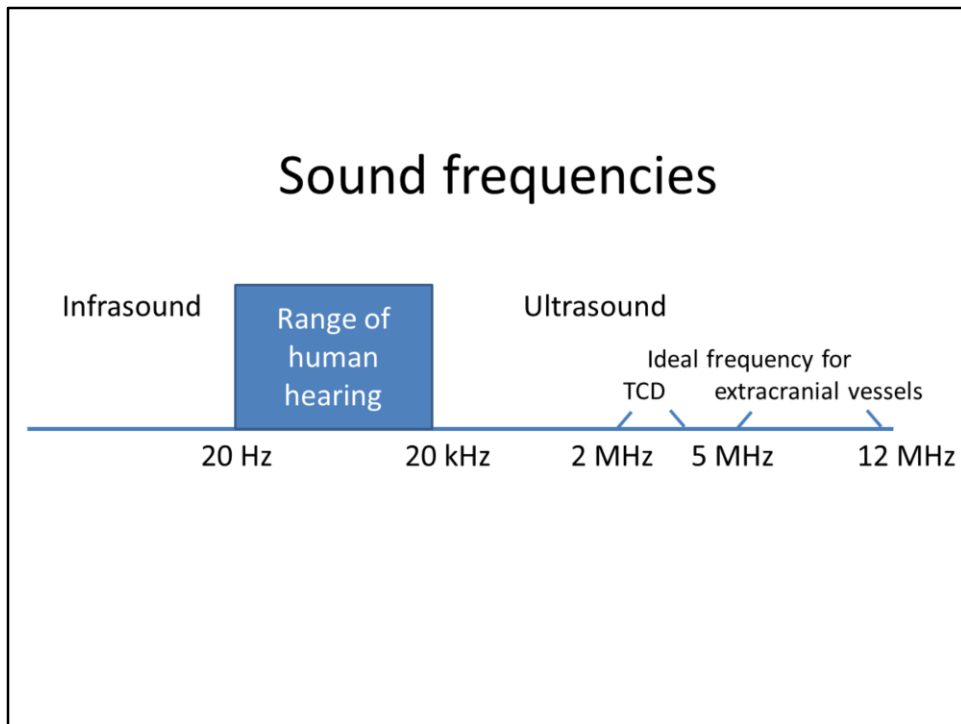


Basic ultrasound principles

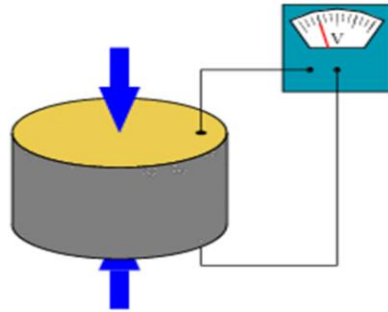
Laszlo Olah
University of Debrecen
Hungary



