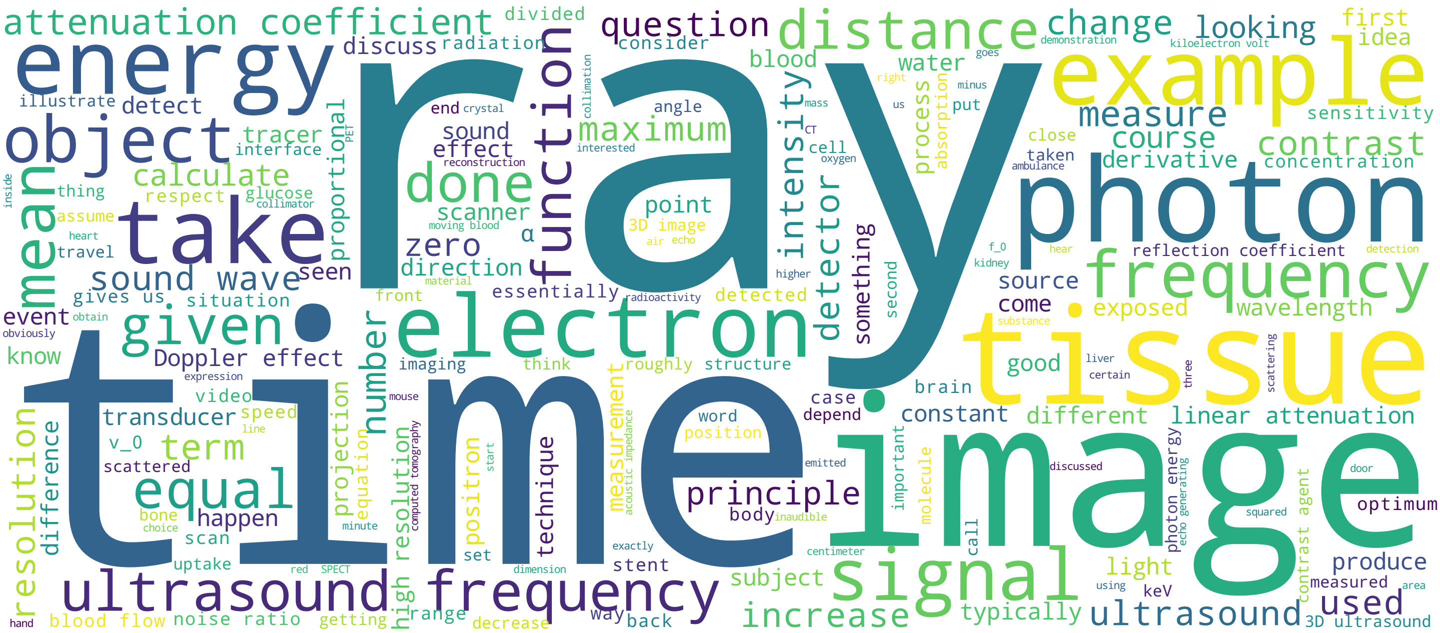
2.2 Optimizing US frequency and examples

