Introduction to Biomedical Imaging Systems
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Lecture - 08
Local Contrast

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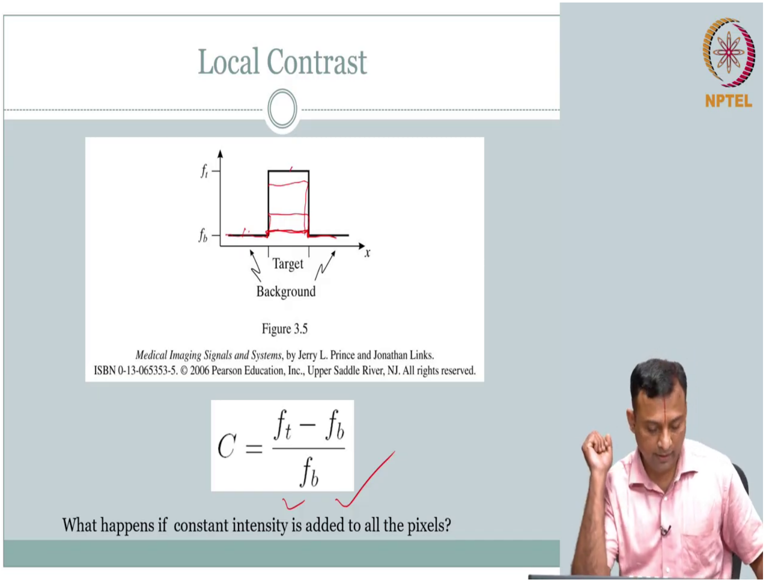

So, contrast; so if you had tried what happens if you add constant intensity to all the pixels, right. I hope you would tried it yourself; and mathematically, it would tell you that the contrast goes down, I hope that is what you qualitatively observed as well, ok. But let us move on beyond contrast to; the other image quality metrics that we listed that we want to proceed towards is another very important one is resolution, right.

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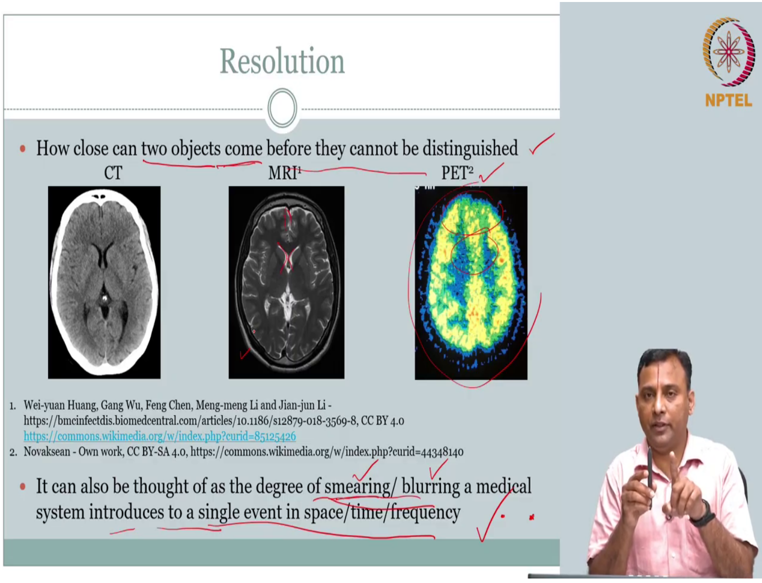

So, what do what comes to your mind? I know you would have use this colloquially. I got a cell phone right, it has much better resolution, right. But did you really give it a thought as to what could be the correct or what could be the most generalized meaning of resolution which can be applied to specific contexts.

So, in your in your cell phone example for example, I have very good resolution this is 8-megapixel camera is what you would have probably conversed with. But does megapixel have you know how does that relate to your resolution right; you did you really pay attention to that?

So, the question is what comes to your mind when it is resolution ok? Resolve, resolution resolve what does. So, when you have two objects right, that come close together until which point you will be able to tell that these two are two different objects right, that is your ability to resolve two objects. So, in fact, we will carefully state it, I will say what I mean by being careful about it.

How close right; how close can two objects come? Why did I say careful? I just said come, I would not say the units, right. So, in the imaging system, at least what we have covered so far, our axis, our coordinate is space right. So, in space, how close two objects can come? So, it can come in x direction, it can come in y direction at least within the variables that we have used x and y were the spatial variables.

So, how close can two objects come in those in space before they cannot be distinguished? So, that means, you can already start to think about come close in space is spatial resolution, come close in time right temporal resolution. In fact, you would have heard all this resolution, frequency resolution, spectral resolution I am sure you would have heard that, right.

When you do time domain to frequency domain, one of the things that we keep you know paying attention to is your; frequency resolution, your spectral resolution how two frequencies in the spectra can be how close can they be before you say that is two different frequencies or is it just the same frequency that is little wider, right. So, this resolution is a big picture you know big concept, it is ability to separate two objects, in this case we will consider spatial ok.

So, that means, that is fine, we will do the same approach. One is qualitative by knowing the definition right, by getting a feel for what resolution means can we qualitatively agree on what it means using some examples. And then, we will have to quantitate I mean then, we will have to put some models, some equations and then, say ok from now on if I want to measure resolution, if I want to talk about resolution, I am going to use this mathematical descriptor rather than English, ok.

So, first and foremost that is your resolution. Of course, another way to look about it, this is the brute force definition, resolve two objects when coming close together. But another way we have been using even in this class is when I showed you some images and we talked about blurring right; blurring or smearing, smearing I think we are using it first time in this course. So, it can be thought of also degree of smearing or blurring.

