Introduction to Biomedical Imaging Systems
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Lecture - 53
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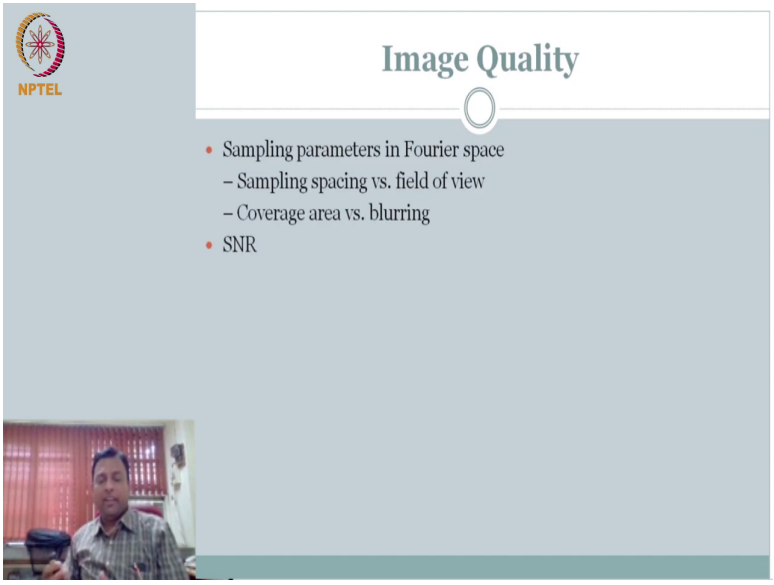

Again here it is a very brief video, the reason for that is by now because of the style with which we covered different modalities it will be pretty you know you could guess what is the image quality that we are going to talk about, what are the metrics right of image quality. And more importantly our interest is to see how do we relate the image quality to parameters that we studied that is their physics and the instrumentation or the data acquisition right.

So, first we will focus on sampling parameters and the reason for this is that is related to resolution. So, first we want to talk about resolution and then signal to noise ratio. Of course,

we already spoke about contrast right, contrast mechanism before. So, once we have noise you know contrast to noise ratio you can arrive at.

But so, the emphasis here will be essentially to bring the noise part of it and the resolution part of it which is very key; and, the challenge with resolution, so we will spend actually considerable time, even within this short module on the resolution part. And the reason for that is everything is in front of the eyes you think you understand, but to interpret that is little confusing right.

So, any time something is confusing; that means, you should really understand it to the core that way you do not have to memorize anything. If you close your eyes and think about the concept the definitions or the matrix should come out as a visualization for you I mean, that is the aim that I have ok and. So, resolution is tricky you might feel like its straightforward, but it is it can get you confused really right.

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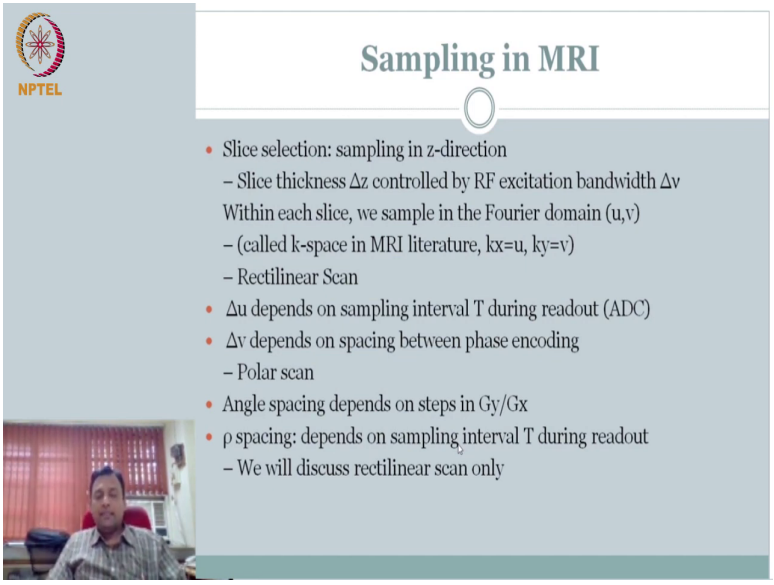

So, we will start with resolution first I mean, before we formally get into resolution we will have to talk about sampling. Because, the data that you are collecting is sampling remember first we started with z selection. So, you already have a slice thickness delta z, then delta z is controlled by your RF excitation frequency bandwidth in fact some level we covered ideal slice thickness and your actual slice thickness because you have a finite sinc pulse right.

And therefore, we already talked about blurring within the edge of the thickness slice ok. So, somewhere you already realize sampling becomes a important issue. But we will now focus on not the thickness as much for a given thickness because we are interested in image.

We will even though we know even in the thickness direction there is blurring happening because of your delta z right, how you sample the frequency of your RF excitation is not hard

limited, but it has a ramp up and a ramp down. So, we leave that we are more interested in plane right, within the image quality or image resolution or rather image sampling first ok.

So, within each slice we are actually talking about sample in I mean this is again the bigger problem just to make. Each time we think about sampling we introduce the concept x of t or y of t in time domain, the signal in time domain and we say oh sample at twice the highest frequency to beat the Nyquist right. And that is how we do the sampling concept, here it is kind of weird. The signal that you are recording as we saw is actually the frequency spectra.