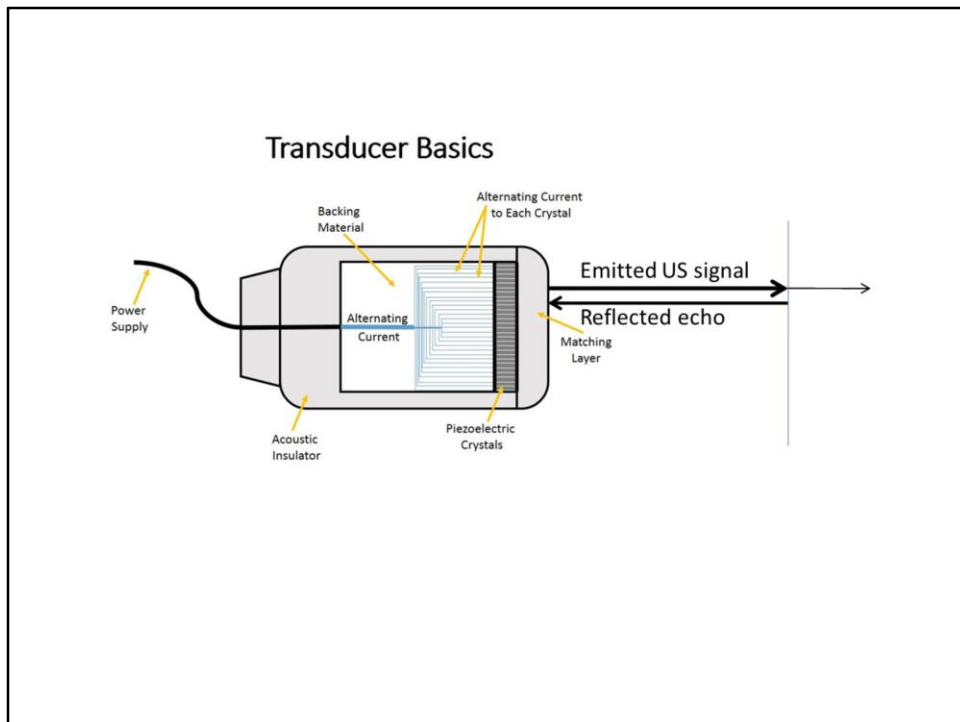
All of you know very well that the human ear can hear between frequencies of 20 Hz and 20 000 Hz. Below 20 Hz and above 20 kHz, which are not hearable for the human ears, the sound is called infrasound and ultrasound, respectively.

Piezoelectric effect

- 1880-piezoelectric effect
- Quartz, Ceramic, Lead zirconate titanate...
- Mechanical stress → electric charge
- Electrical pulses → vibration



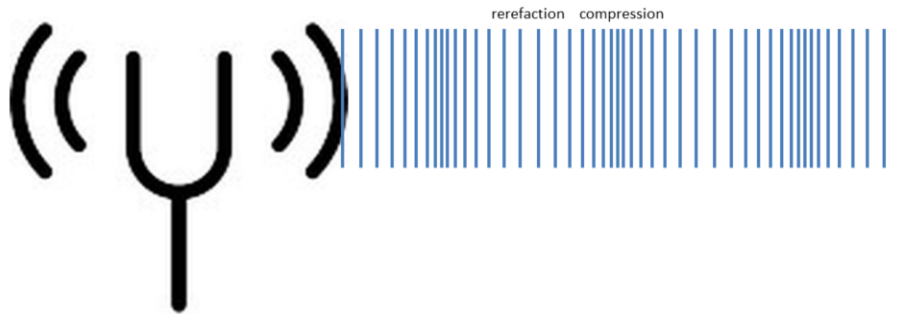
Let's examine, how ultrasound is produced. Investigating a piece of quartz in 1880, the Curie brothers described the piezoelectric effect. It means that certain crystals (e.g. quartz, ceramic, lead zirconate titanate) subjected to mechanical stress generate electric charge on the surface, and vice versa, electrical pulses in these special materials result in vibration, which, if enough fast, generates ultrasound.



Ultrasound transducers contain multiple piezoelectric crystals. Ultrasound transducers have dual function: they transmit (emit) and receive ultrasound. In medical ultrasound equipment, ultrasound is transmitted into the body tissue, and a part of the sound wave is reflected back to the transducer (echo) and converted to an electric signal by piezoelectric crystals. In CW Doppler, one crystal only transmits (continuously transmits), while another crystal only receives (continuously receives) the ultrasound signals, while in PW Doppler systems, the same crystal transmits and receives the ultrasound waves. After transmission of an ultrasound pulse, the crystal in the PW system waits and after a controlled delay it switches to receiving mode. Later we'll compare the CW and PW systems in details.

