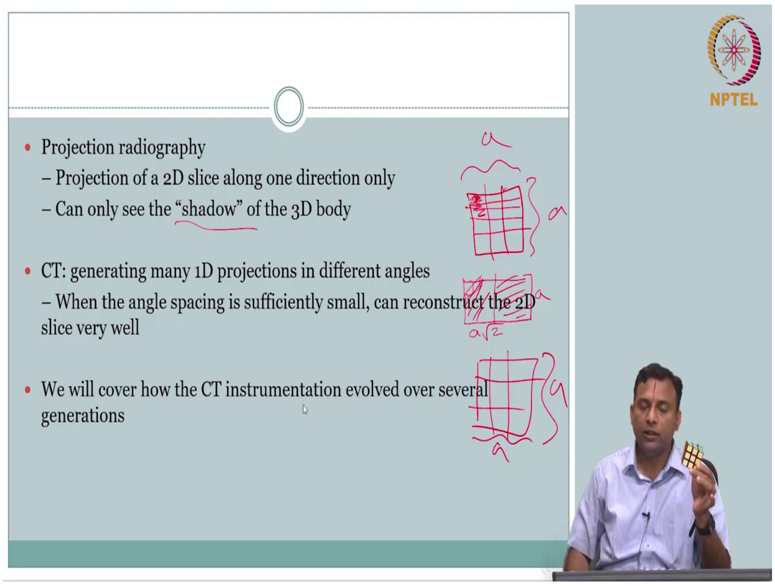

So, before we go into instrumentation right even though I told that you are going to use the previous module to learn about the physics, I think its very important. The way I would like to proposition and take this module its actually very historic facts right I mean instrumentation is there right all of the material that we are going to cover, you will find it is already there you know factually.

But what I would like to pretend right you have to imagine can we grow with the evolution right. So, when roentgen did it right it was 1895 right somewhere there 100 more than 120 years ago. So, that time what did we have? Right it kind of opened up like we said most people agree it opened up medical imaging with the X-ray first.

And then we covered projection radiography. So, suddenly even after discovery you have to have an ecosystem you create a instrument, right you have to have a vendor who manufactures it and then the doctors have to be trained and then clinical applications have to evolve where all they think they can use it and make the diagnosis better. So, it takes time. It takes time and lot of you know pioneers brains of several people have gone into in the evolution of the technology and clinical practice.

So, along the way if that solves all the problem right if it is super good, if you do not gain something people will not evolve right people will not come up with the newer there will not be scope for newer systems right there will not be any need. So, clearly even though projection radiography is very important modality even now right. You would notice that there was a fundamental limitation right that was always probably haunting the scientist at that point of time. So, they wanted to overcome it.

So, first recognize what was projection radiography and what was the major limitation. Projection radiography what did we do? We reduce the dimensionality we were only using the projection. So, for example, even though we know the object is 3D right we collapse to the plane of the paper.

So, essentially this is. So, we will. So, this is the innovation I am trying in a typical class when we have a projector right I could there will be a screen and I will stand in between the screen and the projector So, I could use my hand and you could actually see the shadow. So, it will be easier.

So, here I am going pretend I am going to use the optical system. So, it is not through transmission, but get the idea through. So, what did we do? So, pretend this is all that is your camera right. So, you are sending it. So, pretend the analogous to X rays, but you are seeing this. So, you had X ray. So, this is a cube right your Rubik's cube. So, you have different colours right.

So, optically you see its a 3D thing, but what we were do in projection radiography is say for example, if I showed you like this right. If I showed you like that you will not know whether this is 3D or right you only saw the projection of this. So, you would have if you really look at it you would see a projection where right I mean to make life simple this is what you would have seen and this is I am not going to colour because I do not a whatever colour this pen does I have read maybe I will have to go pick another colour I do not waste time on that.