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



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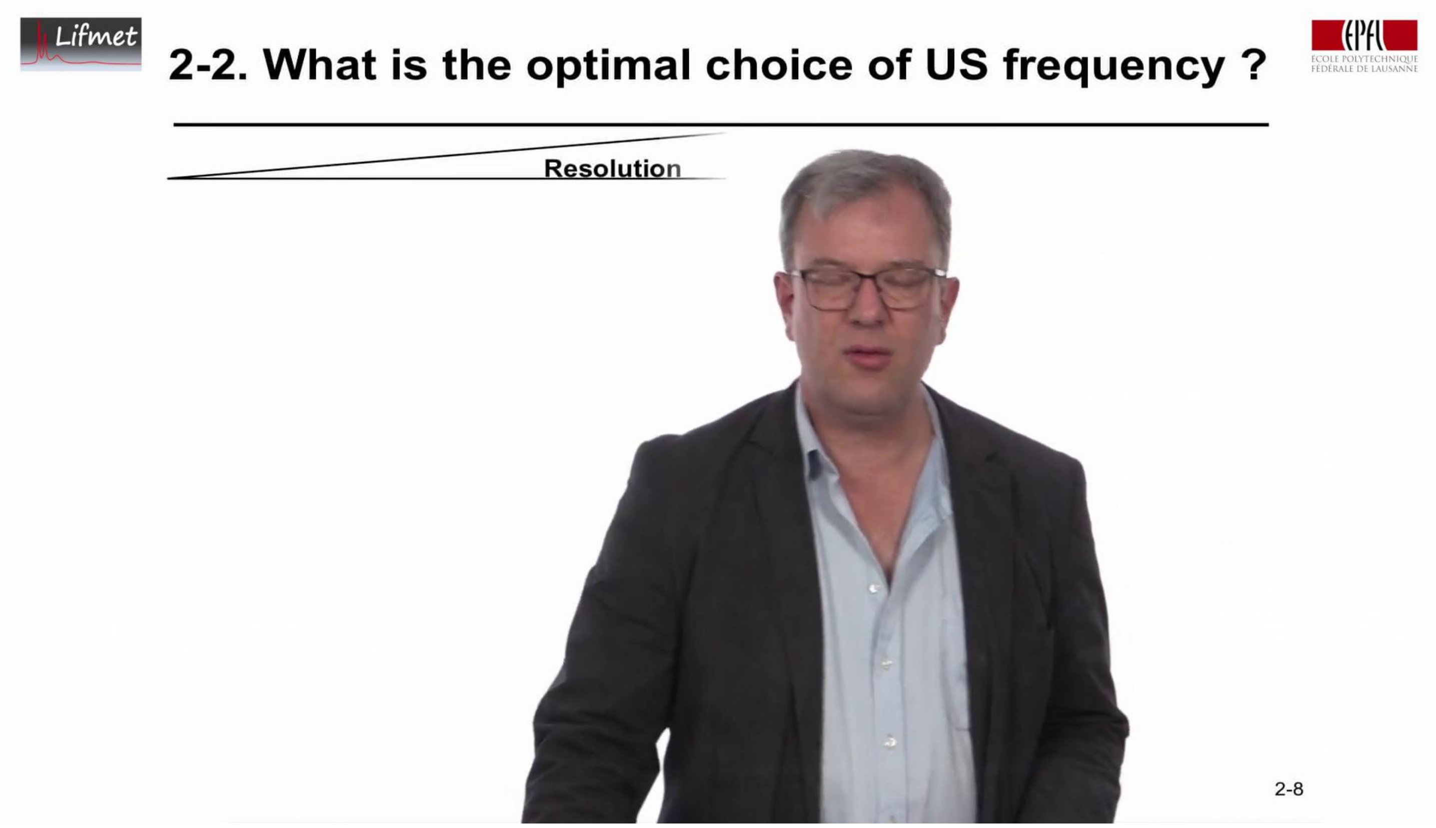
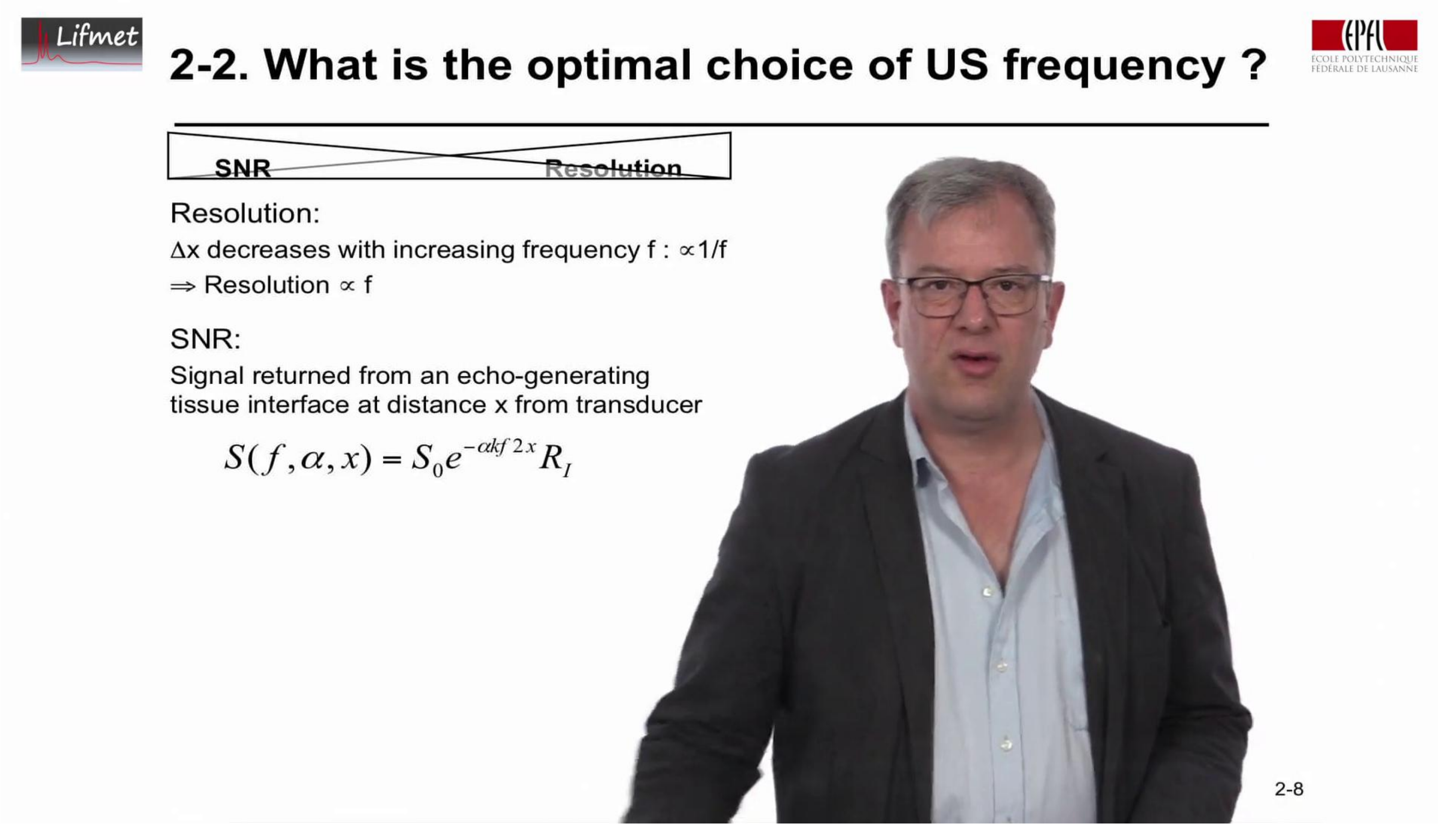


We have seen previously the principle of ultrasound imaging, we have seen that the ultrasound waves are attenuated, that the distance between the object and the transducer and the change in acoustic impedance is what is being imaged, so imaging tissue boundaries, and this imparts some limits on the resolution, and we've also discussed that resolution and the need for more sensitivity are two opposing requirements on the frequency of the transducer. So the question is obviously, we would like to have a good choice in the ultrasound frequency. If we want to see deep, we'll probably have to use a lower frequency, if we want to see close to the surface, probably a higher frequency. That seems logical, but we can actually say something more precise about the optimal choice and put this into mathematical terms. And that's the question we are going to address here, as how do we estimate the optimal choice of ultrasound frequency. So we have the principle that, as we increase the frequency, the resolution increases; but as we increase the frequency-- to the right-- the sensitivity, the intensity of the sound wave, the Signal to Noise Ratio diminishes.

