Introduction to Biomedical Imaging Systems
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Lecture - 51
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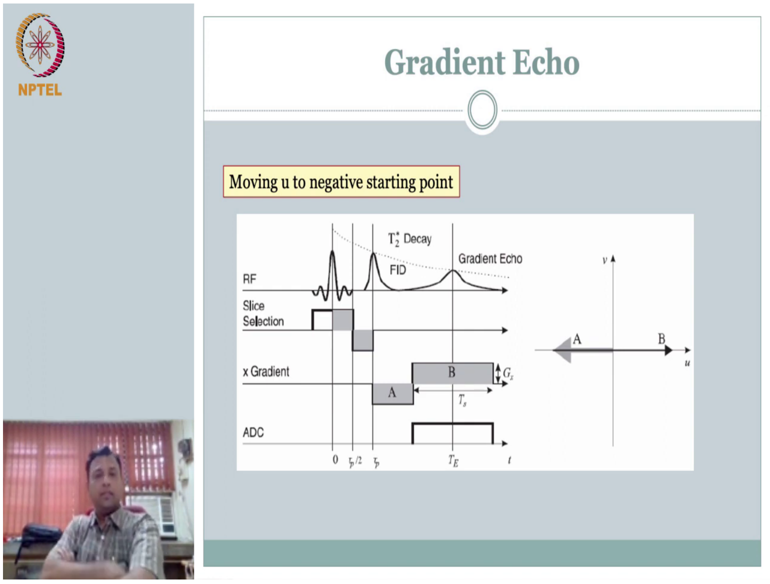

Ok, so welcome back to the next session, where we want to actually we left it at a very nice point right. Previous video we left it at the end of gradient echo, what we were trying to do is, we have a slice selection, we know how to encode the readout direction or the x gradient to obtain how the signal where the signal is coming from along the x direction. In the polar scanning mechanism, that we showed before we said you could apply x and y gradient, and you could cover the u comma v space right.

If the any theta that you want. So, now, what we want to cover is the second one which is rectilinear and in that if you have to do rectilinear scanning you have to go to the negative axis. So, we use the concept of gradient echo to show that we can go to the negative axis what is still pending is, how do you move along v direction. In other words we did z gradient, we have used x gradient.

So, we need to separate it out in the y direction the or which transfer to v direction here how do we do that.

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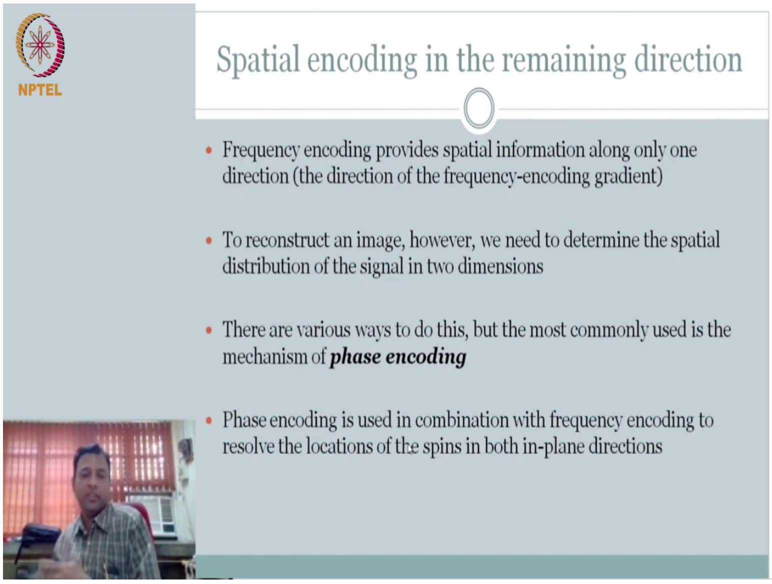

So, again so, the frequency encoding provides the frequency encoding when we talk about convention says, we are talking about x gradient. The frequency encoding provides spatial information only along the x direction, direction of frequency encoding. To reconstruct an image; however, we need to determine the spatial distribution of signal in two dimensions within the imaging plane.

So, we need to know we know along x direction we need to also know along y direction where it is coming from. So, this we try to do, there are several ways to do it. One popular way to do it is using what is called as phase encoding; frequency and phase this is again very with the line if you have trained your line of thinking right for m r using the two other encoding schemes.

And the other concepts that, we have looked, this is straight forward. Essentially what we are saying is, if you can combine this phase encoding with the frequency encoding that we already have then we should be able to tell x comma y contribution right. You know within z gradient provided as this slice thickness or your imaging plane within the imaging plane we talked about x gradient. If you combine phase encoding and frequency encoding then we should be able to tell x comma y which is your image ok.

