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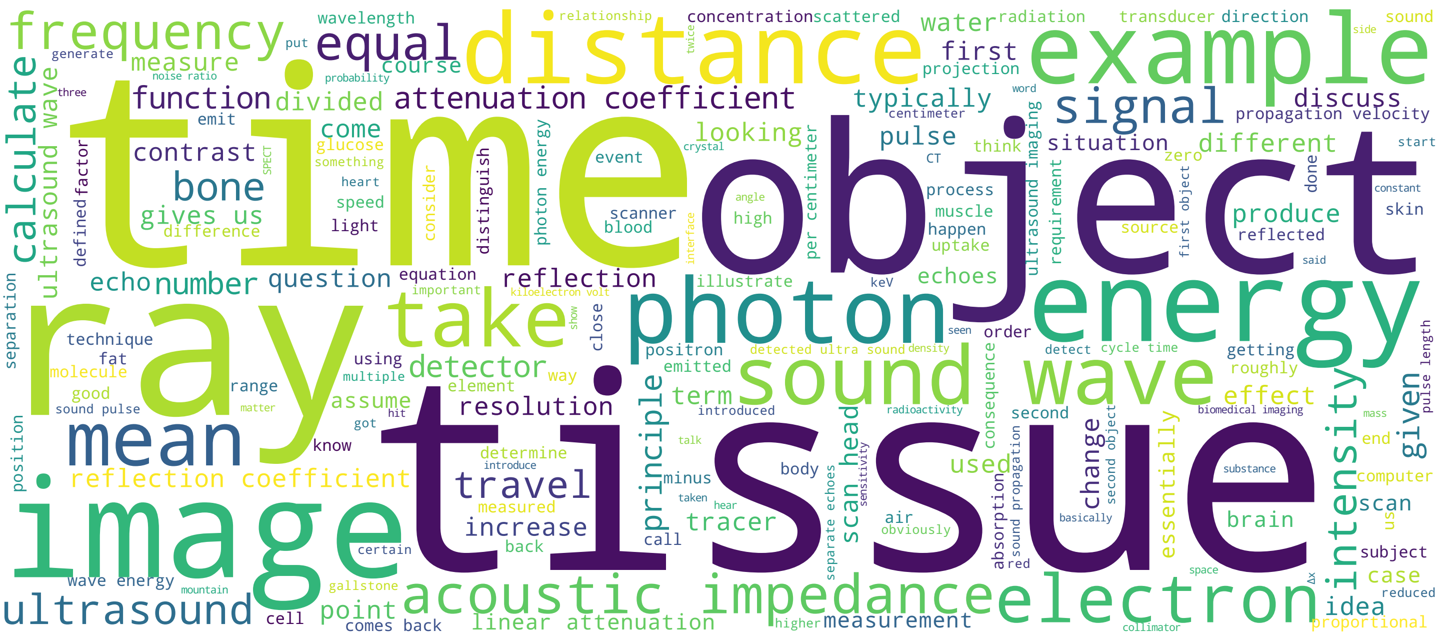
FÉDÉRALE DE LAUSANNE

2.1 Basic Principles & Resolution of US

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



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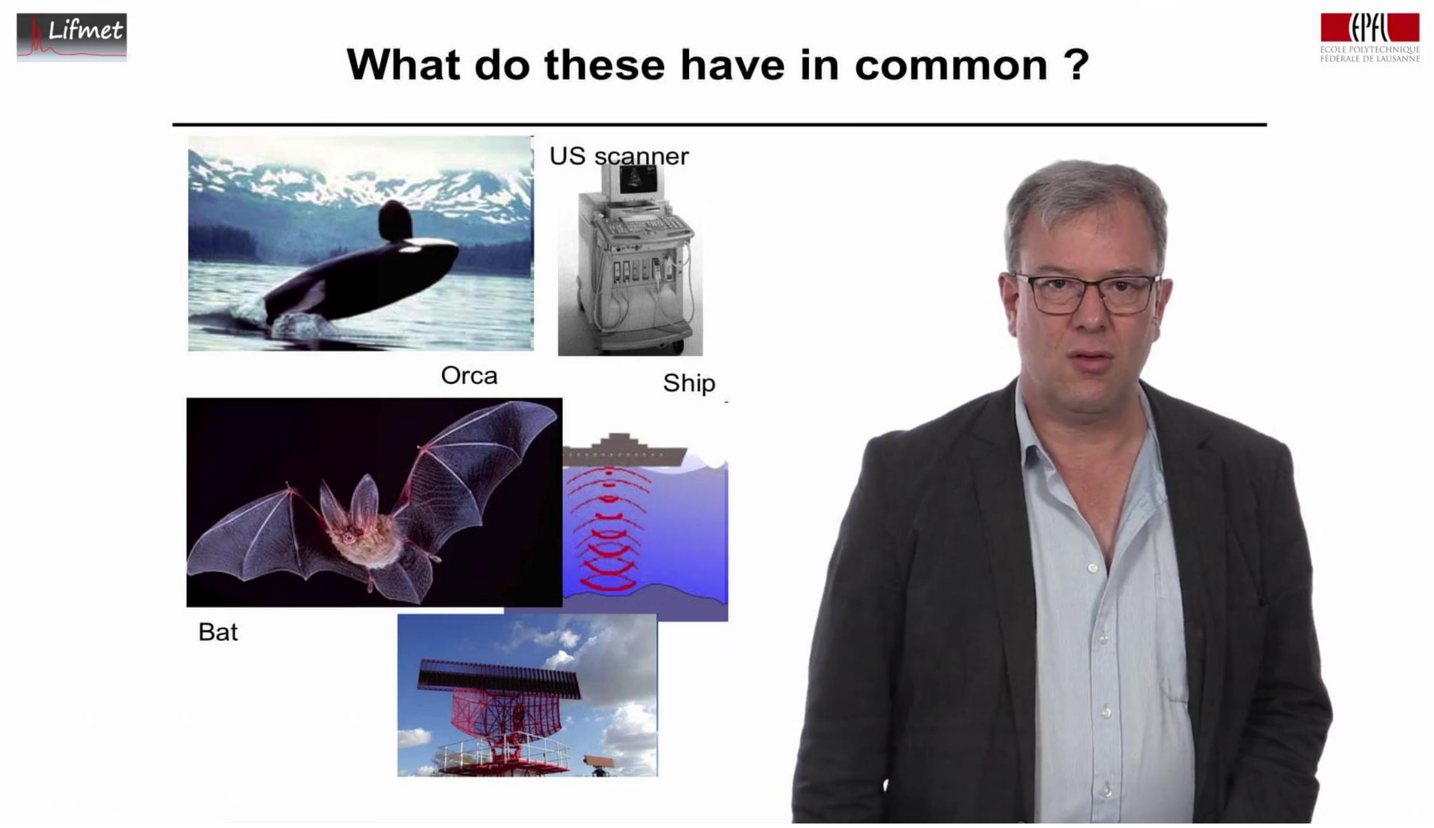
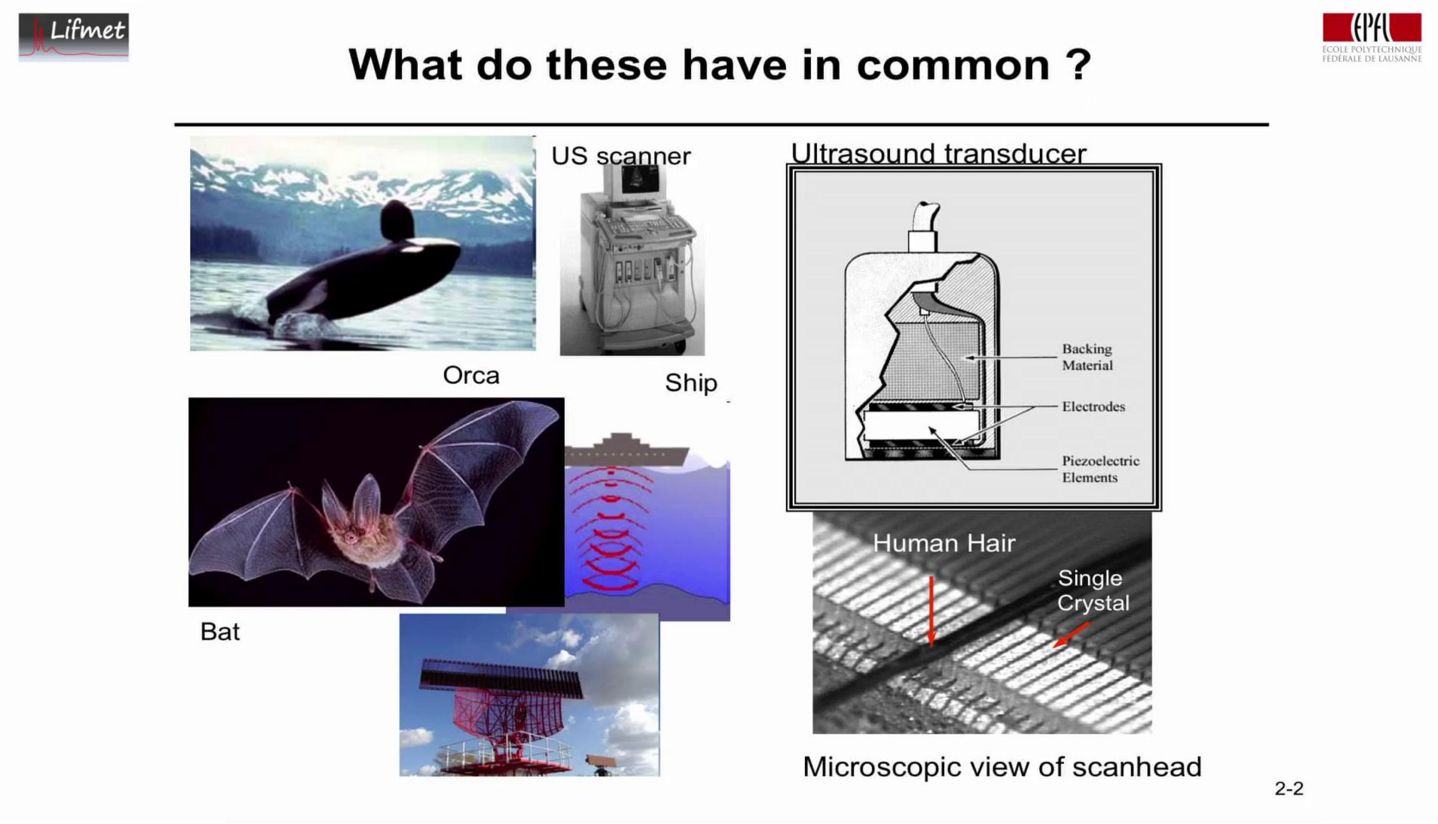


So in this section, we are going to discuss the principle of ultrasound imaging. It's a very basic introduction and it's not complete but what I wanted to share with you is the basic principle of ultrasound imaging and some elements that allow us to determine the estimated behavior of ultrasound that is resolution and the need for resolution and the need for sensitivity. But first I'd like to start out with showing you some pictures, and the question is what do they have in common? So here we have the orca, the killer whale, the bat, and the ultrasound scanner. We have boats, a ship here, and you might recognize this: this is a radar station. Now we might say, "Well, they have all in common echolocation, ultrasound location or communication as the common thing, but clearly with radar, the ultrasound is not the principle of what the radar is using. The principle that's used here is echolocation, that is the position of an object is determined based on the time travel that is taken between the object and the emitting source. So the orca, or the bat, that's how they orient themselves; the ultrasound scanner, as we will see is the same principle; and for the boats to determine how high above they are above the ground.