So, what you are recording is a sampled version of your frequency spectra ok. So, that is where with you know confusion may start to arrive. So, in each slice we are going to talk about the data that we acquired is a sampled k space or sampled Fourier domain is what you have ok. In case of rectilinear we will be talking about delta u right, delta u is in the x direction. You remember that the ADC that we were plotting in the pulse sequence diagram, we just said T s ADC is on for data acquisition time T o.

But essentially that is a sample ADC is analogue to digital right. So, essentially your sampled acquisition of your frequency domain delta v in some sense you already saw, it was a line that we put a horizontal lines that we put right. So, there was a spacing, so that is actually discretized in some sense. u was v put an arrow mark as a line, so we always thought that it is continuous.

But actually speaking with sampled data points is what you have there delta v is more intuitive ok. But we will have to relate these two, in case of polar scan likewise you have angle that is discretized you saw the theta steps say. So, that you it is already vivid that you have discretized. Or, there also along the row we put a straight line we did not put points essentially it is points, but we have been using line right.

So, the sampling that you have there it is also there, so delta row should be there. So, for the purposes of covering the topic and giving this intuition we will strict with rectilinear scans

only if the discussion going forward ok, because it is easier to visualize a rectilinear than angles ok.

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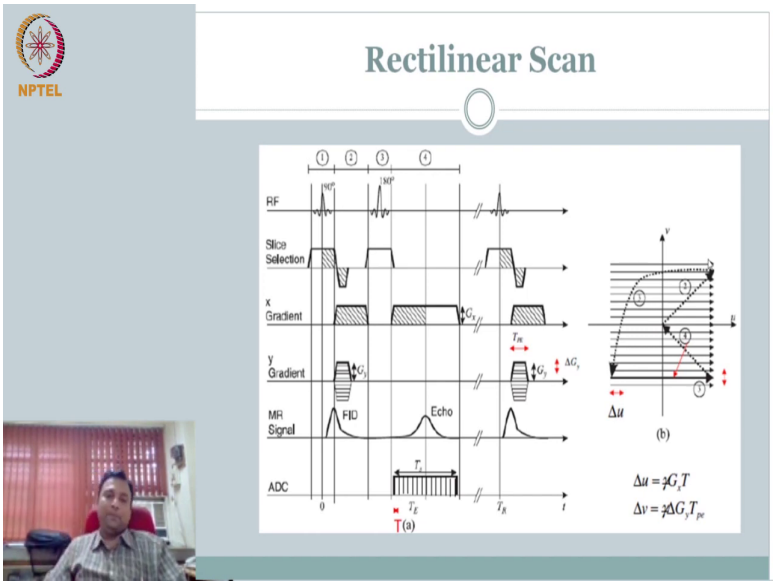

So, let us start with sampling right in u direction, what happens in u direction? So, here is our rectilinear scan, only things that I have added is remember this was T s before one box now we are actually saying this is ADC, so we are actually sampling. So, we are getting, we are recording the signal whatever signal that is coming in this case it is a spin echo right, this is the eco from spin.

So, spin echo signal, the signal is recorded over this time, but with some time period capital T ok, likewise in the other. So, this is your capital T likewise, when you are repeating the experiment you are moving the phase direction. Here your gradient the delta G y and you are applying the phase sequence or phase encoder for T pe.

So, your delta u is gamma G x T, remember we are talking about the highest frequency as gamma G x T s. Now; that means, gamma G x times this T is going to be your frequency delta u, likewise your delta v will be gamma delta G y operated for T pe. So, same jargons that we did before, but now since the T is not before we had T s now this T is on time period therefore, your delta u is your delta u.

So, we have been putting this arrow line, but essentially more correctly what we should have put is we should have put sequence of dots right. And the distance between the two dots or the two samples would have been delta u here. This direction it is intuitive it we always put discouraged ok.

So, this is what we have, now what we need to do is understand the relationship between delta u, delta v, no the total u, total v. More importantly this is just Fourier domain, we are interested in the image resolution right in the imaging plane. So, what happens when you start with this what does its effect on the delta x delta y right that is what we want to see let x and y are spatial domain whereas, u and v are frequency domain.

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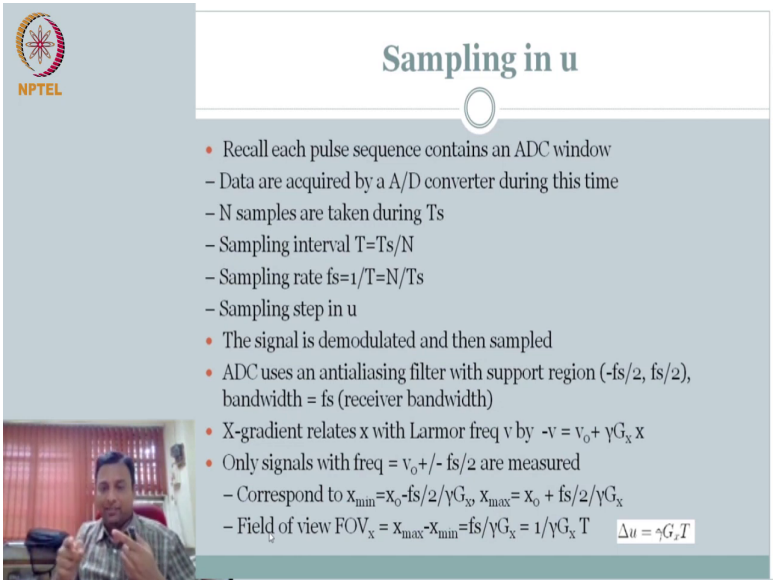

