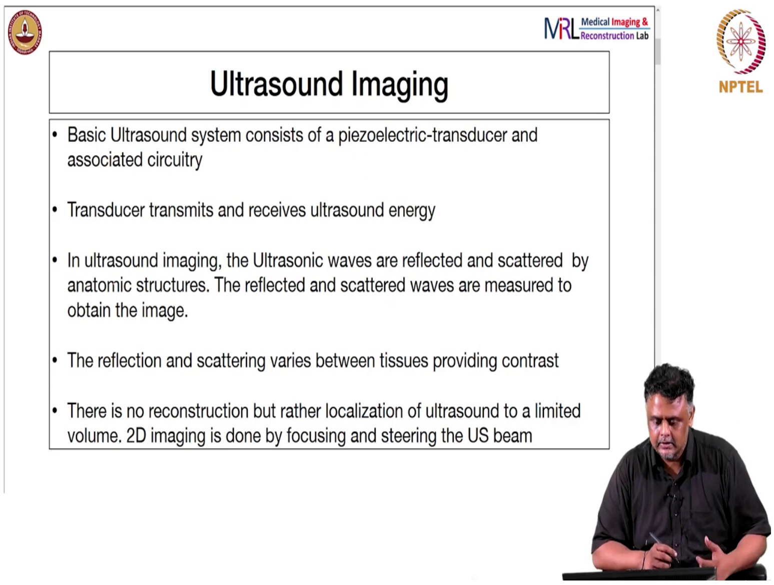
Medical Image Analysis
Associate Professor Ganapathy Krishnamurthi
Department of Biomedical Engineering/Design
Indian Institute of Technology Madras
Lecture 04

Ultrasound Imaging

Hello and welcome back. So, we looked at I think Projection Radiography and Computed Tomography in the last class and other imaging systems. So, we will look at Ultrasound Imaging in this video, a brief introduction to ultrasound imaging and once again understand what the images produced by ultrasound imaging systems actually convey.

(Refer Slide Time: 0:37)



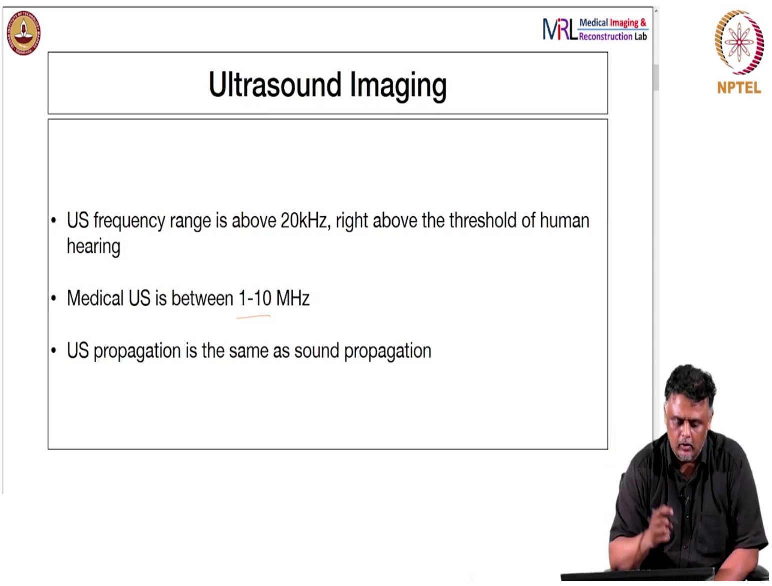
So, as a basic ultrasound system, you know, it consists of a piezoelectric-transducer and associated circuitry. So, we will look at what these are, as we progress through the slides. So, the transducer is the important part of the system it transmits and receives ultrasound energy. We will look at what ultrasound means also in the later slides. And the transmitted, when they say transmitted it transmit them to the human body.

So, the piezoelectric crystal is a external source of the mechanical pulses, longitudinal pulses and they are transferred to the human body through the transducer. And the ultrasound waves which propagate to the body or tissue are reflected and scattered by anatomic structures. And what we measure the transducer once again acts as a receiver and the measures these reflected and scattered waves.

And reflection is scattering between the tissue is what provides the contrast in ultrasound. The difference between the reflection and scattering properties of the different tissue is what is the mechanism of contrast. And this is different from the other imaging modalities in the sense there is no specific reconstruction per say. It is mostly the acquisition; you acquire the signal and you kind of you figured out how to display them as an image.