Notes

Summary

0m 03s

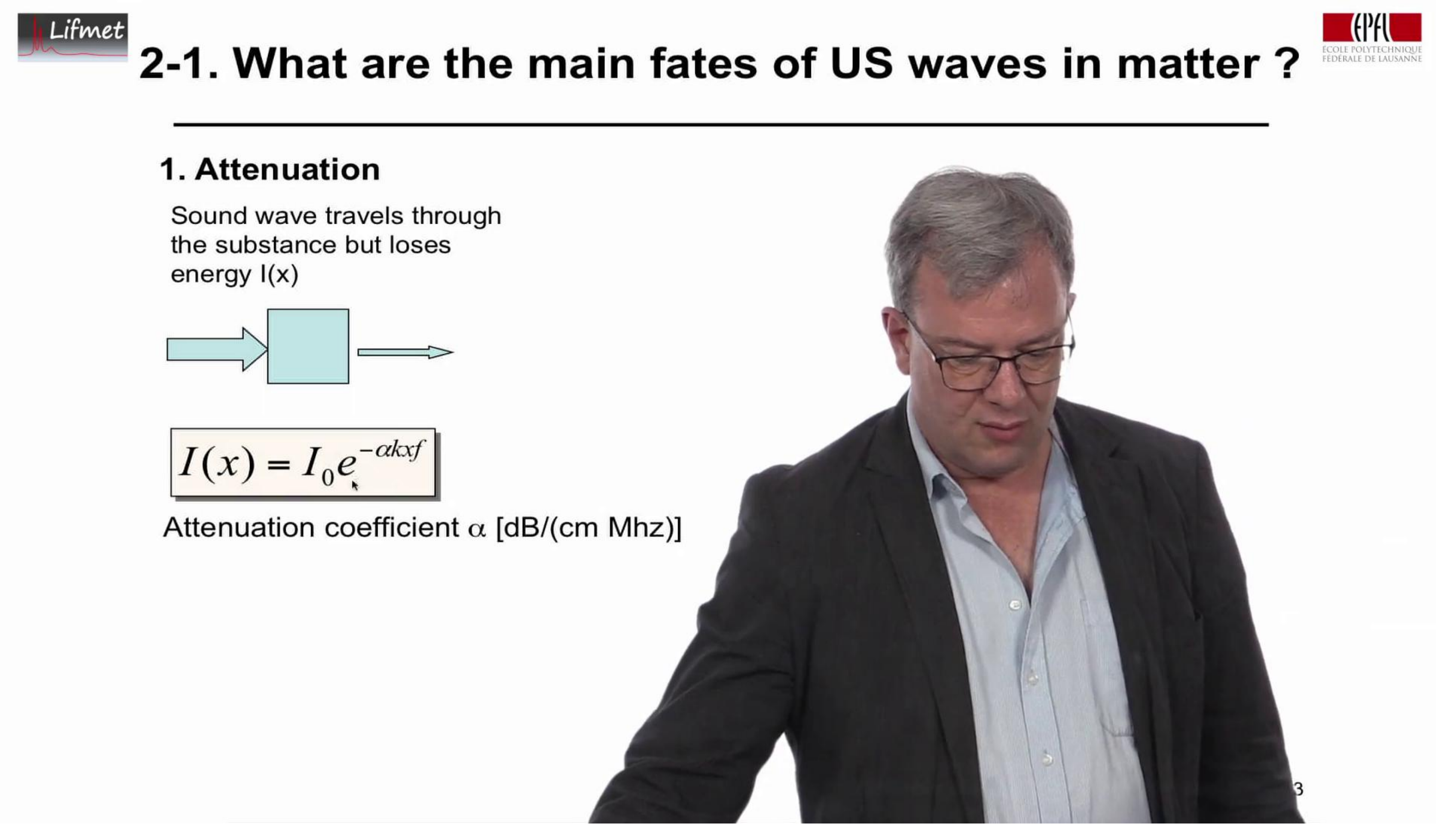


So it is echolocation. I want to briefly talk about the transducer. We will not go into too much details of its functioning, but I just want to introduce here the ultrasound transducer that is the generation of ultrasound waves. It's typically it's like a computer mouse here, and let's look here at the few selected elements at the at the scan head. Let's hit on a zoom in on how this looks like. This is the scan head: a microscopic view of the scan head. We see here the single crystals, and now can you guess what this is? This is for size comparison object placed on here. This is a human hair. It gives you an idea how fine the detector is being built and what kind of technology goes into it.

Notes

Summary

1m 40s

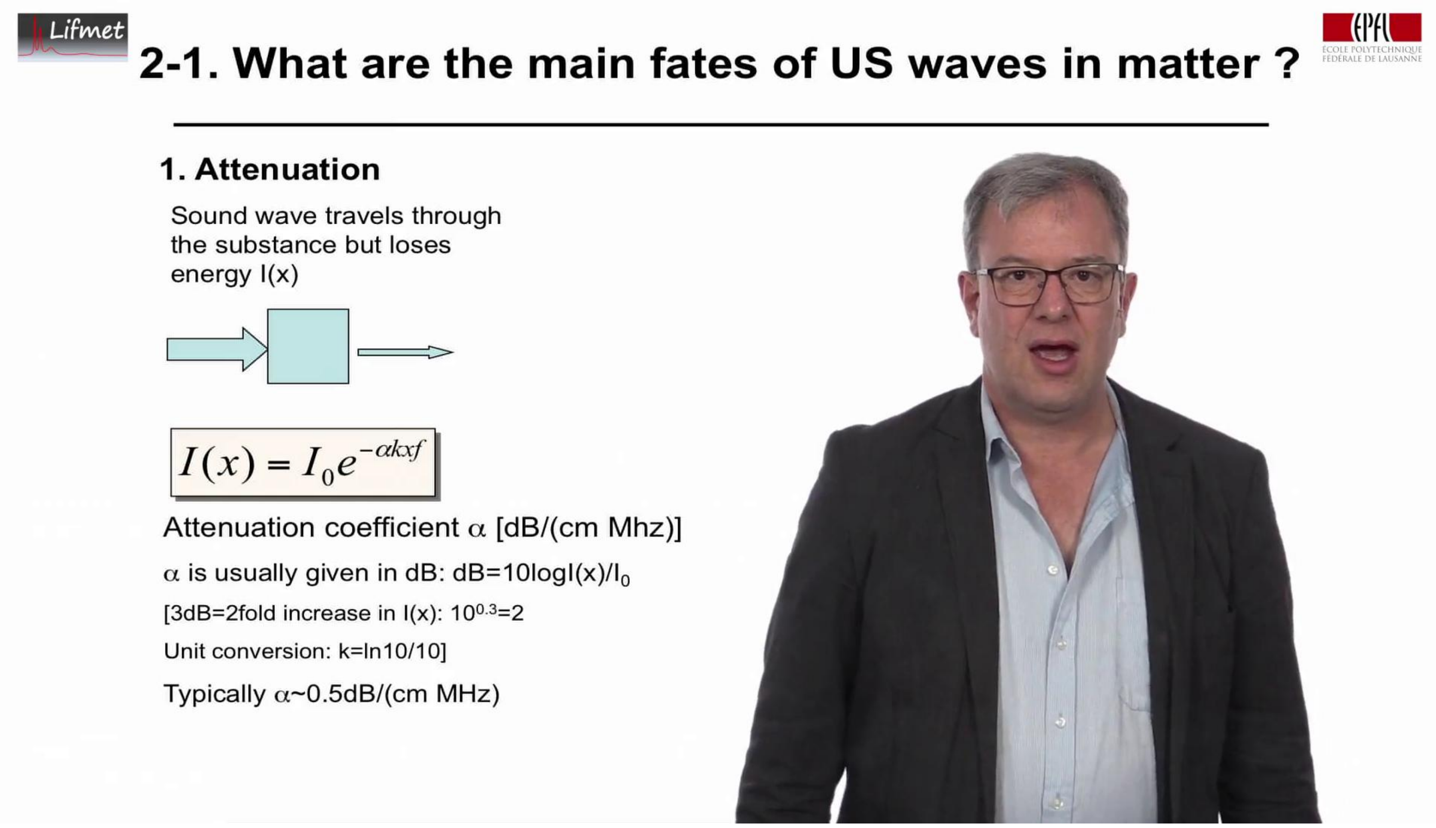


So now the question is, how do we use ultrasound waves in matter? And here, we have to address what are the main fates of ultrasound waves in tissue-- matter, here specifically, in tissue. Clearly, if we emit the sound wave, it will not arrive at the end with the same intensity. This has to do with the fact that there is attenuation, so one effect is attenuation. So the sound wave goes through the tissue, but or through the substance, but as it travels, it progressively loses energy. So the intensity becomes a function of space. And so, we have the sound wave goes here; it comes here with the original intensity. Here, we are assuming just some kind of tissue of a certain thickness, and then, the sound wave here is diminished, as indicated by the reduced size of the arrow. The model that we use, and very often use is just simply an exponential model. We have the intensity as a function of distance here as it travels through the tissue here. It is a function of the original intensity here, and then it's an exponential function with some factors in the exponent. We have one factor that's the attenuation coefficient that's tissue factor, and this factor is given in decibels per centimeter per megahertz, so we have decibels per centimeter per megahertz.