So, recall each pulse sequence contains ADC window data are acquired by ADC. So, if you have n samples over T s then one capital T that red capital T that we showed in the previous slide is nothing but total time period T s of acquisition divided by total number of samples that are acquire. So, your sampling interval or sampling rate, sampling frequency right is 1 by capital T or N by T s. So, sampling step in u. So, always we work with, so that gets your delta u, sampling step in u means delta u in the u direction how do you step delta u that is what we have.

So, if the signal is demodulated and then sampled so; that means, that before you do that if you do a ADC always we are interested in antialiasing. So, you need to do antialiasing filter, antialiasing filter you have to do for highest frequency correct that is the whole idea I want to do Nyquist similar concept here, so, same signal.

So, antialiasing now you do with support of f s by 2 2 plus f s by 2; meaning, your bandwidth is f s right. You have to be sampling better than that, so that you do not lose any information. So, your ADC should have antialiasing filter with a frequency bandwidth that is corresponding to your receive bandwidth. This f s can be obtained from here right f s is 1 by T these all this is coming from them.

So, your read out x gradient relates to your, so this is frequency domain what we want to understand is what happens to your spatial domain because of the sampling in frequency domain. The data is acquired as samples in frequency domain what is its effect on the delta x in the spatial domain right.

So, you can relate the frequency to space because of this gradient, X gradient relates to Larmor frequency by v naught plus gamma G x x correct. So; that means, we can already recognize only signals which are within this bandwidth right, receiver bandwidth or in some sense we have a gradient in field strength dictates the frequency range, the frequency range have the sampling of it should dictate your x direction.

So, your x only signals with frequency within this are measured. So, your x minimum will correspond to x naught minus fs by 2 by gamma G x x maximum right. So, this is spatial, minimum x to maximum x is related to this gamma g x and f s and therefore, your field of view of your image width and image height right.

So, your image width if you will, if call that as the x direction your image width is what? x max minus x min the field r we can call it as field of u in x direction is x max minus x min which is if you substitute this f s by gamma x this is nothing by 1 by gamma x. This we know, what is this?

Remember, gamma G x T capital T is time period of in your ADC. So; that means, this is nothing but our delta u delta u is gamma G x T is it. So, your sampling of frequency domain dictates your field of u. So, the finer I sample the larger the field of u I can get, the sparser I sample smaller will be the field of u that I get in x direction.

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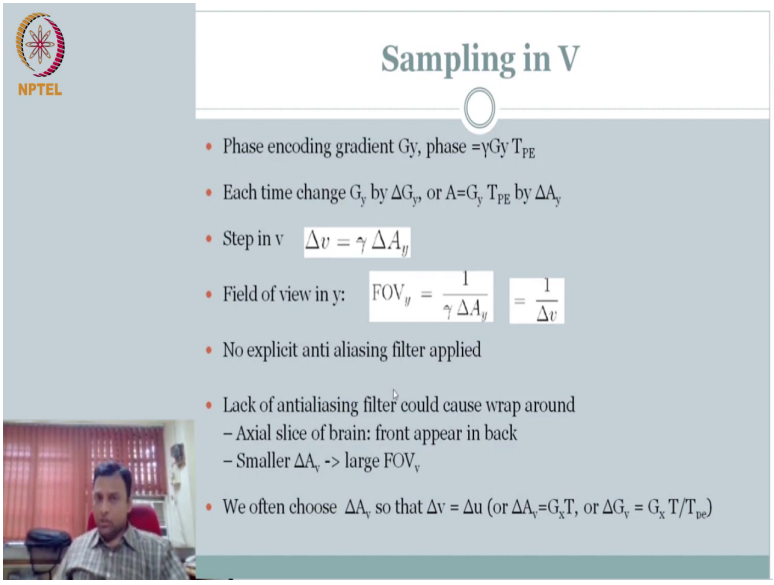

So, similarly you can do think about in v direction right phase encoding gradient G y your phase is gamma G y T PE this is the step size of your v direction. So, each time you change G y by delta G y you are changing right, your A is becoming G y T PE by delta A y. So, recall the previous slide and the plot right how we jump, so this is just extension from there. So, your step size is delta v in the v direction that is dictated by your gamma delta A y clear; that means, your field of view in y direction.

So, this is step size in v direction frequency domain in v direction your field of u in spatial domain is 1 by gamma, so this is also inversely related. So, the idea is if you step finer here that is in your phase encoding, you have a finite phase or fine phase separation. Then your field of u in y direction will be increased clear; however, here notice there is no explicit antialiasing filter you are not.

So, therefore, you can get antialiasing means you are going to get aliasing means remember the crude definition that you will remember from the textbook, high frequency masking or mask riding the low frequency. Here in spatial domain what are we talking about? Here what is going to happen is the manifestation would be the rapper out. So, if you are taking a head scan right, the front part can go in the back it will rap around if you have.