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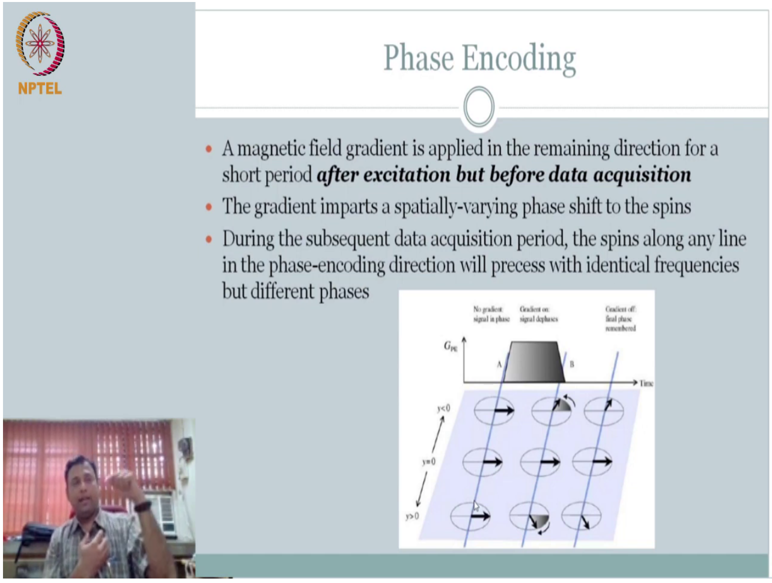

So, let us look at what phase encoding is. So, a magnetic field gradient again we exploited G e z we exploited G x which was called as G e z was called as slice selection; G x was called as readout or frequency encoding. Now you are exploiting the other direction G y, a magnetic field gradient is applied in the remaining direction in our case it is G y importance is when you are applying it.

You are applying it after excitation; if you are applying it with excitation that is what you did for slice selection, selective excitation. So, this is done after excitation, but after excitation during data acquisition, you did frequency encoding. So, this one comes just before that. So, this comes in between you have the RF excitation, z encoding and before you start x gradient you have to apply your phase encoding ok.

What happens if you do that? Same concept if you apply a gradient right, gradient in your magnetic field then the gradient is going to have a spatially varying phase shift to the spins ok. So, now, after you impart that if you disturb the phase shift you give a deliberate phase shift in y direction that is from one end of the y axis to the other end of the y axis you have everything is at different phase.

Now, during subsequent data acquisition, you are doing frequency encoding in the x direction right. So, all the spins are now going to precess according to their you know frequency encoding right along the x at particular x location, along the y everything is going to have the same frequency of precision, but then each one will be at different phase ok.

So, this is the idea behind phase encoding to put it in picture this is how. So, this is the picture of time axis and what happens over time for a given y axis. So, if you notice at the beginning in the y axis when you have a volume you give we have a signal. So, every work cell with this plane is having same Larmor frequency ok and everything is in phase.

Now, just about when it fell on the ground right, after your excitation now I am applying a gradient in the y direction; that means, what will happen. In the y direction one end right now everything is in the same phase and same frequency. If I change the gradient what is going to we apply a gradient one end will have higher field strength compare to the other end.

So, there is field strength is changing, what happens if the field strength is changing? It is going to start to precess slow or slightly slow or slightly fast when it is going to slightly slow or slightly fast what is going to happen? Everything was in phase; I am making some guys slow I am making other guys fast; that means, the phase is going to change.

But I switch off the gradient right. So, when I switch off the gradient wherever it went out of phase, it is now going to precess at whatever field strength that is experiencing right now there is no other field strength right; only the basic whatever you applied is there. So, it is all going to precess at the same frequency, but in the y direction one end will have a different phase compare to the other end and it is linearly changing.

So, each one will have that is what this is saying. When you start with everything is having the same phase, same frequency, same phase. Now I applying phase encoding or the gradient in the y direction as long as the y gradient is on, I will change this phase this becomes slow, this becomes fast.

So, this is where it is. So, I am deliberately inducing this phase change. When I switch off, it will remember that position that phase and each one will precess at the same frequency that it is expressed a the field strength that it is expose to proportional to the field strength it is expose to. So, now, along the y direction even though the frequency is same, each one is at different phase.

Now, if I apply x gradient right. So, along y direction I have phase difference, but same frequency; if I have x gradient along x direction there will be frequency encoding, along the y direction I will have phase encoding. So, I can exactly tell some phase and frequency analysis where the signal came from correct.

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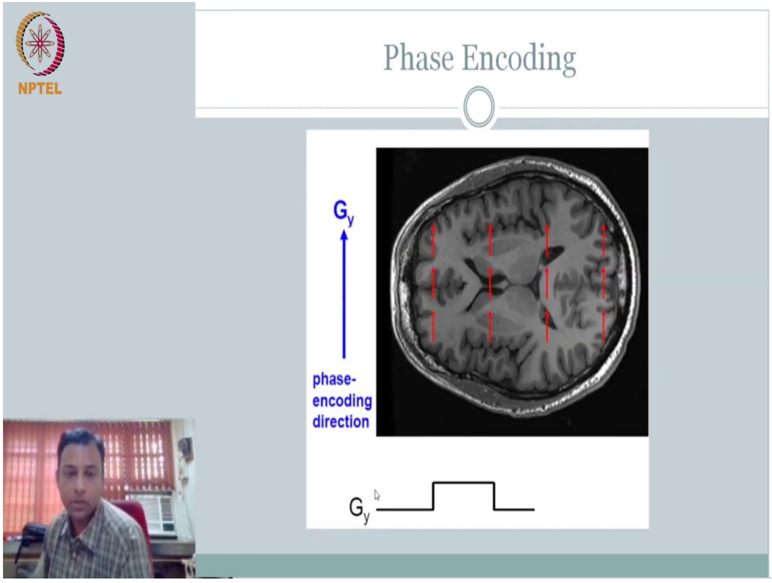