But the idea is you see one square its not a cube that you see because you see the projection and so, you would have seen a square which has 3 cross 3 small squares if you are really able to pick it. Was this good right? So, it had. So, the analogous to X-ray CT is this allowed us to project. So, whatever was there on one side right it got projected, it let us take this example had one side right I got this, but this is nothing, but a projection of all the see all the three. So, you have 3 cross 3 cross 3 Rubik right.

So, it was going through this property. So, instead of 3 cubes I got the effect of all the 3 cubes. So, on the input side say for example, I put orange right some X-ray energy, it goes through it goes through the 3 cube elements here which are green colour. So, it had some property what you record or what falls on the detector is red. So, orange you send in red you get and the difference is because it is attenuated along the path. So, here you have 3 green cubes right. So, it is along.

But you see the challenge the challenge is actually I do not see the 3 of them along this. So, like you have 3 here you have 3 here you have 3 here which comes out to be the 3 cubes on the first row likewise you have the next row third row. So, essentially you have collapsed right all of them into a 3 cross 3 instead of 3 cross 3 into 3 right.

So, essentially you do not see that depth information which was itself very powerful because you did not see anything before that. So, now, at least I can tell when you go when you send the orange I get red. So, when it goes through this path, this is the loss where exactly that loss is distributed within that we do not know it was just line integral but that itself was good enough right.

If you take a picture like this, this itself was good enough for us I do not know if you can see. So, there is a logo right. So, this itself was good enough for us I could see some suspicious you know pixel and I can say that it is within this path it is within the center something has changed which was very good. Even though I could not tell apart the front cube colour to the back cube colour right So, I could not tell what is in the front or what is in the back, but that was sufficient.

So, lot of developments application took place, but one of the fundamental limitation was you ended up seeing only a shadow of the 3D object. So, the first and foremost thing they wanted to do is, is there a way we could actually go not just measure the square ideally, I should get this cube I should be able to tell all the values right sitting from outside.

So, just to make life easy because I cannot break this into pieces. So, this is one piece right one row if you want to call right this is my imaging. So, until in projection radiography we got a projection. So, it was this square that you are seeing whereas, what we want is we want to actually see through the depth right you want to see through the depth. So, our images are going to be we call this as slice.

So, we want this slice and the slice is going to represent how along the path the Mus are the attenuations are distributed this is what we want. If we can do that for one slice if I can do that for other slice you can do for the third slice then actually I have the whole cube right. So, the idea is how do I get the depth along the depth how does the mu change that is the missing part So, how do we typically do that? So, that is the biggest problem.

So, knowing what we know right what information do we have? So, we started with say for example, this red you saw the projection and it goes through this green I get an orange as recorded value right this goes into your detector and you see it as an image. Now what can I do? In reality why we see this as a 3D object?

Because if I keep it exactly you know to my eyesight line of eye sight and I do not create any other if I do not tilt it, then you will actually see it as only red green you cannot tell the depth. But then what happens if I tilt it slightly right? What happens if we tilt it slightly? Well, if I if you do this right if I tilted its like this what do you see? Well, if I did a good job with respect to right keeping it straight then you will see two colours red and yellow.

But you will still see only a projection of this, you will not see the depth you will not see the depth of it you will see only the projection of it. So, only thing that you will see is if that is length is a and this is a you are going to see probably you know square root of 2 a, this will be a. So, let us say this is a, this is a. So, I will still see this as a, but my width will be square root of 2 times a clear.

So, then probably half of it I saw yellow colour, I mean it still it will be cube, but from a from our perspective whichever colour I showed you does not matter ok. I see two colours say yellow and green I think this is what I showed yellow red and yellow right So, you have red on one side, again yellow on the other side. But notice its still projected it still projected.

So, then what can I do? I if I. So, I had orange and red. So, what if I do like this? I have another view red right. I had one view like this and then if I have like this I just rotated by 45 degrees, the view that you see the width is increased, but you still see the projection. So, its a rectangle with two colours, I do 90 degrees what happens? I have a yellow, I see it as right you see a yellow square, this again will be a cross a, but yellow square.