But, so there is no antialiasing. So, you just refine the setting, so that you know from the image that aliasing has taken place or not ok. So, smaller the phase direction encoding the larger the field of u. So, most often what we do is you take similar resolution in both similar step size both in delta v and delta u ok, just to keep life simple. Unless otherwise, it is a specific problem most often choose delta v equal to delta u clear.

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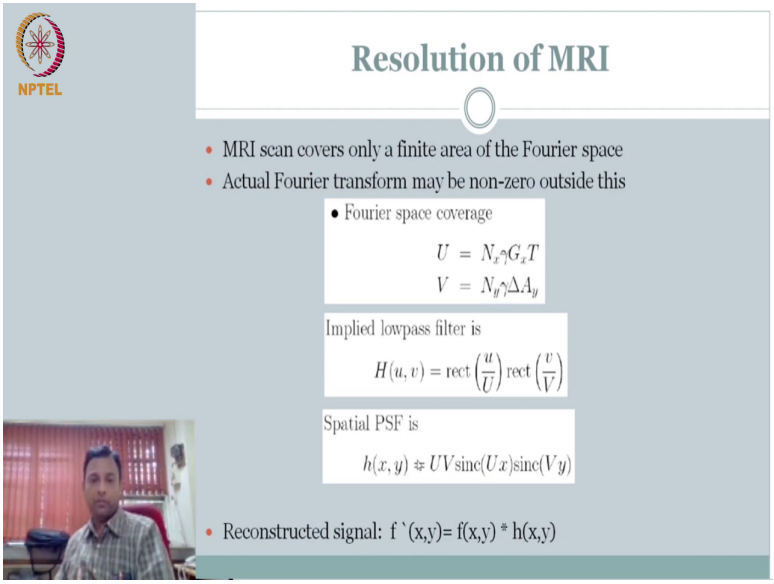

So, now the question is, how do we relate this to resolution of MRI? So, what is becoming clear now is MRI scan we are only covering the frequency space that too we are covering the frequency space only finite right. If you are recording the signal for T s over period of T s right, we already saw the highest frequency is gamma G x T s right. So, we are covering the signal only over a finite Fourier space.

So, the actual Fourier transform maybe non zero outside this, a signal might be present outside this. But we have done antialiasing we have restricted to the highest frequency. So, Fourier space coverage is your capital U is your coverage in Fourier domain like how we use the term field of u f o of v x mean the spatial domain.

We set field of u in x direction field of u in y direction, we can think about field of u in Fourier domain also. Field of u in u direction can be capital u field of u in v can be capital V, but we do not call it like that, but that is what. So, here what is this u you know that number of samples into the time period between the sample in x direction times gamma G x.

So, gamma G x brings you the frequency because G x is just the field strength gradient. Gamma is your gyromagnetic ratio which converts you know gets to frequency, frequency per tesla. So, if you have gamma G x this becomes a frequency quantity this frequency quantity you have so many samples you have n x samples each with time period T. So, N x into T is the total time period of data acquisition, which converted to your frequency that is what right.

Likewise, you will have your v which is your in phase direction N y delta A y times gamma ok. But G y is actually there in your A y in the previous slide if you flip back. So, what is this saying? This is saying image might have several frequency, but we have acquired the data by applying antialiasing filter and having some phase shift in phase encoding. It is implying that you are having data only from a frequency domain space of length capital U in u direction capital V in any implied low pass filter, the signal exist only between within this u and v that is a rect function.

So, H of u is rect of u and therefore, your spatial this is a frequency domain. So, in your spatial domain that will be H of x comma y will be sinc function rect in frequency domain will be sinc in spatial domain. So, now, it becomes clear; however, we been talking about thinking about resolution even in the other modalities we are thinking about it as a blurring function perhaps right.

And we said if we know the system characteristic the spatial PSF Points Spread Function. Then we know the we can characterize or define resolution using the PSF right as a full width half maximum. So, essentially we are now decoupling the reconstructed signal that we have is actually the ideal signal corrupted or blurred with H of a system function this dictates your resolution the point spread function. So, we have decoupled recorded signal as a ideal signal with infinite resolution derated or convolved with your H of x y which gives you your point split function right.

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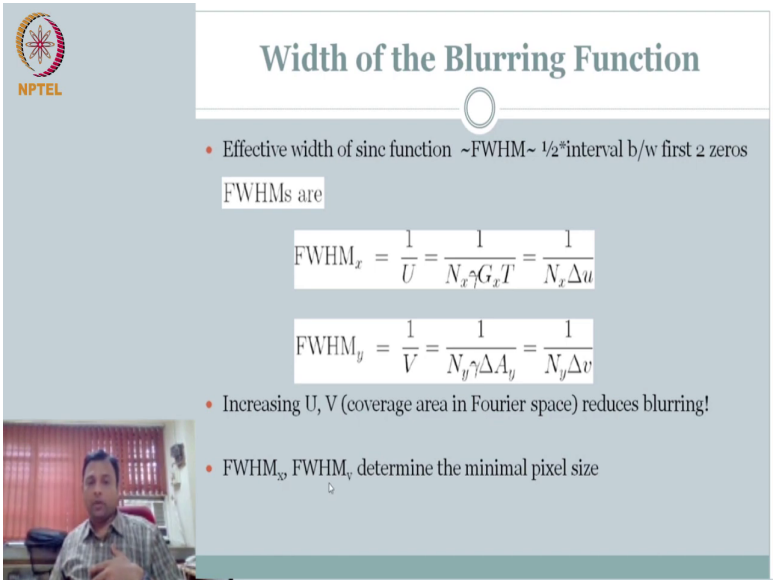

So, now we need to define resolution as what we have done as width of this blurring function or full width half maximum, this we have done again and again. So, now, I know my signal which is a sinc function, I can write the full width half maximum. So, I will write full width half maximum turns out to be 1 by U, what is this U? This is the extent in u direction, what is this capital V? Extent in frequency domain in v direction.

