Introduction to Biomedical Imaging Systems
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Lecture - 50
MRI_Freq_Encode_S42_S60

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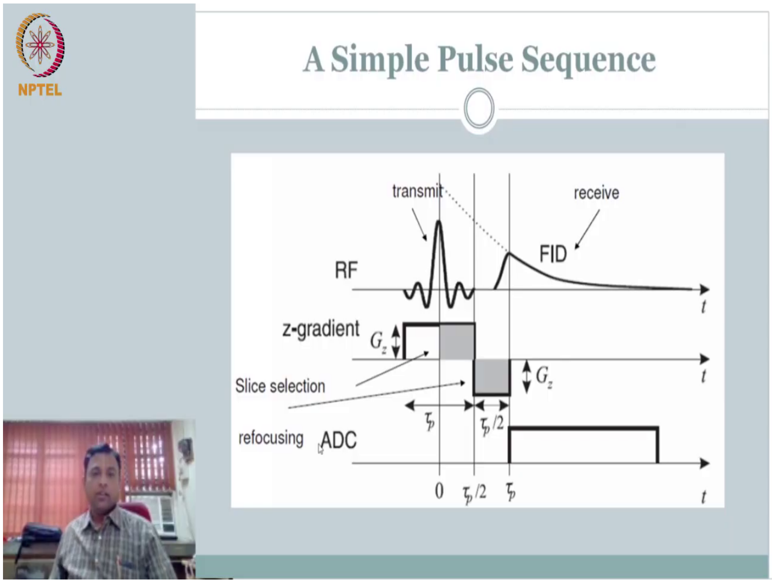

Welcome back to yet another session. Here we want to proceed further last class where we stopped was with regards to Slice selection. So now, than we have selected our slice and this is the sequence diagram that we represent right. So, you had the excitation and during the excitation you enabled a gradient and we enabled for convention we said this is the z-gradient, which will give you axial slices.

And when you do z slice the signal is still not coherent in that volume right. Because it is all diffused dephased because there is a difference from one side of the thickness to the other side of the thickness, there is a different frequencies. And therefore, different grade field strength and therefore, different frequencies right. And therefore, you would not get coherent signal.

So, because of that we apply what is called as a refocusing gradient, which is applied for a short duration t tau t by 2. And immediately when you do that the slow tries to become fast, the fast tries to become slow. And therefore, in that period there is a point where all of them will come together, which is giving you the signal.

And we record that signal we denoted it as analog to digital converter. So, essentially this is how we denoted as a read out signal; we are measuring this signal after this sequence correct. What we need to know is ok. I know how to build a signal from a particular slice thickness. Now, what is the that I am measuring what is the meaning of what I am measuring?

I know the signal is going to come from this volume. First is understanding the mathematics and the intuitive meaning behind the signal. And once we understand the intuitive meaning behind the signal our aim is to actually see the distribution; we want to see the image that is x y x comma y of wherever the signal is coming from not that the signal is coming from this slice thickness volume, you know that is not important for us.

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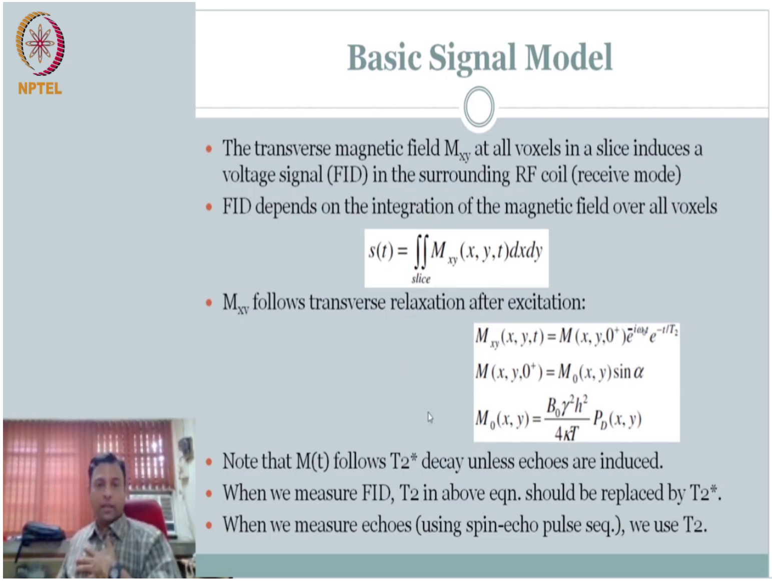

So, first we understand the basic model this is a very powerful concept. So, please pay attention to this. If you understand this which is the most difficult part to understand in an MRI, rest of it with time you will be able to enjoy you your own interpretation and beauty. What we know from before is the signal comes from the transverse component M xy when this transverse component spins you have a coil, you get the free induction decay voltage signal, correct.

So, our s of t the signal that we are receiving is coming from M xy with t from the whole slice. So, the whole slice is contributing whichever got exited. So, your s of t is a net from this whole slice of your M x y component from different locations right. So, what is this M xy?

The M xy is the transverse component what will happen just after your excitation is half, right you pushed it this M x y is going to change with the time. How is it going to change with time? It is going to decay more specifically it is going to decay with some time constant, which we called as T 2 or more precisely T 2 star and T 2, right; that we will make a distinction.