Notes

Summary

0m 04s

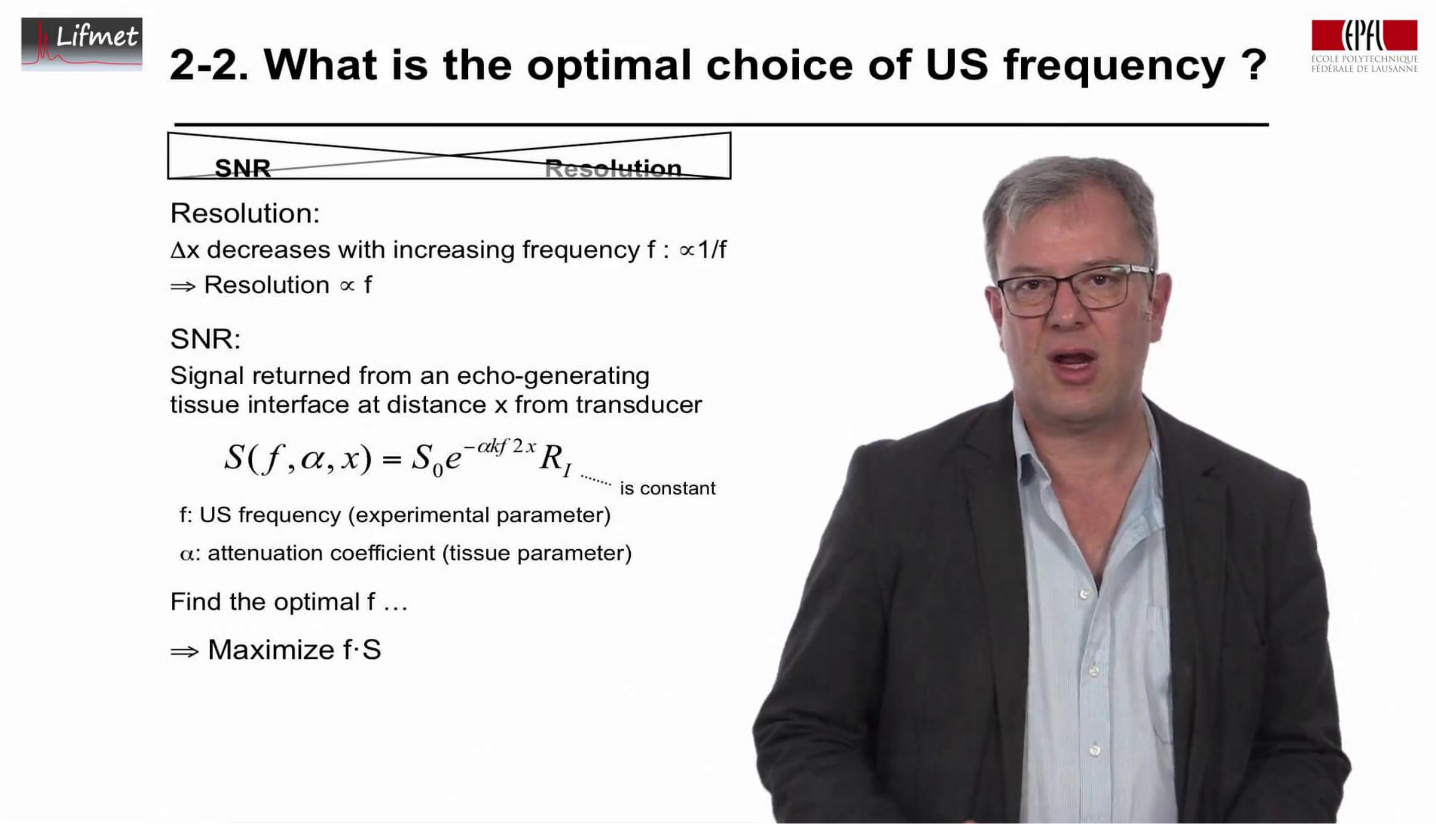


So, if you look at resolution, the Δx is between two objects at which we can discriminate them, we've seen them that this decreases with increasing frequency, so the Δx is proportional to 1 over the frequency. That means the resolution is proportional to the frequency. If you look at Signal to Noise Ratio, we have seen, from earlier, that the signal returned from an echo-generating source, echo-generating tissue interface at a certain distance x from the transducer is given by the original intensity, the attenuation coefficient that we have discussed, and we are multiplying this here by the reflection coefficient which just basically says, "OK, the signal that we see at the transducer is given by the reflection coefficient that's the percentage of ultrasound energy that's bouncing back as an echo; and here we have the factor $2x$ because we are looking at twice the distance. So, if we are at the distance x from the transducer, the attenuation happens twice, on the travel in and on the travel back, and that's why we have the factor 2 instead of x here, in the equation.

Notes

Summary

1m 25s



Now, in terms of--for the sake of the argument here, since we are interested in the choice of frequency, we'll assume the reflection coefficient is constant with respect to the ultrasound frequency. So, in this equation here, we have: f is the ultrasound frequency-- that is an experimental parameter; we choose that, by generating the ultrasound waves. α is the attenuation coefficient that's a tissue parameter-- that one we cannot change, that's given by the tissue under investigation. So now, the challenge here is to find the optimal frequency. And what I am proposing here is to simply look at maximizing the product of the frequency, and the signal. The frequency increases -- is proportional to resolution-- so is a measure of resolution, and the signal is a measure of sensitivity, so, we'll minimize here the resolution times sensitivity by maximizing f times s, so maximizing resolution times sensitivity. It is exactly this function, it's the proposed function. What I want to do here is illustrate the principle of getting an idea of what is a good ultrasound frequency for a good application, So, we want to find the maximum of f times s, and that is, we want to calculate the derivative of f times s and set this derivative to zero to find the maximum.

Notes

Summary

2m 41s

2-2. What is the optimal choice of US frequency ?

SNR Resolution

Resolution:

Δx decreases with increasing frequency f : $\propto 1/f$

$\Rightarrow$ Resolution $\propto$ f

SNR:

Signal returned from an echo-generating
tissue interface at distance x from transducer

$$S(f,\alpha,x) = S_0 e^{-\alpha k f 2x} R_I$$

is constant

f: US frequency (experimental parameter)

α: attenuation coefficient (tissue parameter)

Find the optimal f …

$\Rightarrow$ Maximize f·S

Maximum is where derivative with respect to f is zero

is constant

$$\frac{d\left(fS(f,\alpha,x)\right)}{df} = R_I S_0 \frac{d}{df} fe^{-\alpha k f 2x}$$

$$\frac{d}{df}\left(fe^{-\alpha k f 2x}\right) = 0$$

$$= e^{-\alpha k f 2x} - f\alpha k 2x e^{-\alpha k f 2x}$$

$$= e^{-\alpha k f 2x}\underbrace{\left(1 - f\alpha k 2x\right)}_{\boxed{f_0=1/(2\alpha kx)}} = 0$$