Sound

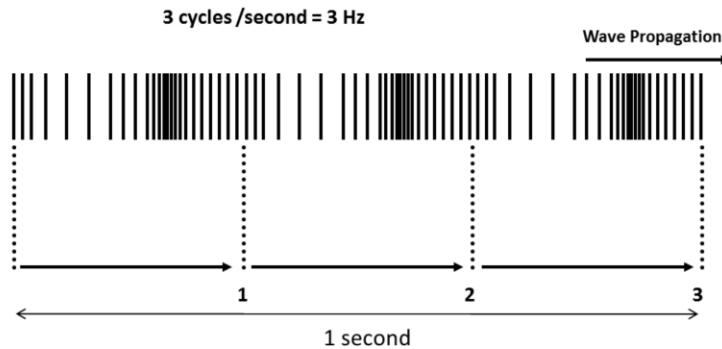
- Mechanical wave: propagates in a medium
- Longitudinal wave: compression waves and rarefaction waves



Sound waves are mechanical waves, that is they only propagate in a medium, but not in a vacuum. Sound waves are also classified as longitudinal waves. Let us now see how sound waves propagate. When a tuning fork is vibrating, it's fork compresses air particles near it, forming a compression. Due to vibrating air molecules, this compression moves forward as a longitudinal wave. As the prong moves back to its original position, the pressure decreases, forming a rarefaction that also moves forward like rarefaction wave.

Frequency of Sound

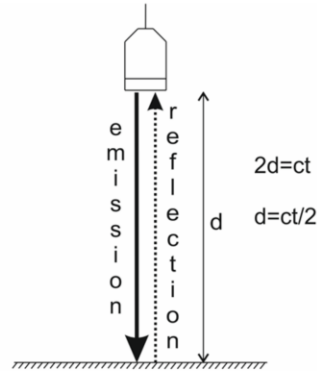
For sound, the frequency **refers to how many cycles of compression and rarefaction occur per second.** Frequency is determined by the source.



Sound wave is characterized by its frequency that is determined by the source of the ultrasound.

Propagation of ultrasound in a medium

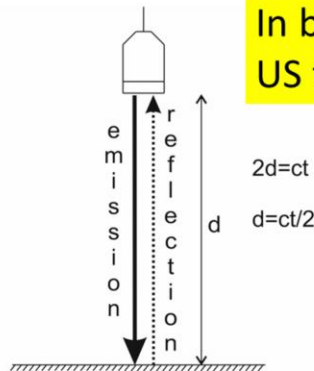
- Speed of sound in a material depends on compressibility and density of the material
- The more compressible the medium, the higher the propagation speed of the sound.
The sound propagates faster in a less compressible material!!!
- $ct=2d$



The speed of ultrasound propagation in a tissue depends on the compressibility and density of the material in which the sound propagates. The more compressible the medium, the higher the propagation speed of the sound is. It means that the propagation speed of ultrasound is determined by the medium.

Propagation of ultrasound in a medium

- $ct=2d$



In biological materials
US takes 1 cm in $6.5\mu\text{s}$

If:

$c=1540 \text{ m/s}$, time delay $=52 \mu\text{s}$ ($=0.000052 \text{ s}$)

$\rightarrow d=1540 \text{ m/s} \times 0.000052 \text{ s} / 2=0.04 \text{ m}$ (4 cm)

Knowledge of speed of ultrasound propagation is very important. **If we know the speed of ultrasound, the distance between the transducer and the target can be calculated from the time interval between the emission of the ultrasound pulse and the reception of the reflected echo.** Let me remind you that the ultrasound has to reach the target and has to return to the transducer, therefore, the distance has to be counted twice.

Propagation speed of sound in different materials

Material	Speed (m/s)
Air	330
Aqueous humour	1,500
Blood	1,570
Bone	3,500
Brain	1,540
CSF	1,510
Fat	1,450
Lens of eye	1,620
Muscle	1,580
Skin	1,600
Soft tissue average	1,540
Vitreous humour	1,520

Baumgartner RW, Handbook on neurovascular ultrasound

Here you can see the propagation speed of ultrasound in some materials. **Observe that except for the air** ($c=330$ m/s) and the bone ($c=3500$ m/s), the propagation speed of the sound is very similar in different biological tissues. Therefore an average value of 1540 m/s is usually used for calculations in biological samples.