So, the point is depending on your view. So, if you actually. So, the reason that you are able to see this as 3 b 3D cube is, when I have it like this when I rotate it like that right and if I am able to record. So, your eyes are doing it you are recording it, you are moving it and you are registering it and your brain interprets and it starts to visualize it as 3D.

So, the same process we can do. Even though projection radiography had a problem with depth now what I have done is by looking at it from different views is still the same thing right we started out if I send r and psi I send on one side, it goes through the green comes to the other side as red right. So, if you take one of these pixels one of these elements right it is along the path. So, it is still attenuating.

So, if I went like this 90 degrees, if you take this element now I send the white I get yellow. I get I send some value I get another value, but along this path it has reduced. So, for every element you see in one of the in all the paths right different angles that you want to go they would have contributed towards that attenuation ok. So, this is the interesting aspect. So, the challenge was how do I get the depth information.

So, this was bothering them because they wanted to see the through slice, they wanted to see what is there along the depth right. So, what they did is in CT they figured out if you can view it from multiple different directions and record the projections, then there is enough mathematics that we can apply to get the what we call is reconstruction right (Refer Time: 18:00) mathematics to get the slice that is the distribution along the line ok.

So, I mean it will take some time I think this is a important thought process you need to start to do because rest of it will fall in place nicely because its all about at that point of time if you have enough information knowledge on what is happening, you will I am sure you and I will also innovate with due credits it was challenging, but I think we have the privilege and luxury to actually look back right after its all done to say its easy. So, let us enjoy that process ok.

So, what we will cover is a very factual material. So, this is the logic. The logic is until projection radiography what we covered is we know the physics you send on one side you receive on the other side along the path there is attenuation and now the objective is I am not happy that this is the attenuation along this path, I want to know if there is a change what is the different attenuation values along the path not just the total that is our goal. In order to do that the idea is you have to get different views. If we can get different views then maybe we can reconstruct. So, how would. So, instrumentation is going to be geared towards that ok.

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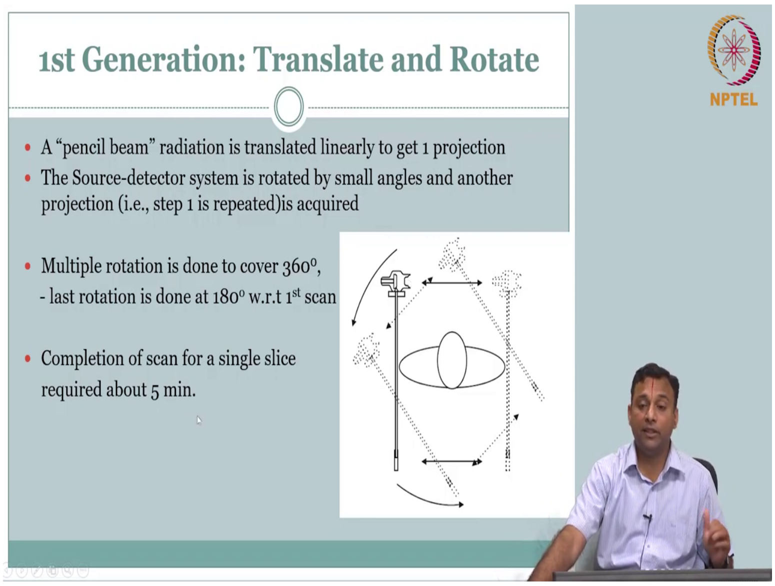

Let me put the first generation and kind of give this proposition. So, you have a patient right that you want to image, you have the source on one side the detector on the other side ok. So, through transmission what is slightly different here? What is slightly different is in projection radiography we talked about the whole chest right.

So, in principle we could have we should have talked about our detector also being an array if that is the case then this cube example is good enough, but you will have to understand that X-ray itself was developed and all the clinical applications came this this idea of depth was bothering them, but then what is their output? Output is photography film alright that was a market that was you know evolving and maturing and so, photography.