So, that is where the lot of the work is, and most of the work is in the hardware side, on how you actually create these pulses, these ultrasonic pulses, how you would direct them at different depths that them to different parts of a plane imaging plane. And you know, how you put them together as a final display. So, there is no specific inversion algorithm like we saw for X ray projection radiography. There is just simply acquiring the signal and displaying them as it is.

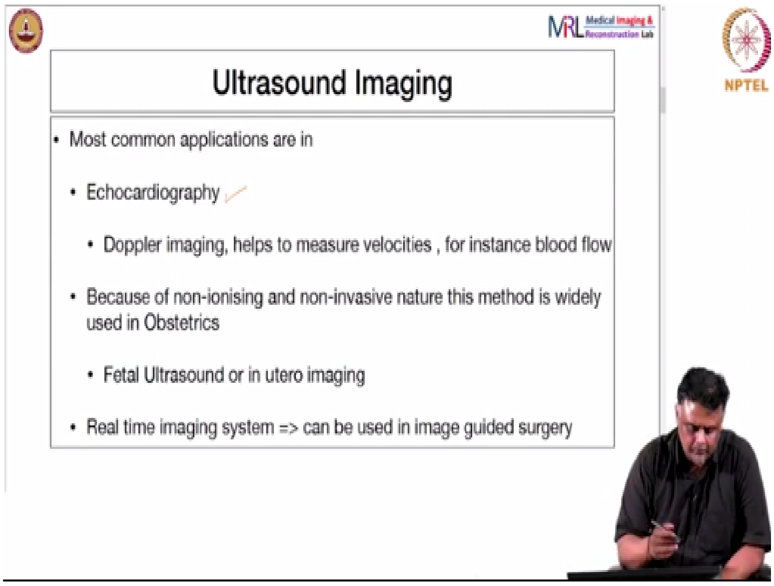
(Refer Slide Time: 02:28)



So, what is ultra sound, any frequency sound frequencies sound, just like SONAR. But the frequency range about 20 kHz, but for medical ultrasound is between 1 to 10 MHz. So, the ultra sound propagation is the same as sound propagation. So, all the physics that you use to describe sound propagation can be used here to typically what it is used.

So, but the frequency range is between 1 to 10 MHz, this is what we call ultrasound. So, this is something we cannot hear, it is beyond the audible range of frequency. So, we are limited to 20 kilohertz, around 20,000 Hz, that is the maximum we can hear. But these are much higher frequency ranges and we cannot hear them.

(Refer Slide Time: 03:13)

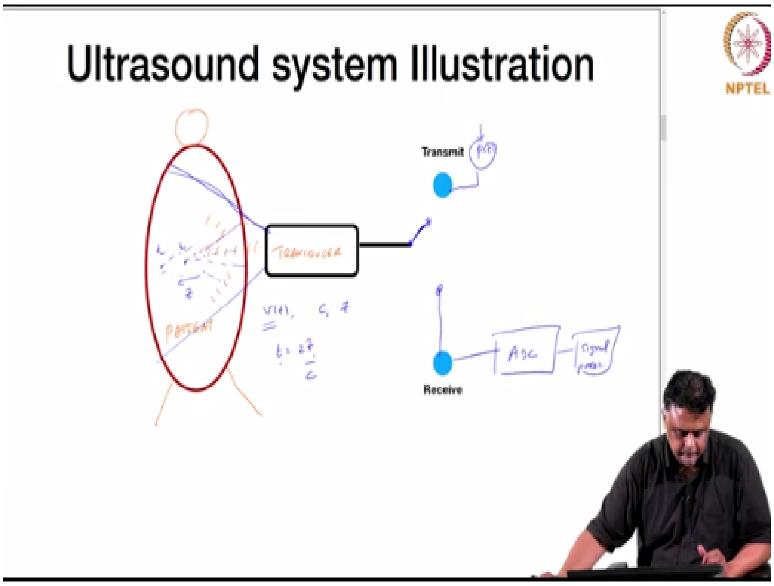


And the most common applications of ultrasound imaging, you would have seen if not, you can always search in the web, lots of illustrations. Echocardiography, which is basically the imaging of the heart. So, you can actually do real time imaging of the beating heart. So, people use that especially even you can also do real time beating of fetal heart. So, inside the mother's womb, you can see its heart. And for looking for abnormalities.

It also allows you to do something called Doppler imaging, which lets you measure velocities for instance, blood flow. Because it is non-ionizing and non-invasive like I mentioned, it is useful in fetal ultrasound or obstetrics as it called. And it also can be used in image guided surgery finally, because surgeries generally take a long time and you cannot constantly expose the patient to some ionizing radiation during it.