So, now you see F full width half maximum is 1 by U substitute for U you get N x delta u. So, you already see that if I have more N x more number of samples and finer step size right I mean, if we if this is this combination is important, this combination goes up this value goes down. What do we want? This value to go down means it is better resolution full width half maximum should go less than less right. That is what is better for us which indicates better resolution our point spread is less ok.

So, it is inversely related here. So, now, you, so increasing U right, increasing your U meaning extent in your U direction frequency space or coverage area in Fourier space reduces blurring which is pretty intuitive right. High frequencies correspond to sharper transitions in spatial domain right. That is the intuition that we have your sharper or rapid transitions in special domain correspond to high frequency.

So, if I record a high frequencies meaning your U and V are large, then I should be able to catch rapid changes so; that means, blurring is lesser ok. But your full width half maximum in x and full width half maximum in y are determined by the minimal pixel size ok.

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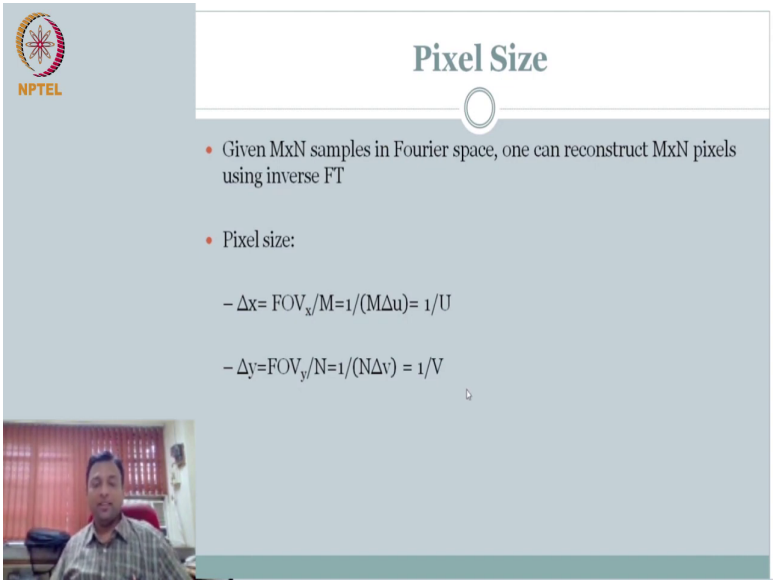

So, let us write it out. So, your what is your pixel size? Let us say if you have acquired the data with M cross N samples in Fourier space, remember Fourier space is already discretized space that we have. Suppose, we have M cross N samples in Fourier space or we can

reconstruct M cross N pixels of the image using inverse Fourier transform. So, pixel size in your spatial domain becomes delta x is field of U in x direction divided by number of cell pixels that are there right.

1 pixel size in x direction will be field of u divided by number of pixels. Delta y would be pixel size in y direction which will be field of y divided by l, number of pixels that are there in that direction. Which you can you know write it as M delta u N delta v from a previous slide you know the field of u x and field of u y are related to inversely to your delta u and delta v. So, you can actually see delta x is inversely related to 1 over U or inversely related to U, delta y is inversely related to V. Your pixel size in spatial domain is inversely related to the field of u in your Fourier domain correct.

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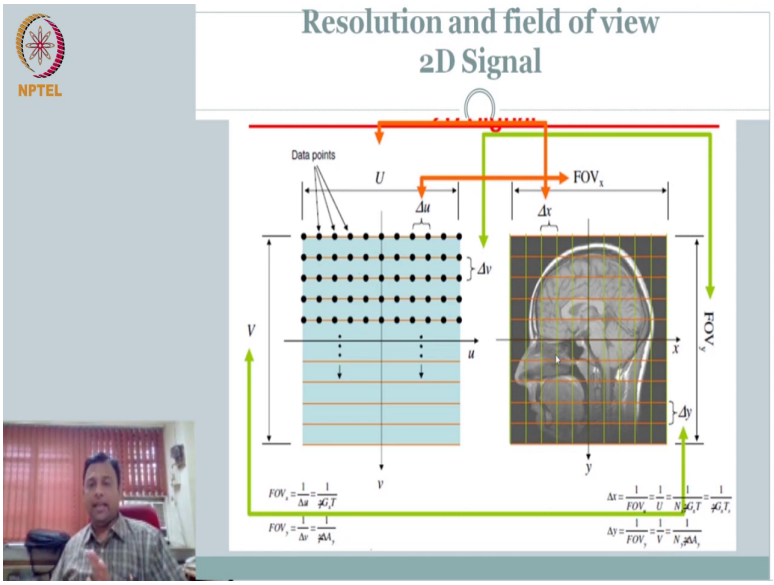

So, it can get confusing, so let us put a slide look at this slide get comfortable with this slide then all of the concepts you will be able to recall. So, this is your acquired data space where essentially I have samples spaced right with delta u where your U direction have sample spaced with delta u this is my V direction I have sample spaced with delta v.

