Biomedical Ultrasound: Fundamentals of Imaging and Micromachined Transducers

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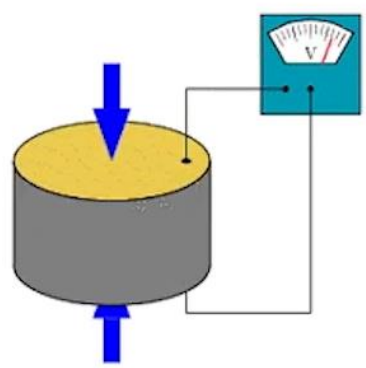
Lecture: 06

Recap of Week 1

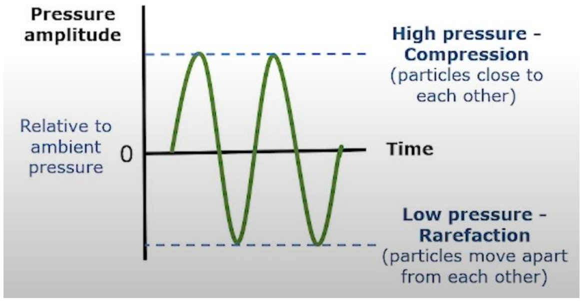
Hello, welcome to today's lecture. Today we'll do a recap of what we have already learned from the various lectures we've discussed. So, what we had learned, giving a brief overview of ultrasound, we had learned the piezoelectric effect, where these piezoelectric elements or materials can send or receive sound waves. We've also looked into different frequencies of biomedical ultrasound. In the imaging range, we look at one to 20 megahertz or two to 15 megahertz. And here I show some common piezoelectric materials.

Those that are used commercially today are PZT, which stands for lead zirconate titanate, quartz, and polymer films such as PVDF are being used for transducers.



We've also talked about ultrasound pulse, and how an ultrasound wave is created. In particular, longitudinal waves have regions of compression and rarefaction. Compression where the density of the particles, when the particles are much closer to each other, and rarefaction, where the particles are further apart.

And in a longitudinal wave, the particles are moving in the direction of the actual wave. So, we'd also talked about what the pressure wave would look like if plotted in this form as a function of time. So typically, ultrasound waves are a sum of sinusoids, and typically they have this cyclic pattern. So, when we talk about one ultrasound cycle, it has this form. The positive pressure amplitude will correspond to the compressional part of the wave, and the negative pressure amplitude corresponds to the rarefaction part of the wave.



We've also looked at various pulse parameters such as the period, the frequency of the sound, the wavelength of sound, which is a function of the longitudinal sound speed, and the frequency of the sound. We also talked about the duration of the pulse, pulse duration, as well as its spatial component, the spatial pulse length. We talked about the pulse repetition period. The pulse repetition period basically says how often a particular ultrasound pulse is being sent over time. And the inverse of that, which is the pulse repetition frequency.

Also, we talked about the duty cycle, which is a function of the on time divided by the on and off time of the pulse. So, this is basically the pulse duration divided by the pulse repetition period.

- Period, ***T***
- Frequency, ***f***
- Wavelength, ***λ***
- Longitudinal sound speed, ***c***
- Pulse duration
- Spatial pulse length
- Pulse repetition period, ***PRP***
- Pulse repetition frequency, ***PRF***
- Duty cycle/factor, ***DF***

Now, let's look at some example problems that delves with using these parameters. So here I have three problems. The first problem is to compute the wavelength of a 2-Megahertz ultrasound field in a soft biological tissue.

And in soft biological tissues, we assume that the speed of sound is 1540 meters per second. In the second problem, we ask what the spatial pulse length is of this 2-Megahertz ultrasound pulse with three cycles. So, you can use the same information from the previous problem as well. And in the third problem, suppose that the pulse repetition period (PRP) was 10 milliseconds. Now what is the duty factor of this pulsing scheme? So here you can pause this video to attempt the problems.

Now let's discuss the answers to these problems. For the first problem, we would like you to compute the wavelength for a 2 MHz ultrasound field in soft biological tissue. Here, we assume that the sound speed is 1540 meters per second. So, if you remember the equation of the wavelength, which equals the speed of sound here, divided by the frequency of the sound, which is 2 MHz here. So, the unit of Hertz is one by second.