So, ultrasound offers you a very good way to monitor during surgery. So, some image guided surgeries are done with ultrasound imaging systems. These are the wide range of applications here because other than this there are a multitude of other applications for ultrasound also they also provide the resolution depth, excreta. And they are used in many applications and it is growing.

(Refer Slide Time: 4:28)



This is my drawing of an ultrasound system, it is terrible but we will have to make do this. So, this is let us say the patient. Let us draw a head here do just make it a little bit better, 2 legs. So, this is the transducer. So, this is the source of your ultrasound so, you can think of it as emanating these waves and I am going to have to rub the patient's somewhere else, write patient here.

So, these waves go everywhere to and you have to of course guide them and these are inside the body they are scattered and reflected back. So, you will have them coming back to you, different colour hopefully it is blue is better. These are reflected once again. So, the transducer either works in a transmit mode or receive mode. So, whenever there is transmitting there is actually a pressure function you call it that is electronics and then in the receive mode there is actually your analog to digital converter your signal processing excetra.

So, in the transmit mode there is a pressure function which is goes to the transducer which causes this ultrasonic waves to be produced this but I call this specific function, of course, you have to it is actually an electrical impulse which causes this. We will look at this in slightly more detail.

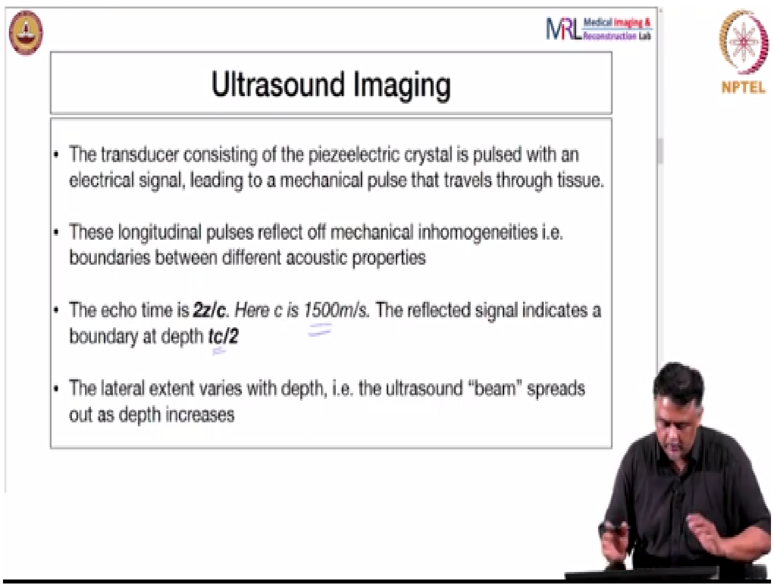
So, the waves go in and at any point, let us say this is some, so any direction of propagation of the waves that typically they call this z and you whatever you send in it comes back reflected, it will be attenuated, reflected, but you assume that you know it is the same form that you are transmitting at some for the theoretical analysis and you will receive it again this the signal acquired for recofinding that question, we will call it V, it is a function of time.

So, you will create a pulse and you would acquire over a period of time. So, the time here corresponds to depth. And the speed of sound so, if the speed of sound is C, depth is Z. So, every time ti will correspond to some depth. So, something from here will be at a later time for this will be t1, this will be t2, but it will be from our data type.

So, this will be the actually 2z times c. So, if I were looking at a particular depth, it has to go and hit something there and come back two times. So, it is what do you what the signal you acquire is a function of time where the time here corresponds to distance travel. Of course, there are specialists other tricks hardware tricks to make sure that you also cover x and y. So, typical ultrasound if you have 2D ultrasound you will have something like a cone which is your which is your imaging cone, which is what you would get as a 2d image.

And of course, you can always move and get volumetric coverage also. So, that is your typical system. So, either you work in this format or either and so the same transducer both does transmit and receive. A transmitting use electrical impulse to transmit, they are mechanical pulses and will receive you are once again using the same transducer, we will see how that works because these are piezoelectric crystals, they have this property.