So, your M xy of t we know is M xy is 0 plus right. What is this 0 plus? This is just after you start, after you pushed the just after you start to receive the signal 0 plus right. What is that? That is going to be your M naught; M naught is your M naught sin alpha. If alpha is 90 degree you are pushed to the equilibrium value to the floor. That is your starting point and the starting point gets to reduce exponentially with the time constant T 2 or T 2 star.

So, this M 0 x y is nothing but your, you know first model we did B naught gamma square essentially it is related to your proton density. So, now, quickly you see the transition the basic signal here, the proton density contributed from proton density right is falling on the floor and that is a starting value that is decaying with time with sometime constant.

So, what you are measuring s of t is nothing but every component that is coming from this complete slice ok. Of course, the M of t we should be careful this is correct like I keep saying T 2 we have put it for purposes of explanation and going forward, but do recognize that technically this is T 2 star rapid dephasing happens due to T 2 star.

Remember the dot T 2, when we did this spin echo right. When we did the spin echo we said we could get the T 2 decay otherwise, it is T 2 star decay. So, if you are just measuring the free induction decay, then you should replace the equation with T 2 star. If you are doing spin echo then it is more appropriate to use T 2.

So, for ease of you know following the concepts, we will go with T 2, but do recognize there is a subtle difference between; whether you are going to use T 2 or T 2 star or the signal that you get is rated based on T 2 or T 2 star depending on whether you are measuring the free induction decay or you are measuring the echo, ok. So, that is a subtle difference that keep in mind. But essentially we see what we are seeing here is a signal is from the whole volume right.

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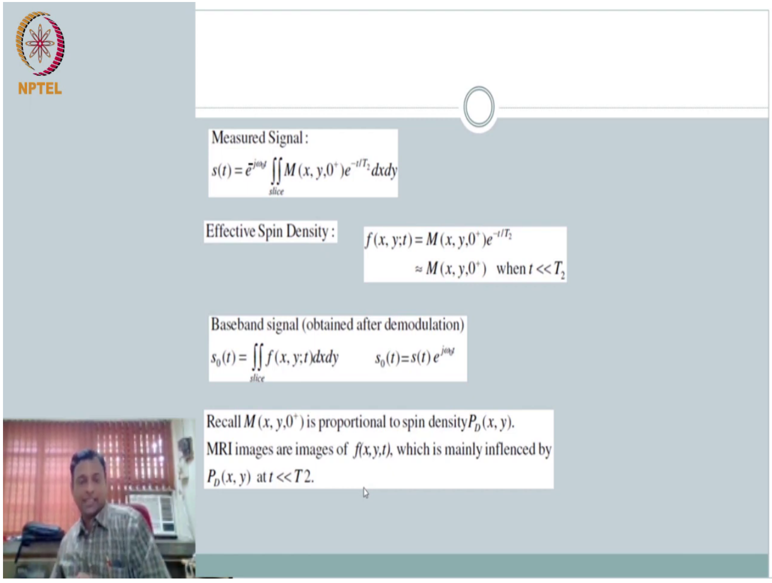

Measured signal is from is modeled like this, this is your B naught right. So, you from your omega naught comes from your B naught. So, you can write it like this. So, I will recognize f of x comma y to be M x y 0 plus the starting value exponential this, this is my signal just I want to write it in signal form so, that you start to recognize in the generic signal form of f of x y, right.

So, of course, this is approximately equal to M x y 0 plus if you if you consider a time instant that is much much shorter than your T 2, right; very straightforward. But what is important for us is to recognize that, this is nothing but your specific density; what is M x y 0 plus right, in the last equation the previous slide we show it is all that constraints are there then you have your proton density. So, your signal in some sense is related to your effective spin density whatever you are measuring here right.

Of course I will first not work with s of t almost all of the instrumentation, all of the MRI processing, signal, acquisition and processing works with demodulated signal ok. So, we will use the base band. So, we will use s of t instead of using s of t which has e power minus omega t, this is a high frequency they will use s of t as s of t into e power so, essentially your removing the omega naught or you are moving it or your demodulating it.

So, you have only baseband. So, we will manipulate this and call this as the baseband signal that we are going to play with. Baseband signal is nothing but f of x y d x ok. So, we will we will interpret this baseband signal going forward. So, we know this M x y is proportional to your P D, and MRI signals therefore what we are doing are mainly influenced by P D in the signal equation that we have shown, ok.

So, what does this say, why is this effort what is the intuition behind this? This is very common sense. If I have a larger volume I will have more signal. If I have less volume, like your slice thickness now you when you have a bigger slice thickness I will have more volume right.

Imaging plane times the delta z, I will have more signal whatever I am measuring we have not gone to that which will go. That the M x y that you are measuring the s of t that you are reading out will be high if you have a larger thickness, if you have it will be low if you have thinner slice. That is what this intuition tells right.

So, naturally you want good signal right therefore, you are not going to have ideally thin infinite a very small imaging plate. So, it is a trade-off with already the trade-off with one approximation that we have done, one slice thickness direction that we have done.