Propagation speed of sound in different materials

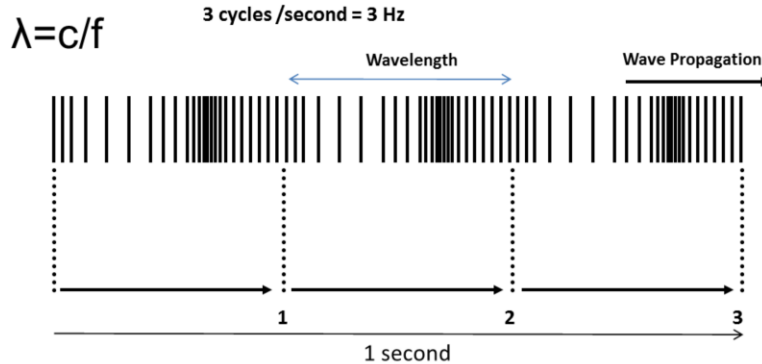
Material	Speed (m/s)
Air	330
Aqueous humour	1,500
Blood	1,570
Bone	3,500
Brain	1,540
CSF	1,510
Fat	1,450
Lens of eye	1,620
Muscle	1,580
Skin	1,600
Soft tissue average	1,540
Vitreous humour	1,520

Baumgartner RW, Handbook on neurovascular ultrasound

An average value of 1540 m/s is usually used for calculations in biological samples.

Wavelength (λ)

The wavelength for a sound wave is the physical distance from one compression to the next compression.



Another characteristic of the ultrasound is the wavelength. The wavelength for a sound wave is the physical distance from one compression to the next compression. The wavelength is calculated as the quotient of propagation speed and sound frequency.

Parameters of a sound wave

The frequency of a wave is determined by the source of the wave.

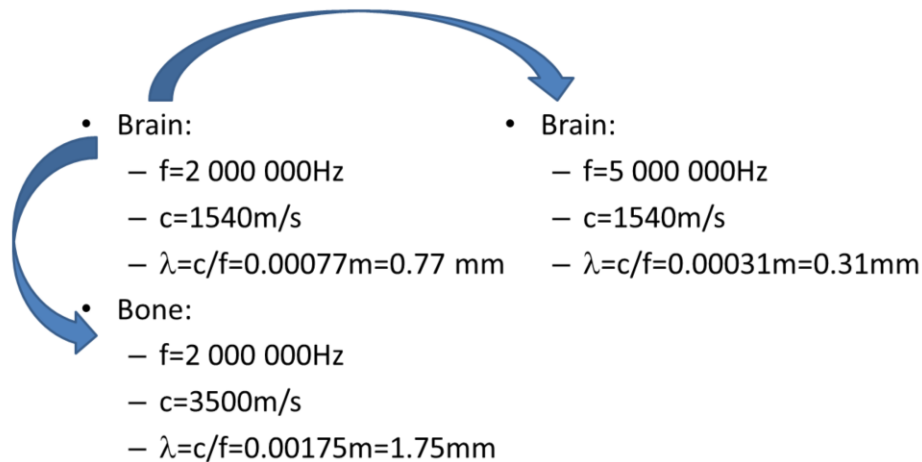
The propagation velocity of a wave is determined by the properties of the medium.

The wavelength is affected by both the frequency and the propagation velocity.

$$\lambda = c/f$$

As it was mentioned before, the frequency of a wave is determined by the source of the wave, while the propagation speed depends on the material. The wavelength, however, is determined by both the frequency and the propagation speed according to the equation: $\lambda = c/f$

Frequency, propagation speed and wavelength of sound waves



Let's see an example. The wavelength of a 2 MHz ultrasound wave can be calculated as the ratio of propagation speed and the ultrasound frequency. The wavelength in this case is 0.77 mm. If we apply not 2, but 5 Mhz ultrasound, the wavelength will be lower (0.31 mm). Note that the frequency and the wavelength is inversely proportional! If the wavelength is calculated in the bone, due to the higher propagation speed, the wavelength will be larger (1.75 mm).