So, their output in some sense you did not measure, it was the output was display right. So, optical density X-ray was converted to optical density and viewed. So, all that development in material science and the ecosystem for making a scanner and the clinical participation matured over 50 years, 60 years.

So, then they said look if we want to do this, if I want to measure from different views and then be able to apply mathematics on it. So, I have to do computation on it if I have a analog right I have this film that is exposed, I get X-ray film in different views right I cannot really do computation on that right.

So, the challenge was even though it is straightforward to think that if you have detector where you can record this, then we could take it, but they did not have computation right. It was starting your electron semiconductor devices started coming, your diode started coming all post World War II right and then your computers started to mature.

So, in that sense it was not until remember the intro not until 70s right for the work they got a Nobel Prize in 72 or something. So, its the 70s where after 50 60s you had all the components. So, the detector. So, what you see here is a the detector is not X-ray film in projection radiography that was the case now you have to record the signal so, that you are you have to do reconstruction compute. So, you cannot just have a X-ray film that is developed ok.

So, you are recording of the signal. So, you need sensors all that kind of read out circuit, registration you have to have you know you have to scan. So, you have to have translation, rotations all that kind of that ecosystem with electronics was also parallelly developing computing was parallelly developing. So, it took about 70s before there was maturity in the electronics and you know mechanical design developments and motors and things like that before they could put a system together ok.

So, what you see even in the first generation is, its not 2D array, I mean you its not just digitizing your projection radiography life would be simple. So, that time what they had is, they knew this business of X-ray tube and you send X-ray tube the X-rays through the body you have to have a detector on this other side.

So, they got the detector on the other side. So, then all they knew from the physics is from the detector sorry from the source to the detector the line joining them right. Whatever is there in the path that is the attenuation along the path that is going to come the line integral is what you are going to detect.

So, the easiest way for them to discretize this is, they had one detector one source. So, they stepped this is translations. So, they moved from left to right. So, if you take this cube right. I had only one I had only one detector, one source, one path line I had the detector on the other side. So, I had only one element. So, if I have to get this cube what should I do? I should move that move that. So, if I move 3 times then I get right I am trying to when I do 3 times what I get? One row. So, one row if I get; that means, all this is collapsed along this path.

So, now, I want the same tissue region, I have to view it from different location. So, we can rotate the 90-degree rotation is simple I said right So, you can step in any direction right any step size for different views. So, the idea here is this knowledge was there what we call this as a pencil beam very narrow beam it is like a pencil right.

So, now, if I have to scan the patient, if I have to get this 3 cross 3 in this example of white what the values are then. So, I am going to get only one slice right only one slices the one row So, I am going to do one translate I can do many right I have to translate many times depending on what how what is the field of view and then I have to rotate for different view and again after one rotation I will have to again do the scanning. So, I have both translate and rotate.

So, brute force you went there, translated got data you had something on the detector then rotate translate you get the. So, you make all these measurements right. You know the positions where the detector is, where the sources, where the ditector this you know. So, where you are recording all the measurements positions you know where you measure you know then you have to do computation. So, the logic was used a pencil beam which was translated to get one projection.

So, here you notice what do we mean by one projection. So, you are going to get one-point right one one pixel. So, if I want one slice, I have to have many of them. So, line I project one I get one pixel move translate next one translate next one. So, I kind of get a line projection right. So, I get linearly to get one projection. So, the source detector is rotated by small angles and you repeat this. So, you are going to get this one line right from different views ok.

So, this is your one first generation set up what is the advantage? Advantage is you can probably see brute force you know this physics if I send here, if I receive here, I know the path is only the attenuation is only along this line path. So, if I move this translate it probably I will go through depending on my step size and view step size, I will probably go through smaller locations right and I will still get data.

So, from the detector point of view you notice, I am going to send only this right along the line it is so, narrow. So, I do not really have to bother about your Compton scattering because even if it scatters, you have only one beam. So, that signal is recorded here if it Compton scattering is there, it probably you are not going to pick several of them. So, in that sense you do not really need a collimator ok.