The story does not end here ok. We will have some slice thickness, that gives us the best signal possible or signal level that is acceptable to us and the resolution is acceptable to us.

Now, what we need to do it still says it is coming from this volume I need to know, where it is coming from this volume, what is the x comma y?

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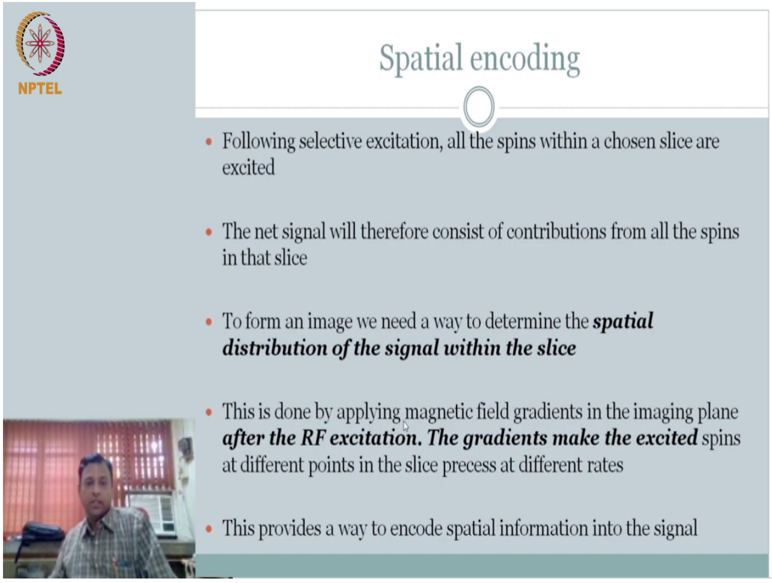

So, for that we do spatial encoding following the selective excitation all spins right, they only within this selected slice is excited. So, a net signal that you get is from all the spins within this volume. Now, I have to recognize within this plane where is this contribution coming from. To do this to form an image we need a way to determine the spatial distribution of a signal within this slice, right. How do we do that? We will again do the same we have the gradients in the two other directions right the x and y this is the emerging plane X-ray.

So, what we will do is, after you apply the excitation do the RF selection, we will apply that time we applied only gradient z G x and G y were 0. Now, what we will do; we will make G 0 0 right I mean G G z 0. So, you have selected the slice that is what is giving signal.

During the signal read out we will enable gradients in the other two directions. We are able to do that then we may be able to say, which location within x y corresponds to which frequency. And therefore we know from the recorded signal where it came from right. So, this is how generally it works. So, we go one step at it and we.

So, 3D volume we collapsed to a slice within the slice we need to now do first row and then column eventually image is a matrix x comma y right. So, we have reduced it to x y now, we need to now use x and y gradients to our advantage and separate x comma y.

So, how will we do that is first within this plane we break it into rows and within the rows we will break it into column right, that is another way of thinking about it.

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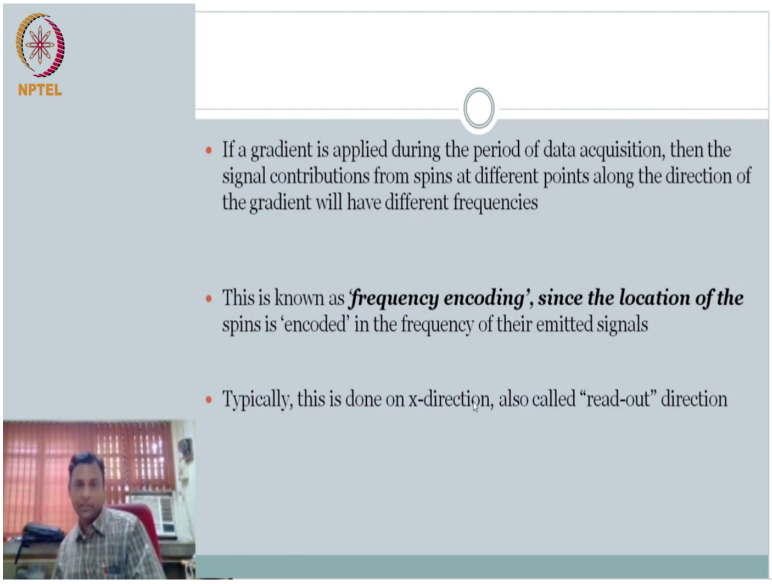

So, if a gradient is applied during the data acquisition, then the signal contribution from spins from different points along the directions of gradients will have different frequency. This is what the exploited in e z direction, we can exploit the same thing in whichever direction we want, right.

If you apply a gradient along the gradient axis the frequencies are different. So, if you record the net signal, which is a combination of each of these signals then you know where it came from. So, this is known as frequency encoding, since the location of the spins encoded is the frequency of their emitted signal, ok.

So, first we will go if you do everything at once it will be confusing so, what we will do is first we will do one, one of the directions typically x is called as the read out direction. So, we can apply a gradient in the x-direction what will happen if I apply a x gradient then along the x direction there is going to be change in field strength and therefore, there is going to be a change in frequency along the x-direction. What I am recording is still the net sum.