So, we compute this equation and we get 0.00077 meters. So now when we think of ultrasound frequencies, we usually think in the order of millimeters. So, we can convert this meter quantity into millimeters. And our final answer is 0.77 millimeters. For the second problem, in terms of what is the spatial pulse length of this 2 MHz ultrasound pulse with 3 cycles. So we know what the wavelength is from the previous problem. And now this wavelength corresponds to the length of the wave in one cycle. Now, if we look into 3 cycles, then we simply get the spatial pulse length, or the SPL, by just multiplying the wavelength by the factor of 3.

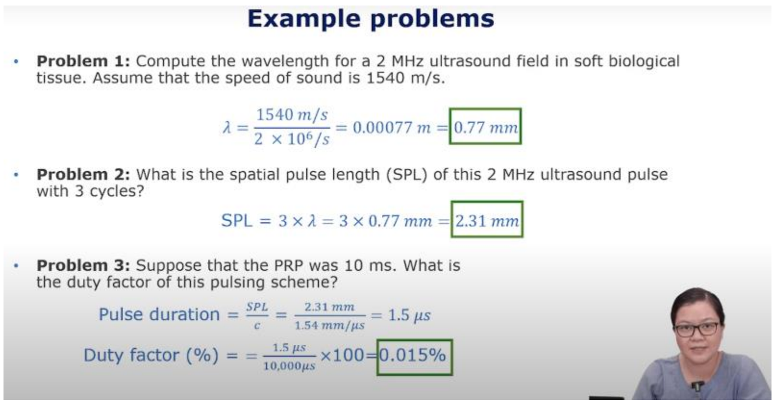
So, we get 3 times 0.77 millimeters. Now our spatial pulse length will be 2.31 millimeters. For the third problem, suppose that the pulse repetition period was 10 milliseconds.

We want to find out what the duty factor is. We first calculate what the pulse duration is. And we know that we have the spatial pulse length from the previous problem. We divide the spatial pulse length by the speed of sound, c, and we get this expression here, where the pulse duration is now computed as 1.5 microseconds. So typically, ultrasound imaging pulses are in the order of these 2 microseconds. So, this answer makes sense. Now, we would like to calculate the duty factor in terms of percentage. So, we also know that the pulse duration is 1.5 microseconds divided by the pulse repetition frequency.

In the problem, we had expressed it as 10 milliseconds, but now we want to make sure that the microsecond units are both similar in the numerator and the denominator of this expression. And that way we can also cancel out the units since duty factor is in the form of percentage. So, we convert 10 milliseconds to 10,000 microseconds, or 1.5

microseconds divided by 10,000 microseconds. And since we're going to express the duty factor in terms of percentage, we would multiply that value by 100.

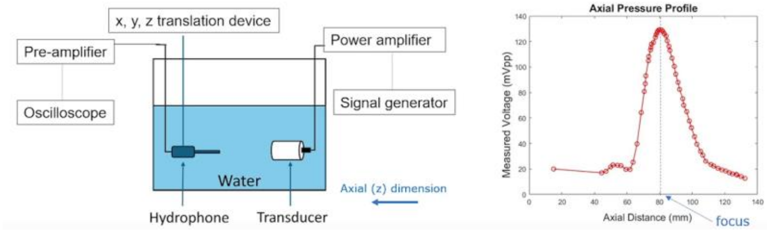
So here the answer is 0.015%. So hopefully you got these answers based on what we have learned on this course.



We have also looked into measurement methods of the pressure amplitude and we had discussed an experimental setup where we have a hydrophone and a transducer submerged in a water tank as shown here. Here, just a reminder that the transducer is being excited by a single generator and then a power amplifier.

And the ultrasound signal is being sent through this transducer and the hydrophone listens. Now remember that a hydrophone is like a microphone underwater. It just listens to the ultrasound pulse. Now this hydrophone is also connected to a translation device that allows the hydrophone to map the beam in 3 dimension. It also is connected to a preamplifier and an oscilloscope right here.

So, the figure on the bottom left just showing an example of a PVDF transducer right here. It's called a needle hydrophone and a couple of ultrasound transducers ranging from 1 to 20 MHz. What you would get from a hydrophone signal, something looks like this. So you can map the measured voltage, which you can convert to pressure based on the hydrophone sensitivity. And you can map it as a function of the on-axis distance or the axial distance from the transducer.