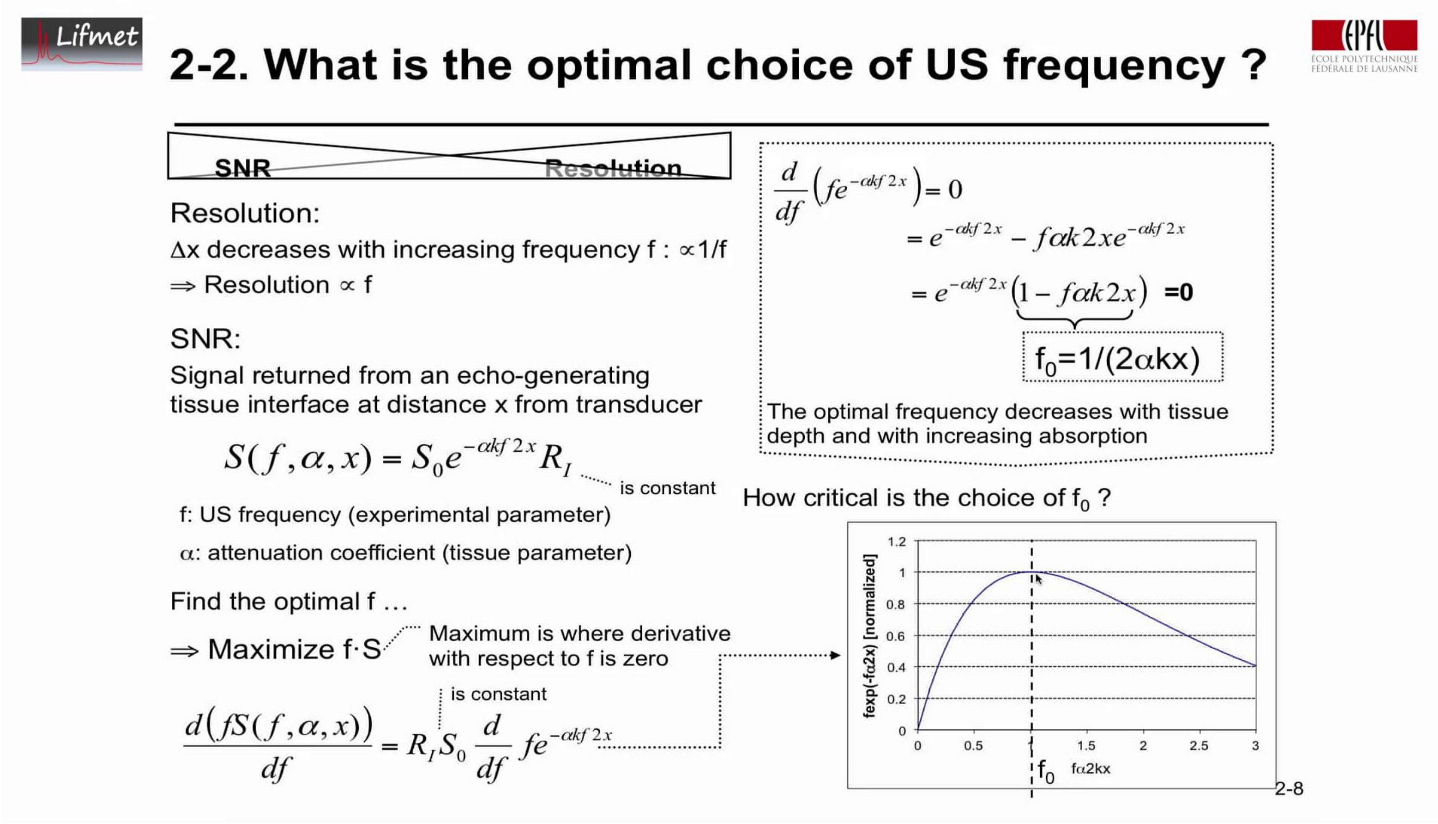
2-8

So that is, in other words, we'll take *f* times this function here, derive this with respect to *f*, take the derivative with respect to *f*-- which is here; we've taken out what is constant-- the reflection coefficient is [inaudible] to not depend on the frequency. The original signal intensity is also constant, and now we have to find the derivative of this function and set this to zero. So these are the constants moved out, and now, we are going to look and be interested in calculating the derivative of this and setting this to zero. So, we have the chain rule here; that it supplies then the two rules of derivation. We separate out, multiply out the exponent factor and now we got the thing in the parenthesis here. Exponent is never zero, so we are interested in finding out when this is zero, and this happens to be if the ultrasound frequency equals to *f_0*, which equals to *1 / (2 α k x)*. Remember, *k* is the conversion factor between decimals and physical units. So, what does this mean? Well, what it basically means is with increasing absorption-- that is with increasing *α*-- the optimal frequency decreases, it's *1 / α*; it also decreases with distance.

Notes

Summary

4m 15s



So, if a distance x is long, that the sound wave has to travel; x increases, then the frequency has to decrease too if we want to stay at the optimal frequency. So, how optimal is this choice of *f_0*? We can, of course, say, "Well, we want to measure at different depths. We are not just limited to one depth." Here we're saying, mathematically, that's just one optimum. We might have also different intonation coefficients for different tissues, so this gives us a spread of optimal choices of frequency, and the question is how critical is this choice. Are we really bound to an exact formula, exact equation, like this one here, or can we be a bit more subtle about it? So, what we are doing now here is we are plotting exactly this function here, normalized to *1* at the maximum, here, and we are plotting on the *x* axis, *f* times *α 2 k. x* --this is just making-- this is the argument of the exponent here; this is dimensionless, and the optimum here is at when *f_0 = 1 / α 2 k x*, so that is written this term here, and equals to *1*. So that is the optimal here.

Notes

Summary

5m 37s

2-2. What is the optimal choice of US frequency ?

$\cancel{\text{SNR} \quad \text{Resolution}}$

Resolution:

Δx decreases with increasing frequency f : $\propto 1/f$

$\Rightarrow$ Resolution $\propto$ f

SNR:

Signal returned from an echo-generating tissue interface at distance x from transducer

$$S(f,\alpha,x) = S_0 e^{-\alpha k f 2x} R_I$$

R_I is constant

f: US frequency (experimental parameter)

α: attenuation coefficient (tissue parameter)

Find the optimal f …

$\Rightarrow$ Maximize $f \cdot S$ — Maximum is where derivative with respect to f is zero

$$\frac{d\left(fS(f,\alpha,x)\right)}{df} = R_I S_0 \frac{d}{df} fe^{-\alpha k f 2x}$$

$R_I S_0$ is constant

$$\frac{d}{df}\left(fe^{-\alpha k f 2x}\right) = 0$$

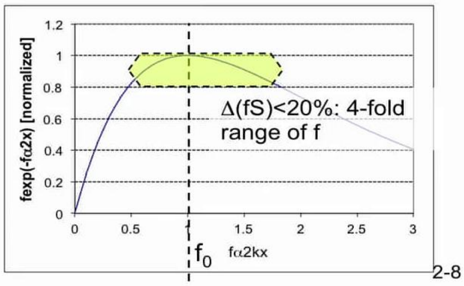
$$= e^{-\alpha k f 2x} - f\alpha k 2x e^{-\alpha k f 2x}$$

$$= e^{-\alpha k f 2x}\underbrace{\left(1 - f\alpha k 2x\right)}_{f_0 = 1/(2\alpha k x)} = 0$$

$\boxed{f_0=1/(2\alpha kx)}$

The optimal frequency decreases with tissue depth and with increasing absorption

How critical is the choice of f_0 ?



2-8

And now, we can say, "Well, you know, we are willing to compromise, to be within, let's say, 20% of the optimum, and the question is how much of a range, of variability in frequencies do we have? And so, if we actually allow this to be within 20% of the optimum, then we can see that we have a range from f_0 of 0.5 to almost 2. And that is a nearly 4-fold range in the frequency, or, in other words, for a given frequency, we have a 4-fold range in $1 / x$ that we can choose, or a bigger range in attenuation coefficients. So, in other words, this means we are not crucially linked to a precise choice of the ultrasound frequency to stay close to the optimum, but we have to have some idea where we are with respect to the wanted application.