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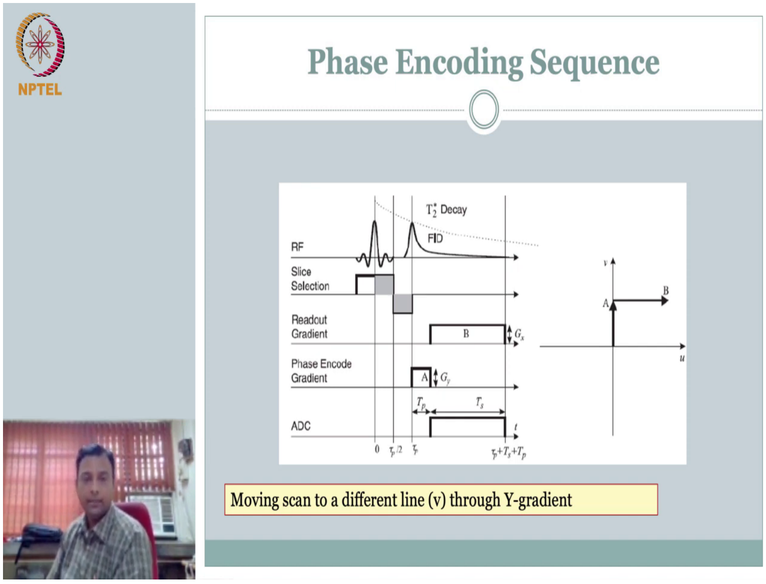

So, this is my y direction. I apply gradient just before recording. So, more importantly we want to put everything in the terms of sequence right. So, no issues here I did R F I do slice selection that is your z gradient refocusing I get my signal, but notice, I am not recording the signal yet. Before recording the signal I am applying a start of data acquisition, before start of data acquisition. So, this we did before you acquired signal and then at the start of data acquisition we applied a gradient.

Instead we are now just before start just after here applying a phase Y gradient for short duration. A short duration when I did this what happens is each of the phase is different now I apply the same x gradient. So, I have differentiated the y direction, I have differentiated the x direction that is from the volume how my signal that I am recording can be distinguished from x and the phase or the; or the or the frequency and the phase of the signal will tell me where it is coming in x comma y ok.

This is my data read out how do you put this in terms of our vector you know your spatial frequency domain representation this is same as a before right I am applying Y gradient, no Y no is not gradient, no x gradient. If I apply only Y gradient I will move, I will have only y frequency component I will move a here right that is what we did. when we applied only x gradient no Y gradient it moved along y u direction.

If I have Y gradient no x direction, it will move along v direction very straightforward nothing new, but the thing is I am not recording any signal. I am applying x gradient now. If I apply a x gradient and read out I am restarting from here I am reading out. So, now, we have seen two cool things not only can be go in the negative and start using gradient echo.

I will start from negative axis I can use Y gradient or phase encoding to move in the B direction. So, what happens, when we combine these two we should be able to cover the rectilinear space right?

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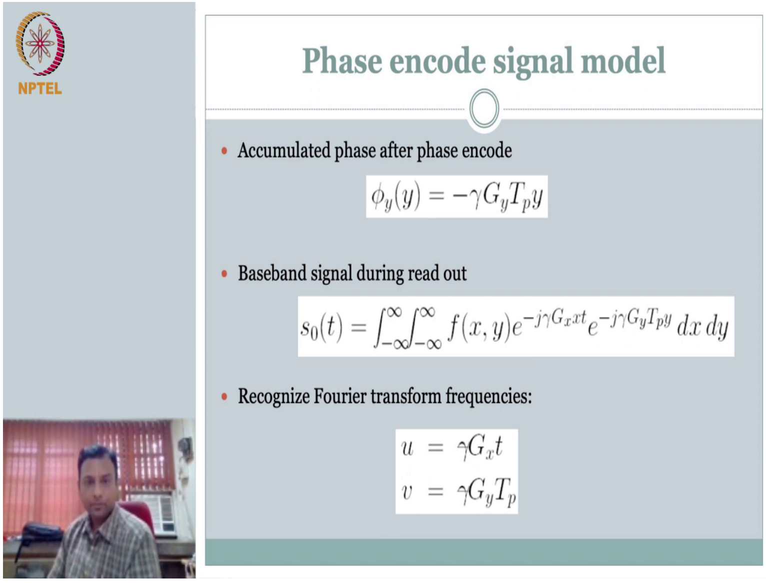

So, what is the signal phi y is the accumulated phase for the duration over which you are applying the phase encoding gamma G y T p and whenever it is at y. So, it is gradient is applied along y direction right G y y. So, this is the maximum phase will be G y T p y ok. So, your phase is given like this. So, how does your baseband signal change out? In baseband signal, same as before only thing x is varying with the t read out direction near y direction you have this phase information.

So, if you have to recognize this you will quickly recognize this is also a Fourier transform. If you make appropriate variable identification. So, your u is gamma G x t as before your v is gamma G y T p right. So, essentially what you have recorded is a Fourier transform data corresponding to this frequency u comma v right, along the direction it was shown in the previous slide.