Notes

Summary

2m 33s

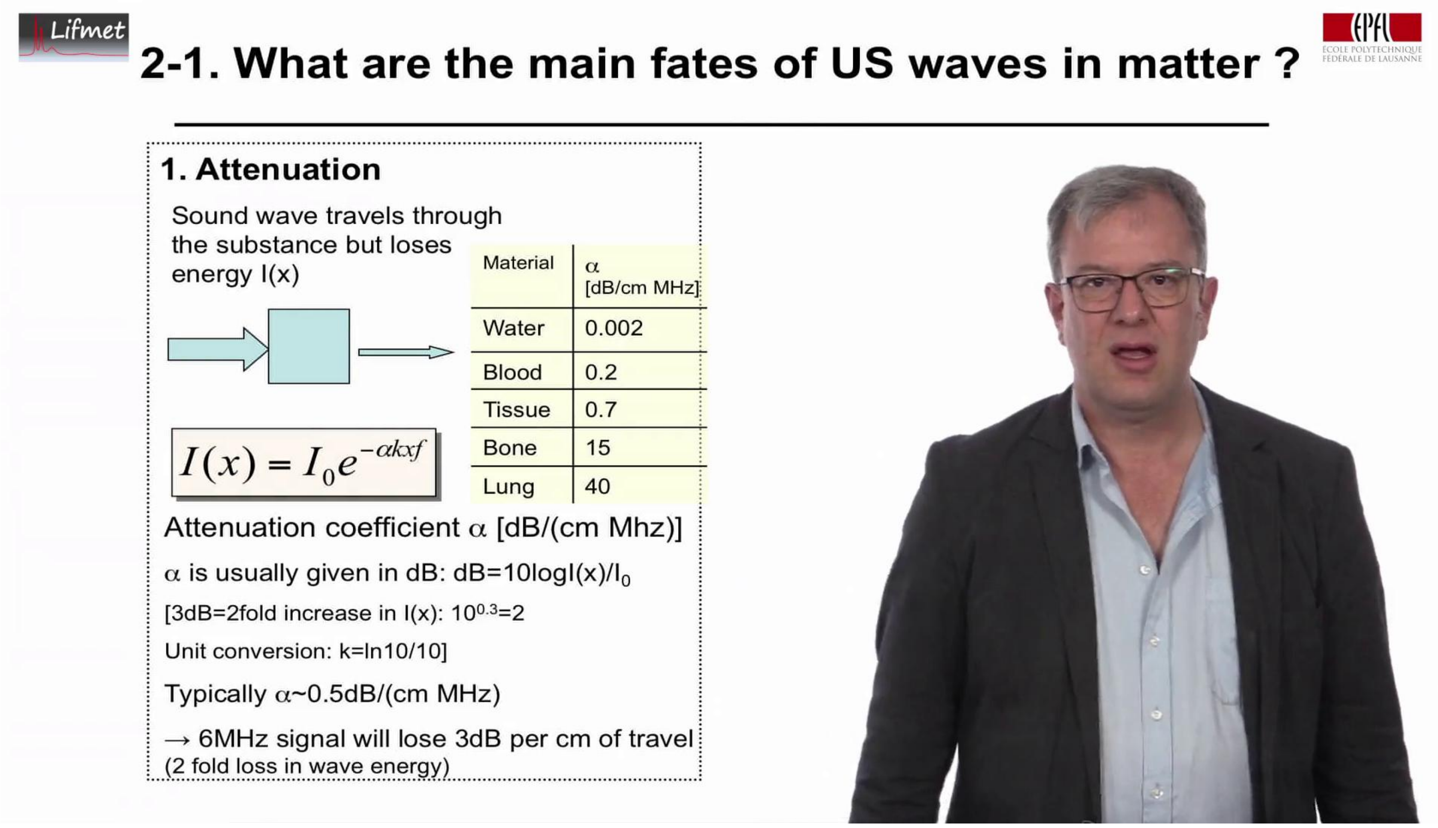


We have to have an exponent, the dimensionless term, so we have the frequency here that is in megahertz; we have the distance that's in centimeters, and this gives us a dimensionless term. Now, I'm not a engineer, so decibels I have to remind myself -- what it is, the definition -- here the decibels is 10 times logarithm of *I(x)* over *I_0*, and to give us an idea again to remind ourselves a three-fold decrease, a 3dB, three decibels is a two-fold increase in the intensity or change in intensity, so 10 to the 0.3 is equal to two. so in order to come from the engineering units, *alpha* being given in decibels to physical units, we have to have a unit conversion factor here and this is this factor K that we've introduced here which is equal to logarithm of natural logarithm of 10/10. So it's roughly 0.3, So typically, this attenuation factor alpha is roughly opened five dB per centimeter per megahertz, that's a typical value that we have in tissue, and so let's see what this means in specific terms. And basically, it says that it implies that if we have a six megahertz ultrasound signal, it will lose 3 dB per centimeter of travel.

Notes

Summary

3m 59s

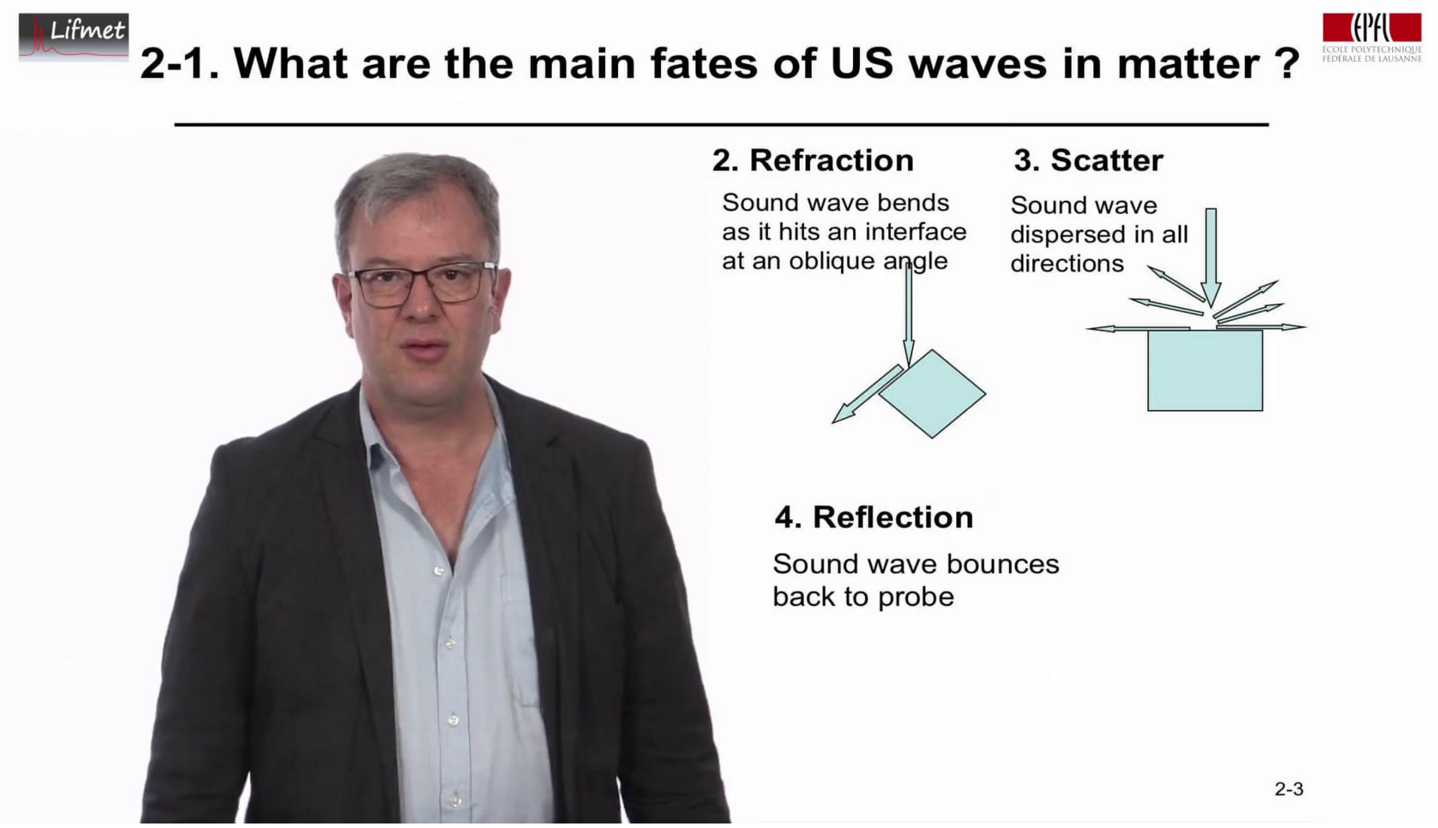


It's just we take α multiplied by six megahertz; this gives us three; and then we have for a distance one centimeter so that this means 3 dB loss of signal intensity, and that corresponds to a two-fold loss in wave energy. So six megahertz per centimeter, we lose a factor of 2 in energy; So this is an important mechanism. Here are some specific attenuation coefficients: see for example in water, ultra sound travels in water basically without attenuation, hence the orca uses it to locate objects at a great distance as the echo bounces back with very little loss. Then we have blood tissue; bone has a strong attenuation, and finally, the lung; these are just some examples.