In the spatial domain we have delta x in this direction delta y in this direction field of u x direction, field of u y direction. Likewise, field of u in v field of u are extent in v extent in u look at this relationship if I have delta u this is going to dictate by field of u in x. If I have delta v this is going to dictate my field of u in y. [FL], sampling distance in one domain is going to dictate inversely the field of u in the other domain.

So, likewise the extent or you can I mean, you can think about this is a sampling width in one domain delta x dictates the extent in another domain right U. Or, if you acquire large U you can have shorter delta x smaller delta x, if you acquire large V over a large V you can get smaller delta y remember.

So, try to let us of course, all of this equation that you see we I will list it out in the next slide as well, but essentially you got the concept here it can be confusing. But if you understand what is happening and you do it multiple times you will get a feel for it, then even if you do not know by heart, you will be able to quickly relate the concepts.

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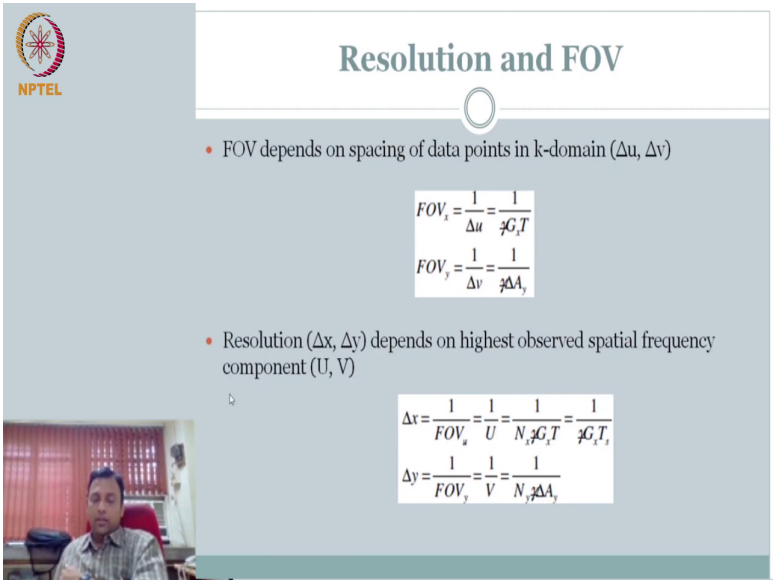

So, the relationship between resolution and field of u field of u depends on spacing between points in k domain which is delta u and delta v likewise right. So, field of u x is 1 by delta u y is 1 by delta v which we saw before. Likewise, your resolution delta x delta y depends on the highest absorbed special frequency which is U and V which are intuitively makings an highest frequency is going to dictate your resolution right. So, delta x is 1 by field of u in U, field of u in y or capital U and capital V represents the extent of frequency in U direction extent of frequency in V direction you can get it like this clear.

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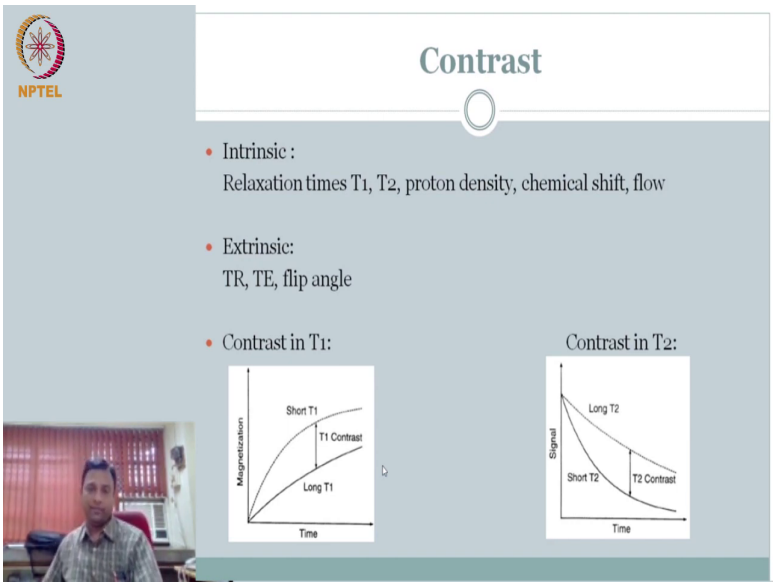

So, that is for resolution, contrast there was not much that we are going to cover because we have covered this extensively. So, your contrast is due to two things one is intrinsic we covered relaxation times T 1, T 2 and proton density. There are actually other properties also people are researching and trying to use ok, there are chemical shifts the, nowadays susceptibility is becoming a parameter with people are working about.