(Refer Slide Time: 8:34)



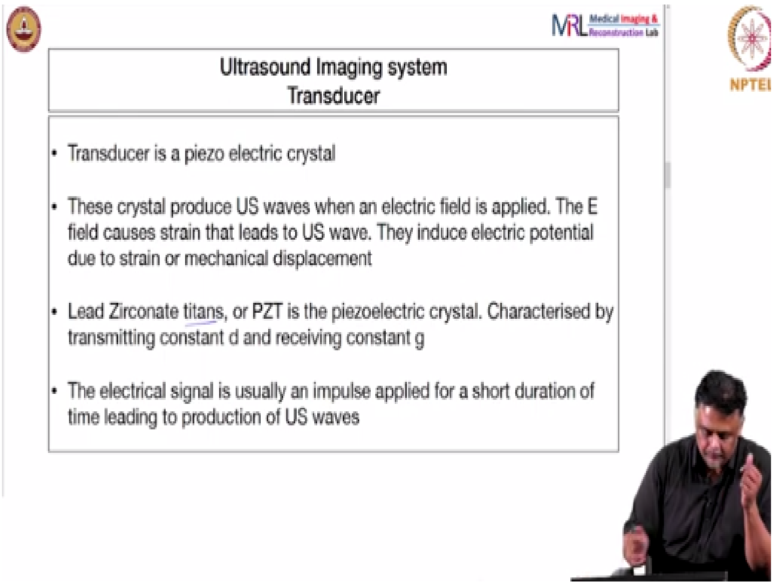
So, here is what I had said before is a transducer which consists of a piezoelectric crystal is pulsed with an electric signal. Because of this pulsing, it starts to vibrate mass fast vibrations, which leads to a mechanical pulse transmitted through the tissue, so you will hold the transducer on top of the tissue, they will also be a gel, which prevents the pulses you generate from being reflected back too much, where there is always some impedance so called acoustic impedance mismatch that occurs so that for that there is a gel which is used.

Usually they usually apply a gel before the ultrasound scan they start so the transducer you put on top of the gel, the transducer, you would put on top of the gel. So, this longitudinal, these are called longitudinal waves, we will look at why they are called longitudinal waves, they reflect off of the mechanical inhomogeneity. So, it is basically whatever structure you have in your body, they are reflected and this is typically boundaries between structures with different kinds of acoustic properties.

The echo time is $2z/c$, I will not use time to echo because it is used in an MRI also. So, the echo time is $2z/c$, z is the depth at which it was reflected. And here it says here this c is the speed of ultrasound in tissue, it is typically 1500 meters per second. The reflected signal, depending on the time, we keep track of the time following, when you start when you started the pulse, I really can calculate the depth at which it is coming from, that gives you an idea of, so those images that degenerate typically then have meaning in terms of your position coordinates.

The lateral extent of coverage varies with depth because the ultrasound does over time, so it does not remain as a thin cylinder, it does spread over time. So, there is a loss of lateral resolution as you go deeper, but there are ways to get around it. So, we will not go too much into detail there, but we will just look at qualitatively how images are acquired.

(Refer Slide Time: 10:36)



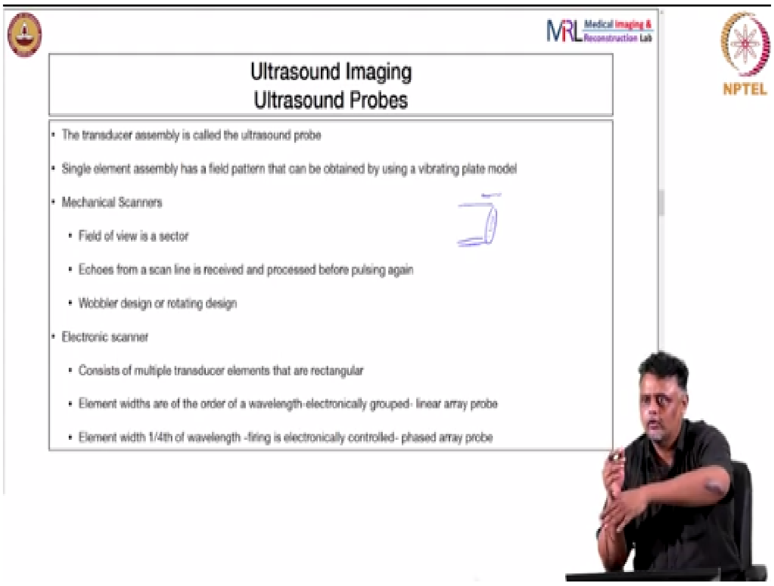
So, the transducer like I said is a piezoelectric crystal, these crystals they produce a ultrasound wave when an electric field is applied. This is a property of the crystal, this is like the other ways if you if you give it a mechanical pressure it will generate an electric field. If you give an electric field, it will generate mechanical pulses. So, they induce an electric potential due to strain. If they experience some strain which is basically some displacement of the crystal elongation or compression, you do, this lead to an electric field.