Notes

Summary

6m 48s

Examples

2-9

High-resolution US at the surface:
Skin, subcutaneous tissue

Low-resolution US of deep tissue

Liver metastases

I'll give you some examples here to illustrate the case. So if you take a high resolution image, at high ultrasound frequency, this is an ultrasound scan at very high resolution of the skin and subcutaneous tissue. So we have here the epidermis, at the surface, we have here the loose connective tissue and subcutaneous fat-- that's this layer here; we have the muscle interface, so that's between fat and muscle; and you can see the interface is not just one line, it's actually, there is some dimensions to it that shows the high resolution. And here, we have the muscle fibers interface. We can actually see illustrated its function so we can nearly see the individual muscle fibers, so it's a very high resolution. And, finally, we have, down here, we have the interface to the bone. So, to be able to see with an ultrasound image to see almost nearly the individual muscle fibers here, you see the structure, this means that the ultrasound frequency was very high resolution to obtain such a nice high resolution image of the surface tissue. Another example is liver. In the liver, deep in the liver here, we take low-resolution ultrasound, we cannot use the same resolution, because we would simply not get with the wave energy all the way down here.

Notes

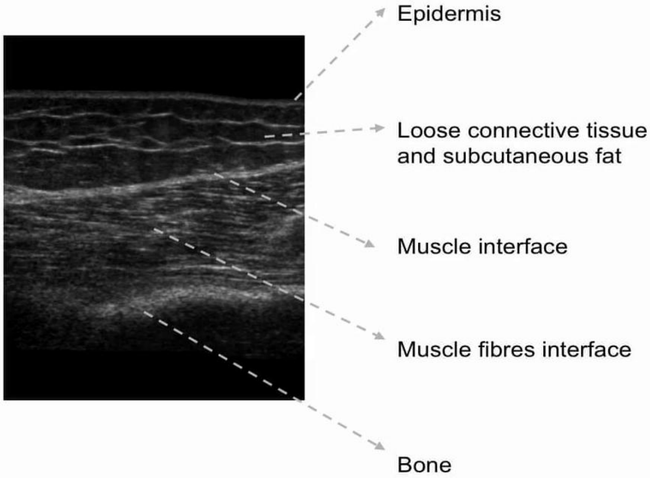
Summary

7m 43s

Examples

2-9

High-resolution US at the surface:
Skin, subcutaneous tissue



Low-resolution US of deep tissue

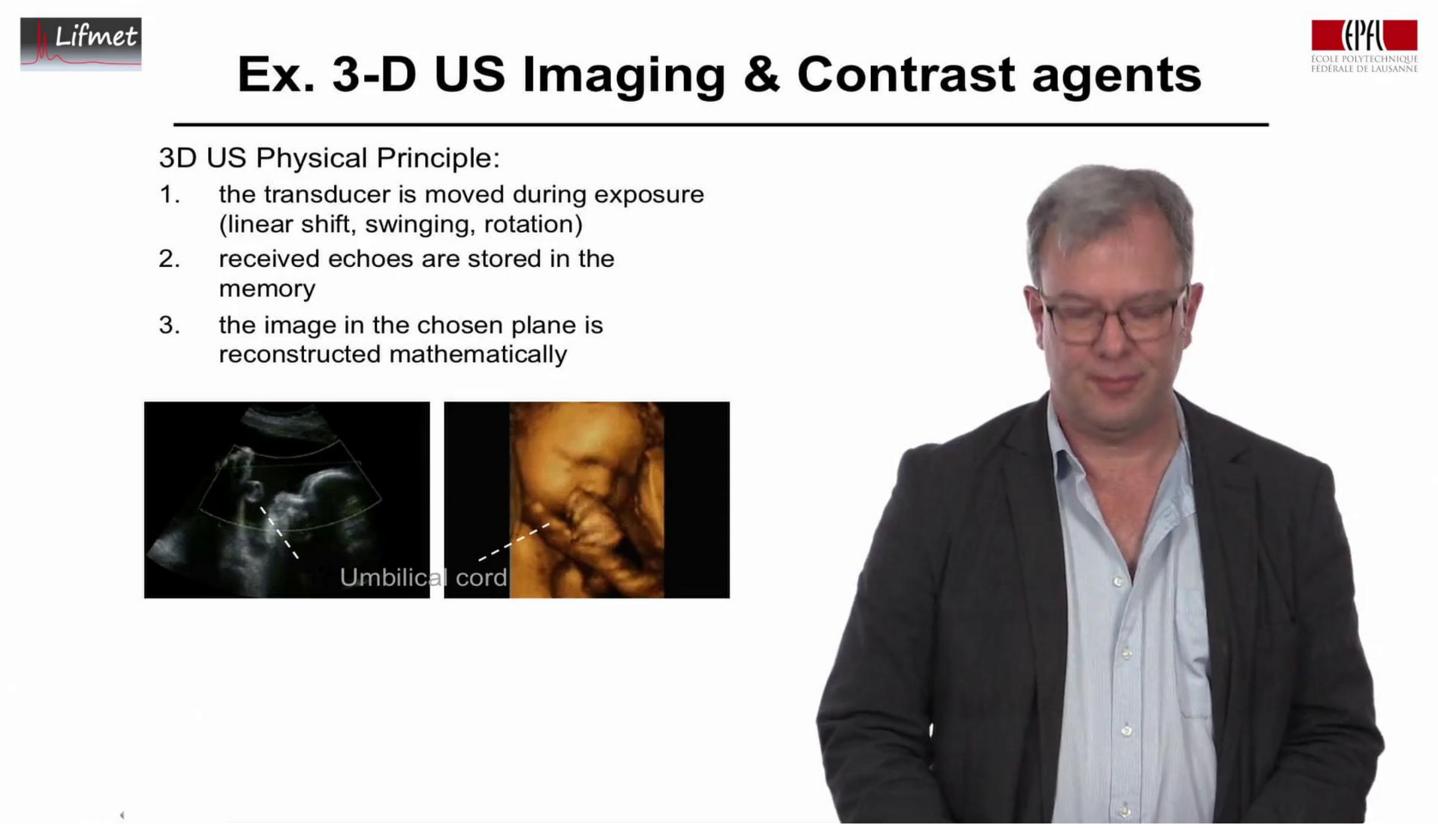
Liver metastases

This is a liver here, and you can see all these spots here, these are metastases that have been formed but we can nicely image them, even at the base here, but we will never be at anywhere close to the resolution that has been done here on the left for the subcutaneous tissue. So this requires high ultrasound frequency and here, we are required with low ultrasound frequency to obtain the depth penetration.