So, with the model of line integral that we saw in projection radiography the physics, I think this kind of helped them achieve when this is plugged into your reconstruction, it achieve made them get the slice. So, the disadvantage of course, you have to cover the entire thing after 360. So, you have 3 the idea is you get from all around 360 degrees, but you notice if I say for example, we talked about send orange, I get red through the yellows ok.

If I go completely the other way after 180 degree what is happening? I will send red I will get orange along the same path the same path participated right. So, in some sense after 3 180 degrees, you are not getting a new view its the same line path you will get and therefore, even though you cover 360 degrees, you want to cover such that after 180 degrees you do not want to get the same information again ok.

So, that has to be ensured, but otherwise the idea is you get multiple rotation is done. So, good news about this is good news about this is, the image quality because you do not have collimator, you can the scattering is not an issue you just send one beam there is no scattering that you have to worry about and therefore, this is simple straightforward the detection is also reasonable.

So, you have you get some say for example, you get some image quality let us say. Image itself is new because it is going to give you for the first time information through the slice ok. So, whatever image quality that you have, it is as long as you see what you see which you did not see before its already a huge step. So, you had some acceptable image quality to begin with, but the major challenge was you know you have to really move translate rotate and translate.

So, to gather this mechanical translation and rotation it took time how much time? it was in the order of about minutes 5 minutes 6 minutes kind of deal of course, it depends on the field of you and your step size rotation step size all that you know put, but roughly its in the order of several minutes 5 6 minutes just to do the data collection not accounting for after you get the data you have to do the reconstruction ok so, that is not what just the data collection ok.

But it allowed you the first generation it allowed you to see for the first time what is there through the slice ok. So, that was a huge step. So, if you were right working on this in the 60s and 70s, 70s when you know they put the first system together if you already are an engineer working what would you do right? What would you do?

First and foremost would be well I see new things, but 5 minutes 6 minutes is still order of minutes how can I improvise? How can I improvise and reduce that time right? So, the logic would be instead of logic would be instead of having only one at a time and then scanning right why do not we have few more of these detectors right? Why do not I have few more of these detectors so, that at one shot I can have few parallel lines ok.

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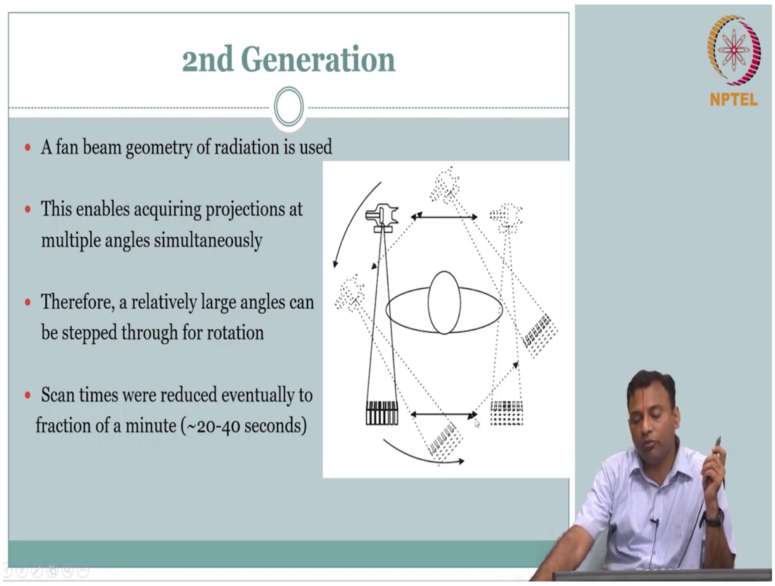

So, in some sense at that point of time if you are the engineer you have worked out this ecosystem you put this thing, one of the major bottlenecks could be your acquisition time is order of minutes, how do I reduce it? Can we improve that further instead of having one detector can I have simultaneously deduct few more detectors right.