On the other hand, if you give it an electric pulse, it will (revert) oscillate rapidly. So, if you sit selected pulse appropriately, it will oscillate (rapid) rapidly and that leads to the production of ultrasonic views. So, these are some of the materials lead zirconate titanium I think, you will have to correct this or PZT is the piezoelectric, this is a typical material used or other materials, but there seems to be a choice, they can be easily manufactured, cut in different sizes, shapes, etcetera. So, that is why it is much preferred.

The optical signal like we talked about, which actually gets the ultrasound pulses going is an impulse applied for a very short duration of time, a very, very sharp electrical impulse, which causes the production of the ultrasonic waves, that is what it is typically used for. So, this is the most important component of the, one of the most important components of the ultrasonic imaging, the transducer itself.

Of course, the associated electronics etcetera, also are also equally important, but this is the important, as far as signal production mechanism is concerned.

(Refer Slide Time: 12:10)



The transducer assembly is called the ultrasound probe. So, it is not like yeah, this crystal like bear and walk around with it, like we will have to put it inside a assembly and it is called ultrasound probe. That is what you see people using when you do an ultrasound scan.

So, usually, for theoretical analysis, if you want to understand the signal, the form of the signal etcetera, to get an analytical expression, etcetera, you would, for a single ultra element ultrasound probe, there is one piezo electric element, the model is that of a vibrating plate model.

So, you can think of it as so, the model would be very, very crudely think of a circular this is like a membrane, circular membrane right here, this membrane you can think of it as oscillating back and forth very rapidly that is the model for ultrasound generation. You can use this model to actually understand the form of signal you will get, attenuation of the signal etc.

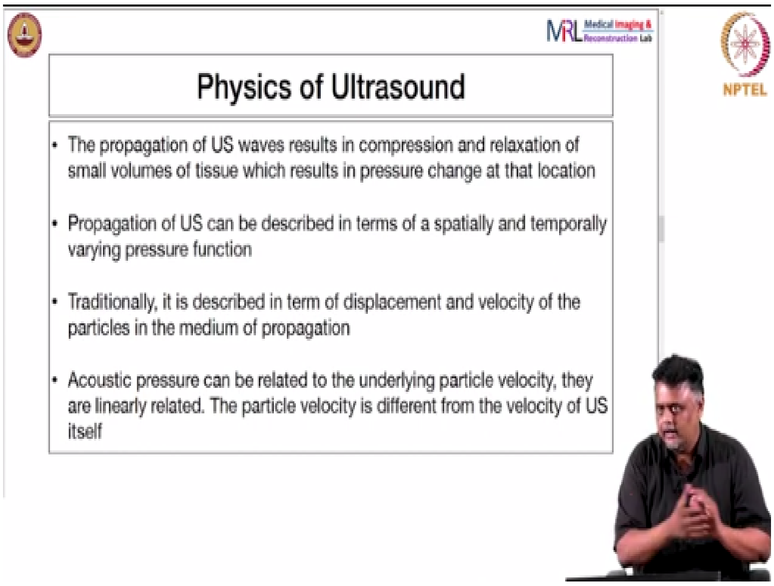
There are two ways of, two types or two of this ultrasound probe for covering a field of view, one is a mechanical scanner, it basically has to (trans) to transducer element rocking back and forth mechanically and as it rocks back and forth to acquire the entire 2D structure. The other one is electronic wherein the electronic scanner wherein it has multiple transducer elements, it will be array of transfer elements, but they will be fired based on a certain pattern so, that you get a coverage so, that that is it helps you to get a particular angle of coverage as well as a particular depth coverage depending on how you find them.

The way to understand this is the following since the ultrasound is a wave, they can interfere with each other. So, if you have multiple ultrasound probes, or even if you think of this membrane, there will be each point in the membrane can emanate one ultrasound pulse wave, and so, they can construct or they can interfere constructively or destructively. .

So, if you so, in the case of an array, if you time the pulses properly, then you can have enough delta t between them time difference between them so that at some depth they can they inter they interfere constructively to get maximum signal. You can also do that so that they go along a particular direction data, this is exactly what helps, happens in an actual modern ultrasound scanner.

You use the diffraction properties of the wave to direct it along certain directions as well as a certain depth, because these waves, this is a wave, it can interfere constructively or destructively. So, you would time them introduce phase shifts, so that they will actually interfere constructively along a certain direction or at a particular depth. So, you get focus when you get steering both of them as possible.

(Refer Slide Time: 15:00)



So, why is it the longitudinal wave etcetera? So, it is, the way it generated and wave propagates it is, it is, it is propagates by compression and relaxation of small volumes of tissue. And also it depends on the elastic properties and inertia of the tissue.