Behaviour of ultrasound at tissue interfaces

Now let's examine what happens when the ultrasound passes through a medium and reaches a tissue interface. When ultrasound enters the body, it travels through different tissues.

Sound passing through a material and reaching tissue interface can be

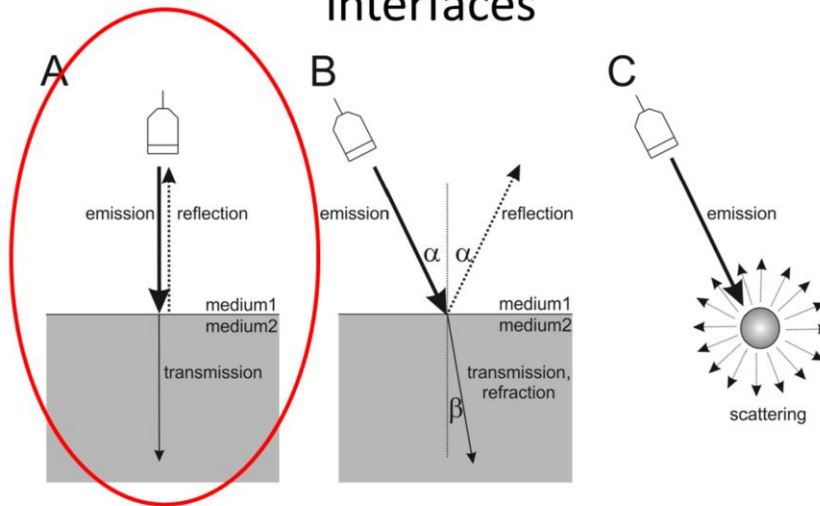
- transmitted to deeper structures
- reflected back to the transducer
- scattered
- absorbed



imaging

Ultrasound waves may be transmitted to deeper structures (transmission), reflected back to the transducer (reflection), scattered, or partly absorbed and converted to heat. **Certainly, reflected and scattered waves (echoes) are the most important, since these waves provide information for imaging purpose.**

Behaviour of ultrasound at tissue interfaces



Let's examine what determines the proportion of the ultrasound which is reflected or transmitted

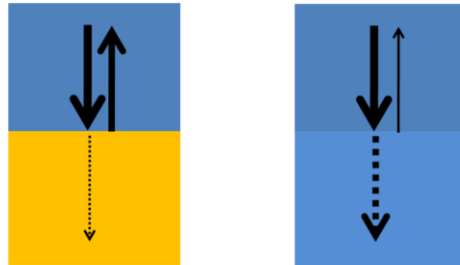
Specific acoustic impedance

- Property of the medium (ρc)
- **Acoustic impedance** refers to the resistance of the particles of a medium to mechanical vibration (**resistance of a material to transmit sound**)
 - Air $4 \times 10^2 \text{ kg/m}^2\text{s}$
 - Liver $1.65 \times 10^6 \text{ kg/m}^2\text{s}$
 - Bone $7.8 \times 10^6 \text{ kg/m}^2\text{s}$

To answer this question, an important intrinsic property of the medium, the so called specific acoustic impedance has to be discussed. **Acoustic impedance** refers to the resistance of the particles of a medium to mechanical vibration (**resistance of a material to transmit sound**). The acoustic impedance of some materials are shown.

Behaviour of ultrasound at acoustic boundaries (tissue interfaces)

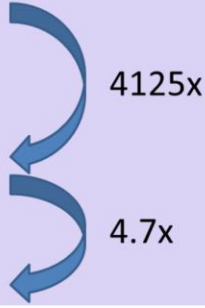
- If there is a DIFFERENCE in **specific acoustic impedance** at a tissue interface, some of the sound will be reflected
- The bigger the difference, the bigger the reflection, smaller the transmission.