But here I know signals that are coming from along the x-direction will have different frequencies. So, what I am going to capture is going to have multiple frequencies, but I know which frequency came from which x that much I know right. That is your frequency encoding direction.

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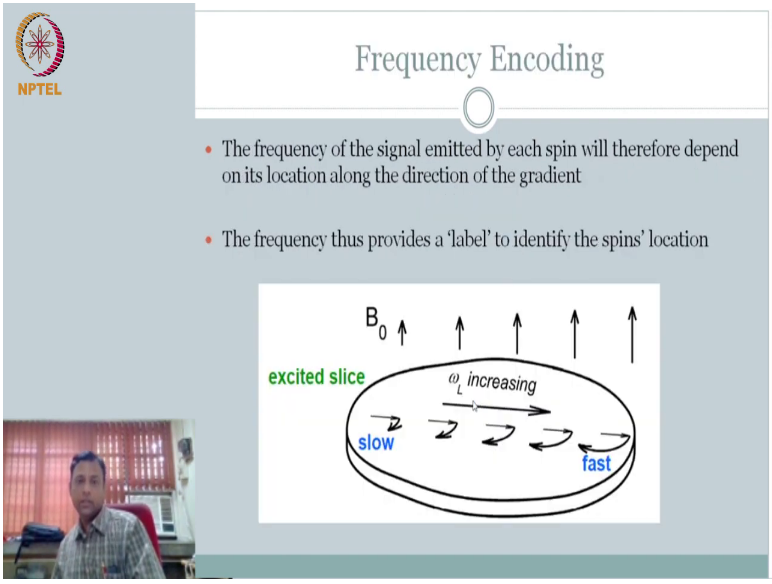

So, to look at this slice so, we have selected a slice if I have x-gradient right. The arrow mark is changing right. That is field strength is changing in only x-direction then you notice that within this volume I know along the x-direction right along the x-direction everything the frequency is going to change because your B is changing.

So, you will have on one end you will have lower frequency, the other and you will have faster frequencies. The lambda frequency increases from left to right because your B naught decreases from left to right. So, the frequency thus provides a label to identify the spin location.

So, what I can say from here is not only this the signal is coming from this excited slice, I can also the recorded signal also has information of at least one another direction, I should be able to piece out that it came from this x location y x location.

I still have to do the y location right x comma y, but at least here I will be able to say within the slice all of x. So, I have sliced it along x in some sense if you think about it ok. So, we have so, the signal that you are recording have this encoded signal right information how do I decode this information. For that we need to understand the signal little more detail; the mathematics of the signal that we modeled right we should start to see it not just as the mathematical equation, but also as the physics of the operation that we are doing.

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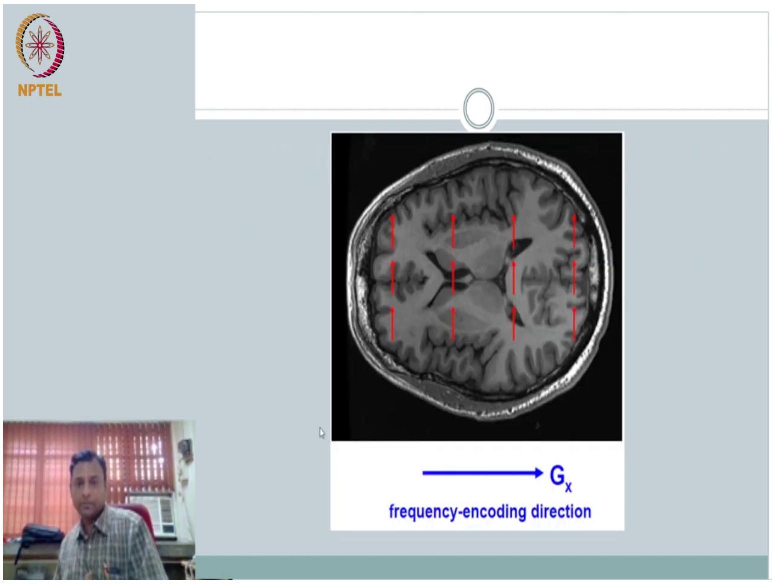

So, what we have done is in the in one direction x-direction we applied a gradient. So, we know the signal, that you are recording is going to have multiple frequencies and we know each of this frequency is changing along the x-direction, right.

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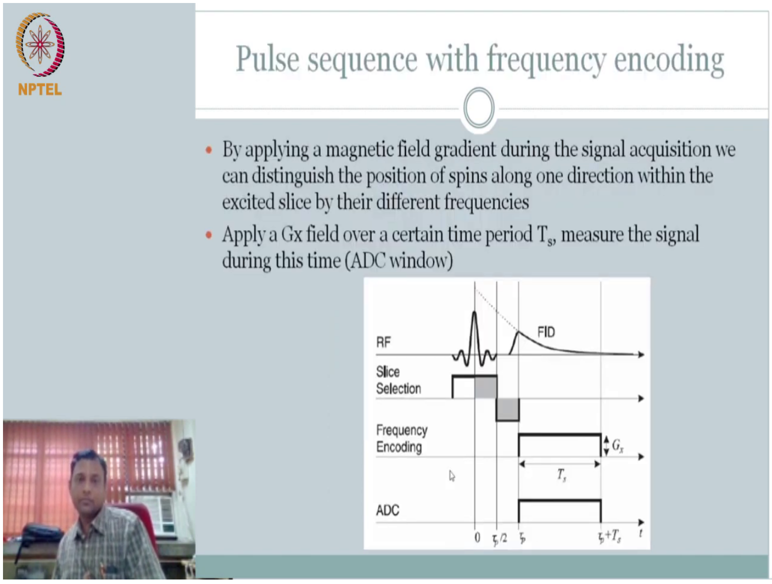