Notes

Summary

5m 25s

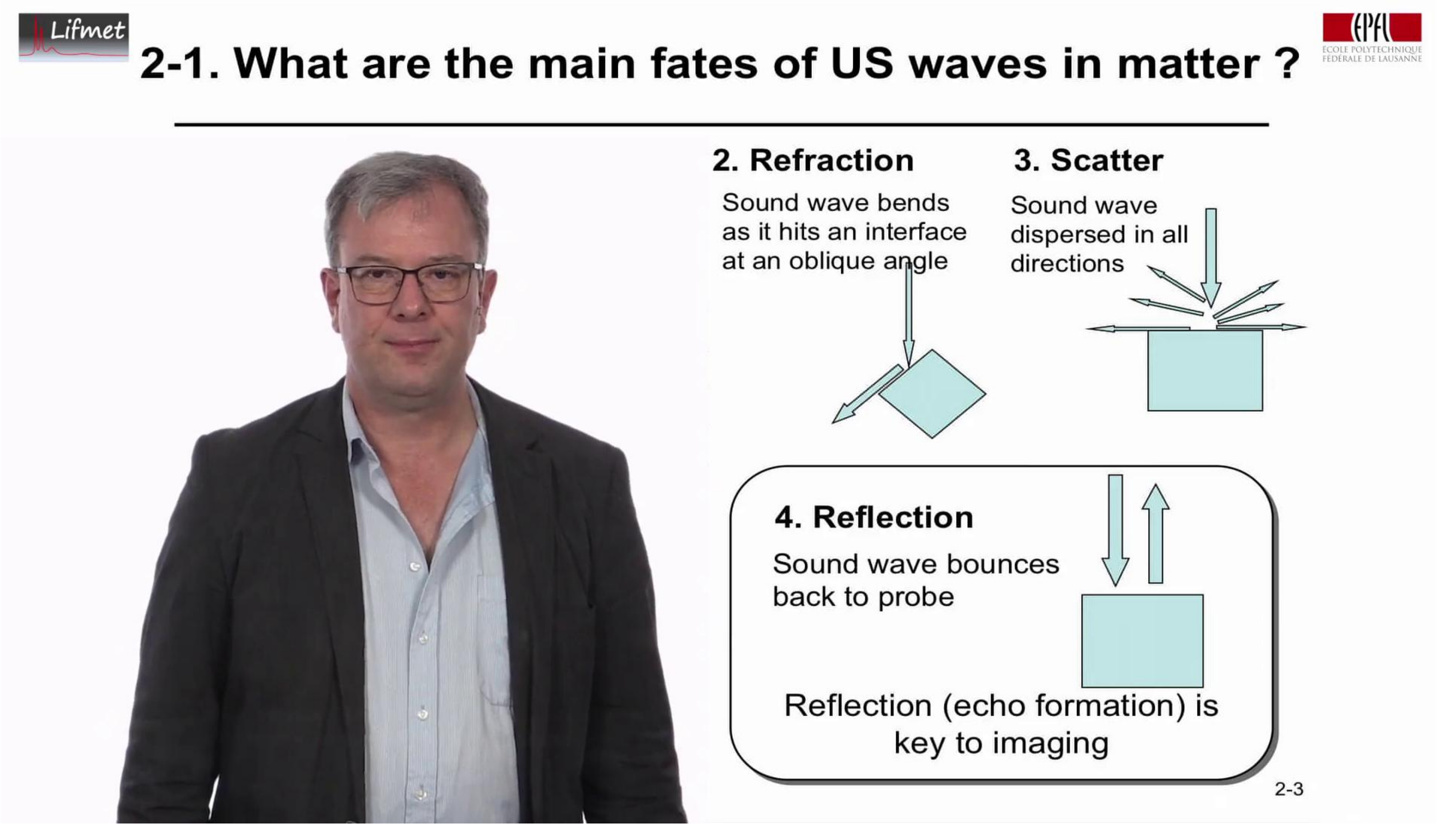


The second example I want to talk about is refraction. And what is refraction, refraction is we have an oblique surface, the sound wave arrives at the surface and is deflected; that is refraction. We are not going to discuss it in this course in much detail, but for completeness sake this is a second fate of ultrasound waves. Then, we have scatter, and in scatter, we have the object here. The wave arrives on the object, and then is dispersed into all sorts of directions. Scatter is a source of noise; we are also not going to quantitatively address the effect of scatter, this one is also mentioned here for completeness sake. Then we have reflection, and reflection is basically, what you see when you are in a tunnel or next to a mountain, to a wall, and you holler at it; you hear the sound coming back, you get an echo. It's what we use here in Switzerland in the mountains when we hear thunder. We want to determine if the lightning, the thunderstorm is close that we have to take shelter, and typically, we count to three; for every three seconds of delay between the sound of the thunder and the lightning that gives us the distance so that's the generation travel of sound.

Notes

Summary

6m 21s

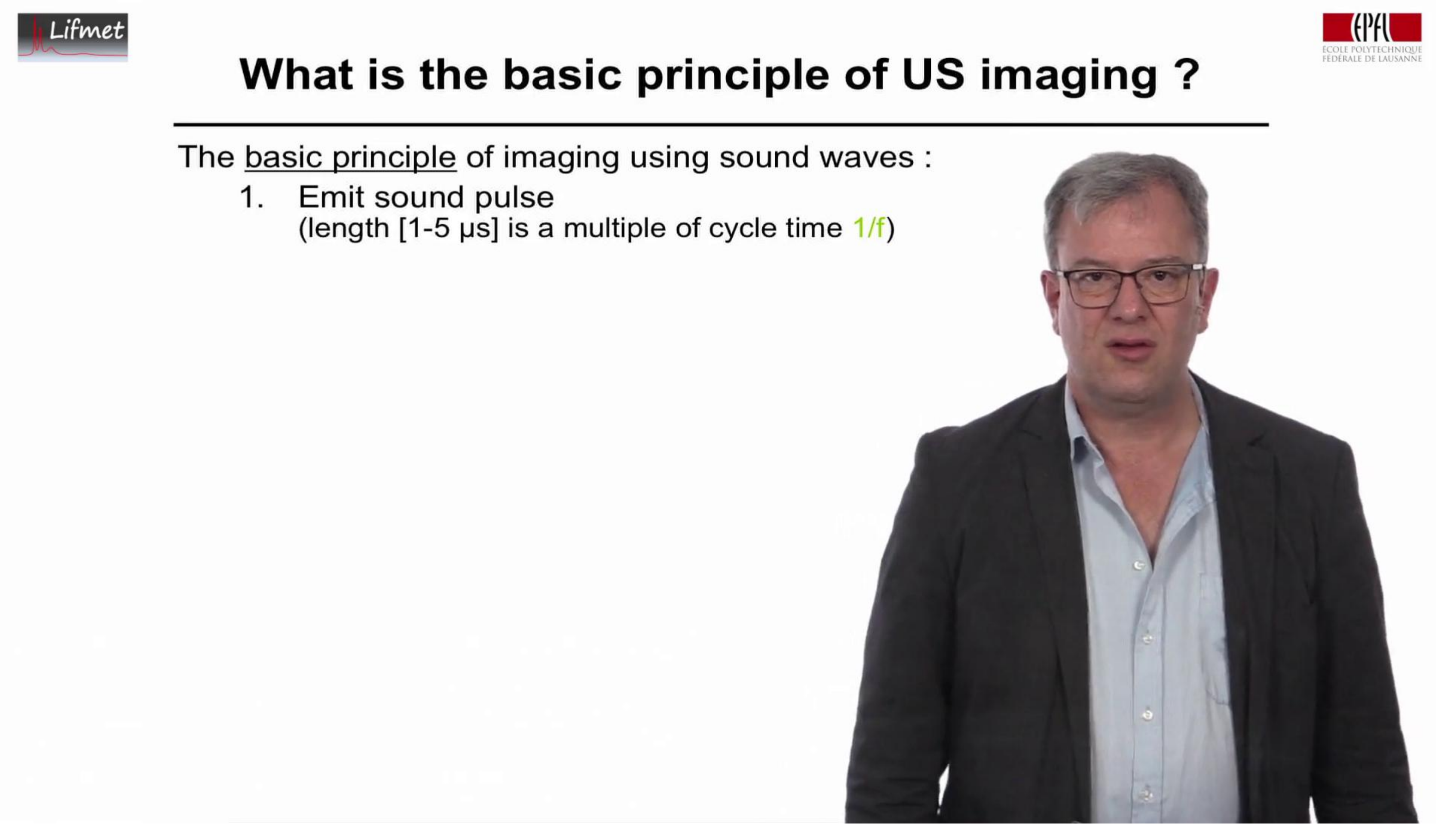


Now here's a bit different when we're looking at reflection, so we're looking at emitting a sound wave, it bounces off at an object, it comes back to us from the time that we emit the sound wave, that we hollered at the wall to the time that we hear ourselves, hear the echo, we can calculate from that the distance of the object. So that's the reflection of sound waves. And now this is a reflection, is actually a key element to imaging with ultrasound, it is *the* element that we exploit to generate, to image tissue with ultrasound.

Notes

Summary

7m 55s



So what is the basic principle of ultrasound imaging? I already alluded to it, it has a lot to do with echo formation, and so we will take here the basics in principle in very simple terms. First, you have to emit the sound wave. Typically, the sound wave or the pulse is emitted in a short time. It's typically 1 to 5 microseconds. Ideally, and as we will see later, we would like to have an infinitely shorter sound pulse, but here we have the requirement that the sound pulse has a duration that is a multiple of cycle time. Now, why is that so? Well, we want to have a defined ultra sound frequencies so we have to give the ultrasound wave as it is being emitted, the pulse, we have to go through several cycles so that in the packet there is essentially, just that frequency we've presented as you might remember from the Fourier transformation, if we take a signal that's infinitely short, the Dirac Delta, then the spectrum that is representing, the frequencies that are in there are all over and they are white spectrum, so we don't have a defined frequency and that is not what is desired. So we do have a limit on the pulse length that has to do with the cycle time that is with the inverse of the ultra sound frequency.

Notes

Summary

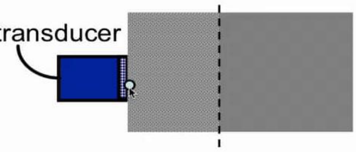
8m 35s

What is the basic principle of US imaging ?

The basic principle of imaging using sound waves :

1. Emit sound pulse
   (length [1-5 μs] is a multiple of cycle time 1/f)
2. Measure time and intensity of echo
3. Reconstruct using known wave propagation velocity c

Ultrasound: frequency f=1-20MHz
(not 20kHz)



2-4

Now here, and typically, for ultrasound imaging, the frequencies are in the megahertz range, typically, 1.20 megahertz so it's not 20 kilohertz which is what for example bats use, what we typically refer to in an everyday use as ultrasound. The frequencies that are used for ultrasound imaging are much higher than that, so they are in the range of megahertz. Then the second, once the sample is submitted, the echo comes back and in the detector, in the scan head, we measure the time between the emission of the pulse and the return, the time of travel, as well as the intensity of the echo that is registered. and finally, the distance is then calculated of the echo generating object using the known wave propagation velocity *C* and from the time. so this could calculate a distance. I'll give you an example here: we have an object, this object has a boundary here that generates an echo, here, this is the boundary; we'll now attached to it the transducer, and we will now emit a sound wave so the sound wave it is indicated here by this square object. We'll just indicate with that the sound wave of the pulse as it travels through the tissue so it travels to that issue, and we'll assume here it's perfectly bouncing back that is we only consider that part of the sound wave that is being reflected.