Notes

Summary

9m 14s



Now, I want to finish with some examples, so let's take the 3D ultrasound. The principle--I would not go through the mathematics here; the movement, the image and construction is that the transducer is being moved during the exposure; it's either a linear shift, swinging, or rotation. The received echoes are stored in the memory and based on the movement that the transducer has done. The image is then in the plane mathematically reconstructed. So this is the base image of a fetus here. This section here is then chosen to reconstruct the 3D image, and this is the 3D image here; and you can see here, on the umbilical cord, in the 2D image and the 3D image we can see the umbilical chord, we see the hand; and as you see in the sequence of the video, this can be done in real time, so one sees the baby move in the belly; this is actually one from the 31. We call it fetus and 3D ultrasound; if you search this on YouTube, you'll actually find around 28,000 hits of people who have uploaded their 3D ultrasounds of their babies at 31 weeks of gestation; so it's a very popular means and showing how the babies smile, how they move, how they suck their thumbs etc., already at that age.

Notes

Summary

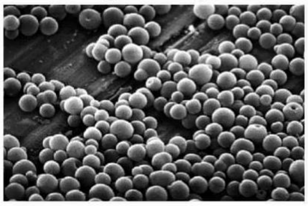
9m 41s

Ex. 3-D US Imaging & Contrast agents

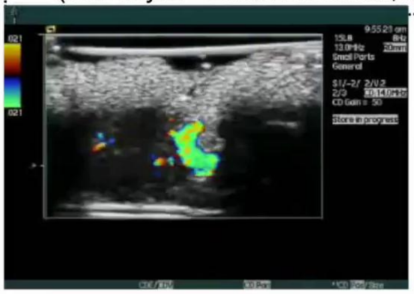
3D US Physical Principle:

1. the transducer is moved during exposure (linear shift, swinging, rotation)
2. received echoes are stored in the memory
3. the image in the chosen plane is reconstructed mathematically

Contrast agents: gas-filled Bubbles



Gas : most contrast (plus resonance and higher harmonic imaging)
(see tiny Z → total reflection, R_I~1)



Kidney perfusion (mouse)

2-10

We'll take the video here, and if you look at the sequence, we'll first see the basis on the image, and then the reconstruction. As this is done in real time, the baby moves in the womb. This is observable, the baby smiles-- this can imaged. We also see here the doctor ultrasound, the beating is the characteristic sound of newborn babies in the womb and then, again, the 3D image. Another way to ultrasound an image is the use of contrast agents. Now, the term *contrast agents* means the substance that alters the contrast of the imaging modality. In ultrasound, this is gas-filled bubbles. Here's a microscopic view of the gas-filled bubbles. Why gas filled? Well, we have seen that air in tissue there is a very high change, a very big change in acoustic impedance, so there is a big reflection of echos, but then there is also a higher harmonic imaging that is introduced here, and resonance effects on these micro bubbles that makes them a very good tool to generate very strong echoes. So for the purpose of this course we'll stick with the idea that they have tiny Z inside, the air bubbles, so there is a total reflection of the ultrasound. And here, we have an example of kidney perfusion.

Notes

Summary

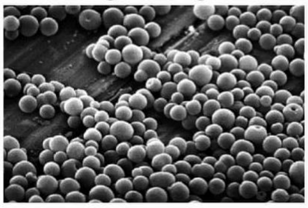
11m 16s

Ex. 3-D US Imaging & Contrast agents

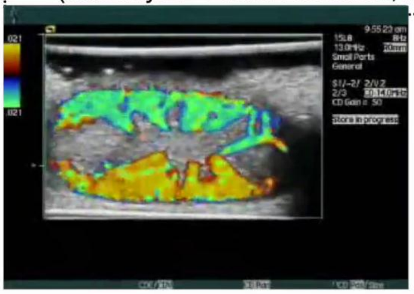
3D US Physical Principle:

1. the transducer is moved during exposure (linear shift, swinging, rotation)
2. received echoes are stored in the memory
3. the image in the chosen plane is reconstructed mathematically

Contrast agents: gas-filled Bubbles



Gas : most contrast (plus resonance and higher harmonic imaging)
(see tiny Z → total reflection, R_I~1)



Kidney perfusion (mouse)