And you can see here that as you keep moving farther and farther away from the transducer face, the hydrophone will detect a peak at the focus right here, located at 80 millimeters axial distance. Now what is the recommended hydrophone size? We had discussed this earlier that the IEC has a specific standard for what a maximum effective hydrophone radius would be to try to avoid spatial averaging or disturbance of the ultrasound wave field as the hydrophone is scanning the beam. So, here's the equation that is given to us where the radius is b_{max}. So, what this represents is that the maximum hydrophone size should be this. And you should select the hydrophone that is much, much less than this radius.

$$b_{\text{max}} = \frac{\lambda}{4}\left[\left(\frac{l}{2a}\right)^2 + 0.25\right]^{\frac{1}{2}}$$

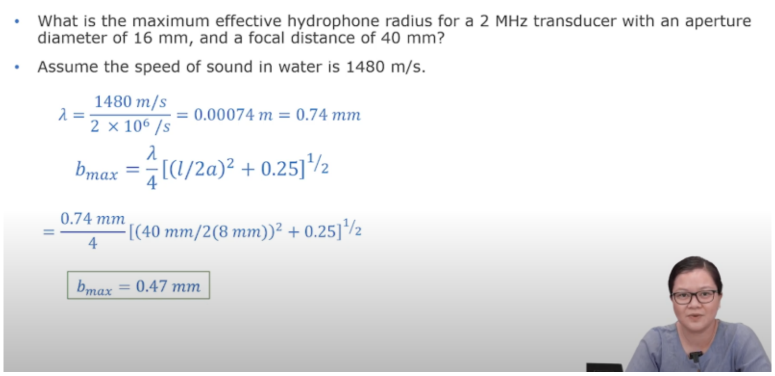
So, it's a function of the wavelength in the water. It's a function of the axial distance between the transducer and the hydrophone, as well as the transducer radius. Now let's look at the answer to this problem. So first we would calculate what the wavelength of sound is. So, the wavelength equation would be the speed of sound divided by the frequency of the sound.

So here we have that the speed of sound in water is 1480 meters per second, and we have a 2 MHz transducer. So that would be denoted by 2 times 10 to the sixth per second, where again, Hz is one by a second. We plug this into our equation, and we get 0.00074 meters. Now again, when we talk in terms of ultrasound and MHz frequencies, that corresponds to wavelengths on the order of millimeters.

So, our wavelength would be 0.74 millimeters right here. Next, we would plug these values into the equation. So, this was the equation given to us for the maximum hydrophone radius. We plug in our value for the wavelength here. We also know what the focal distance is, which is "l" here, and that is 40 millimeters.

So, we plug that into this equation. We also know the radius or actually the diameter of the transducer. So, then we would want the "a". So basically, we would divide the diameter by 2 because the diameter is twice the radius of the transducer. And so here, 16 by 2 would be 8 millimeters. Now we plug all these values into the equation.

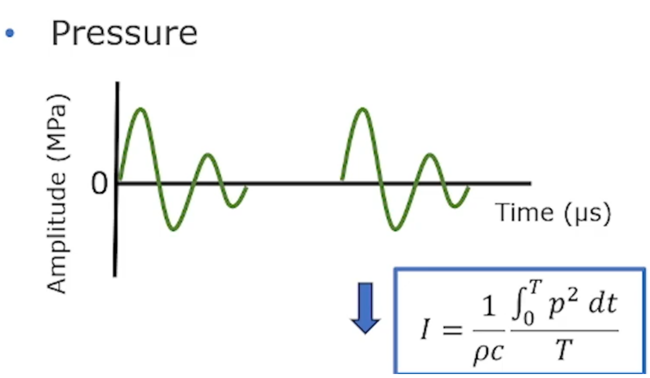
Using your numerical tool, you would be getting a radius of 0.47 millimeters right here.



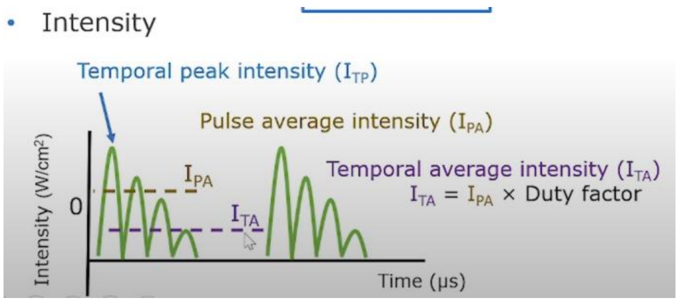
So, what this means is that this is the maximum radius of the hydrophone that you can use to avoid spatial averaging or even disturbing the ultrasound field. This means that you would be able to, you would need to use a hydrophone that is below this value right here.