Notes

Summary

9m 59s

What is the basic principle of US imaging ?

The basic principle of imaging using sound waves :

1. Emit sound pulse
   (length [1-5 μs] is a multiple of cycle time 1/f)
2. Measure time and intensity of echo
3. Reconstruct using known wave propagation velocity c

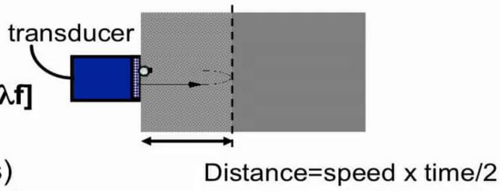
Distance of tissue boundary from probe (transducer)

Ultrasound: frequency f=1-20MHz
(not 20kHz)

Sound wave propagation velocity c [c=λf]

~330m/s (air) = 0.33 mm/μs

~1.45-1.6 mm/μs (tissue) ⇒ (1cm~7μs)
(increases with density ρ, bone ~ 4 mm/μs)



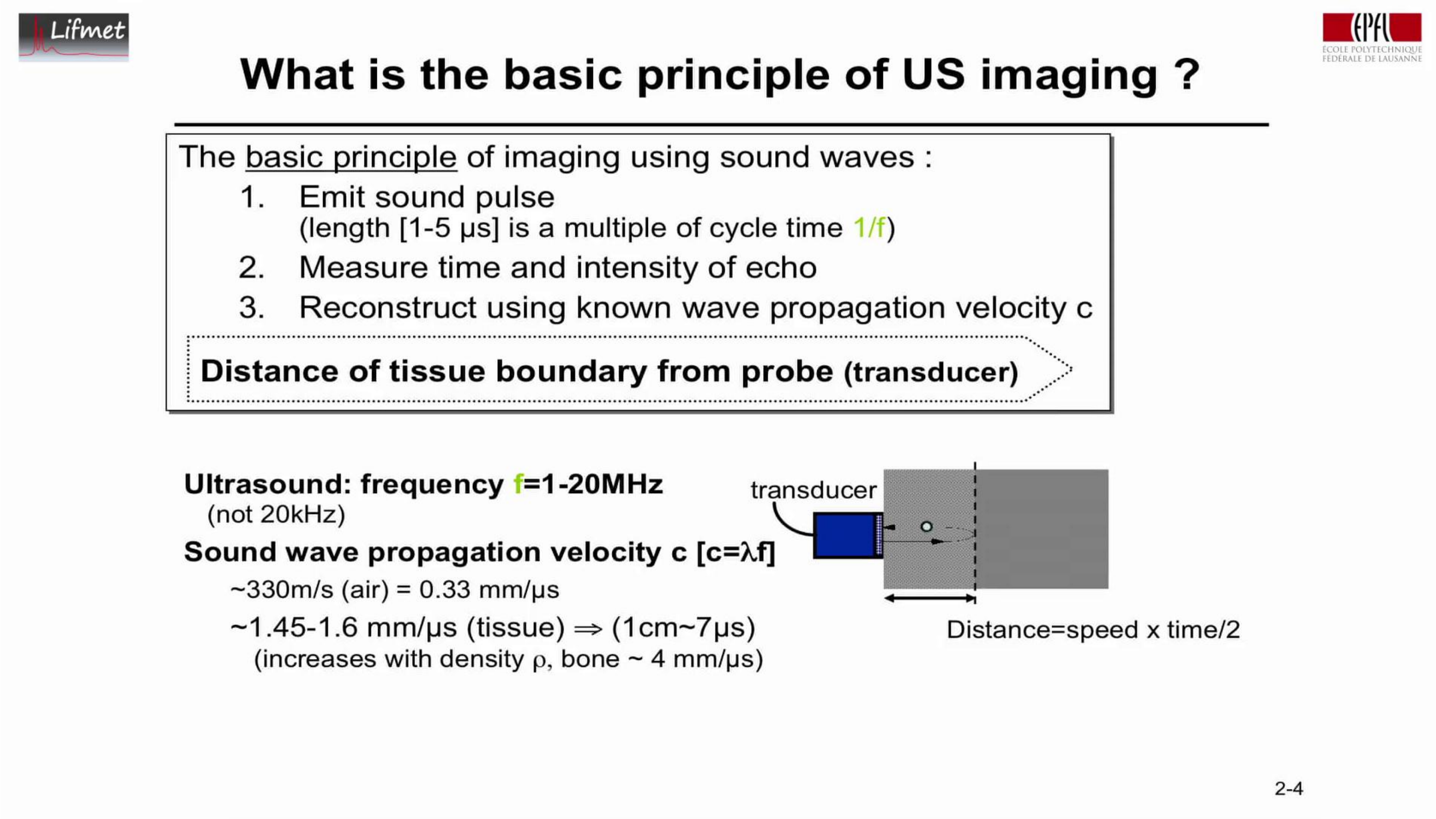
2-4

So now, we will get from the known wave propagation velocity, we are getting a calculation of the distance of the tissue boundary. It's this object here, this distance we can calculate: we have the time between the emission of the pulse and detection of the pulse, we have the sound propagation velocity, and that allows us to calculate this distance. This distance is given by the speed of sound times the time that we have measured with the probe head, divided by two. Why would it be divided by two? Well, we have to take into account that the sound wave once traveled from the scan head to that issue boundary that is from here to here, and then back, so travels twice the distance. What is the sound propagation velocity in tissues or in general? It's we have their value equations so the sound propagation velocity is equals to that wave times the frequency In air, it is 330 meters per second, and I've already given you the example, this is what we use in the mountains to determine how far the lightning is from us and whether we need shelter, so this corresponds to, as an idea, what we have in air, is 0,33 millimeters per microsecond. Now in tissue we have the sound propagation velocity which is about five times longer.

Notes

Summary

11m 39s



Here are the values, so it's five times faster I mean, so this means that a sound wave travels about one centimeter in seven microseconds. In general the cells propagation, velocity increases with the density of the tissue and in bone it's about three times as fast so it's four millimeters per micro second so I will mean it would take about two microseconds to travel one centimeter in bone.

Notes

Summary

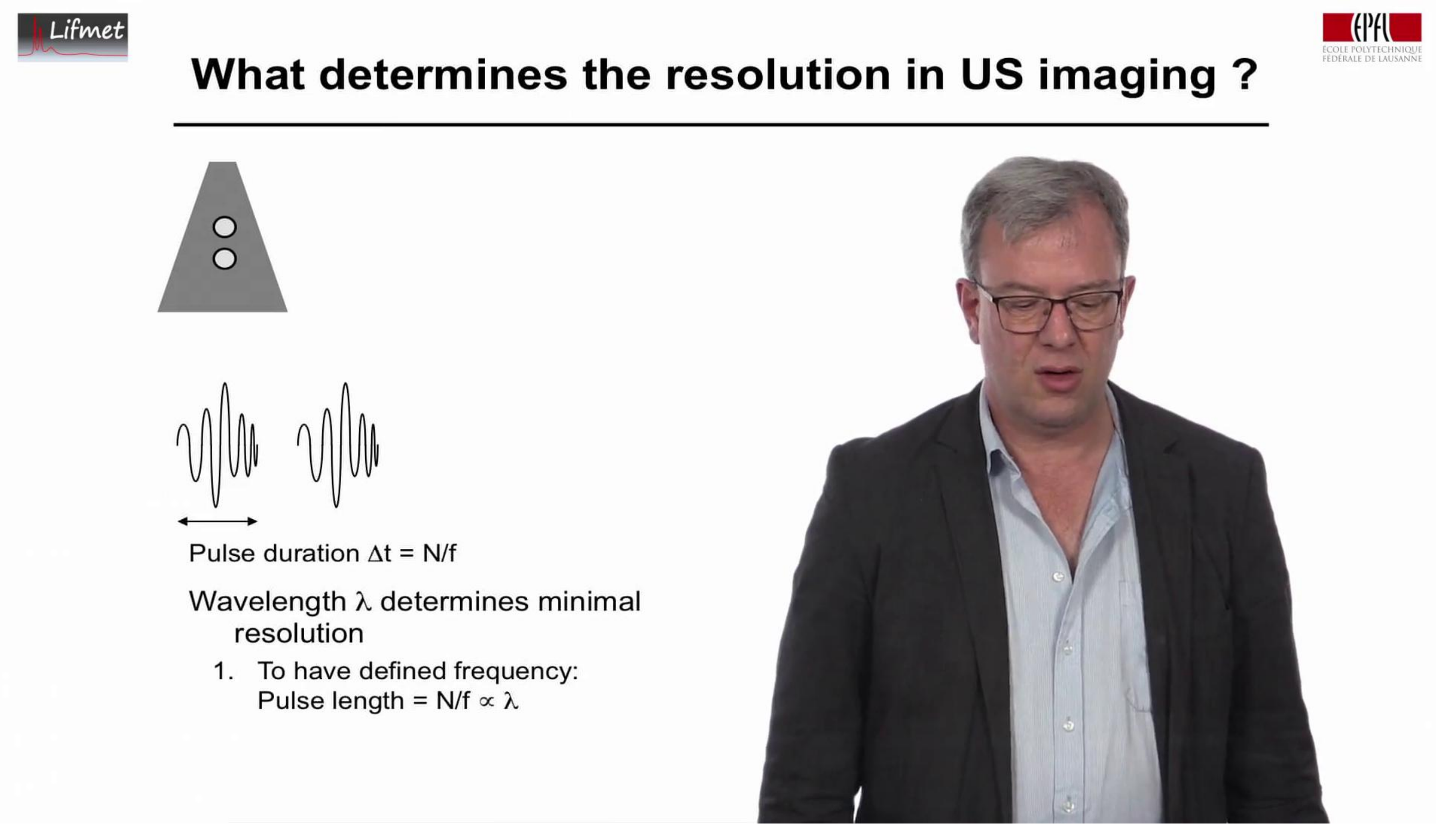
13m 02s

We have talked about the principle of determining a distance between a tissue boundary and the transducer, so now let's assume, we have two tissue boundaries close to each other and here, the question is can we distinguish those two tissue boundaries as being separate? In other words, how is the resolution in ultrasound imaging determined? And it's in essence this is much related to the wavelength lambda of the ultrasound wave that we are using here it is to determine the minimal resolution. I'll show here: the scan head is up here, and this is what they feel they feel that in ultrasound the typical pyramidal view that the sound waves will travel through, and we'll put an object, an square object here, at this position. So, what the transducer sees is after a certain time corresponding to this distance here. It sees-- here on the horizontal time -- it sees this echo being generated. So we have said that the pulse duration has to be a multiple of the cycle time of the frequency, so it is equal to *n* divided by the frequency. This is the requirement that we have a well-defined frequency in the pulse, so the pulse duration cannot be infinitely short.