We did the show an example where the sharp edges were blurred and then, we said this is to do with resolution right. So, blurring; so, it can be thought of as a degree of smearing or blurring ok. A system introduces in a single event in space, time or frequency. Why is that important? In fact, we in fact, defined when we talked about here it is smear, it is blur, but we also talked about spread remember.

So, if you have one event instead of two events, technically you have two events come close together, you have to be able to say, the system is able to say that this is a different object, this is a different object. If I have only one object right, did we cover something?

If you can recall point right I put a point, I said this is the ideal point infinitesimally small, but if you take a imaging system to image that point you may get a slightly bigger point; basically a blurred version of that point right that is when we used. So, point spread function remember.

So, essentially, you can also think about resolution means it is some kind of smearing or blurring ok. So, if I can measure that; that will also relate to resolution. So, I can think about it whichever way. So, we will see, we will cover in some sense given orientation in this intro part, introduction part as a how all we can think about how all we can capture, how all people try to capture resolution, defend resolution. And then, when we get to individual modalities, we will relate the specific context.

So now, what we will do is ok, let us give some image example right and talk about whether we are able to appreciate resolution in the form it is defined, the same image. Same image we introduce to introduce different modalities, we also introduced it in the last lecture as an example to comment about contrast. Now, we are introducing this again to see if you can relate to resolution.

To, when you look at this what do you think, which image do you think has the poor resolution, which image has the best resolution, can you comment on that based on the definitions or rather descriptions of resolution that we have covered so far.

Well, if you really look at it; if I go by the first one right, two objects, where are my objects, how do I define? Well, I do not know. So, you can say my object could be I see lines right, I see this is an object so, I see right, I see this oh, I can resolve the two sides, left side here also right, I can see two parallel lines whereas so here also I can see, right.

Whereas, in this image, I cannot see that. So, clearly even though we observed that contrast was much better here in PET, the resolution is poor. But you see the challenge, if I have to then I have to define two objects and then see if they are close enough.

And just because we can say that these two are resolved does not mean that is the resolution right, resolve resolution means it is in the limit, how close can two objects be before you say that I cannot see them as two anymore. So, here you have several places where you can see two that does not mean that is it is just resolving that, but it need not be the resolution limits of the system ok.

Another way to look at it is this one right blurring. Even that way if you look at it, you can clearly see that this is poor resolution, it is blurring, the edges are really spread out; the edges are really sharp here right. So, you can see that the MRI has better resolution than your CT which as better resolution than your PET.

In qualitative terms, we still have not really captured any metric, but qualitatively if by using these two sense of what resolution. Means, either ways you look at it, it is not that difficult to appreciate that this has, this modality has better resolution. Remember I keep reiterating this because resolution also affects contrast that is why we are using the same image ok.

So, let us dwell a little bit more on this resolution idea ok. So now, what do we want to do? Fine, we appreciate what intuitively we can feel, what resolution is; can we capture it, how do I capture it, the easiest way is brute force right; easiest way is brute force.

What do I mean by brute force? Have a ground truth right, make sure that you have two objects and you keep the two objects a different, bring them as close as possible and each time at each location, you take the imaging systems output and see at which point it ceases to be seen as two objects.

That means quantitatively I have to measure the output of one object the other object and say right these two are different. If I can do that in space, then that is the brute force way of saying it.

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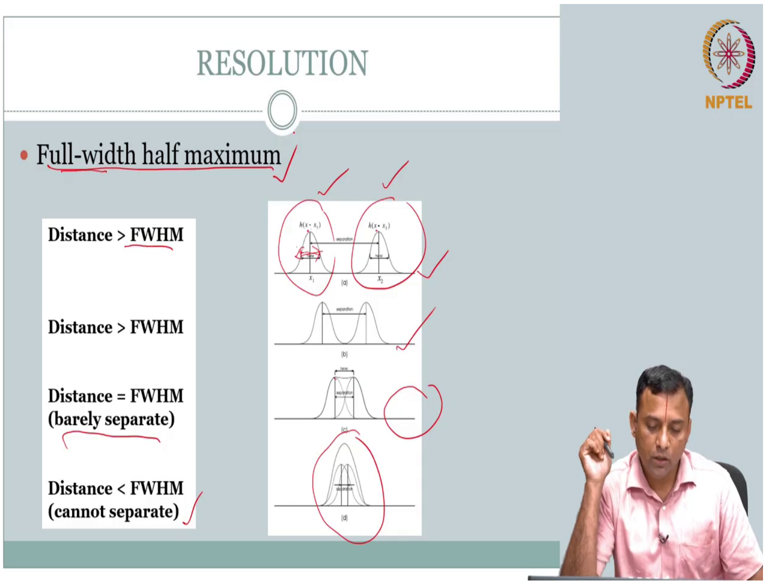

So, in order to do that, we may introduce this idea of full width at half maximum. Why is this important? Well, I kind of say this is just for convenience. In the sense that I have a object, you know these are ideal objects that is it is at only one location it is infinitesimally thin for example, this is infinitesimally thin at one location.

So, I bring them close together, but when it goes through the system, this will have a spread, this will have a spread right. That is what the system introduces because of its resolution limits, it is not ideal right.

So you have; so, when you bring them close together, you may still see the peak right, but then, you may not be able to contrast them as they get closer together. So, somewhere you have to draw a threshold and say look, if it is greater than that value, I can still say I can detect it ok.

So, what typically is done is that definition each one can do in their domain, in their context people vary that threshold; I will comment on that little more, but generally this is a very good measure full width at half maximum is a standard way of using.

So, essentially, we have to just for the sake of explanation, we are using only one direction x, because just to introduce the idea of resolution, but you can imagine that this can same done at different direction y. In fact, if you assume the system is isotropic right resolution in any direction is same, then one direction that we use here is good enough. Again, that may not be true all the times, but at least to get the idea started this is fine.