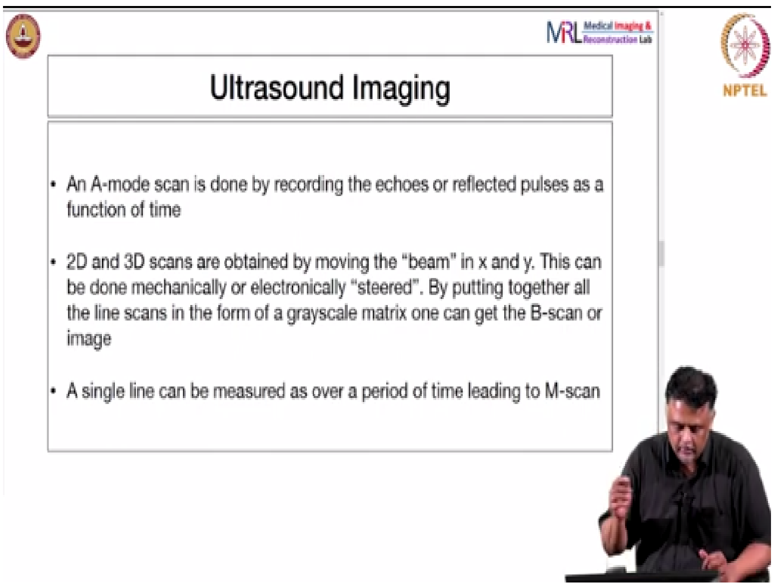
So, when you compress a piece of tissue, it of course, it gets compressed, and then it tries to expose back to its original position because of inertia. But because of inertia, it overshoots its resting position, so then it will go and compress the neighbouring volume of tissue. That is how it propagates.

So, this creates regions of high pressure and low pressure, this is your longitudinal wave. So, basically, that is what it means by a description in terms of spatially and temporally varying function, because over time, the wave will dissipate, but then also spatially, it will vary because of the compression and rarefaction.

So, you can describe this wave in terms of how, let us say the speed of the particles in the medium, there is one wave speed that is different. This ultrasonic waves, wave itself has a speed, the particles in the medium will oscillate, vibrate along with certain speeds, so that is different speeds. So, you can describe this wave in terms of the speed of the particles in that medium, these are microscopic particles, and the medium could be anything you can, there is one abstraction.

It can also be described in terms of acoustic pressure, like I said, these, the product, the transmission of the longitudinal wave is done by the compression and rarefaction of the materials in a tissue in the body. So, you can always describe them in terms of pressure function also. So, the all of these satisfy the so called wave equation. So, that is how the signal itself is modelled. That is how you would understand the, what is the magnitude of the signal that is received by the transducer after a certain time.

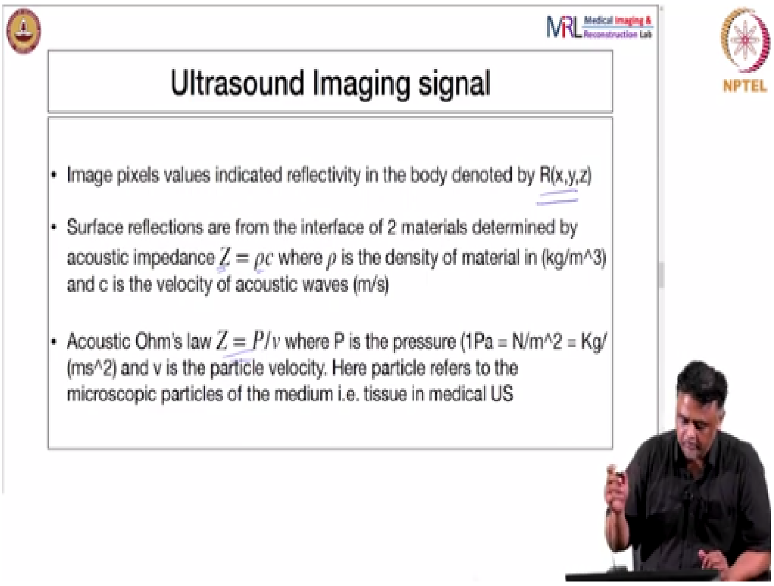
(Refer Slide Time: 16:56)



So, there are different modes of scanning, one is called A-mode. A-mode is basically you have a transducer facing along particular z, let us say, and you pulse it, and then you record that echos, it is called Echo and it gets back for a period of time. Like I said, time translates to depth. So, you can just plot that (fun) signal out, that is your A scan. You can translate your transducer mechanically or electronically, like you saw, and do a bunch of A mode scans. And that will be your B scan, but I will give you like a plain image.