So, we will write this in our right as an. Now put the sequence diagram to explain this this we know RF, this is the slice selection, this is your refocusing. So, your signal started to appear right when you pushed it on the floor, but while it is on the floor just after you pushed it you are encoding you are oning the x-gradient G x. That means, you have encoded the frequency and you are recording the signal during the read out when G x is on.

So, the signal that you have recorded is going to have the signal that you are recorded is going to have information in our sense, it is going to have information, which is going to compose of different frequency content, right. Because you have a gradient on in x-direction. So, each location along the x-direction is experiencing different Larmor frequency you are doing net sum correct. And that is why you going to have the recorded signal is going to have all the frequency components, right.

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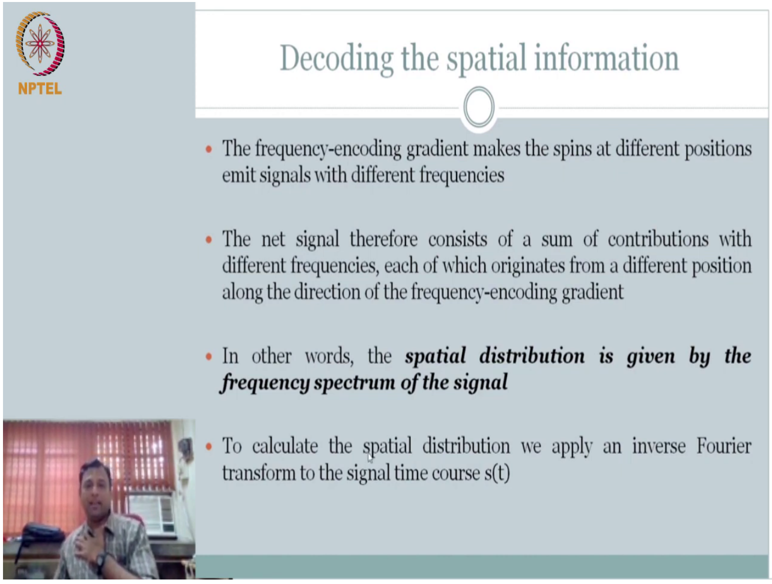

We will we will look at it little more.

So, when you are going to decode the signal information the frequency encoding gradient right makes it possible, because it spins different locations in x are going to have different frequencies. So, let us read the English form of the signal that we are acquiring and then look at it from Physics, and then go into the Mathematical understanding of it.

So, what we are saying in other words is the net signal right, is now consisting of sum of contributions of different frequencies why is it different frequencies? Because you have a x-gradient so, each of which originates a different position along the direction of frequency encoding gradient, which is G x in this direction.

Is any mathematical concept being of any mathematical concept comes in by reading understanding the meaning here? When you talk about frequency contribution your sum, you are going to have contributions of different frequency what does it sound, it sounds very similar to what you talk about frequency spectra, right.

In other words the spatial distribution is given by the frequency spectra of the signal, I have contribution some different frequencies what is that? That is your frequency spectra. So, the frequency spectra contains information about the spatial distribution this is very powerful ok.

So, now this we understand this meaning so, the signal that we have capture is having contribution from different frequency components. So, we get a feeling that whatever we are capturing is actually the frequency spectrum, but let us put the equation and see whether we recognize that ok.

So, clearly that means, there should be some relationship between the spatial distribution and the Fourier transform right, of the signal sin time close that we are doing. So, we will we will see the signal that we have and see whether we are able to appreciate the meaning of the signal.

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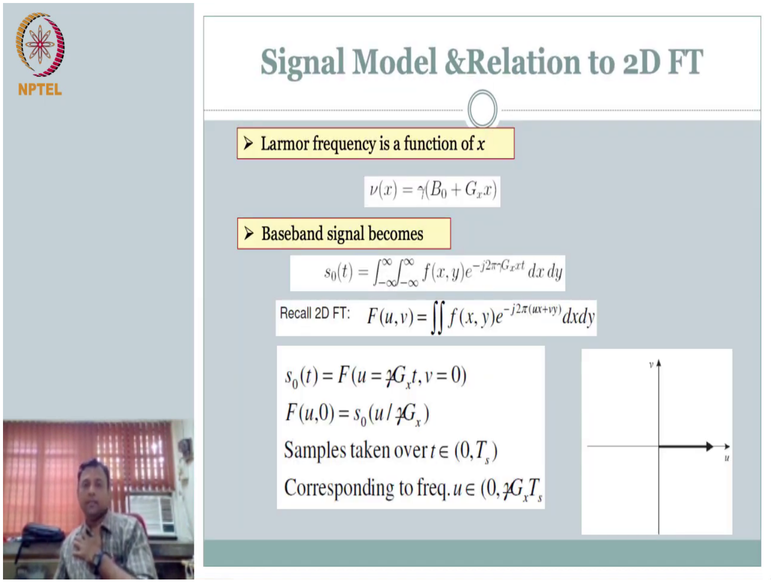

So, you have Larmor frequency along the x-direction so, this is nothing our Larmor frequency is changing because I have only gradient in x-direction. If I write out my signal the baseband of the signal is nothing but F of x comma y e of I have just expanded this right, that v frequency that was there in the previous slide when we wrote the signal equation, I am expanding it using this, right. So, if I do that I get e power minus j gamma G x x t d x d y.