So typically, a hydrophone that's 0.2 millimeters, 0.1 millimeters that you can use for characterizing the beam of this 2 MHz transducer. We also discussed a couple of intensity metrics. So, for instance, when you measure the ultrasound pressure field from a hydrophone, the output signal can look something like this. It can be an asymmetric sinusoidal wave like this.

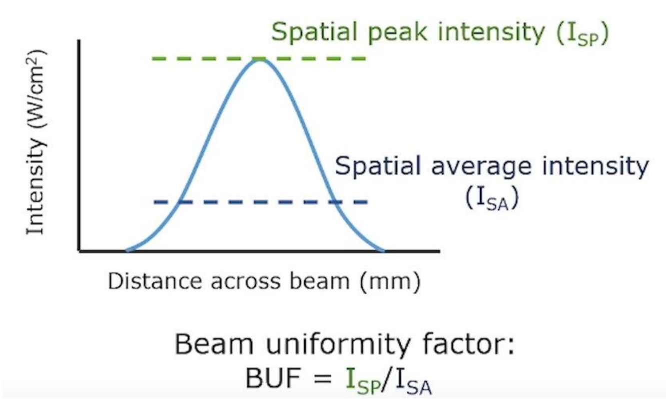
So, to calculate the intensity, you will need to perform this integral using this equation and to get the intensity that looks like this in terms of watts per centimeter squared. Now there are several intensity metrics that we had discussed. The first being temporal peak intensity or I_{TP} right here. And that is the peak intensity of this intensity waveform. We also have the pulse average intensity, which is the I_{PA} here.



And that is the intensity of the waveform that is averaged during the pulse duration of the signal. We also looked into the temporal average intensity, or I_{TA}, and that is the intensity of the waveform that is averaged during the pulse repetition period. So, the "on" is divided by the "on" and "off" time of the waveform. And we also noted that the temporal average intensity, I_{TA}, equals the pulse average intensity times this duty factor. In terms of the spatial intensity metrics, we had discussed the spatial peak intensity I_{SP} here and the spatial average intensity I_{SA} right here.



Now this is a profile of the beam, a sample profile of the intensity. across the beam in the cross section of the beam. And we also talked about the beam uniformity factor. This basically tells how uniform the beam is. And that's a function of the I_{SP} or the spatial peak intensity divided by the spatial average intensity.



Now putting all these intensity metrics together, we know that a waveform has a temporal and spatial component to them. So we put together these six intensity metrics, spatial peak temporal peak intensity, I_{SPTP}, spatial average temporal peak intensity, I_{SATP}, spatial peak pulse average intensity, I_{SPPA}, spatial average pulse average intensity, I_{SAPA}, And the final two, which are more widely used in ultrasound, is the spatial peak temporal average intensity, I_{SPTA}, and the spatial average temporal average intensity, or the I_{SATA}. So, as we move up here, we know that spatial peak temporal peak would be the highest value, wherein the spatial average temporal average intensity would be the lowest value. Now let's look at some example problems. So, for the first problem, suppose the I_{SPPA} or the Spatial Peak Pulse Average Intensity of a 2 MHz ultrasound beam was 100 watts per centimeter squared and the beam uniformity factor was 10.

The pulsing scheme occurred with a duty factor of 1%. Now we want to find what is the I_{SATA} or the Spatial Average-Temporal Average Intensity. For the second problem, suppose an ultrasound beam has a cross-sectional profile resembling a half-cycle sinusoid. Now what is the beam uniformity factor? So please take a moment to pause your video while attempting this problem.

Now let's look at the answers to each problem. So, what we do for the first problem is that we want to calculate I_{SPPA}. So, what you can do is you can either assess the problem in terms of the temporal part, PA and TA, or if you want to also look into the SP and SA. So, it doesn't matter which direction you go, either temporal or spatial, you will get the same answer. So, in this solution, first we would like to focus on the temporal intensity metrics. So, we know that temporal average, the temporal average intensity equals the pulse average intensity times the duty factor.