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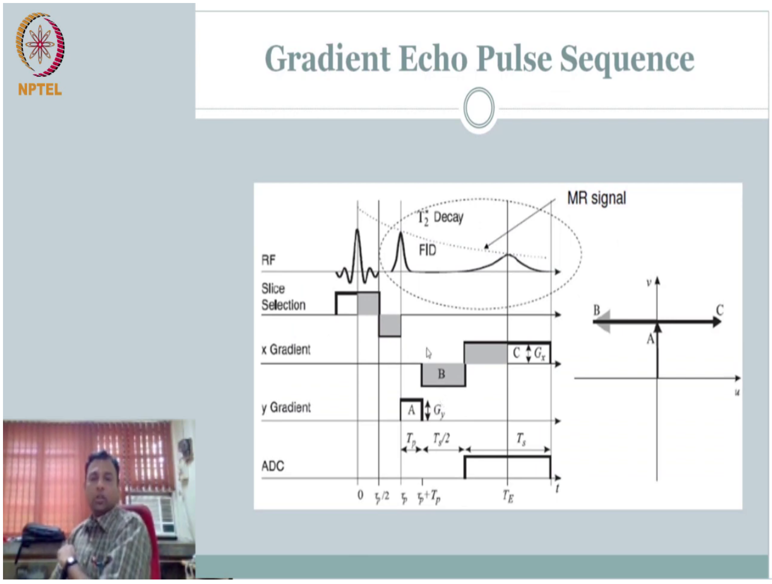

So, we can combined right you are combined your gradient echo and your phase encoding we can travel to the negative axis and move up and down in the u. So, this is the pulse sequence RF excitation, slice selection, refocusing. I am not recording the data. So, ADC is not your free induction decay here rather I am applying a phase encoding just after that, I am doing a frequency encoding and I am reading out the gradient echo during the frequency read out encoding right.

Wow this translates to our diagram here in this space by doing this one experiment in this one sequence we are acquiring data. So, A is moving it in the B, here B is moving it to the negative axis by read out therefore, starts at the negative axis and ends at G x tau whatever time duration over which you acquire T s gamma is your highest frequency over C. So, one gradient pulse echo sequence will give you one line like this.

You have to repeat this experiments to get different lines you have A could be different each step right therefore, you will get parallel lines moving around clear.

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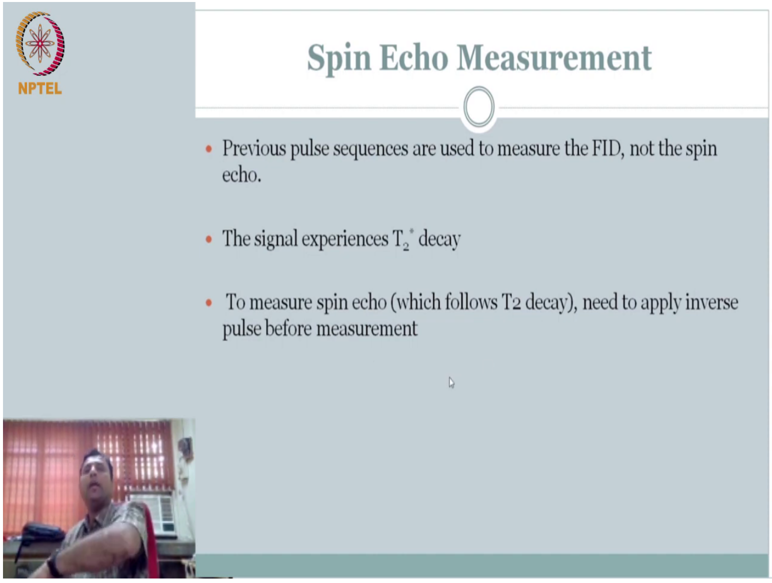

So, let us also complete right at the same token we talked about gradient echo we will also talk about our pulse spin echo that we did before and how to represent that also in this sequence diagram that we have built to communicate. So, recall previous pulse sequence that we have done. So, far is free induction decay or a copy of the free induction decay due to the gradient echo not due to spin echo which we covered before. So, the signal experiences whatever they have covered.

So, far the signal actually experiences T 2 star decay remember what I told you in the last lecture and the previous one. That is the fundamental the echo gradient echo you are re dephasing happens because of change in magnetic field therefore, it is related to T 2 star whereas, in spin echo we recognise it is due to spin interaction right. It is not due to change in magnetic field; it is due to the material property. So, T 2 to measures spin echo that is we wanted to T 2 decay.

We need to apply a 180 degree pulse recall our sequence that we did before or the sketch that we shown before.

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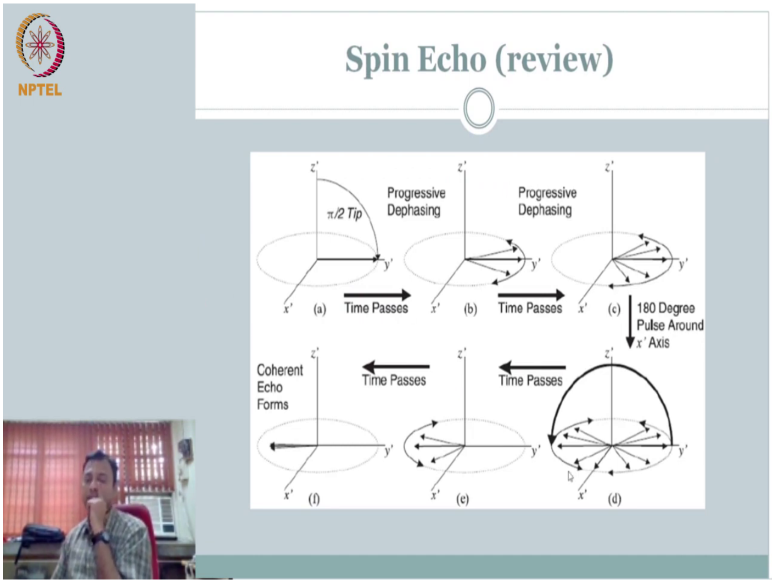

Before we write do the tiny sequence and see how it travels the frequency space recall this is what we did pi by 2 you allowed it to dephase and then immediately you apply 180 degree pulse and then it starts to re come together and you slip to this many times to get what is called as spin echo.