Notes

Summary

13m 37s

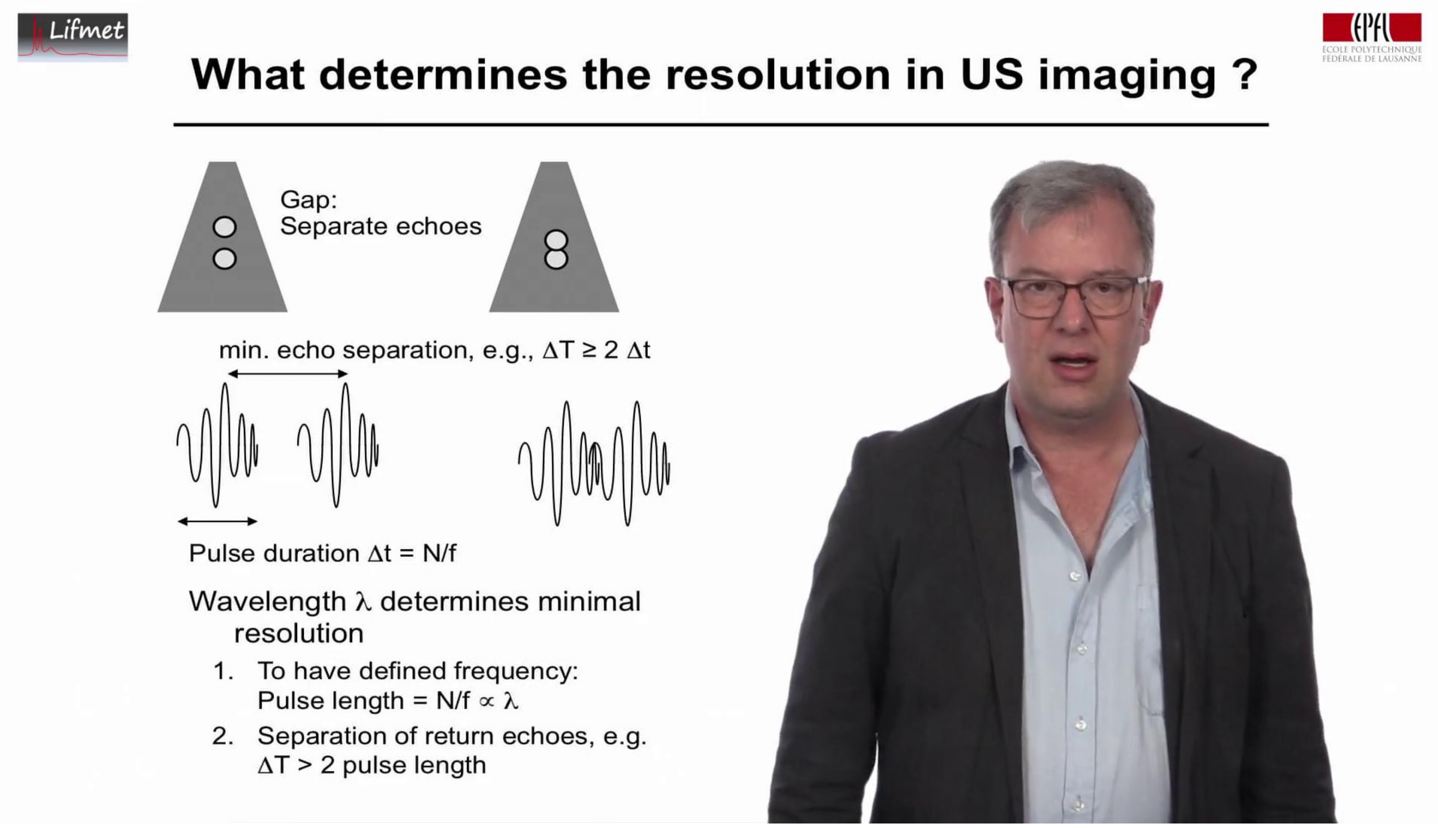


It doesn't matter here for the sake of the argument how big this *n* is. We can say it's any natural number that is sufficiently long that we can say, "Yes, we have a single frequency in this pulse that is being represented. So to have a defined frequency, we have this relationship that the pulse length is a multiple of the period of the ultrasound wave, and from the wave equation we are getting that the pulse length has to be proportional to the wavelength of the ultrasound wave. I'll introduce here a second object; this is here, which is adjacent to the first object; we will assume that this is such that we will see this packet, the echo-generated from the second echo is at this point. I guess we are not arguing here that for a computer, these two echoes, that you see here, that are suggested sequentially here, that these two echoes are easily distinguishable by computerized means. We can see them that they are two distinct echoes, we can define them, so this means that we can calculate two separate distances from these two echoes. So we have a gap between the echoes, this generates separate codes, and this allows us to distinguish the two objects.

Notes

Summary

15m 00s

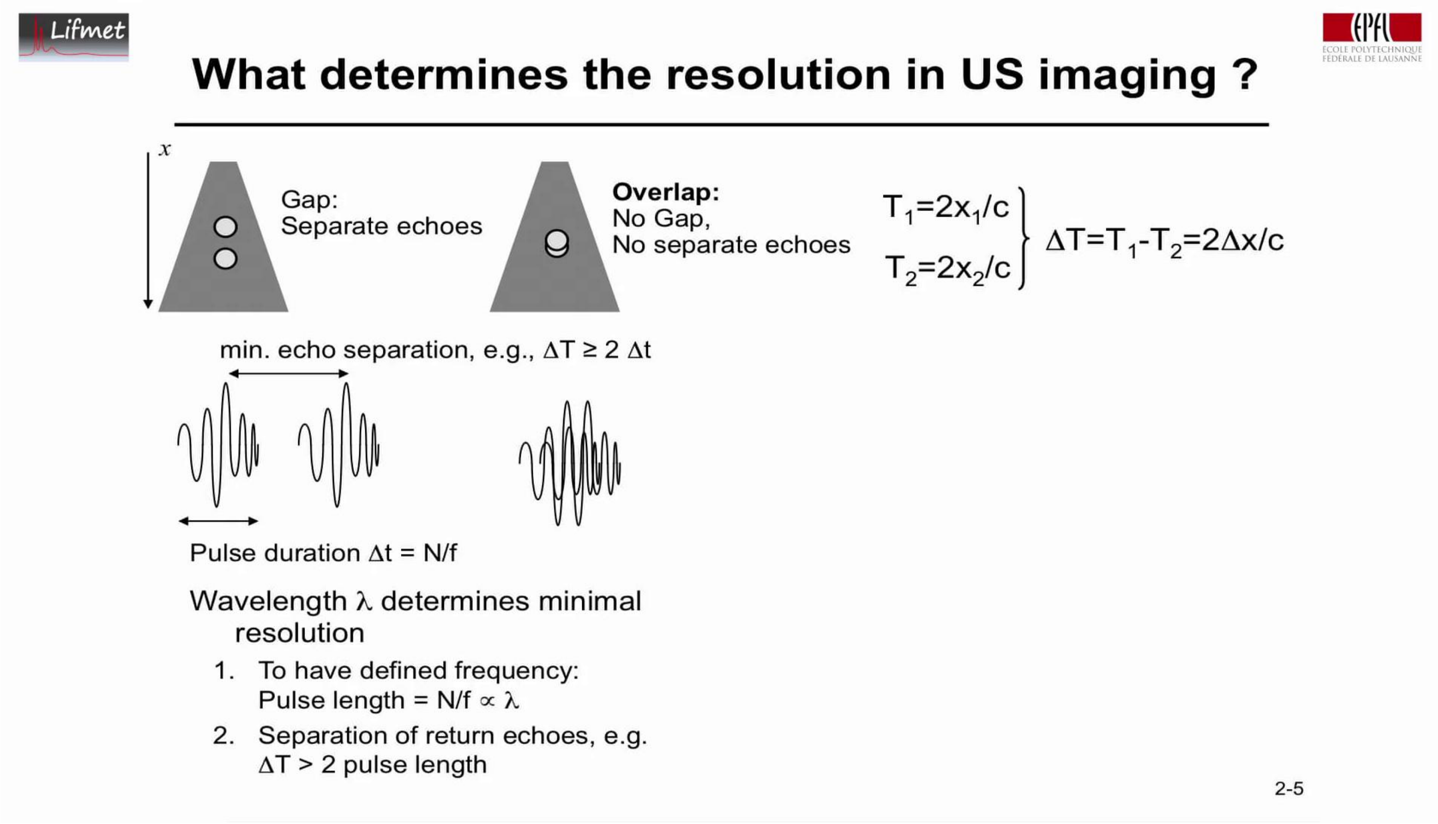


So this also means because the pulse duration is defined by the wavelength and the echo separation here, the *ΔT* has to be some function of the duration of the pulse. And here, I'll give you a very qualitative idea-- this is not a strict rule here but will say, "OK, to have a minimal echo separation for the computer to be able to say, "Yes, I've got two separate echoes"-- will say that requirement here is that the minimal echo separation that we can have is twice the duration of the echo of the ultrasound pulse that's being sent. So this is the resolution, and is defined by the separation of the returned calls, and we have introduced here the arbitrary criterion that the returned echoes should be separated by twice the pulse length. So now let's look at the same situation: I have again the object here at some place, here is the echo that it generates, again in time. So the horizontal time you see again here: we have the echo from the first object that is here, and now the second object will produce an echo that's closed to the first object because it is closer in space, so they are not as well separated. Now look at what is happening if we pretend that the second object is increasingly closer to the first one.