So, what we're given is the I_{SPPA} times the duty factor and we can get the I_{SPTA}. So that equals 100 watts per centimeter squared and you multiply that by duty factor we're given that is one percent so and it would be 0.01, and so you would get the I_{SPTA} as one watt per centimeter squared. Next, to get the I_{SATA}, we deal with the spatial intensity metric. So, we know that I_{SA} equals I_{SP} divided by the beam uniformity factor here.

So, what you would do is you would get the I_{SPTA}, divide that by the beam uniformity factor. So, 1 watt per centimeter squared divided by 10. and that would equal 0.1 watt per centimeter squared. So, this is your I_{SATA}, or your spatial average temporal average intensity.

- **Problem 1:** Suppose the I_{SPPA} of a 2 MHz ultrasound beam was 100 W/cm^2 and the beam uniformity factor (BUF) was 10. The pulsing scheme occurred with a duty factor (DF) of 1%. What is the I_{SATA}?

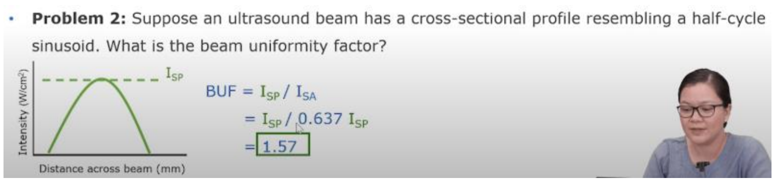
  $I_{TA} = I_{PA} \times DF$ $I_{SPTA} = I_{SPPA} \times DF = 100\ W/cm^2 \times 0.01 = 1\ W/cm^2$

  $I_{SA} = I_{SP} / BUF$ $I_{SATA} = I_{SPTA} / BUF = 1\ W/cm^2 / 10 = 0.1\ W/cm^2$

For the second problem, we have, suppose an ultrasound beam has a cross-sectional profile resembling a half-cycle sinusoid. So here on the left, we have an intensity profile as a function of space, the distance across the beam here. We can see that it's a half-cycle sinusoid here with a peak of spatial peak intensity right here. We want to know what the beam uniformity factor is. So, we know the relationship of the beam uniformity factor and the spatial peak and the spatial average intensity.

We also know that if you integrate across the half cycle of a sinusoid, it would be 0.637 of the peak intensity right here. So, what we would do here is substitute the spatial average intensity with this 0.637 spatial peak intensity right here. So the nice thing about this equation is that you won't need to know the exact factor, the exact value of the I_{SP}, because I_{SP} will cancel out in the numerator and the denominator.

So, what's left is 1 by 0.637. And when you would compute that, you would get a beam uniformity factor of 1.57. So, this is your answer.



Now let's talk about decibel notation. Decibel notation is a standard notation that is used for comparing two signals either in pressure, amplitude, or intensity. Decibel notation is frequently used to describe changes in attenuation, signal amplification, signal compression to vary the dynamic range in an ultrasound image. You might have recalled from a previous lecture when we talked about attenuation. We expressed attenuation in terms of nepers per centimeter and then we also converted it to decibel per centimeters. Now what is this decibel notation? So, decibel by definition is 10 $\log_{10}$. So here I show the intensity, differences in intensity equals 10 $\log_{10}$ by I_2 by I_1.

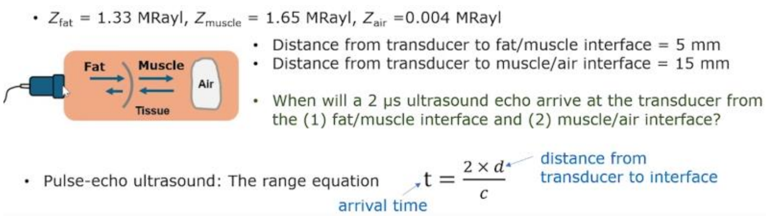
$$Intensity = \Delta I_{dB} = 10 \log_{10}\left(\frac{I_2}{I_1}\right)$$

$$Pressure = \Delta P_{dB} = 20 \log_{10}\left(\frac{P_2}{P_1}\right)$$

So, these are the two signals with different intensities. Since intensity and pressure are related by P squared, then the pressure equation for decibel notation turns into the change in pressure in dB equals 20 $\log_{10}$ of P_2 by P_1. Here, I show a table of the decibel notations that are frequently used in ultrasound. So, if the amplitudes and the intensities are the same, then the decibel is zero. If the intensity is doubled, you get a decibel of 3, an increase in the intensity of 3 dB right here. Now, in terms of amplitude, if the amplitude ratio, the amplitude is doubled, then the dB notation for that is of an increase in 6 dB.