So, you have x 1 and x 2, these are ideal objects right, you have two objects, but then, when you present it through the system that is spread out right that is going to be blurring so, this is going to be spread out.

But, if they are separated beyond their resolution limits, I still will not have trouble in saying this is one object, this is another object right. If even though this is not thin right infinitesimally thin, it has some still I do not have any ambiguity in saying these two are two different.

When they are here, well, I can still, say here probably, but when they come here right. Now, depends on the resolution of the system right, whether a system is able to present this as two objects or it is one fat finger right. So, if you are viewing it with a very poor streaming system right, your internet is poor, it pixelated images, you may think that it is a one fat finger, right. So, that is what is shown here.

So, if they are able to separate right, then there is no problem, this is resolvable. So the separation, if you are able to make a threshold and the separation and say the separation allows me to differentiate these two as two different objects, then that is resolvable. Here again, the separation is sufficient for us to say there are two hills.

So now, what is full width at half maximum? Maximum is this right. So, you can have half the maximum value, the full width at half maximum. So, that is a length scale along x, separation is a length scale along x; the distance between these two objects in the direction you are measuring the resolution.

So, it turns out, we are doing linear systems. So, the moment it comes to close together, this will all start to add up right. You get the response from each other points when are contributing.

So, when you come just close enough to your full width half maximum, you will see that this will try to go down, this is trying to come up, so both will start to add up so you will have settle right two hills. You would not see the two hills, it will be kind of one fat shallow hill I mean you know obtuse hill. In fact, if you push it any further, you will kindly you will see only one hill with one maxima right.

So, somewhere here it is clear it is resolvable, here, it is resolvable, here is when you start to question whether is it two hills or one hill that is having a flat contour or a very minimal valley, here no issues, I see only one hill right.

So, that means, if the distance of separation is greater than your full width at half maximum right, then it is resolvable. If it is barely separate that will be your resolution in the limits. Of course, if you cannot separate, then it is beyond resolution limits.

You see the advantage of this operation, I mean very strictly speaking resolution has two objects has to come together. But by using this full width at half maximum, I could instead; I could instead going forward, I can actually have only one object and measure the present that one object to the system and measure the full width at half maximum and say that is my resolution you see.

So, if I have a point and I have a point spread function, then that is good. If I can do a point, I can measure the point spread function that gives. So, it actually a makes it convenient instead of having two objects coming as close as possible to realize that may be a challenge right. And so, this might be a very good attractive you know tool to measure your resolution using this definition of full width at half maximum.

Of course, you can do this for; why they are just pretending that it is you know if it is isotropic, it is going to be same in all directions which need not be the case. For example, if you take ultrasound right; ultrasound we know that the resolution is good only along the direction of depth where you want the sound to go through or the wave propagation at high frequency; in the other directions, the resolution is poor so, your spread will be more.

So, it need not be you know the full width at half maximum need not be same for all theta, right. So, it depends on the modality, but the concept is very powerful that you can use.

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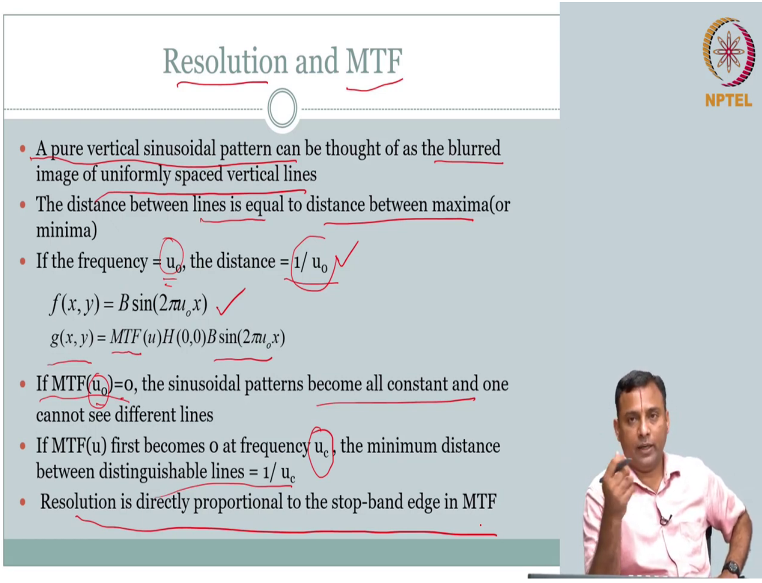

So, what we need to finally do is connect what we have introduced about resolution to what we already talked about in terms of transfer function; modulation transfer function. Why modulation transfer function?

We introduce the idea of modulation function and modulation transfer function to essentially capture contrast, but even that time, we kind of alerted that when you; how was the modulation transfer function, typical modulation transfer function plot? You had MTF of u in y-axis and u in x-axis remember; that was frequency.

And we observed a low pass filter behaviour ok; so, clearly that. And that time if you actually carefully observe the axis there, you had a frequency axis and that can be written and that was written as go look at the units, it was written as millimetre inverse ok.

So, now, you see that you have resolution is when two lines come close together right either peak or valley does not matter; two ideal objects coming close together. So, can you now have a sense of how we want to attract the problem and relate the two concepts?

What did we do for modulation function? We took a test signal to characterize the systems at modulation transfer efficient, we took a test signal. What was the test signal? Sinusoid right parallel bar white, black, but it was; so, now, it is all they you know imagination.

So, if you imagine that I have several bars right and whatever sinusoid you saw is nothing, but a blurred version of ideal objects. So, I have 1, 0, 1, 0 like target, no target, target, no so, I have some and that is repeated in certain frequency right, the minimum separation of distance. So, you can, and you can see the modulation function, sinusoid that we showed right the plot of sinusoids that you can actually think about as a blurred version of your objects, right.