Notes

Summary

16m 24s

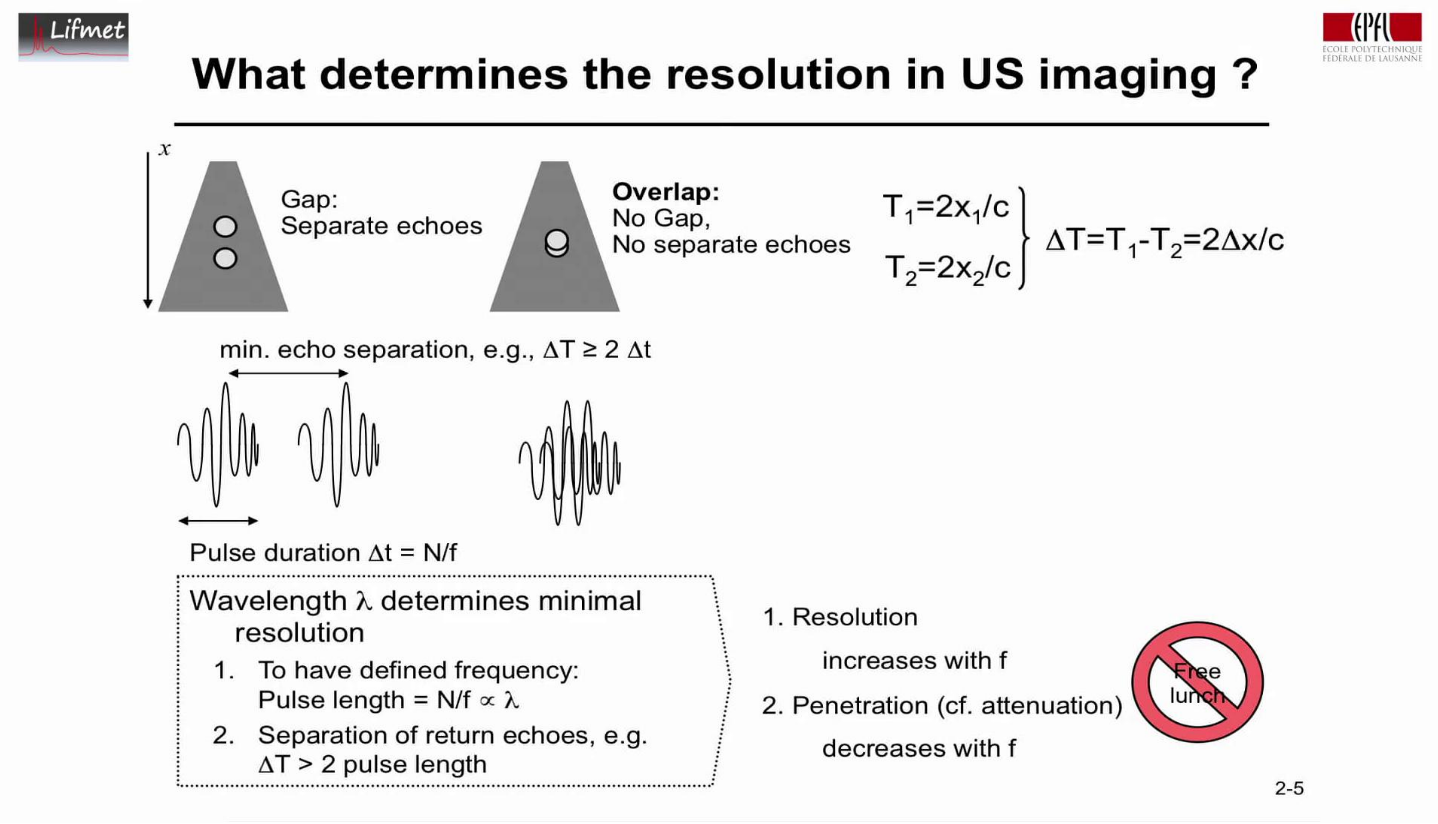


We will do this by animation, and we'll see the echo is moving closer. Now we have two objects that are very close to each other and in the bottom here can we actually say that these are two different echoes? Can the computer distinguish these ones as two separate echoes? And at some point, the computer will not be able to say, "Well I've got two echoes, or I get a single echo which is dispersed in time. It cannot actually attribute to the measurement a very well defined echo time, and therefore, at this point, we won't be able to say, we've got two objects separated as here. So there is no gap between the echoes, we have no gap between the objects, we have no separate echoes; and when you have no separate echoes, we cannot distinguish between the two objects. So we'll look at the time for the first object here: *T1* is equal to two times the distance divided by this distance *x*, divided by the speed of sound; and for the second object it's *T2*; is twice the distance divided by the speed of sound, and this gives us now the difference in echo time. This is *T1-T2*, and that gives us two times the distance between the objects *Δx* so *Δx* being the distance between this object and this object divided by speed of sound.

Notes

Summary

17m 59s

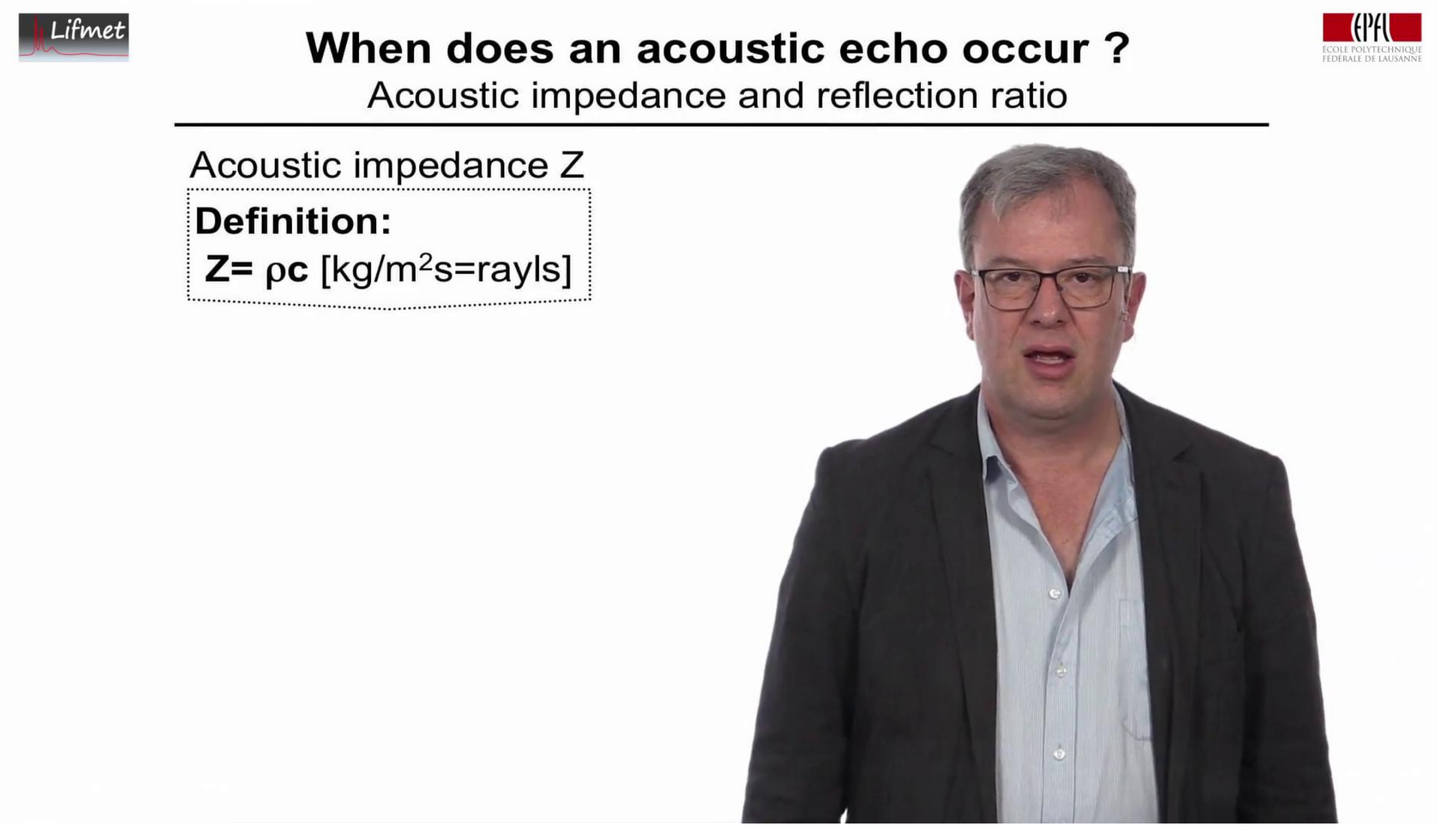


And now, we can conclude, since the distance here, the time here is linked to the wavelength that is the inverse frequency-- this is the time, the separation of two objects minimal separation *Δx* given by that. So in conclusion, because the separation of objects is linked to the separation of the echoes in time, which is linked to the cycle time of the ultra sound frequency being used which is one over the frequency, we can say that the resolution increases with frequency, that is the Δx* diminishes with frequency, therefore, the resolution increases with frequency of the ultrasound. However, as we have seen earlier in this segment, the penetration that is the attenuation of ultrasound waves decreases with the frequency-- we've had the exponential law with the attenuation coefficient alpha. So, if we want to have good resolution, we want to increase the frequency, but if you want to have good penetration, we want to decrease the frequency and so the consequence is that also here this is a very practical example that there is in biomedical imaging really no free lunch; we are caught between the need to increase the resolution which calls for higher frequency, and the need to have higher sensitivity with the tissue depth which calls for a reduction in frequency, and those two requirements are opposing each other.

Notes

Summary

19m 27s



We've pretended it has been an acoustic echo recorded, and the question is when does an acoustic echo occur? And here I'll introduce briefly the background of it, we won't go into the theory of acoustic impedance too much, and what it means for the reflection intensity. Acoustic impedance is defined as the density of the tissue times the sound of the velocity. It has the units of kilograms per meter squared per second, or have introduced a new unit for that, they call it *rayls*. Here are some ideas of the acoustic impedance, so this is a measure of the mechanical properties of the tissue: we have air here which has a very low acoustic impedance and we have skull bone for example which has a very high acoustic impedance, and you'll notice between fat, water, kidney, blood, liver, and muscle, the acoustic impedance is actually fairly similar --the lung is much lower-- but for the all the soft tissues that we have, the acoustic impedance are different, but they are very similar compared to the other cases.

Notes

Summary

21m 15s

When does an acoustic echo occur ?