And similarly, if there is an attenuation in the signal, for instance, if you get half of the amplitude, the signal is attenuated by half, then the dB notation would be negative 6 dB. When we talk about dynamic range in an ultrasound image, we usually express it as 60 decibels of dynamic range. And what that means is the amplitude of the highest signal that is being displayed in the image and the amplitude of the lowest signal that is being displayed is different by a factor of 1,000. In terms of intensity, that difference is of a factor of 1 million. Now, this is because of that squared relationship of p squared is proportional to the intensity.

We've also talked about reflections at interfaces, and we had an example of calculating the reflection coefficients and the transmission coefficients of interfaces in this scenario. So, what we have here, you would recall that we have a transducer that is sending an ultrasound signal through fat and then muscle and then air. And some of the signal is propagating through these interfaces and because of differences in the acoustic impedances, between these tissues, then some of it will get reflected back. We also have here a scenario where the distance from the transducer to the muscle fat interface would be 5 millimeters. Let's say that the distance from the transducer to the muscle air interface is 15 millimeters.



Now we want to find when will a 2 microsecond ultrasound echo arrive at the transducer from the fat muscle interface or the muscle air interface. So here we introduce pulse echo ultrasound, this term. So, what we're actually doing, we're pulsing an incident pulse through, and we're receiving the reflected echo back. Now here, what's important to know, okay, when does the signal echo actually arrive back to the transducer? Now, we introduce this range equation, which is the arrival time here, t, equals 2 times the distance from the transducer to the interface, divided by the longitudinal sound speed inside that particular tissue.

So this factor of 2 here that is presented, it's because of pulse-echo. Previously, in a previous lecture, we had talked about space and time relationship of a signal that's propagating through. But here, since that ultrasound signal is being sent and received back, that signal has to travel twice the distance, and hence this factor of 2 right here. So, what you would get if you had detected the signals from the interfaces, and you can get it from a oscilloscope and plot it as a function of time, you would get a signal that looks something like this, where you have high amplitude signals at the interfaces of fat-muscle, and another one between muscle and air. Now because the, as you would have remembered in the previous lecture, that we had calculated the reflection coefficient of muscle and air. If you compare that to the reflection coefficient of fat and muscle, the one with muscle and air is very, very high, almost 0.98. And because of that, you would receive a signal echo that is much, much higher than that of the fat-muscle interface. Now what you will do here is we'll answer the question using this range equation of when will this echo from the fat-muscle interface and when will this echo from the muscle interface arrive. From here you can take a minute to pause the video to attempt these problems.

We also talked about scattering. We know that scattering has a dependence on the object size relative to the ultrasound wavelength. We also discussed that the "ka", depending on its quantity, it will also depend on the type of scattering, wherein for specular scattering, we have "ka" being much, much greater than 1, and we use this as reflections from smooth planar interfaces.

$$ka = \frac{2\pi a}{\lambda}$$

For Rayleigh scattering from really, really small scatterers relative to the ultrasound wavelength, "ka" is much, much less than 1. And in the intermediate regime, diffractive Mie scattering, where "ka" is on the order of 1, means that the size of the object is on the order of the wavelength. Now let's look at an example problem for this case. So here we are measuring scatter from an oil droplet of radius 2 micrometers. At 1 MHz frequency, the backscatter is I units. At 2 MHz frequency, what will be the backscattered intensity? Would it be 2 by I, 4 I, 16 I, or 64 I? You can pause the video to attempt this problem. Now let's look at the answer.

Let's look at the answer now. So, the correct answer is 16 I. And why is it 16 I? So, what we had noticed is that the frequency has doubled from 1 to 2 MHz. And what we know is that the intensity will also increase a factor of frequency to the 4th power. So then, if we double the frequency, then that means the intensity to the 4th power will be 16.

So, it'll be increased by a factor of 16. And this is the answer. In summary, we have discussed ultrasound pulse and intensity metrics. We have discussed the concept of acoustic impedance, reflection, transmission, as well as scattering. And these give the foundation for understanding ultrasound imaging, which we will discuss in the next lecture. Thank you.