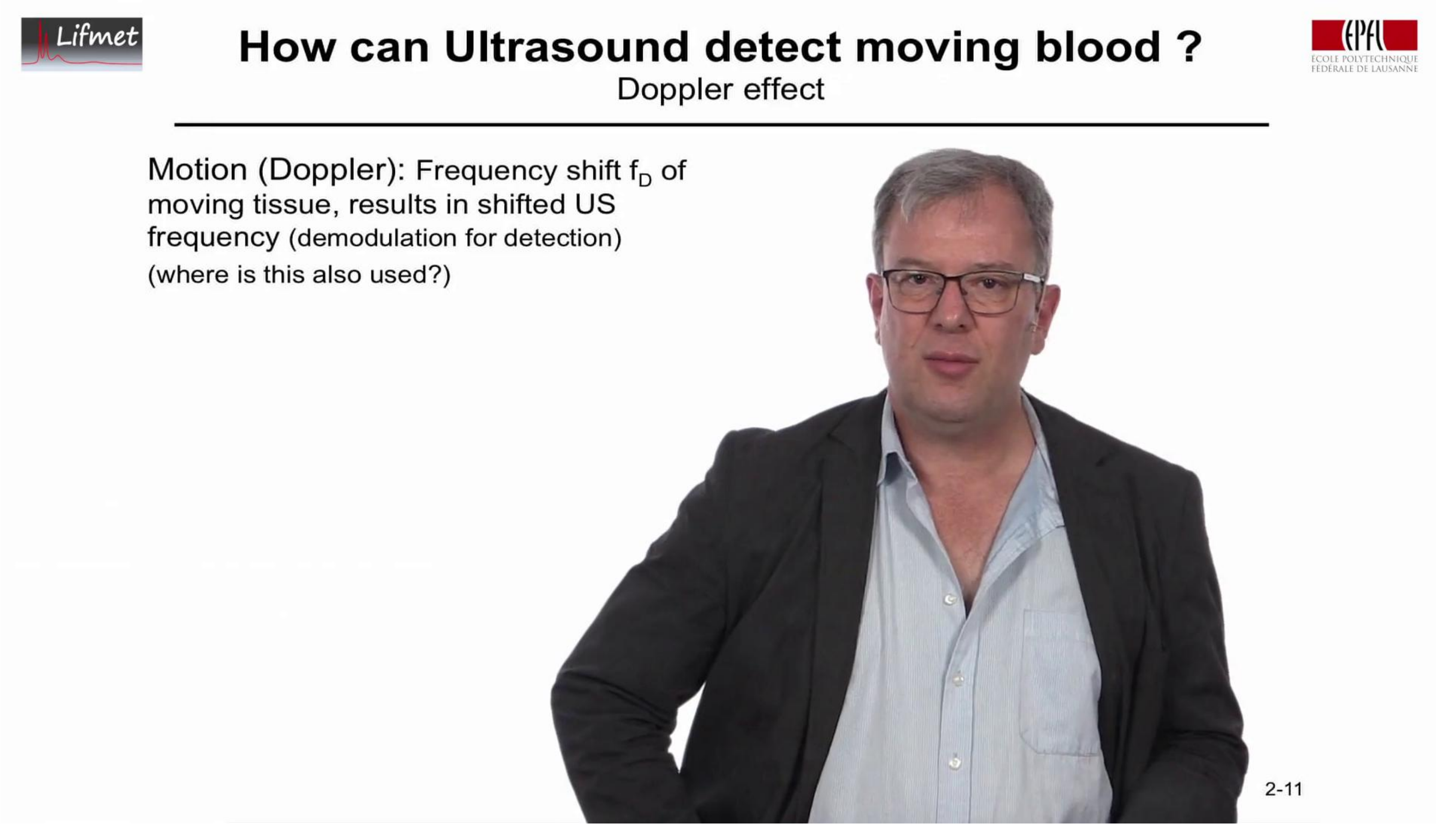
2-10

If we look at the perfusion of the kidney, we can see that these micro-bubbles arrive in the kidney, the change in signal is color-coded, and once it's very nice here in the mouse, the arrival of the micro-bubbles in the kidney, then we can measure the kidney perfusion.

Notes

Summary

12m 51s



And the last example I want to discuss here is how can ultrasound detect moving blood? And here, the effect that is being used is the Doppler effect. So, what happens if the tissue is moving, if there is a moving tissue? This results in a shift of the frequency, shift of the ultrasound frequency, and this is the well-known Doppler effect, and this is detected by demodulation for detection. Now, question: are you familiar with the Doppler effect? Where have you been exposed to it? I am pretty sure you've been exposed to the Doppler effect, maybe you have not realized it, but maybe you have. Well, I'll give you one example. You hear an ambulance, or a police car, when it drives to you. Is the pitch of the sound higher than when it drives away from you? This is exactly the Doppler effect for sound waves. Now, what we are doing in ultrasound is the same principle: you have a change in sound frequency, and this is due to the fact that the source of the sound, or the interface of the tissue is moving. The Doppler effect is a more general principle and, depending on where you are, you have most likely being exposed to it, even today, as you are watching it, or at work; you have been exposed to it.

Notes

Summary

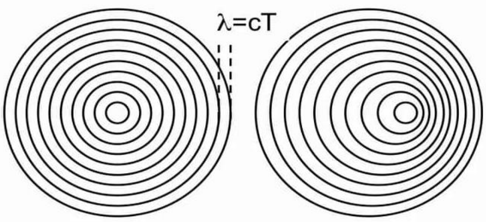
13m 10s

How can Ultrasound detect moving blood ?

Doppler effect

Motion (Doppler): Frequency shift f_D of moving tissue, results in shifted US frequency (demodulation for detection)

(where is this also used?)



2-11

Ever walked through an automatically opening door? Try standing in front of the door when you are alone, and just stand there. Most likely, the door will close. It will not stay open as you are standing in front of the door. The minute you move your hand, it will open the door. Typically, this is done with infrared sensors, also using the Doppler shift, but now the Doppler shift is in the optical range, it detects a moving object by detecting small changes in the wavelength of light; it's the same phenomenon there that's being used. Let's look at the propagation of sound waves: I will stick with this very empirical, very qualitative... For a stationary object, the sound waves travel into, with the same sound speed in all directions, so we have here indicated: the maximum between sound waves, that's the wavelength here, and it equals to *z* times *T*. If you have now a source moving with the velocity *v_0* and appear at *T*, the source will soon move closer to the detector, by *v_0 T*. And then, this is what we are observing: here's the source moving to the right, but now we have the maximum between the sound waves is now given by *(c-v_0) T*.

Notes

Summary

14m 49s

How can Ultrasound detect moving blood ?

Doppler effect

Motion (Doppler): Frequency shift f_D of moving tissue, results in shifted US frequency (demodulation for detection)

(where is this also used?)

Doppler frequency shift f_D

$$\boxed{f_D = \frac{2 f_0 v_0 \cos\alpha}{c}}$$

c: speed of US, e.g. 1500 m/s

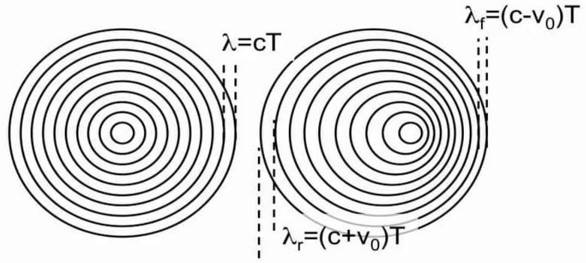
v_0: speed of source, e.g. 50 cm/s

f_0: frequency of moving source, e.g. 5MHz

stationary

Source moving with v_0

In a period T, source moves closer by $v_0 T$



2-11

And the maximum here is *(c+v_0) T*. That's the wavelength that's observed here, and *T* here is the same time. So, in the direction of the motion, in front, the difference between the sound maximum, that is the wave length, is shorter, and in the back of the source, the difference between the maximum is longer, so this is a longer wavelength and ends in lower frequency, and that's the characteristic sound that you hear where the ambulance is. Now, I'll give you here just a formula from the literature: we have the difference in frequency, between the front and the back here is given by two times the frequency of the sound wave, the velocity of the object, *cos α*, where *α* is the observer frequency divided by the speed of sound. So *c* is the speed of sound, *v_0* is the speed of the source, so, police car, or ambulance; here, we'll say it's blood-- it's 50 cm/s. And let's say the frequency of the moving source is 5 MHz. If you take the speed of sound from the tissue, 1,500 m/s, the characteristic assumed value of blood flow, 50 cm/s, and an ultrasound frequency. We'll just say that we are at an angle where we can detect it, and we'll now estimate the Doppler effect that we can have.

Notes

Summary

16m 18s

How can Ultrasound detect moving blood ?

Doppler effect

Motion (Doppler): Frequency shift f_D of moving tissue, results in shifted US frequency (demodulation for detection)

(where is this also used?)