Therefore, I can reduce the number of steps I need to do rotation or steps. So, they had few more detectors next to each other of course, your pencil beam instead of pencil beam we wanted to send a small fan its not complete, but then you see that it is wider than your pencil beam was narrow.

So, this is already diverging but then you had more number of detectors. So, in one go you could get multiple lines right so, if you. So, detect this if you so, arrange this few angles you already pick right because this is that angle right. So, few different angles you already pick from one location. So, now, the job is maybe I could step better maybe I could rotation step right I could be little more lenient because I in one step I already have depending on the arrangement of this what angles are covered in one fan beam I can skip those right.

So, in that sense same geometry same everything else instead of one to one, they kind of loosened this had few more what did that have that impact? That impacted the data acquisition time how did it impact? It brought down the time naturally right because your number of stepping size was reduced number of steps that you need to do reduce because in one go you got few more ok. So, it did have a very good effect this enables acquiring projections from multiple angles simultaneously and therefore, you could do faster ok.

So, therefore, large angle can be stepped through for rotation. So, you could actually see one part of you as an engineer says, wow now you know I have reduced the time this was the challenge posed to me, I have come up with the strategy I was able to you know I had a vendor who could do the source X-ray tube has been there from before.

So, the detector somehow, we have multiple detectors there are there is vendor who know how to manufacture give me a few different detectors that are next to each other. So, I have solved the problem, but then when you do this what are the physics issues that come in? When you had pencil beam the you had some quality.

So, now you go tell your doctor I have reduced your time he will be happy, but then he wants to make sure that what happens to the image quality that is an important aspect. So, what do you think is going to be the are you going to gain image quality? Loosen image quality? What do you think is going to happen? Your conveniently gaining time the reducing the time for acquisition, but what about the quality any comments?

Well, you look at it what is the proposition you are going to have multiple beams right that are that are going to multiple lines of right that is going to go source to detector. So, in pencil beam first generation you had only one line. So, there was no question of the you know angular incidence Compton scattering getting detected whereas, here if I do not make extra effort, I could pick right multiple I could pick it pick from other angles.

So, one of the things is we know this we solved it before. So, we will put collimators So, we address there you know we will address that problem. So, they had to use collimators, but what did that do? That essentially did one thing is ok you put collimator when we talked about this collimation in detector right when we talked about the physics and the instrumentation, what was the deal? The problem is the signal to noise ratio is important.

So, you had Compton scattering, but when you try to reduce that your detection your efficiency also goes down. So, now, because you are not allowing all the signal you are you have some threshold, you have some tolerance you are accepting only through that. So, what happens is, your for the same if you will for the same number of projections that you would use in your first generation if you use it here, the quality goes down because of your Compton scattering is now coming into picture ok. So, the image quality goes down.

So, in order to overcome that they kind of increase the dose slightly the exposure slightly. So, when they increase the exposure slightly. So, you can. So, from a image quality point of view, you are now slightly compromising on the safety aspect, but it is still safe I mean we you have to look at 70s 80s when they were doing this, they did not have I mean all the things were parallelly evolving right.

So, how much dose? How should we do? All that for also parallelly happening. So, they said ok this is still ok we will have a slight increase in exposure, but we will get the about the same quality as your first generation, but more importantly you have significant gain in your time. So, what are we talking about? From minutes you are able to get it down to some 10s of seconds like 20, 30 seconds 40 seconds in that range.

So, it was a significant reduction right. So, now, you see the. So, now, you get this feedback you are the engineer, you go back you say look my competitor we have this edge we can sell this its only 20, 30 seconds we can get the data. So, its not that bad for you know reasonable adult we could even ask them to hold their breath while you are taking the scan so, that you can reduce motion artifact.

So, it was fun right good problem solve then what do you do? Then you say I want to work on the next product what the challenge is I am happy that it came down to 20, 30 seconds 40 seconds, but I am greedy what will I do? By that time you have a ecosystem all the materials right manufacturing is improving instead of only few detectors why cannot I have more of them right.