Then flow tensor flow you here about that a lot. So, there are other things we did not go into the advanced recent ones, we restricted our self to intrinsic contrast that are reasonably well understood and currently used in several clinical applications. Extrinsic are your data acquisition parameter TR, TE, flipped angle right

So, we already talked about how to maximize internal contrast right if you have T 1 contrast to different materials with the different T 1 property you will get the difference as contrast,

likewise for T 2. So, we covered this signal contrast or weighted wait for T 1 waited for T 2 waited imaging for photon density. So, we will not there is nothing much to cover on contrast, rather we will cover spend time on noise. And therefore, signal to noise ratio maybe you can always combine that with contrast to noise ratio also in later ok, so noise.

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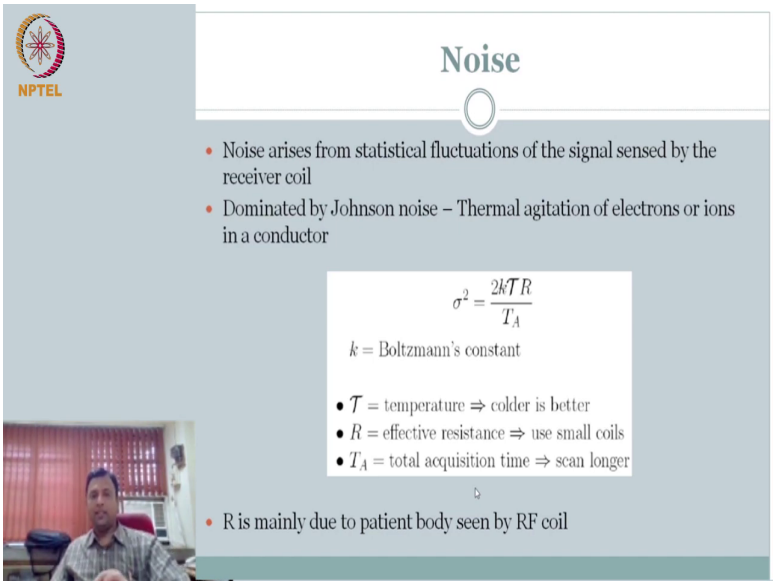

So, where is the noise coming here? So, the noise that we are interested that ah interested to cover is coming from during the measurement, here we do only one measurement. What is that measurement? We are doing a receive coil and receiving the data that is the only place we are actually doing measurement ok, after that you digitize you do all computation.

So, the only data noise that comes during data acquisition comes from your receiver coil and that to is a well characterize statistical fluctuation. Because when you have a receiver coil and

you are doing this operation it gets heated up. So, noise essentially comes from very well modelled Johnson noise or thermal agitation in electrons ok.

So, there is a noise model for this, this is where the noise comes into the measurement. And as you can see the parameters that are under our control these are Boltzmann constant with temperature right. So, you want to do the measurement at lower temperature possible, so that the numerator here gets reduce ok. Effective resistance needs to be reduced, how do you reduce that, use small coils ok.

Now, you recall we talked about coil design and I told you that, that is a big electronics measurements part that you can work on, so now, you understand there. So, if I did this I told you there is a body coil and then they make dedicated coils wrist coil, knee coil, head coil name it that is there. Why do they do that? I want to use small coils. So, if I want to image wrist rather than imaging it the whole you know the receive coil in the in the bone on the body coil, I would rather have a receive coil that is small right, so that I can get reduce the noise. Therefore, I can have better signal to noise ratio correct.

So, reduce noise by having reducing this effective resistant which essentially comes from the body resistance ok. Then total acquisition time should be as long again this is the trade off. So, already when if you have gone to MRI scanning you would realize it maybe uncomfortable or several.

I do not know if you would have felt uncomfortable or not, but know people find it uncomfortable right. Especially, if you are a patient and you are going there you have breathing and that causes artifact and you have to be there otherwise, you will have to make you slow down and then sleep it is it can be. So, you do not want longer acquisition times.

But what our noise says is you acquire longer I will behave well, I will reduce my RF or let us say trade off right, you can already see. R is mainly due to your patient body seen by the RF coil ok. So, always we are not interested noise alone, always we are interested noise in terms of signal, rather signal in the presence of noise.

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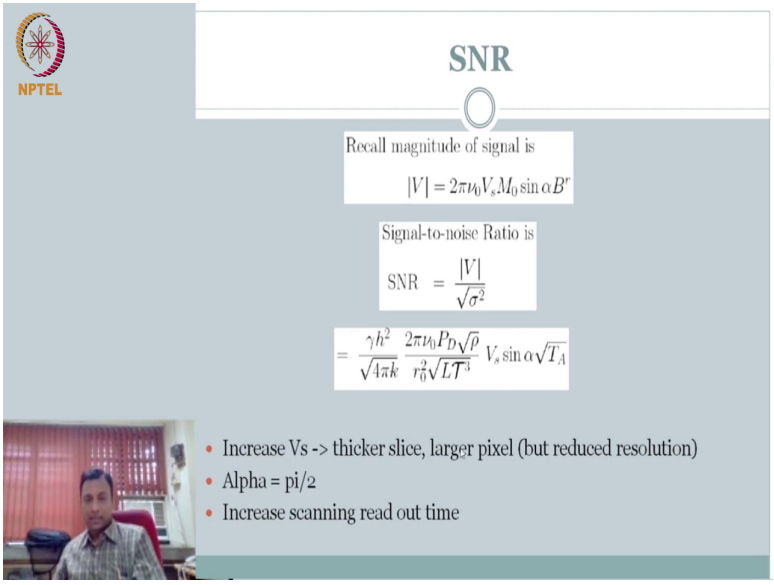

So, signal to noise ratio we will recall our signal equation this is volume not voltage right, volume of the sample. So, signal to noise ratio is mean of the signal divided by magnitude of the signal divided by square root of variance. So, you substitute all these you get some value ok, what we are interested is interpretation. So, what is this say? Increase your signal to noise ratio increase Vs, what does that mean?