So, you can intuitive sort of start to think that these two are related, we reiterated several times, but can we use the same formulation? So, we can use the same formulation. If you think about a pure vertical sinusoidal pattern which is what we use sin of u naught x right, we used sin of u naught x somewhere.

If that can be thought of, a blurred image of uniformly spaced vertical lines, so all I have is vertical lines. So, these are, these are vertical lines ok. These are vertical lines infinitesimally thin, there is no oscillations present, absent, present, absent, present, absent.

But if I throw this ideal frequency right separated by a certain distance if I put it through the system, the system makes it as a sinusoid because of blurring. So now if that is a definition, you could now connect our contrast and resolution ok. So, the distance between the lines is equal to the distance between the maxima or minima. So, now you can see how we are going to interpret this thought process of.

Vertical distance, how close two lines can be before they are seen as one line right, two objects how close can they come before you see is the system; does not see them as two objects anymore. So, you can have them as close as possible by increasing the frequency. If I increase the frequency, then it will come close together right. So, distance between the lines is equal to the distance between the maxima.

So therefore, if the frequency is u naught the distance is 1 by u naught. So, if I want to reduce the space, I can increase the frequency right. So, now, this should naturally lead you to what we already observed. So, let us do that observation one more time.

So, let us take f of x comma y your test signal, for simplicity again we are just doing a vertical direction, the lines are in the vertical direction right so, y is not there. But that is just a simplicity, the you know the concept holds good even if you write x comma y.

So, B sin of u naught x, this we did and this we figured out; g of x, y is the output of the system when presented with the sinusoid ok; which is you have modulation transfer function and this guy. So, what do we do now?

Well, somewhere we see that we use this for contrast modulation transfer function and now, we also see that there is this frequency and the inverse of that frequency, the distance and which could essentially talk about the closeness or resolution aspect. So, if MTF of u is 0, what does that mean? The modulation transfer at a particular frequency is 0 that means, if I have vertical lines right as input, the output I have 0.

There is no modulation is not transferred to the output, what is happening that means; that means whatever lines were there, whatever frequencies are there was is blurred so much that I do not see any vertical lines, I see that everything is blurred and there is only one output right; I do not see vertical lines anymore. I give vertical lines input, but if my MT at certain frequency.

But if my MTF at that frequency is equal to 0 that basically says at the output, I do not have any vertical lines anymore, I just have one what went in like this out through the system I see two lines at the output it comes as; so, now, at the output I do not see two lines, I just see one fat line ok, it is not able to resolve. That is what this implies, becomes all constant and cannot see the different lines.

So, if MTF of u first becomes 0 at certain u suffix c, what is that cut off frequency, critical frequency right, we use I had mentioned that it is kind of a low pass filter. So, you can think about this as a cut off frequency. So, in the frequency terms, it is easy right. After that cut off frequency, the system is not passing, but our interpretation is in the length scale. So, the minimum distance between distinguishable lines is 1 by u c.

So, if you make the lines any closer together, any more than 1 by u c of the system, then I would not be able to distinguish the two lines in the output. That means, that is my limiting resolve resolution of the system. Any frequency lower than that, I will be able to see it, whether the amplitude comes through or not depends on the MTF behaviour correct, but at least the frequencies will be there. Or depending on the threshold of how you define whether you see the vertical lines or not you will see the pattern, clear.

So, resolution is directly proportional to the stop band edge in MTF, this is how we relate resolution and modulation transfer function. Life is very simple in simple cases. So, if you actually go back and look at the example MTF that we have given so far right there was one with the hand X-ray image of your hand where we showed what happens if the MTF pattern changes right.

It was wide and falling down and it was becoming falling off more rapidly and the third plot was it was very narrow. And then, we saw the effect and we commented that time that the contrast is poor and also the image is blurred. So, there is a relationship between blurring and contrast; resolution and contrast right through the MTF.

But now, so, if I give you that plot, you will be able to appreciate for like contrast if it has similar pattern and if it is dropping off one is at u c 1, another is at u c 2, you will be able to quickly say ok, if u c 1 means if u c 1 is less than u c 2, you have better resolution with u c 2 because that means, you have more frequencies that are passing through the system, ok. That is not a problem.

What happens if you have the complicatedness in all of the real practical systems is going to be; you are not going to gain anything in absolute term. If you gain something somewhere you have to compromise somewhere else ok; amongst the image quality metrics ok.

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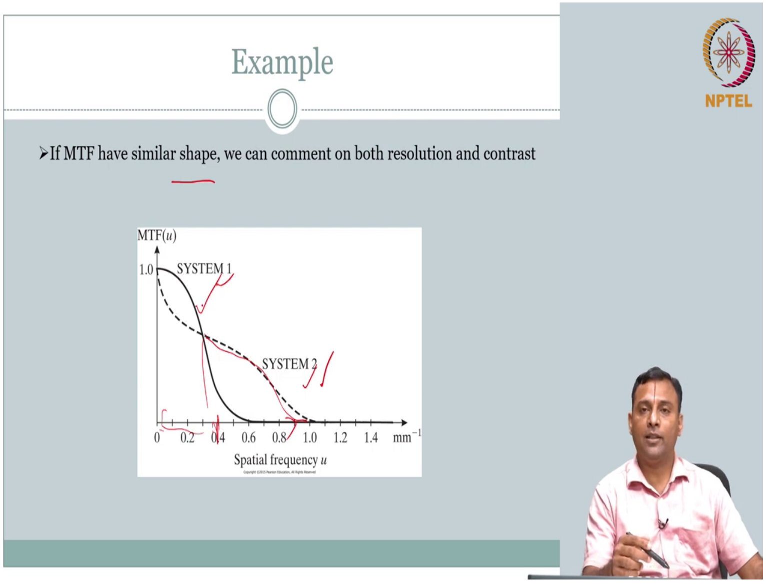

So, you do not really have much problem with the MTR, MTF have similar shape, we can comment. The challenge is going to be what if you are going to get a response like this. Essentially, you have a system 1 that is characterized to have a MTF with the solid black line that you see and a system 2 that is characterized to have a MTF. So, which one will you choose right?