Doppler frequency shift f_D

$$f_D = \frac{2 f_0 v_0 \cos\alpha}{c}$$

c: speed of US, e.g. 1500 m/s

v_0: speed of source, e.g. 50 cm/s

f_0: frequency of moving source, e.g. 5MHz

α: Rel. angle at which blood is moving

Example:

$f_D = 2 \cdot 5 \cdot 10^6$ [Hz] 0.5 [m/s]/1500 [m/s]

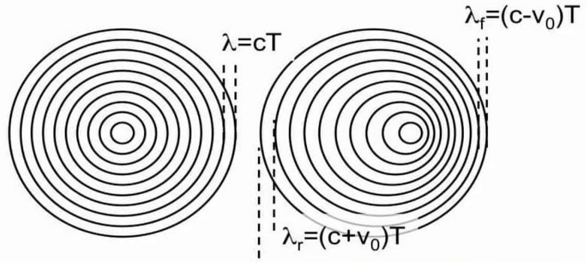
~ 3kHz

~ 0.05% of f_0

stationary

Source moving with v_0

In a period T, source moves closer by v_0T



Doppler US of internal carotid artery stent

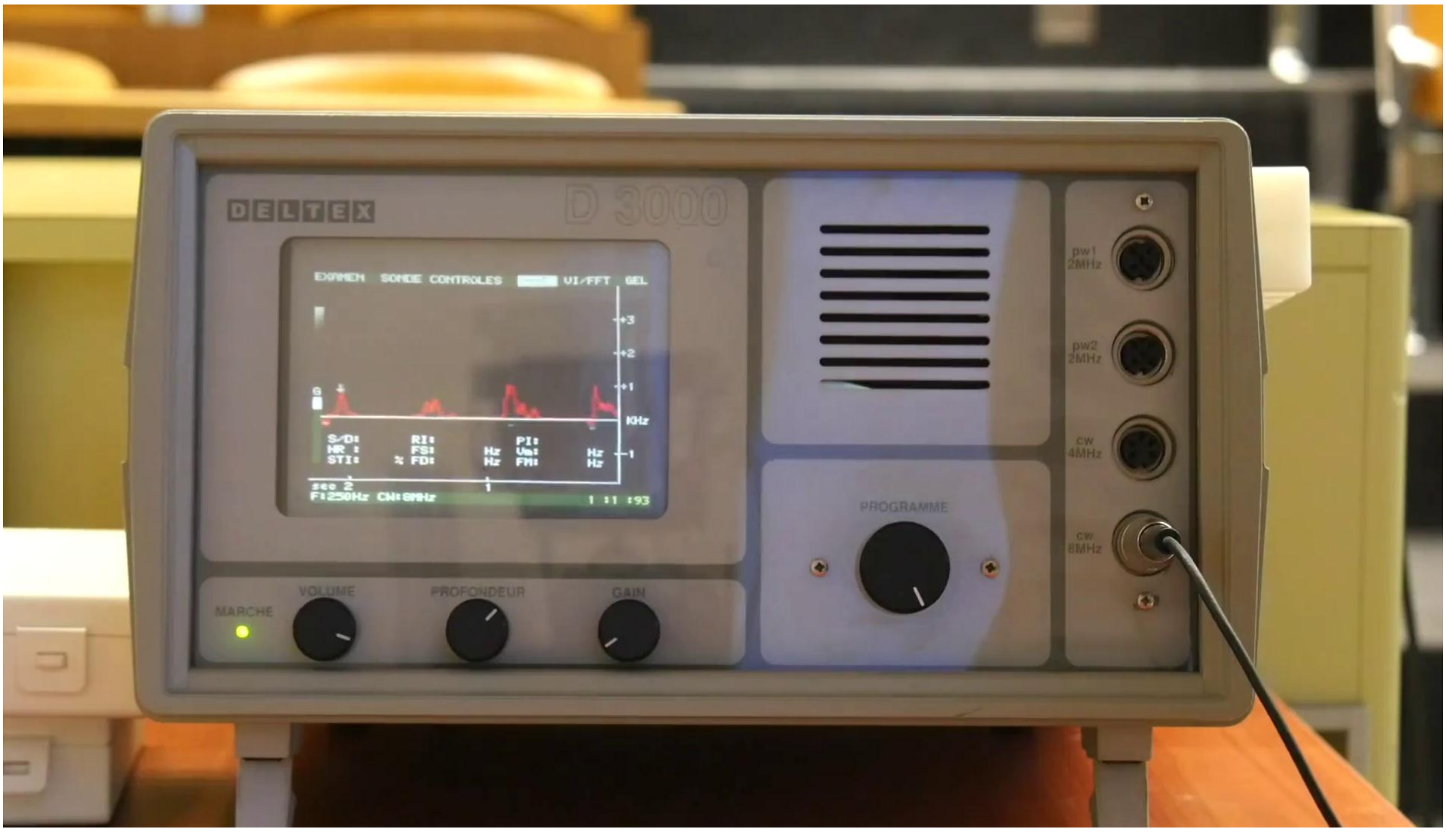
2-11

And if you take this with these numerical examples, we can calculate out the values, we'll take punching the numbers, and we can calculate. But this is roughly, a shifting frequency of 3 kHz. 3 kHz is 0.05% of the original ultrasound frequency; that's very low, but 3 kHz in absolute terms is easily detectable with a demodulator to be able to calculate that there is something moving. The moving source that we are talking here is of course the moving interface of this blood. Then we have moving blood; that is what we mean here: the source means here the echo-generating object, our interface. So, here we are looking at the image. We see, over time, the blood flow that's done with the Doppler ultrasound that's taken from the 3D ultrasound example of the newborn baby that I have just shown you earlier. And we have here a video of a stent-- this is from the internal carotid artery stent. The stent is typically a spiraled object, it's like a spring, that is there to reinforce the vessel walls, and as you can see, in this video here, you could see very nicely the blood flow, and you see also from the stent the changing blood flow at the location of the stent is [inaudible] of the structure here corresponds very nicely to the structure of the stent.

Notes

Summary

17m 52s



So what we have here is an ultrasound transducer which detects the Doppler effect; it is used to detect the moving blood, as I just explained, and I am going to use it here on myself as a demonstration. The sound that you will hear is actually something for those of you who have been involved in ultrasound of newborns, unborn babies, that you are very familiar with. It's the typical sound of ultrasound. So, I'm going to try to find a sweet spot; This may take a while until I find it, but you will see on the screen here that is on the overhead, you will see the heartbeat. (sound of ultrasound) OK, so that's a demonstration of the heartbeat, that's a typical sound of ultrasound, and here, it was done with moving blood.

Notes

Summary

19m 26s

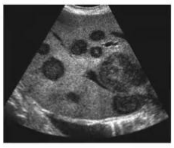
That's the demonstration that concludes the ultrasound section.

Notes

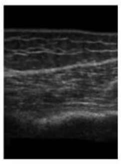
Summary

20m 37s

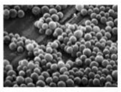
Credits



Brent Burbridge, MD Saskatoon Medical Imaging, Saskatoon Canada
http://www.cancerquest.org/ultrasound-results.html



Centre d'imagerie médicale Luton
http://www.radiologie-luton-reims.fr/echographie-doppler.php



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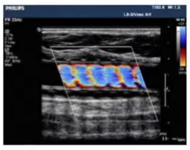

Carotid Stent Color Doppler *(video extract)*
https://youtu.be/B-awx3Td0Sc

Notes

Summary

20m 40s