How many more? Well instead of having 8 to 16 its incremental, what I want to do is I want to get the next best scanner out next generation out what will I do? I will say you know what here I translate and rotate what if I have capacity to put detectors right sorry right.

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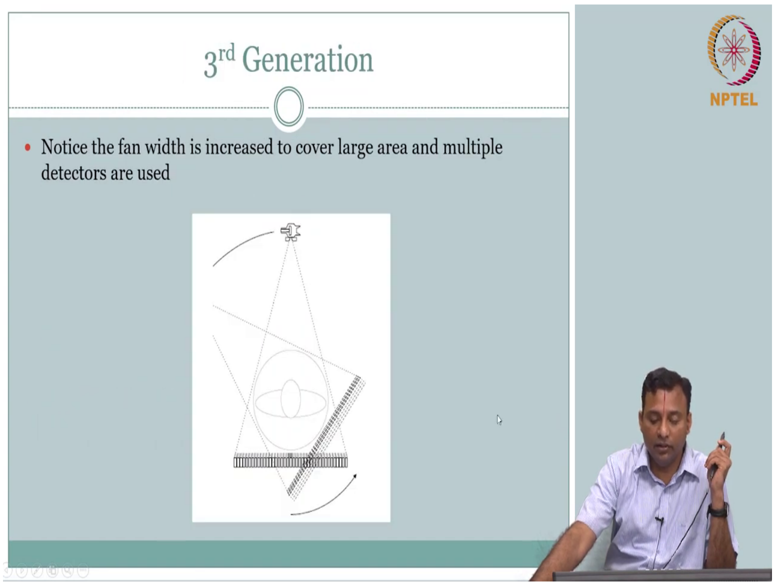

I have capacity to put the detectors so, that I entirely avoid the idea of translation I will only rotate. So, I will increase the fan angle so, that it covers the entire patient in one go. So, I avoid the translation and I can have look at the increase in complexity and cost right because now you have so, many detectors small detectors that are placed next to each other to cover the whole line right.

But the advantage is, I could get multiple lines recorded at the same time. So, I do not need to do translation, I will just worry about doing rotation. So, I could significantly reduce the time even further. So, I could get it in the order of seconds data acquisition, the recon part we will come this is just recording the data right.

So, the idea is fantastic, I could still say this is a good advancement where I have reduced the time even more significantly, but is there then the natural question is what happens to the quality. Are you losing somewhere? Well you notice even in the second generation when you had multiple lines you have to do collimator. So, the effect of collimator is going to be there.

So, starting up front your image quality right because you are going to have Compton scattering effect that is going to have a negative you have to account for that. Adding to it you have many elements which are now the element size is small you have you are packing many elements. So, the detector efficiency also goes down slightly.

So, everything said and done, you get significant reduction in time, but then you have really increased the cost and to get the same quality right like your before generations you have to increase the exposure slightly, but again this is one of those you have to look at it from that era right. So, you started seeing CT you started people are now going to use start to see slices of kidney or abdomen through lever which they did not see any time before. Now, they are able to start to see it right.

So, their concern is can we see it, see these new things at a quality that we are now trained, but if you can you know increase the speed throughput even if there is a slight increase in exposure that is fine the benefit outweighs the risk. So, this is again very popular generation that generation of CT scanner that really pushed the CT to main stream where lot of application start to follow up.

Because no note that I mean you are now talking about not even big breath holder right. You could just hold on for a breath for few seconds and your you can take the data. So, its very significant advantage in that regard. So, fine, you are the guy who join now the you know biomedical engineer who was joined, you are working your boss is working in the third generation.

You are the engineer who are working on this detail, you are going to become the project lead and you want to get to the next generation what would you suggest? What would be your approach? Well, by looking at all this 1, 2 and now third what else can I do right? What else can I do?

Now I am rotating my source and detector right this geometry, I am I am rotating both the source and detector. So, next you are going to say why should I rotate both. I have my detector technology evolving right and why instead of rotating what if I can arrange this instead of just line, what if I can arrange this around the circle.