Looking at it, you will say, you know what I want higher resolution and so, I will go for system 2. But then, you clearly notice that until this point right, your response is better with respect to your system 1. That means, the contrast is going to be better with the dark contrast and resolution go together, right.

If you, if there is a good contrast, then maybe I will be able to differentiate the two objects right, whereas, here, the contrast goes down. Technically maybe the resolution may be good at least the higher frequency that I can see might be more the you know the dynamic range might be more with system 2. But, if this frequency is presented in the image, system 2 will be poorer compared to the output system 2 will be poor compared to system 1.

So, you notice the challenge that means, depending on what you want so, if I want high contrast, then I would and if I know my object frequency is going to be the frequency that are present in the object that I want the image is going to be somewhere less than this guy; I would rather go with the system 1, I would not go with system 2. But if I have more frequencies in the object, then I may go with system 2.

Of course, we will have to look at what the system 1 is system 2, these could be in a same system physically, but one setting; this could be another setting. So, in which case this is where your job as an engineer will come into picture.

Can I come up with; I have this instrument that is given to me, I know the physics, I want to increase the application, I want to you know make sure that I the imaging system is good irrespective of which frequency is presented, as wider frequency content as possible should be imageable with that system.

Then you might come up with two different algorithms and you know combine these two right, you can combine these two or do something like that. So, that is where the real challenge comes in. So, for all practical reasons, this is a conflict that you will be encountering.

So, you need to really understand how, what aspect of this system 1 contributes to this response and how I can engineer it to my advantage. So, the understanding of this is critical, because it does not going to be a one-way street ok.

And that will be the hope of this course. When we introduce specific modality, we will use the same you know metrics and there we will contextualize this with respect to the physics and instrumentation of the modality.

And therefore, you will be in a better position to comment on how to improve the image quality or at least tell why the image quality is dropping out, what are the factors ok, good. So, that is with respect to your difficulty in commenting on your systems capability, because you may not have one system that can be good in all situations, ok.

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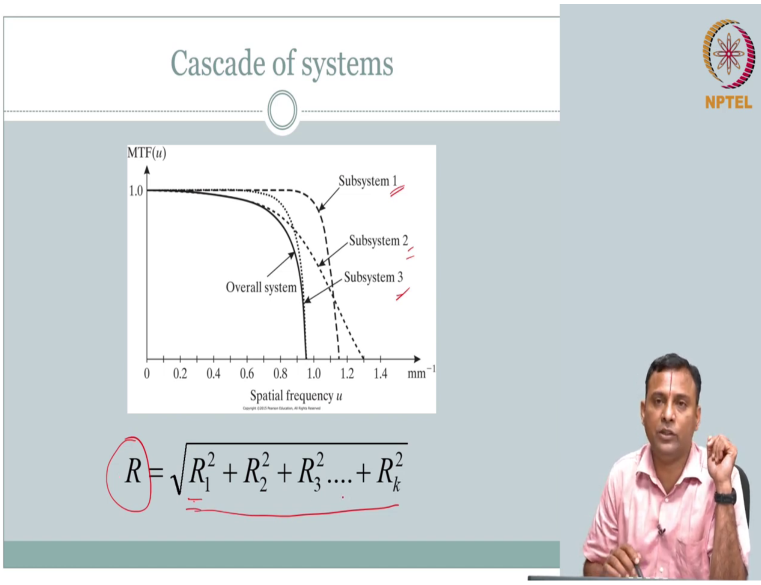

So now again, in some sense it is a continuation you can actually start to look at the previous slide and you had system 1 and system 2 right. So, now, the question is if I break the system into a cascade of system; which is not difficult right I mean we talked about this, even when we talked about the system h system impulse response.

We talked about the cascading of the system and we talked about how h 1 convolved with h 2 all the commutative property, associative property right, parallel in series, we talked about that.

So, here when we talk about cascade of system, what happens to the resolution? So, before we just put what it is again, this is pretty intuitive. So, take for example, in fact, I started with that example at the beginning of this lecture, but let me now give more you know better background of what I mean by that.

So, I have a microphone and I have a marker here, I keep them next to each other right, I keep them next to each other. So, the question is how many subsystem so, you are you are looking at the image and the idea is can you able to separate the two objects right.

Take it from me that I have kept them these are two different objects and I have tried to keep them close to each other, but ground truth is these are two different objects, I am not tricking. So, now, the question is are you able to resolve these two as two different objects?

So, if you actually look at the process, what happens? So, there are two physical objects which are captured by the camera that is recording this video right, and that video feed is taken to the PC right so that the audio and video can be integrated. And that feed is processed in the PC and it is saved in some format right.

And then, it is uploaded on to website for example, YouTube. After that it is coming over the internet, you download it right or view it online. And then your PC or your for cell phone whichever you are using that is going to read the data and display it in its screen depending on its system specification. And then you, the final end observer are looking at that video and making out whether you are able to resolve or not.

So, a simple system is not one system right, you have several sub, you can start to see that has several subsystems. So, this recording camera that has a specification, that as a resolution. Did it see these two as two different objects in the first place, right? Did it capture?