I would have thicker slice. So, they have thicker slice, what will happen? Your resolution in the z direction larger, pixel in the delta z will become big. So, this resolution, so if I am do in axial slices going from head to within the head right, from or here. I want to have different slices of my heart, axial slices of my heart I want to have thin slice as possible.

So, I will have very many of them, but if I do that and I lose signal to noise ratio will be problem. So, if I have to increase the slice thickness I may have only 3 slice covering the

entire heart right. So; that means, I will get good signal to noise ratio, but I would not be able to say whether it is the upper part of the heart or it is I mean, I would not have any resolution that is its on slice thickness.

One other thing you can maximize is pi by 2 meaning, you apply for an enough duration, so it goes down to the flow. But then increase the scan read of time ok. So, this is more practical I mean and in comfort point of view that is the only problem with this this is signal point of view ok.

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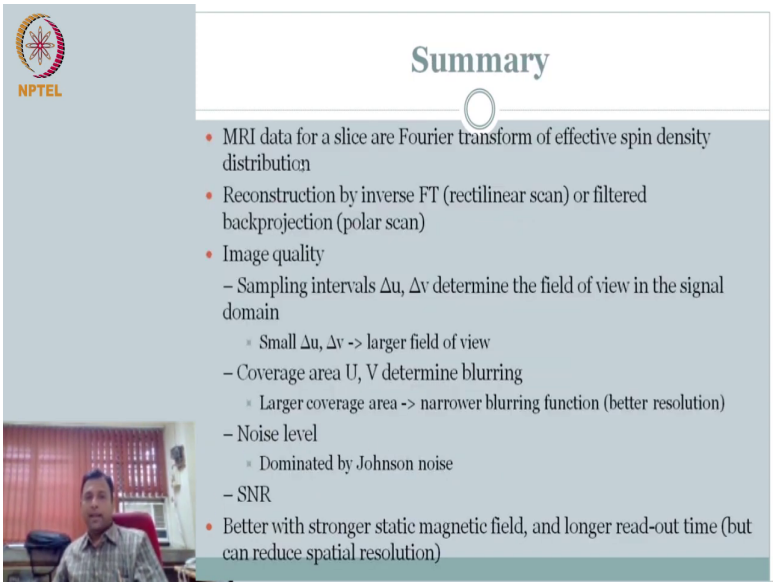

So, summarize MRI data of a slice what we saw is nothing but Fourier transform of the effective spin density that is what is distributed, that is what you are capturing. So, you can calculate or reconstruct the image by doing inverse Fourier transform depending whether our rectilinear scan or polar scan.

And we also saw the image quality in terms of resolution we talked about sampling intervals delta u delta v are the frequency domain. We saw this very confusing, but very in some sense if you understand this is very straightforward and intuitive nothing no big deal. If you have a higher frequency highest frequency dictates in the frequency domain dictates your finest variations that you can catch or your spatial resolution. Well, we know that it comes out very sophisticated here.

So, delta u, delta v we related into your field of u in your x y direction. Likewise, your coverage area of capital U and capital V determine the blurring. And then finally, we talked about Johnson noise and we concluded about signal to noise ratio. Actually, this completes whatever we wanted to talk at a introductory level for MRI.

So, as you will see, so very neat concept and it require so many different fields understanding right. The scope if you recall of a AM 5160 is covering multiple modalities to the extent that recall your objective, course objective. If you look at that image hopefully you will close your eyes at least this exercise I would like for you to do.

You look at the image right you close your image and see, I know how to interpret what this white means, what this black means, what this gray means, I know its units, I know what if the physics of the signal. And I know what instrumentation dictates the limits of or interpretation of the signal that we are having. I think that you should do it for each of the modality quickly ok.

If it is X-ray CT I know it supposed to be related to X-ray attenuation to the X-ray energy the materials attenuation property for the X-ray coming at that particular energy that is the fundamental signal. Then of course, you convert in the in the Hounsfield's unit the X-ray CT image you will have Hounsfield unit. And then likewise in your ultrasound we send sound you receive sound.

So, essentially we are characterising the scattered signal that is the echo that is coming back at least the echo mode that we covered. We send the pressure signal it scatter how much you

scattered from a particular location depends on the acoustic scattering property which is related to acoustic impedance properties. So, the reflectivity at each location is what we are going after, here in MRI your several different properties that are coming in right there it was mu in CT, X-ray based CT.

Then we talked about the only essentially your acoustic scattering or impedance mismatch that gave out. Whereas, here look at the different fundamental properties of the tissue that is happening, spin density, the relaxation time, relaxation time in transverse, relaxation time in longitudinal this is what we covered. There are other parameters as well ok. So, I think this summarizes what I wanted to cover please play the video several times get yourself comfortable.