Now, when you look at it should be strangely similar to a standard formulation that we know and what is that? A 2D Fourier transform. Recall, when we did the first few classes right 2D Fourier transform F of u comma v is f x y e power minus 2 pi u x v v u x plus v y right u u and v being the frequency directions of x and y right.

So, now you clearly start to see something that it is viewed at beginning, but we know the mathematics. It is just that our mind is difficult to comprehend because we have always used to looking at Fourier transform as a you acquire the signal in time domain and then you transfer it to frequency domain.

Now, I am saying we are acquiring s of t, but that s of t itself looks very similar to the Fourier transform. So, what is it that we are recording right? So, your s of t is nothing but Fourier transform of F of x y right. It is a, Fourier transform of F of x y. F of u is you recognize the variable u is gamma G x t, v is 0 right in this equation.

So, when we compare s 0 of t and the standard 2D Fourier transform of F of x comma y, you recognize s 0 of t that your measured is nothing but it actually a Fourier transform with frequency components u and v mind boggling right.

So, what I have said what we are realized now that we are not actually measuring the time domain even though we plotted the free induction decaying time, it turns out that the signal that you are you are measuring is nothing but Fourier transform the Fourier transform of the object F of x comma y.

So, from what we have measured so, far if we have to put it in the space of u and v, you have measured this fantastic right. Now, you recall something similar we did when we did 2D c t. You had a detector array, a Famous theorem right Fourier slice theorem you have a 2D; you have a detector array you measure the signal, take the Fourier transform, the Fourier slice theorem said this is one slice in the 2D Fourier transform of the object.

So, then our entire concept changes. So, then we say, why do not we acquire several projections. And therefore, populate the Fourier space, once you have the Fourier space of the object that is the Fourier transform of the object, I can get the object as the inverse Fourier transform.

So, we acquired different views, acquired different projections, took the Fourier transform and constructed the Fourier space Fourier transform of the object. And then obtained the object as inverse. Here, what we have seeing is I am actually measuring directly the Fourier transform, the Fourier space of the object and actually measuring the 2D Fourier transform space of the object F x; F of x comma y fantastic.

So, now it tells you that if I want to acquire the MRI signal image MRI, then if I can repeat this experiment and cover the whole space, then I can take inverse Fourier transform and I will have the object. And the object in this case would be proton density, where it is coming from right, clear. So, fantastic. So, let us see how we have to do all this we need to be able to cover different strategies we can use to cover.

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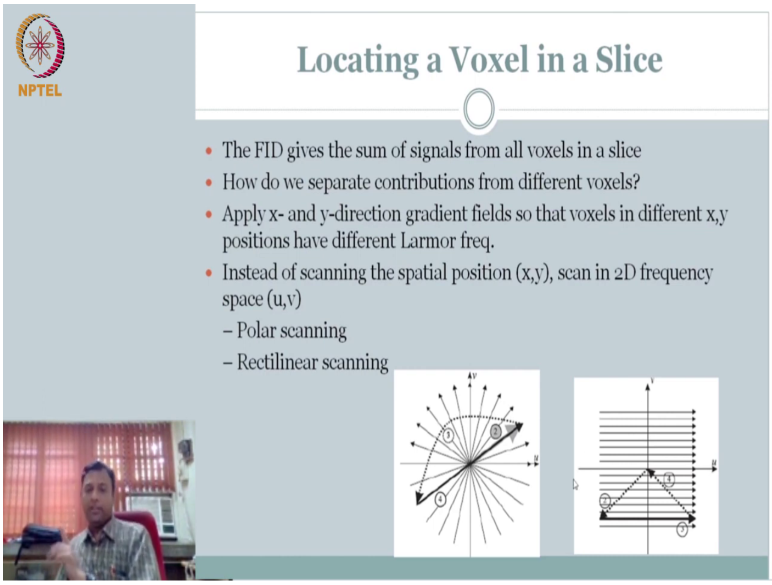

So, first is our objective is still locating the voxel in the slice. Your FID gives sum of signals from all the voxels, you are getting one from the whole slice. Now, our objective is to separate the contributions from different voxel. So, what we have seen now is if I apply x-gradient I can separate it out at least the x so, if I can apply y gradient then I may be able to also separate the y-gradient right. Therefore, I can get my F of x comma y.

First we can do this in a several ways so, instead of scanning the spatial location we are actually acquiring a Fourier transform space of the object. Once we get that we can do the inverse Fourier transform and get the object itself.