And you can do something similar for 3d, you can move a plane around and you get a 3d scan stack planes are rotated, or rotate an 1D array, and each of them will give you a very nice 3d scan. If you measure a line single line scan over a period of time, so you can actually follow things over time, we keep pressing the same place over time, it will use something called a M-scan. So, each line will be at a different time point that can also be done, these are different types of acquisition modes.

(Refer Slide Time: 17:56)



So, what is it that we are mentioning, so that is a very important? More than these are now we understand a little bit of what we are, how the measurement is done. So, idea is to create an echo, create a pulse, ultrasonic pulse, which is a longitudinal wave, send it through the human body, and you do that by coupling it to a transducer, extracting the transducer or the electrical pulse transducer oscillates very rapidly. And you couple those oscillations to the human body, and then it travels through the body.

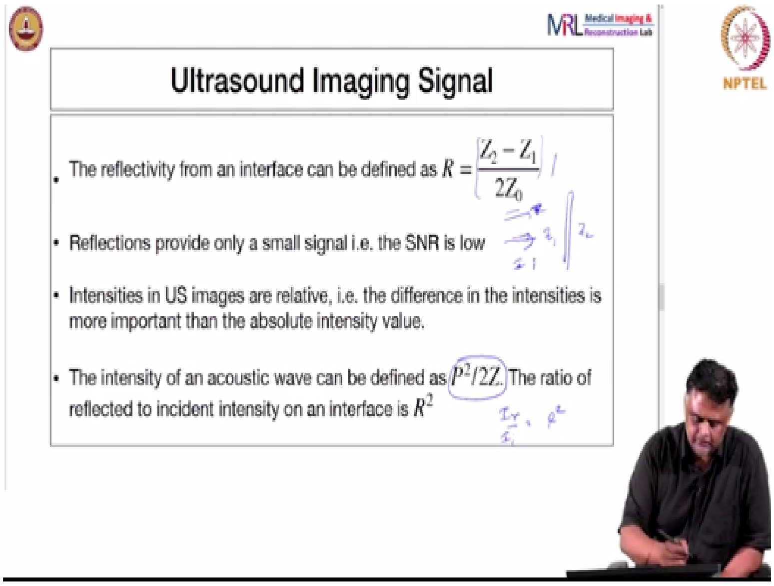
And then you of course, the pulses reflected and scattered and you are measuring the scattered and refracted signals. Over time, time translates to distance. So, that is the idea. Now, what is it that we are measuring, that is idea? So, you create a certain, when you when you create the pulse you are giving it a certain energy and energy is being reflected, what is it what is causing that?

So, the image pixels typically, you would understand them as indicating the so called reflectivity of the tissue at any point, so, if you take a picture at any point is a pixel, value of that pixel is indicators reflect reflectivity. So, what is the reflectivity mean? So, it happens from the interface of materials. So, if your body is made up of different types of the organs of different densities, etc and they have different acoustic, what I call acoustic impedances, just like there is a resistance to current, there is a resistance to transference of ultrasonic waves.

So, that is denoted by this quantity called Z acoustic impedance. It is given by ρc, where ρ is the density of the material and c is the velocity. And there is an equivalent of the acoustic Ohm’s law, which is the $Z = P/\nu$ where the P is the pressure at that point. So this is, these are the ways of looking at what quantity you are measuring. It is related to Z and not only just Z, it is basically the interface of materials which caused it.

There are two types. One is there is reflection from interfaces. There is also scattering or volumetric reflections from objects or structures, which are smaller than the wavelength that you are sending. So, these are the two main sources of the ultrasound signal. That is the important point.

(Refer Slide Time: 20:05)



So, the reflectivity then can be defined in terms of the acoustic impedance between let us say, here I am calling Z2 - Z1 is where I have like an interface. There is no here, it is Z1 here it is Z2, there is an incident beam, and it is reflected. So, the reflectivity, or the fraction that is reflected, if you can call it that is the ratio of this. So, Z_0 is an average impedance, like I call it (Z1 + Z2)/2. That is how it is.

But still, this reflectivity excreta is still a very small portion of the signal. The sense that even though the measured signal comes from reflections and scattering, the amount the absolute SNR is very low. So, that is one of the drawbacks of the ultrasonic sound system, it is still very effective is that the signal to noise ratio is attenuated lost, but majority of the signal you receive comes from reflections and scattering.