So, there is a MTF there. So, it has its MTF, then you get the data into PC and then if there are some filters that the video is processed right; I am sure they are doing some processing and integrating all the audio and video.

So, they are doing some smoothing, equalization so, there is some loss so, there is a subsystem there; there is a loss, there is a MTF there. And then to your PC, then network, bandwidth let us pretend that is coming through, then you are displayed, your PC and your display device. That system has a MT; MTF.

So, what do you think would be the resolution of this system which is comprised system as in the whole there is 3D, right, I have two ground truth here, I have two objects, you are viewing at the video. So, this is input, what you are viewing is the output; everything in between is the system right. So, that means, that is characterized by the MTF of u.

Now, I am saying that system actually is composed of a series of or a cascade of subsystems. So now, the question is what is the resolution of the system, which is composed of several subsystems, what do you think? Will it be more, less, same?

So, common-sense tells without knowing much technicality. Common-sense tells if you have your PC, if you have your phone and you know you have dropped the phone couple of times right and you have a poor display, you would not be able to see, right.

But you cannot complain that this whole MOOC, whole NPTEL system right, the system that is capturing the input and presenting remotely, virtually whichever is poor, it is not able to resolve the pen with the microphone, it is only your phone. So, subsystem that is poor in this case right, because you broke, you put it down and you broke the screen.

Or similar thing, you have poor internet, the streaming quality is poor right, data size is reduced and therefore you are not able to see it. So, you cannot complain that the whole system is bad right, but there is a fact; fact is the whole experience of using this system will be poor right.

So, even if there is one subsystem that is limiting, then the whole system is limited. No matter if I have a great Panasonic camera that is recording, does not matter. If I talk about this as a subsystem, it has its own response so be it.

But if I see a full system as a cascade of subsystem, then the weakest guy or the poorest guy determines my limits of the whole system; that is true with everything right. So, it is common-sense is sensuous answer. So, let us see how we you know put it in terms of the plots that we have seen so far and try to explain.

So subsystem, relates subsystem 1, 2, 3 to the different subsystems that I gave you as examples in the video recording system, this is medical imaging system right. So, you have subsystem 1, 2, 3, each one has its own response.

Actually, notice subsystem 1 is you know very wide or widest goes till 1.1 before it starts to drop ok, whereas subsystem 3 if you look at it, it drops after 0.8. And you will see something like a subsystem 2 which starts to drop, but its drops at a slower rate than your subsystem on so it actually covers more frequencies where it is non-zero, right.

But what is the overall system? Overall system is coming here, it is tracking the weakest guy right, so from here the dash line is not weakest, this one becomes the weakest so, it bends here, and it falls down. So, if in some sense you look at it, the overall system response is the poorest amongst the different things, different subsystems that are shown clear. So, from the

MTF, you can clearly comment that your overall system response is always limited by the weakest individual response, subsystem that is there in the cascade.

So, if I want to put it together, I can talk about the effective resolution as square root of sum of squares of independent right, subsystems resolution. So, if you actually look at it if R is a resolution in length scale right how close; that means, good resolution means length should be small, poor resolution means length should be large right.

If I am not able to separate these two right, that system has poor resolution than a system that can separate these two. So, R large means so, you have to be very careful in when you read material how they define R, but you know the idea of resolution and the definition is spatial is what we are talking about how close the two objects can be in space. So, other units of resolution is in terms of length, ok.

So, R is in length scale. So, if you look at this formulation, clearly you can see that if there is a it is a sum of squares so, if there is a poor guy that means, if there is a large R, that is going to dominate this. So, if you are going to do small improvements here and there in one of the subsystem, the effective sub systems resolution will not change that much, because there is a weakest guy, he is going to dominate this sum of squares, clear ok.

So, much for; be very important concept I mean that is why I want to spend this time, you do not get anything for free. You have to really understand the concepts and how it is captured so that you can customize it for each imaging modality is going to have its own constraints, physics, instrumentation constraints, end user constraints right; what is acceptable in one may not be accepted in another, because it is a host of different parameters that come into rescue.

So, you might be more tolerant with respect to poor resolution in PET image, because you are gaining something that you could not gain in other modality right. But the same resolution you will not be tolerant or you will not be happy if I show a MRI image ok. So, you need to really understand the basics.

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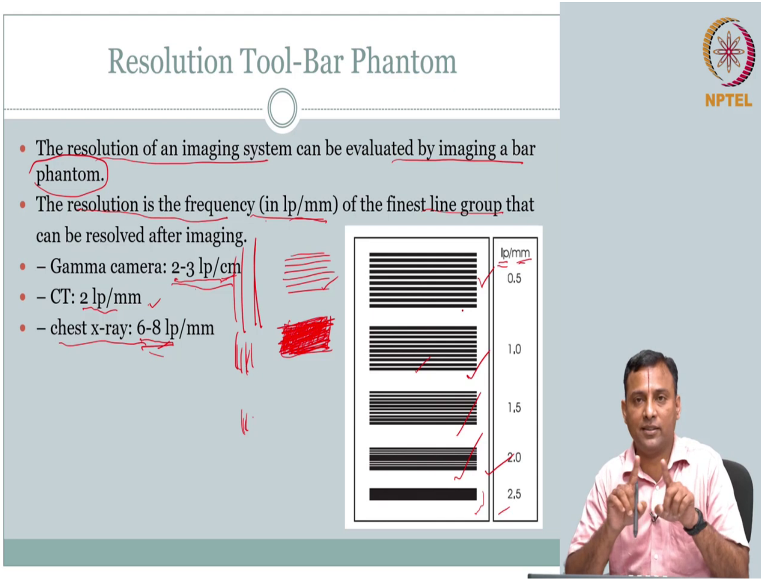

So, how do they do this, right; I mean this is fine, but how do they typically do, how do you calibrate, how do you say the imaging system resolution is one thing or the other? Most of the times, what they do is you have imaging system, you have a ground truth. So, the example that I showed here with a pen and a microphone, this is very arbitrary right, it is ok for a concept.