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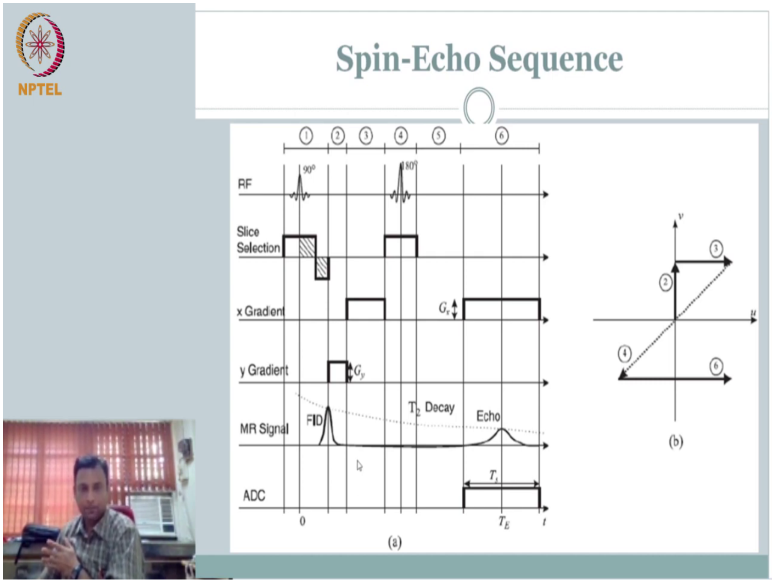

So, how do we write the spin echo sequence? Ok, so, nothing changes. So, RF is same you do 90 degree you do the slice selection. So, you have picked your slice now known nothing new here, once you pick the slice selection you are you are getting some signal right when you do the slice selection you are getting the signal, but immediately I am applying phase encoding, but I am not recording the signal. I am applying the phase encoding the moment I apply phase encoding, I start my frequency encoding.

However I am not if it was just recording the signal right then this is good enough I would have recorded the signal with phase encoding, frequency encoding, I would have got the signal, but this is not what I want. Now I am applying 180 degree pulse it starts to dephase quickly thereafter I am applying 180 degree pulse. What this 180 degree pulse does is it groups the signal together right.

Now, once I do that it will take some time right for the signal to regroup right, it is dephasing I apply excitation again, but I applied so that it is 180 degree shift. So, when I do the 180 degree it starts to regroup. So, there is after I apply this, there are some time it takes before which and then the signal starts to form back echo. I am actually measuring this echo while I am measuring this echo I have already imparted phase, I am just doing frequency encoding.

So, I am measuring the echo that is due to the spin and therefore, this is the spin echo sequence. So, the data that you are recording is a echo due to the spin. So, it is called spin echo and the signal is related to T 2 not T 2 star, that is the difference. So, how do we look at this in the diagram in u v, I started applying the signal, but I am not measuring it. So, 2 allowed me to do phase encoding meaning moving in the y direction.

Once I moved there in 3, I should have had signal right, but I am not measuring the signal. So, this three regular it is the signal, but I am not measuring it yet. At 4, I am applying 180 degree meaning I have flipping. So, when I am flipping u and v it will come here. So, essentially I am at this location whatever signal that, I am going to record is going to have minus u minus v as the starting location here.

And then record until your T s right, for the period of T s along the read out direction which is u clear. So, what we have seen is even a spin echo can be represented using this sequence diagram and I should know how to represent it as a coverage in the frequency domain.

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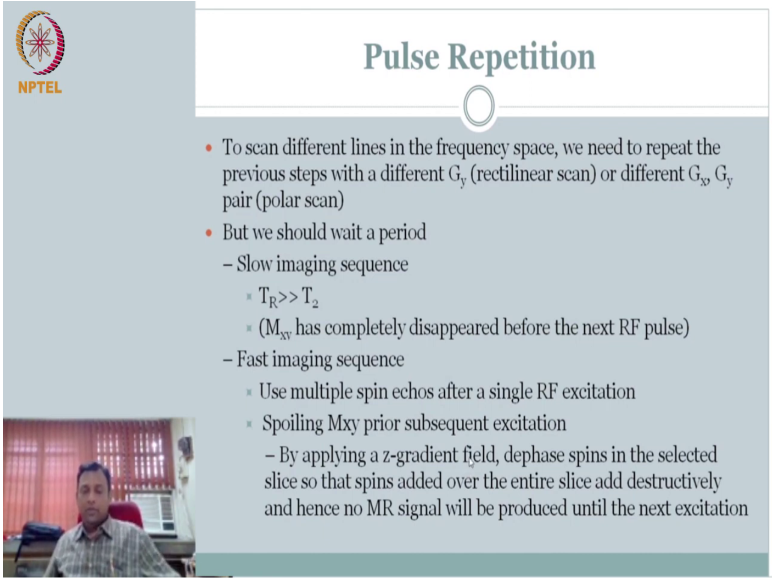

So, clearly what we have done so far is for one sequence. If you have to cover the whole u v space I have to repeat the sequence therefore, it becomes important we kind of complete what are the important aspects for pulse repetition. So, to scan different lines in the frequency space we need to repeat the steps; you take cover it with rectilinear way or using polar scan ok. But you have to wait for a period so that all comes to the signal origin right. So, if it is slow imaging no problem, in slow imaging you wait for a long time.