So, which means that see the intensities in the ultrasound images are relative. So, for instance, if you saw if you remember, if you saw in computer tomography, the value of a pixel or even for, let us say, projection radiography, the value of a pixel in the image, a point in the image has an action absolute meaning it is not just it is a measure of the attenuation coefficient, which is related to the density of the object, or electron density.

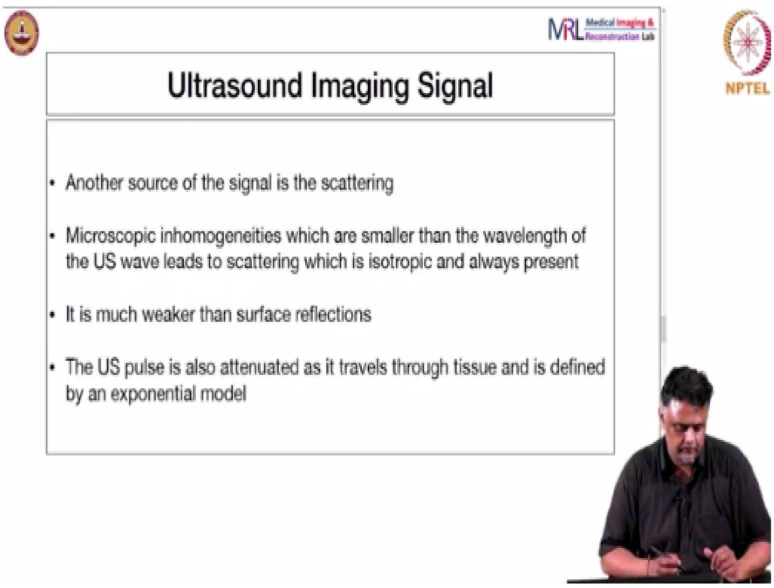
Here, it cannot make that judgment here, all we can say is, if something is brighter than the other, it is more reflective than the other, that is something like that. So, it is, it is the, it is the relative contrast, that is important. So, this leads to actually, images in ultrasound have a lot of texture. So, a lot of the diagnosis is done based on texture of the ultrasonic, but different tissues will have different types of texture, which basically arises from the reflectivity.

So, once again, you know, when I say keep saying intensity, energy, etcetera, you know that this quantity is well defined. So, which basically, if you want to look at the intensity of an ultrasound where that is $P^2/2Z$, at any point, that is that is how it is defined. And if you are looking at the ratio of reflected to incident intensity, so basically, you have interface, there is one like I said, there is an incident wave and there is a reflected wave.

If you look at the ratio of the reflected r over i, if you want to call it, then it is actually proportional to, $R^2 = \frac{I_r}{I_i}$ So, this is why were you know, so this way to understand what the ultrasound image pixels mean, there is just a very qualitative way of understanding it just tells you how reflect to that particular tissue is, give you an idea of the, the acoustic impedance is in the medium. That is one of the things.

There is one other aspect that I have not talked about (bless) you should look it up yourself. It is called speckles in these images. So, some of these reflections also gives rise to so called speckles in many of these images, it is a very bright spots that you see in a picture. And that is again, it is because of the nature of ultrasound propagation and how do you do the measurements.

(Refer Slide Time: 23:27)



So, there are two, like I said, there are two sources of the signal major sources for the ultrasound signal that you receive. One is the reflection, the other is a scattering. There are always microscopic inhomogeneities in our tissue, these are smaller than the wavelength of the ultrasound wave. And they scatter in all directions. Relatively weaker than surface reflections.

But it is, again one of the strongest source of the ultrasound signal, I, like you said, lot of the signal is lost. Most of what you get is reflection as scattering. There is one more aspect which I have again, not talked about is that the ultrasound pulse is attenuated as it travels. Also when it travel, attenuated, when it travels through attenuated when it travels back. So, this is an attenuation, it depends on frequency.

So, if you use very high frequencies, there is a lot more attenuation, but so then you cannot go very deep. On the other hand, we give high frequency, you will also get good resolution. So, that is one compromise that you have to choose. So, you cannot do if you want to do deep structures, you cannot do high frequency ultrasound, very hard to do. So, that leads to so there will be some attenuation because it is attenuation increases its frequency.

So, we will we will then now proceed look at some of the mathematical models for ultrasound propagation, and just how just look at a general expression at least for an A scan, what is the form of a signal that is received and how to understand it and from there to understand what are the compromises in terms of how is a lateral resolution degraded, how is depth-wise resolution degraded, etcetera from those equations. Thank you.