Acoustic impedance and reflection ratio

Acoustic impedance Z

Definition:

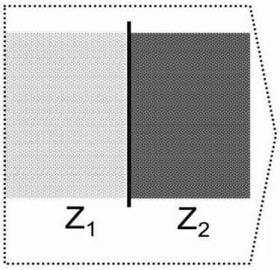
Z= ρc [kg/m^{2}s=rayls]

Tissue	Z (rayls)
Air	0.0004×10^6
Lung	0.18×10^6
Fat	1.34×10^6
Water	1.48×10^6
Kidney	1.63×10^6
Blood	1.65×10^6
Liver	1.65×10^6
Muscle	1.71×10^6
Skull bone	7.8×10^6

Amount of reflected wave energy

$I_{ref}=I_0R_I$

At interface between objects with different acoustical properties



Reflection coefficient

$$R_I = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2$$

2-6

Now, the amount of reflected wave energy that we have-- this is the intensity I reflected-- is equal to the original intensity, the incident intensity, times the reflection coefficient *R_i* And this reflection happens when you have different acoustical properties that is when you have a discontinuity in acoustic impedance, so two different tissues with different acoustic impedance at their interface apart of the sound wave will be bouncing back, will be reflected. So we have here as to illustrate the case, we have a tissue one with an acoustic impedance *Z_1*, we have here issue 2 with an acoustic impedance *Z_2*, and here's the tissue boundary between the two tissues. And now we can calculate from the acoustic impedance, we can calculate the reflection coefficient *R_i*, and this is essentially given by the difference in acoustic impedance divided by the sum of the acoustic impedance and the whole thing squared. This is what this formula here says, so the acoustic impedance between for example air and fat is, because one of the acoustic impedance is 0, is essentially one. We have *Z_2* equal to 0, so we have *Z_1* squared divided by *Z_1* squared, and this gives us a full reflection between the fat issue that is skin, and the air.

Notes

Summary

22m 26s

When does an acoustic echo occur ?

Acoustic impedance and reflection ratio

Acoustic impedance Z

Definition:

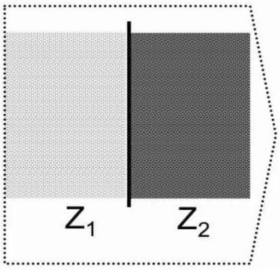
Z= ρ**c** [kg/m²s=rayls]

Tissue	Z (rayls)
Air	0.0004×10^6
Lung	0.18×10^6
Fat	1.34×10^6
Water	1.48×10^6
Kidney	1.63×10^6
Blood	1.65×10^6
Liver	1.65×10^6
Muscle	1.71×10^6
Skull bone	7.8×10^6

Amount of reflected wave energy

$I_{ref}=I_0 R_I$

At interface between objects with different acoustical properties



Reflection coefficient

$$R_I = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2$$

Probability of reflection + transmission is = 1:

Transmission $T_I = 1 - R_I$

$$= \frac{4Z_1Z_2}{(Z_1+Z_2)^2}$$

2-6

Since the probability of reflection transmission is assumed to be one, we can calculate from the reflection coefficient-- with that relationship-- we can calculate the transmission, so the transmission is equal to 1 minus the reflection; So reflection plus transmission equals to 1, and then we can calculate this out by putting the equation of the reflection coefficient into this equation here, and we get the transmission coefficient. I'll just show this for completeness sake, we're not going to make much use of this.

Notes

Summary

24m 01s

Lifmet

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What are the reflection coefficients R_l between tissues ?

R_l	Fat	Muscle	Skin	Brain	Liver	Blood	Cranial bone	Plexi-glass
Water	0.047	0.02	0.029	0.007	0.035	0.007		
Fat		0.067	0.076	0.054	0.049	0.047		
Muscle			0.009	0.013	0.015	0.02		
Skin				0.022	0.006	0.029		
Brain					0.028	0.00		
Liver						0.028		
Blood								
Cranial bone								

2-7

So now let's discuss some reflection coefficients between some tissues; to give us an idea what this means, we now have been very theoretical linking acoustic impedance to reflection coefficient, but what does this mean in practice? So, we'll have here now on this matrix display: we have, on one side, we have the different tissues here, and we will look if the interfaces between fat and water what is the reflection coefficient. Here, the reflection coefficient is 0.47; is basically means that 5% of the wave energy bounces back as an echo if it hits a interface between fat and water. Between muscle and water, we have 2% that bounces back, between muscle and fat it's 7%-- surrounding it off here-- then if you look at skin, we have the skin and water, skin and fat, and skin and muscle; this ranges from 1% to roughly 8%. Before looking at brain, liver, and blood, I'll just give you more instead of going to read through them. Look at these values: and you see that they are all on the order of a few percent, so this means, if we send out a sound pulse, the echo, the energy that comes back from the echo is a signal that is on the order of a few percent of the emitted sound pulse energy, so it is a relatively weak signal.

Notes

Summary

24m 33s

What are the reflection coefficients R_I between tissues ?

R_I	Fat	Muscle	Skin	Brain	Liver	Blood	Cranial bone	Plexi-glass
Water	0.047	0.02	0.029	0.007	0.035	0.007	0.57	0.35
Fat		0.067	0.076	0.054	0.049	0.047	0.61	0.39
Muscle			0.009	0.013	0.015	0.02	0.56	0.33
Skin				0.022	0.006	0.029	0.56	0.32
Brain					0.028	0.00	0.57	0.34
Liver						0.028	0.55	0.32
Blood							0.57	0.35
Cranial bone								0.29

Reflection by solid material

e.g. bone-tissue interface

⇒ Shadow formation: ~45% of energy transmitted

2-7

We'll take the next example that's cranial bone, and now the situation is different. Now we're having quite a substantial reflection of the sound waves; is actually on the order of 55% of the instant energy that comes back as an echo. And this is a perfect reason why we cannot image for example we cannot easily use ultrasound image our brains. Here's another material, Plexi glass that has a high reflection coefficient. So I want to now discuss the effect of bone; like I said,we cannot in adults use ultrasound very easily to do scanning of the brain. in newborns is different because we have at the top of the head the faux opening in newborns, and so this is a place where sound waves can easily pass through because the bone is either not present or very thin. So now we have to deal with about 55% of the bone that reflects the tissue and there is a consequence and that is a shadow formation that is in cranial bone, behind the cranial bone, we have only 45% of the energy that passes through the bone, and I want to discuss that.

Notes

Summary

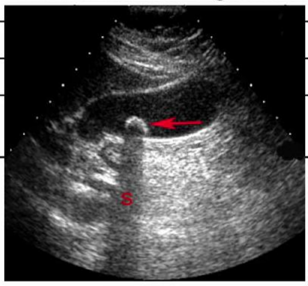
26m 07s

Lifmet

What are the reflection coefficients R_I between tissues ?

R_I	Fat	Muscle	Skin	Brain	Liver	Blood	Cranial bone	Plexi-glass
Water	0.047	0.02	0.029	0.007	0.035	0.007	0.57	0.35
Fat		0.067	0.076	0.054	0.049	0.047	0.61	0.39
Muscle			0.009	0.013	0.015	0.02	0.56	0.33
Skin				0.022	0.006	0.029	0.56	0.32
Brain					0.028	0.00	0.57	0.34
Liver						0.028	0.55	0.32
Blood							0.57	0.35
Cranial bone								0.29

US shadow due to gallstone



Reflection by solid material

e.g. bone-tissue interface

⇒ Shadow formation: ~45% of energy transmitted

2-7

First, the example: here is a gallstone-- there's an ultrasound here-- here's a gallstone, and you can see that there is this shadow formation. This is an artifact because we have solid material that is reflecting just like the bone a large fraction of the sound wave back to the transducer. This energy that is reflected of course is missing behind the gallstone, so there is less wave energy that continues beyond that. I want to illustrate this with an abstract example here, so we'll take the case of the bone so we have 45% of the energy is transmitted; as a reminder, the transmission is 1 minus the reflection, so we have the reflection coefficient here, we'll say this is our bone interface here, Here's the tissue interface that we'd like to image but we're passing through bone, so let's say we come with 100% wave energy, then the 55% of reflection implies that there is a 45% of the energy that's transmitted, so only 45% of the wave energy gets to this interface; We'll assume that the reflection is perfect so then we are just looking at what is reflected; the 45% bounce back, and then they are losing again 55% of the energy when they come to the bone, so in the end, it's only 45% of 45% that is received at the scan head, or in other words, 20%.

Notes

Summary

27m 22s

Lifmet

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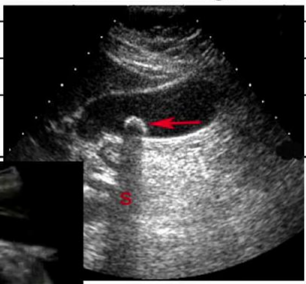
Blood							0.57	0.35
Cranial bone								0.29

US shadow due to gallstone

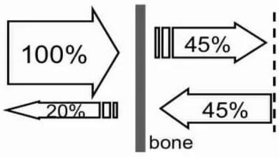


Dolphin fetus

Reflection by solid material

e.g. bone-tissue interface

⇒ Shadow formation: ~45% of energy transmitted



$(T_I=1-R_I)$

2-7

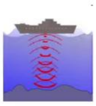
And this explains in this image here why we have the shadow here, a big portion of the sound is being reflected here back to the transducer. The energy that comes back here is reduced, and then when it passes again through the gallstone it is again reduced and therefore, the echo amplitude is reduced, and that produces this shadow formation. Here's another example: can you see what those stripes are due to? Do you have an idea? When we have multiple stripes to dolphin fetus, it's the bones from the rib cage, so each one of the ribs in the dolphin fetus produces this little shadow image here as the scan head is placed above it. Obviously, we cannot control the movement neither of the dolphin very well or of the fetus, and so occasionally, you see on an image the stripes, and this is from the video I showed in week one, of the SeaWorld Aquarium, the ultrasound scan of the dolphin fetus; just an image.

Notes

Summary

28m 53s

Credits



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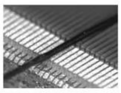
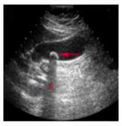
Eldis RL-2000 Radar
http://www.eldis.cz/rl-2000-primarni-prehledovy-radar

Siemens Acuson Aspen Ultrasound Machine
http://www.aspenultrasound.com

Ultrasound transducer
http://www.slideshare.net/ahmedhassan1970/u-ltrasound-physiscs



Ultrasound
https://www.med-ed.virginia.edu/courses/rad/edus/technique3.html

Notes

Summary

30m 01s