But if every lab, if every instrument has to be checked out right to calibrate it to say what resolution it has, you better have every else same only the system should be different. That means, your target, the ground truth should be same, the same environment. You have one imaging system, you take another imaging system, we take a third imaging system all of them are trying to capture the same ground truth, then you compare the output and say, this is resolvable in the system, this is not resolvable in the other system.

So, that means, it is important that you present to the system, the same object with the same ground truth ok. So, how do they do it in that sense? Resolution of imaging system can be evaluated by imaging a bar phantom, bar phantom is bars right, nothing more just bar; phantom means is just a material that is created, it is not real.

So, bar phantom is you have several parallel bars that are there. Remember I told you can imagine that sinusoid as a blurred sinusoid if you have bar, so this is a bar. So, I can have them precisely fabricated so that they are at different locations which is the ground truth right.

So, mostly, what they do is you have this called lp, what is the lp? Line pairs per millimetre. So, again for the purposes of demonstration, these are just bars or horizontally oriented, but you can have them vertically oriented also right, I mean there is nothing sacred about it.

If that the thing is you have when there is a horizontal bar, you have some spacing between them so, you have line pair per millimetre. If you pass this calibrated bar phantom present it to the imaging system, the output better be some bars; similar looking bars.

Whether the imaging system is able to right; see this as parallel bars or see or not see right. For example, instead of seeing it as parallel bars, I am trying to shade, I have not used this before let us me yeah, ok. So, the idea is ok. So, you are not supposed to see parallel bars here that is the logic.

So, maybe here the system you can see parallel bar, input is a parallel bar, output is a parallel bar so, the imaging system is able to resolve it. Whereas, here the input is bars that are parallel with certain lines per line pair per millimetre, but the output is one flat image with the red colour; it does not really see the parallel lines that means, it is not able to resolve.

So, if you present this, so there is no use, you can have a phantom which has parallel bars like that right close together, even close together or in any direction. Just for simplicity I am showing. So, it is called line pairs per millimetre.

So, if you present this bar, you can talk about resolution is the frequency. Remember now, I told you resolve in length scale, but now if you use this bar they might say resolution is the frequency of the finest line group that can be resolved after imaging. So, it is now be line pairs per millimetre, it is not length scale, clear.

So, you have to really understand how; it all means the same, if I say line pairs per millimetre that frequency you know in the length scale, it is going to be 1 by that separation between these two so, you know you can get to that. But you have to be careful with units depending on the setup what you have access to, it will be defined as this, ok. So, resolution is the frequency in this case of in line pair per millimetre.

So, if you look at this image let us see through our optical imaging system right our eye system, human vision; I will say at least I can see this clearly line pair per millimetre. So, I have a better resolution than this one, in fact, I can see this also so, I probably have a better resolution than that.

In fact, I can see this, here I can see that right, here I am not able to see anything right so, two lines per millimetre. I think I can see it, maybe you can also see it or if you are looking at it in the phone right and if you have it in you know very small font, you may not be able to see. So, that is a different aspect.

Point is depending our human vision system, we can see that we can relate if we are able to do this, we can say I can see so many lines per millimetre. So, I can resolve these two right. If you through see this through different imaging systems, what are the typical numbers we get?

So, if it is gamma camera, you get 2-to-3-line pairs per centimetre, this is in millimetre, 2-to-3-line pairs per centimetre. So, gamma is what you have PET right positron emission tomography. We had one image colour, image that we saw right that is PET. You can see a how lousy right 2-to-3-line pairs per centimetre, whereas CT it is 2-line pairs per millimetre. Look at chest x-ray which you have seen wow 6-to-8-line pairs per millimetre.

In fact, you look at it, even at 2.5 the way it is presented here, we are not able to see right. I say we because probably you are also able to see the 2, 2.5 is tricky, but chest x-ray 6-to-8-line pairs; so, clearly the resolution is good here.

CT resolution is good. If you look back at the images we saw we compared the CT and PET. Clearly, CT we were able to see some you know lines which we could not see in gamma camera; your PET image, right. There it was subjective.

Now, if you do a calibrated study, you can actually come up with limits on what is resolvable and what is not resolvable, right. The concept is same, how close to objects can be before you say they are one I mean two different things, before you lose to see them as two different things. So, you have a phantom where it is placed at different closeness at some closeness beyond which their system is not able to say right, good.

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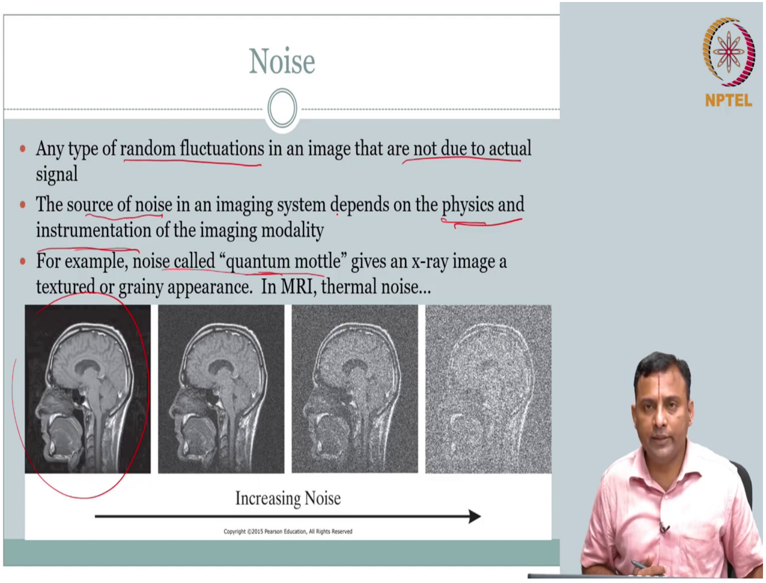

So, we will quickly start with the next idea right there is a contrast, resolution, third one was noise. So, noise we will just take a big picture view of noise. What is noise? Well, it is a signal, at least I like to think about it as a signal, but then, it is not; in some sense it is like it is coming when you measure a signal, but it is not related to a signal. So, the undesired signal right, undesired measurements or the fluctuation around a ground truth that you want to measure right that is noise, ok.