So, that it is T R is far greater than T 2. M xy is completely disappeared you apply that. So, in slow sequence whatever we covered you just repeat, but that might not be the case for fast imaging sequence when we do fast imaging sequence what happens, is we have an already doing multiple spin echo right. You are try to get your signal as fast you do not wait for the multiple always remember you have to wait for it to go back to equilibrium and then repeat the exam.

So, we do not want to do that. So, spin echo if you want to go fast sequence you do multiple spin echo, but the problem is how you do it fast; that means, I do not want it to naturally dephase which it takes. So, much time right dephase and then it comes spin lattice interaction your T 1 it comes to equilibrium. Now if I want to do all this, if I want to repeat the experiment multiple times that is select the same slice apply different G x, G y same z gradient apply or do this repeat several times.

I do not have a better way of losing the signal from one acquisition before I start the next acquisition. So, what can we do? We will do what is called as whole idea is I am getting the signal from z from a volume right from a slice thickness. How did we do that? We applied a z gradient not only that, only apply z gradient you do not get signal because it is all cancelling it. We applied a polarity switch for a short duration.

So, we made what is called as refocusing pulse in z gradient. Why did we do that? when you do the refocusing it will focus back and the signal will start to obtain. Now what I want? I want the signal to the coherence to go out I do not want them to come together, then what will I do? Apply another z pulse; so, that you accelerate the dephasing right. So, you spoil the signal before the next signal.

How do you spoil the signal? In the volume whatever is coming, if you do not get anything from the volume there is no point in x and y right. So, I spoil the signal. How do I spoil the signal? Apply a z gradient we got focusing pulse by applying a z gradient, now apply another z gradient you will spoil that pulse.

So, spoiling M xy prior to subsequent excitation is important step. How do you do that is applying what is called as spoiler pulse or spoiler in this sense is this is the z gradient ok. So, it will dephase the entire slice volume that you have. So, how now let us look at updating our pulse sequence diagram to be more realistic including representing how we put a pulse repetition also in that diagram ok.

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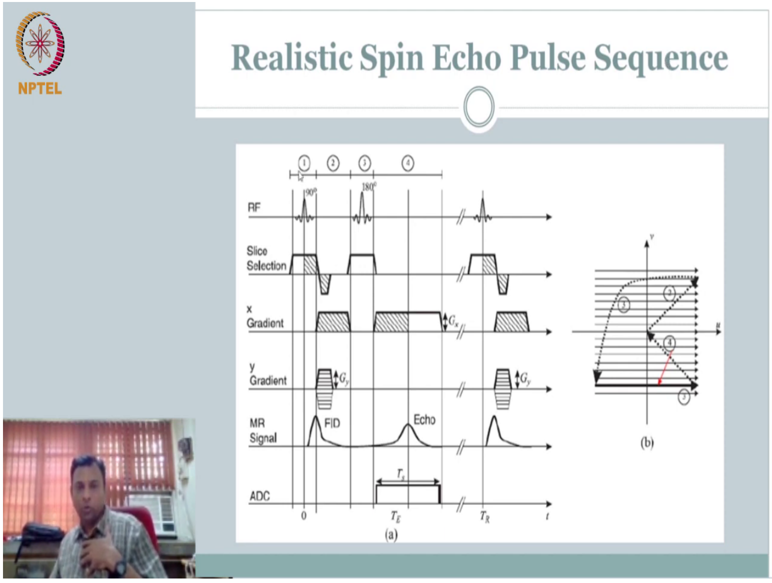

So, here we will start to call the sequence that we have seen, we will see again, but now we will call it realistic pulse sequence. This missing link we need to look at this and see if you have understood what this filling the blanks is ok. So, here we start with RF you do the slice excitation like before, but there are two or three important points that I would like for you to pay attention to why this becomes realistic.

Notice, when we showed our you know in the previous pulse even you would have notice only rectangles that is the gradient is r it goes from zero state to the highest G x or G z without any time gap. In reality there is a slow rate right. So, in reality it is going to take some time before it reaches. So, in the previous sequence that we showed it was all ideal that is turn on means it goes from 0 to maximum instantaneously.

Likewise it drops from maximum to 0 instantaneously. Realistic means I am now saying now it takes some time to go up it takes some time to come. So, all the rectangles became trapezoid that is one form of realism that we have incorporated in explanation of this diagram ok. Then what you notice is, each of the slice selection after slice selection I did gradient Y gradient.

After Y gradient, I did x gradient correct and then add a switch again, but then notice now that I have essentially put everything about the same time right. I am switching my z gradient, I am switching on my x gradient and switching on my y gradient almost simultaneously yeah, because your signal of interest is all happening rapidly and is all happening simultaneously right.

So, you do not want to waste time. So, essentially for all practical reasons they apply all of them, they are simultaneously. So, that is also explained here. So, that is making it little more practical realistically that is what they do and then one another thing that you see is you just saw one rectangle and shaded area right.