If there is a DIFFERENCE in acoustic impedance at a tissue interface, some of the sound will be reflected. The bigger the difference between the materials on each side of the boundary, the bigger the reflection and smaller the transmission! Vice versa, the smaller the difference between the materials on each side of the boundary, the smaller the reflection and larger the transmission!

Acoustic impedance of some biological tissues (AI=pc)

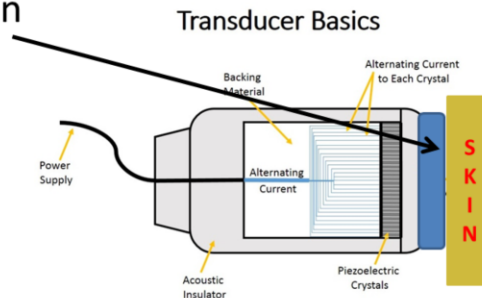
Body tissue	Acoustic impedance (10^6 Rayls)
Air	0.0004
Lung	0.18
Fat	1.34
Liver	1.65
Blood	1.65
Kidney	1.63
Muscle	1.71
Bone	7.8



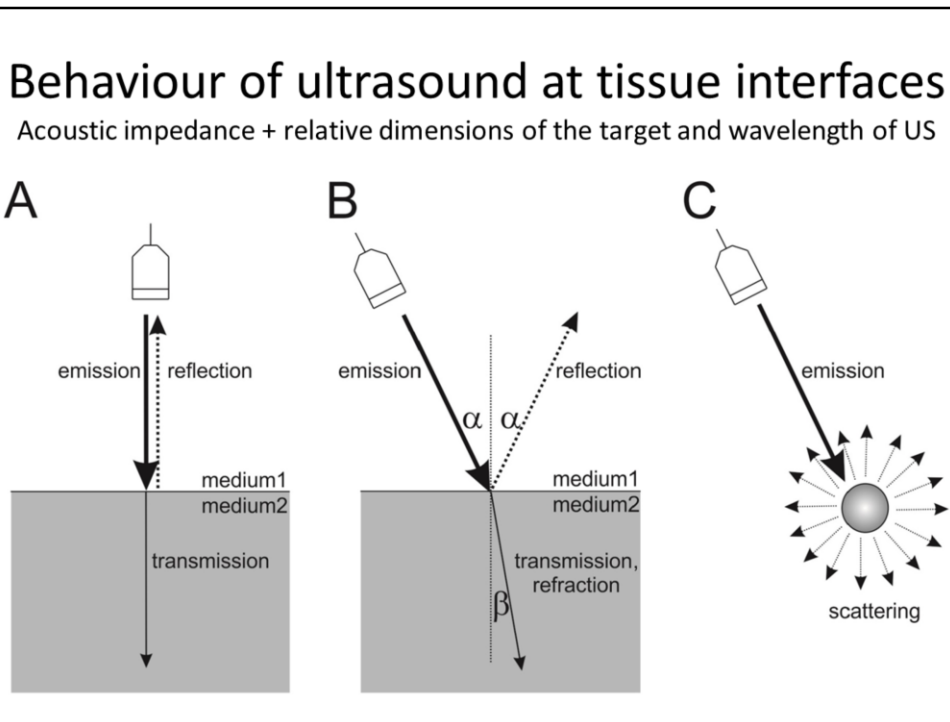
The acoustic impedance values of some materials and biological tissues can be seen here. Please note that the air has very low and the bone has high acoustic impedance. The biological tissues has several thousand times higher acoustic impedance than the air. The bone has relatively high impedance value compared to the other biological tissues.