So, how can you scan the Fourier space? You can scan it with the different strategies. One is polar scanning, where you essentially rotate right. We saw one; we saw a u here in the previous sequence why? Apply one particular gradient G x we got along this so, if I have to repeat this experiment multiple times perhaps I can repeat it with different value so, I can manipulate. So, that is one polar scanning.

Other way to cover the Fourier space would be I can do rectilinear scanning right. So, we will go into each of them with little more detail also how do we saw one; we saw how you started the origin and cover positive u right, we saw that. Now, how do we execute this strategy, how do we execute this strategy we need to understand.

So, to execute this strategy I need to be able to move along u y at different angles. To execute this strategy now, I know here to execute this strategy I may be able to not start from the origin, I should be able to start from negative axis and then move left to right. Not only that and, I should be able to move like parallel like in the v-direction also.

Right now, I know only how to do start at the origin and acquire data your gamma G x t you see highest frequency, I will stop here. So, I can start with 0 I stop with gamma G x t t s right acquisition time; highest frequency, but I need to have a way to start on the negative axis not only that I should be able to do that at differently; how do we do one right.

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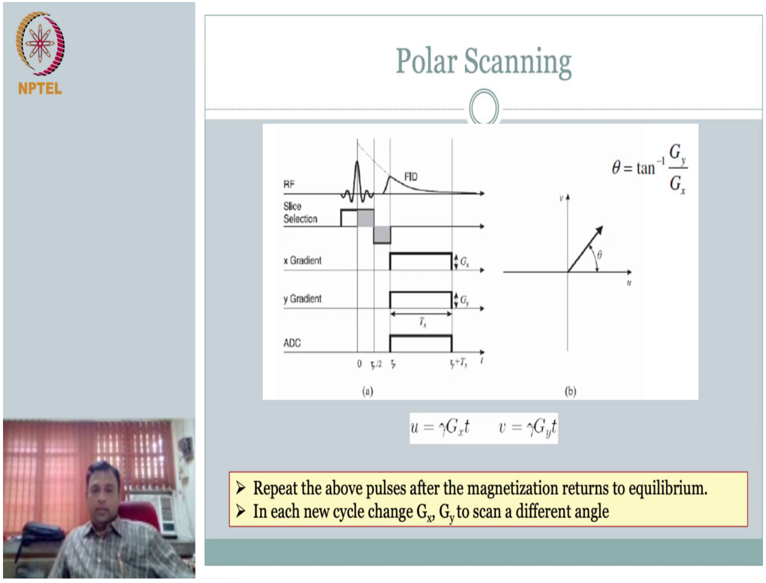

So, there are several strategies let us start with polar scanning. When you do polar scanning you straight forward. We put the timing equation like the pulse sequence diagram and it will become very vivid.

So, this is nothing new you apply the RF pulse in this and then you do the slice selection, you do the slice selection with z-gradient I could have marked this as z-gradient. But it is given that with the convention that we are following z-gradient is used for slice selection right.

Slice selection, refocusing you make a signal come out, when the signal is coming out if I apply G x and G y right, I can move this vector. So, when I add only G x no G y it was lying here at 0 degree. If I want some other theta I will have to apply G y I it is G x and G y is in my control. So, I can get any theta I 1.

I can repeat this experiment I am reading the signal the signal is now a contribution, that is encoded with G x and G y. So, I know where the signal is coming from. If I repeat this experiment several times with different G x and G y I may be able to cover the whole space.

Of course, the only thing is each time in order to come to the origin you have to wait, you put one sequence you get one thing you wait so that the signal comes back and then you repeat the experiment ok. Highest frequency will be, I mean your frequency axis will be gamma G x t gamma G y t; the highest frequency will be until how much ever you are recording you are according it over t s.

So, gamma G x t s gamma G y t s would be your highest frequency that you have recorded in that u v space. So, you repeat this with different G x and G y value you can comma the entire space fantastic right, simple. Once you have the entire space you not take inverse Fourier transform we will get the image. So, job done ok. So, now what we need to do is we need to have a way to do two things, if you have to do rectilinear. You have to go to the negative axis and you have to move along v ok.

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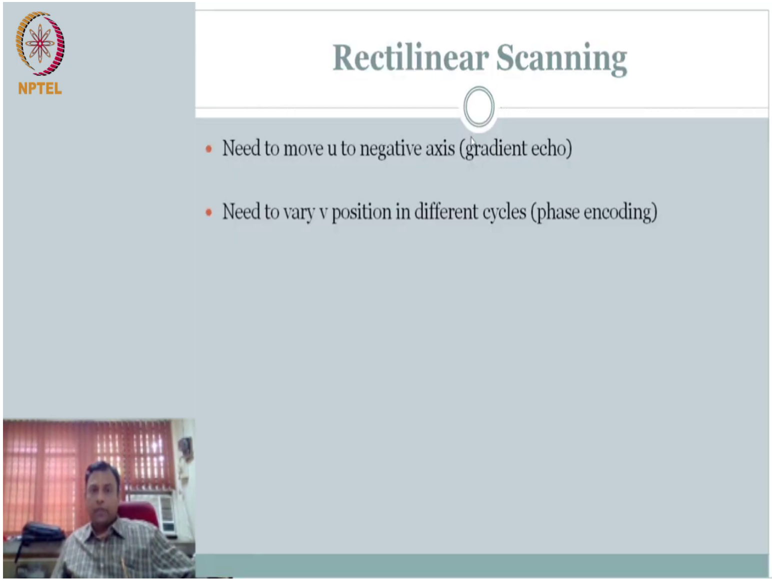

So, for rectilinear scanning you need to move to negative axis and we will use a concept called gradient echo for that. Likewise we need to move along the v position right there we will call it what is called as phase encoding ok.