Now, what you are seeing is parallel lines here. What are these parallel lines, these basically says that we are repeating this experiment each time different value of G y or G z right of course, G x. So, varying G y in each cycle, so we are saying that by putting this hash line; we are saying that, each time we are repeating the experiment with different value of the gradient this is the new guy.

So, this is for one sequence you repeat the sequence multiple times. So, we have put a breaker here the time axis and said we are repeating and next to repeat sequence starts. So, you are repeating; so, we have incorporated repetition also in our pulse sequence diagram. Now when we talk about pulse sequence just before you repeat we talked about including as spoiler gradient which is z.

So, the spoiler gradient each time is at different values just to spoil. So, now, this is the realistic sequence where we have made it clear, the realism with respect to slow rate, realism with respect to starting times of application of the different gradients, realistic with respect to showing the repeat time and also showing that each time you repeat, you repeat with different G x, G y value all of this full process is vividly explained right.

In form of a diagram which is pulse sequence diagram this I would expect you to also understand in relation to how you are able to travel the Fourier space this will be the our if you understand this, this is the scope of the lectures I would at least like for you to understand this sequence given the sequence; you know how to, you know tease out and understand where you are moving in the u v space.

So, for example, here 1 is z selection, 2 is I am applying Y gradient. So, I am moving in y direction and then, 2 I am applying x direction also right; in 3 I am doing read out x gradient. So, 1 is z gradient, 2 I moved in G y of course, here if you are assume I mean just to demonstrate this is one of the lines right you have repeated the lines. So, you got one of the lines you are moving to you are moving here and then immediately thereafter you are applying gradient and reading out.

So, you are starting from here, you are reading out you repeat this for different v right you will have different lines. So, this explanation you should be able to do last but not the least, that, you get a chance to realize what this should be ok. So, realistic what sequence are we talking about straightforward pay attention to the detail what is the signal I am reading it is a echo signal.

So, it has to be some sequence with the echo in the echo the echo due to what? I do not see 180 degree pulse here; the echo is coming previously I know if there is 180 degree then it is spin echo. Now I see a echo, but this echo is coming because of gradient switch. So, this is the gradient echo. So, the realistic gradient echo pulse sequence.

So, can we do the same exercise for the, sorry next sequence can you recognize what the sequence is, well, everything else is same as a previous slide. What is different here is you see a this is a echo signal that you are measuring, but in the echo signal I have 180 degree pulse therefore, this echo is spin echo everything else is same right realistic spin echo pulse sequence. I hope you will do the same exercise of seeing how 1,2,3 how you go here do you understand your travel path.

This is something that we need to repeatedly do to get your own appreciation ok.

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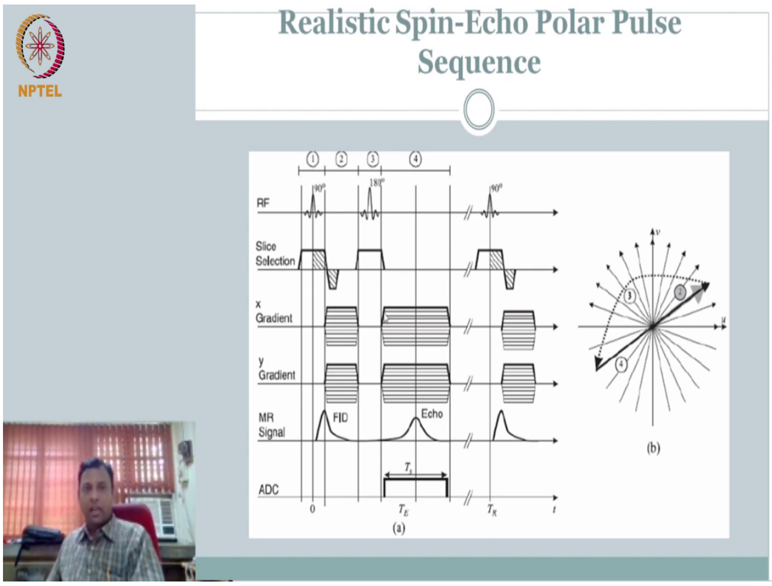

So, now, what we will do is last but not the least. Can you again do the same exercise this should be fairly straightforward right. I see this, I should have not shown this perhaps may be that will be a task in exam or homework right. So, the idea is look at the sequence can you guess the path look at the sequence I have RF pulse.

But I am applying x and y simultaneously along with slice selection right. So, I am not having a gap the read out direction, I have both x and y on that gives me the clue that, if x and y are on simultaneously it has to be a polar ok. So, this is a polar sequence of course, it also polar, but echo is due to spin. So, realistic spin echo polar pulse sequence clear.

So, I would like for you to go over this again and again try to see if you understand basic sequence and how do you represent if a problem is given in English, description is in English and they tell you this is the sequence. I want you to realize can you draw the pulse sequence representation of it, can you show how the data is acquired these two are the take if you understand these two, then you understood the physics, then you understood the data acquisition scheme right. Then reconstruction is not a big deal.