Type of random fluctuation that are not due to actual signal. I have a actual signal, when I tried to measure the actual signal this also happens, but this is not signal. So, it comes as a signal, but it is essentially a fluctuation around the signal. That is my noise ok. So, any type of this random fluctuation gives rise to noise.

So now, the question is obviously, it is detrimental, it is going to affect your image quality ok. So, if you look at it, this is an image that we had. If you start to had more noise right by increasing the noise, you can clearly say that the image quality is poor. Why is; in in what sense? Quality is poor because I may not be able to start, I may not be able to it affects both right contrast, resolution everything goes haywire.

So, it affects the image quality because I will not be able to either say so, take the extreme case. I may not be able to say where the nose is right, where the spinal cord is, I am not be able to say anything here, leave alone resolving to two lines right. We may not be able to say even contrast or big picture; the medulla or the nose or the mouth there are. So, both contrast and resolution are affected and the noise therefore affects the overall image quality ok. So, this is an example of increasing noise.

So, what is important is the source of noise right. Problem is the source of noise depends both on physics of the modality right, physics and instrumentation of the modality. When I say physics and instrumentation of the modality that means some things are inherent right because of the nature of the signals that you are probing, the other one is your instrumentation, instrumentation means it is a measurement noise ok. So, that is one thing. So, you can have both.

For example, right in x -ray imaging right; in x-ray image, you have something called as quantum mottle, this is not because of your measurement, this is because of the way the signal is generated ok. So, that gives rise to; that is because of the when we cover the physics in each modality right and then, we will cover the image quality, aspect in the end, that time you will, we will connect this again, but for now, it is quantum mottle. Meaning there is something is happening because the x-ray is interacting right.

So, this is a physical phenomena; so because of which the signal that is coming as some dictates, some fluctuations so which is called as quantum mottle. The other one is right then you are in the MRI for example, you have thermal noise ok. So, you can have different sources for the noise, some dependent on the physics, some limited due to your measurements and instrumentation, ok.

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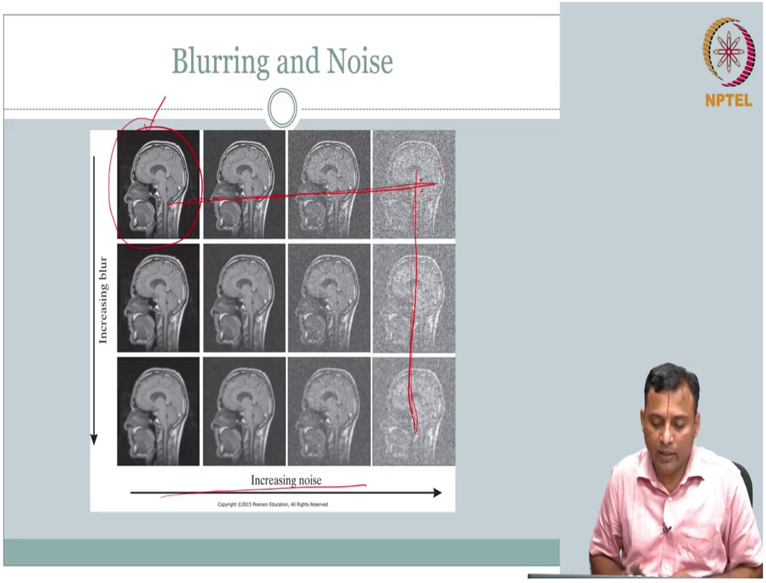

So, we will just do one big picture appreciation and then we will jump into quantitative, how do we measure the noise ray, how do we model the noise, how do we then infer about how to compare different noise source, right all that we will do.

But clearly when we talked about image quality; we did contrast, resolution and we said through MTF both contrast and resolution are interrelated. Now we talked about noise clearly, we said noise is having an influence on the image qualities, it is making the image quality poor. So, all the three should be related, right.

So, in some sense, you look at it, this is a image of certain quality. If you either increase the noise which is a first row or increase the blurring, either ways the image quality is becoming poorer, right.

The worst thing is going to be going here and going here, meaning I have lot of noise and I have increased a blur, clear. So, I can have all of them are affecting the overall image quality, ok. So, you may have, you may end up trying to reduce the noise in which case sometimes you have to blur the image, ok.

So, if you look at these two for example, right this looks little blurred compared to this one right. Visually, if you look at these two, you might look at it and say this is increased noise right so, this is supposed to be more noiser than the preceding image. But if I compare these two, this actually has reduced noise right, the speckle, the fluctuation is reduced. But then, here I see the lines are little sharper whereas, here it is blurred, clear.

So, there is a cost that is associated. So, I can increase the blurring right, perhaps reduce some noise or the other way. You do not get everything, you want to be here, but you are always going to be playing around whether you want to go here or here; you are going to be playing around within the constraints and the what the instrument allows you to do, ok.

So, we will stop here. We will come back again, continue further on the noise characterization.

Thank you.