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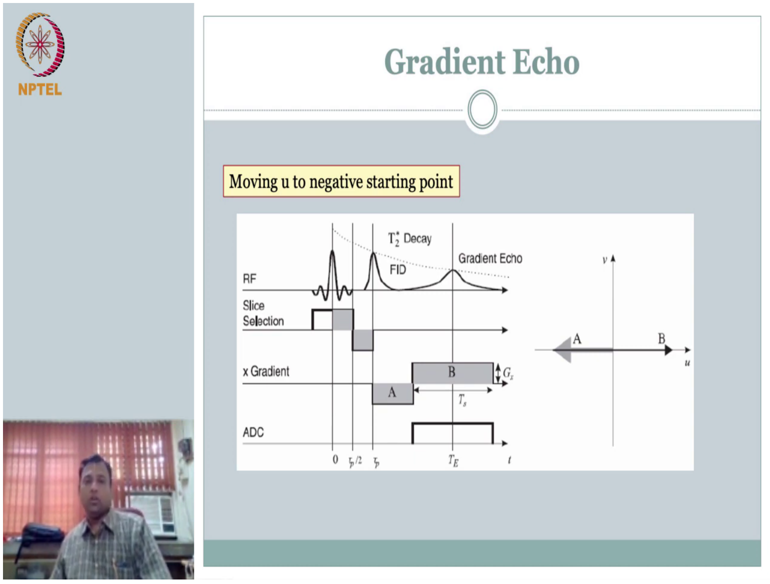

So, let us start to understand how do you gradient echo or how do you move the starting point to the negative u axis. Everything is same, you apply the signal you do the slice selection you do refocusing you get some signal, but notice that I am also applying a gradient axial; the only thing is I am applying a negative gradient axial. We can apply positive gradient or negative gradient right, where G x you can apply minus G x or plus G x just the direction. But notice an important point I am applying a negative G x ok the signal is there.

So, I am actually I can also encode this right the signal is that the free induction decay is there all negative gradient, but I am not recording the signal at all; I am not interested in that signal. What I am interested is after I apply the x negative x-gradient I switch to positive x-gradient.

Remember cunningly how we did this here. We switched the gradients here, why did we do that, because there was a slow end there was a fast end right, within the slice. When we switch the gradient the slow became fast, fast became slow and therefore, the signal started to add up, very similar.

So, I have a signal free induction decay signal, but I am not recording it instead the gradient is switched the x-gradient is switched when I make it opposite polarity the signal. Now, which was dying starts to build up again the slow guy tries to become fast, the fast guy tries to become slow and therefore, you are going to have high signal add up. And then of course, it will die down.

You are recording actually there echo signal not the original signal. And therefore, this is called as echo signal not only that, this echo is coming because of the gradient. The signal is coming the echo of the signal is coming from the gradient, which is what you are recording. And therefore, it is called as gradient echo.

Remember distinguish this from the spin echo that we did fundamental differential; that echo there also it was the same idea right, it was dephasing you made rephasing you got the echo signals so, we called it echo. But the rephasing started because of applying RF excitation pulse that flipped to 180 degrees, clear.

So, you are dephasing was happening because of spin-spin interaction ok. Whereas, here the echo is coming because I am changing the magnetic field, not because of spin-spin interaction, I am actually changing the magnetic field. Remember your T 2 star was due to change in magnetic field, your T 2 is due to spin-spin interaction.

So, here I am deliberately changing the magnetic field so, that I make it in phase ok. So, this is also an echo, but this is coming from gradient echo. So, it is T 2 star taken that is the fundamental difference between spin echo and gradient echo both are echo, but the spin echo you get it from applying RF excitation pulse whereas, gradient echo you get because of switching gradient.

But therefore, the fundamentally the decay constant in gradient echo is due to T 2 star; changes due to signal loss due to change in magnetic field strength right, that is T 2 star.

Whereas, your spin echo is based on T 2. Very fundamental concept, but easy to get confused, but I hope you listen to this lecture few times and you know get a feel for it.

So, what does this do; this essentially has pushed to a. This is no big deal actually think about this. When I applied this negative x-gradient naturally I would expect when I apply positive, it was in this direction the previous slide right u it was this direction. If I apply a it is in this direction, only thing is I am not reading out the signal, I am reading out the signal just after I switch.

So, I am starting to read the signal from here left to right. I have moved here and reading from left to right, I am not reading why a is on I am reading only with B. So, I moved it to the left. So, I can when I start to acquire the data now, the data will starts from negative u-axis and go all the way have up to positive u-axis with gamma G x at t s of the maximum frequency right, fantastic. So now, the question is how do you move in this direction.