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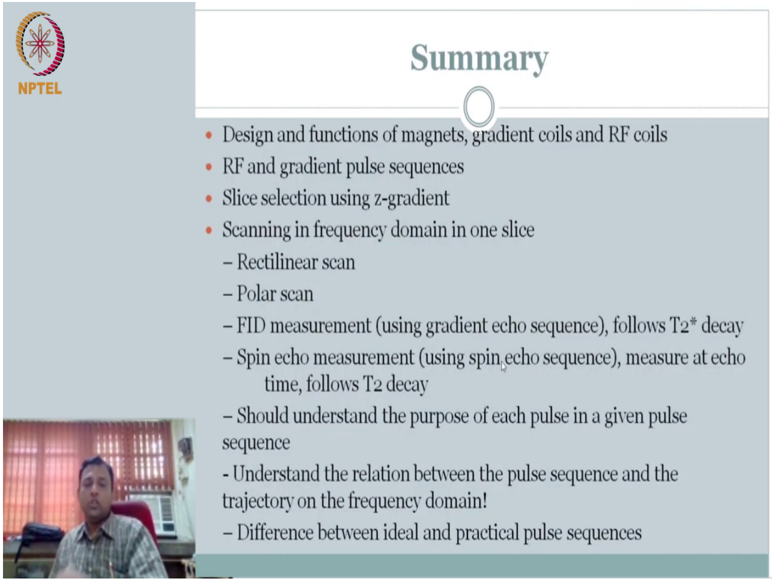

So, to summarize the data acquisition we covered design functions magnets, gradient coils all those things. We also covered the gradients pulse sequences and then we talked about slice selection is usually z gradient and then the forms of scanning rectilinear and polar scanning ok. We also made distinction between your T 2 start which is your dephasing due to change in magnetic field. And spin echo; that is due to your spin interaction that will come in your spin echo machine.

All this time we have repeated several times. So, I hope you get this. But critically I would like for you to pay attention to the last three, that is the most important take home that I want you to understand from this module, which is you should understand the purpose of each pulse, your pulse sequence right. Each of the pulse you should understand the physics what the aspect of the physics that we understood this pulse is exploiting.

And therefore, the signal is having the contribution it is always f of x,y; physics gives the meaning for this f of x,y. So, can you see that; second is the relationship between the pulse sequence and the trajectory in the frequency domain right. The 1,2,3,4 right, polar sequence or rectilinear how you know that sequence I would like for you to connect between the pulse sequence diagram and the trajectories in the what you need to understand.

Of course last is difference between your ideal and practical pulse sequence right. This I think you should these three are very critical, if you understand that MRI is you will understand why people rave about MRI is being a be Allendale modality.

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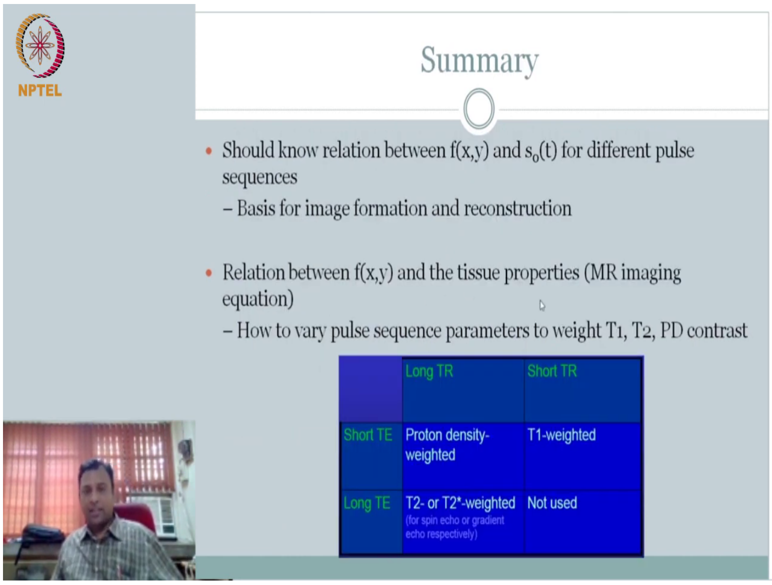

So, last, but not the least you should understand this very important concept of the signal that you are measuring s of t right.

It is very counter intuitive I am saying s of t we are always trying to think about a time domain signal. It turns out s of t here that you are measuring or s 0 of t which is a demodulated signal is actually doing measuring the Fourier transform of the signal ok. So, more the time you allow, more the frequency content you capture you can think about it that way.

So, you are actually capturing the Fourier transform of the object f of x,y is your object you are capturing you are measuring the Fourier transform of the object when you are actually measuring s 0 of t. Once you have that basic image formation reconstruction is straightforward right, this is the important aspect. So, relationship between f of x comma y and the imaging properties that is f of x, y we showed this pulse proton density.

But we have already covered in physics how you wait the basic different time sequence of acquisition to different properties of T 2, T 1 weighted image right. Same thing you will have to be able to explain. So, you should understand the combination and how you realize that combination using the pulse sequence diagram, and how you understand from the pulse sequence diagram the Fourier space or the Fourier space how you have travelled and therefore, your s 0 of t ok.

We will stop here. So, what we need to still cover is, from here it is little straight forward; from here what we need to cover is, I have the data how do I get my image right you know inverse Fourier transform. So, conceptually you know from here everything you should be able to nothing should look new. We will just formally completed, but from going from now image reconstruction should be a cakewalk if you understand this because we have done this for ct here we have understood what we have recording which is Fourier transform of the object.

So, I should be able to go back to the object or the image. I should be able to talk create the image then we need to talk about the image quality ok. So, may be another two lectures we will be able to complete the syllabus. So, we will stop here for this module.

Thank you.