Behaviour of ultrasound at acoustic boundaries (tissue interfaces)

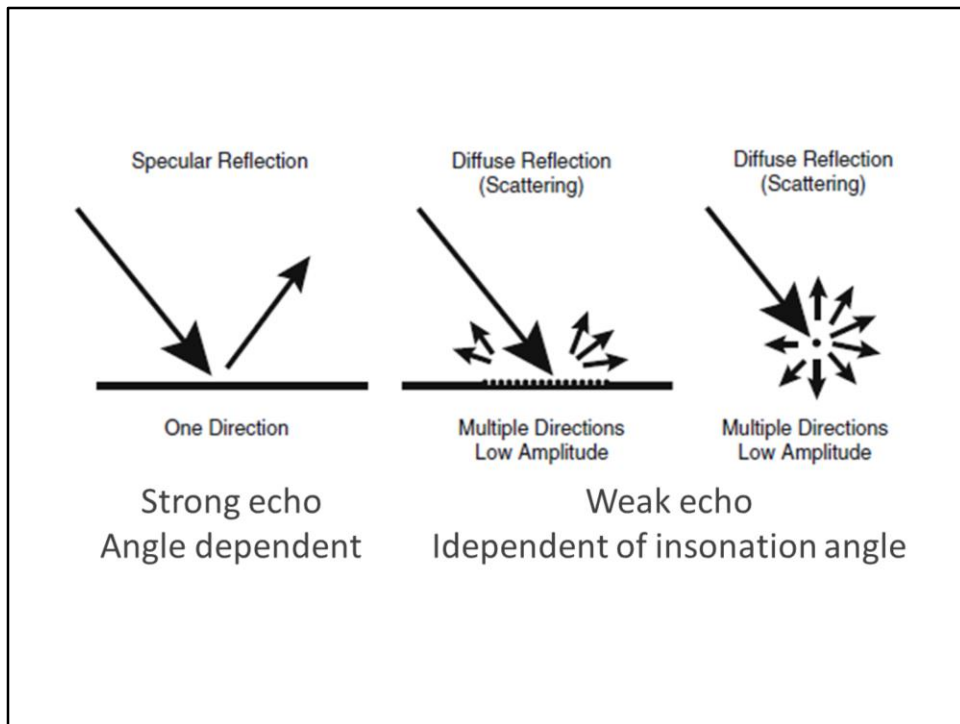
- If there is a BIG DIFFERENCE in impedance at a tissue interface, most of the sound will be reflected
- The bigger the difference, the bigger the reflection



As it was mentioned before, if there is a huge difference in the acoustic impedance values between the materials on each side of the boundary, the most of the ultrasound energy will be reflected. The acoustic impedance of air is so low compared to the skin that practically the whole energy is reflected from the air/skin interface. This is the reason why it is impossible to image through air and why it is essential to use gel in order to exclude air from the boundary of transducer and skin.



Behaviour of ultrasound at acoustic boundaries depends on the relative dimensions of the ultrasound wavelength and the target. **When an ultrasound wave reaches a large target with smooth surface**, part of the ultrasound wave continues to penetrate into the deeper structure, while the remaining part is reflected back from the boundary of tissues with different acoustic properties. The fraction of the reflected and transmitted ultrasound waves depends on the acoustic impedance of the materials on the two sides of the boundary. The greater the difference in impedance between the two materials is, the more sound will be reflected rather than transmitted. If the emitted ultrasound hit the target at 90 degree, the reflected echo will reach the transducer. However if the angle between the ultrasound beam and the target surface is different than 90 degree, the reflected echo will miss the transducer. In this case that part of the ultrasound which passes on and crosses the tissue interface becomes slightly bent away from its original direction (refraction). **If the ultrasound pulse encounters targets which dimensions are smaller than the ultrasound wavelength (e.g. red blood cells), or when the surface of the reflector is rough and irregular**, scattering occurs. In this case, **echoes are reflected through a wide range of angles. Although scattering results in loss of a huge amount of the sound energy for imaging, some echoes will invariably reach the transducer regardless of the angle of the incident pulse.** It means that **echoes due to scattering are relatively weak, but they depend much less on the insonation angle.** Since most biological tissues are filled with small scattering structures, scattering allows to visualize blood flow and the parenchyma of the organs.



When ultrasound reaches a large, smooth surface, specular reflection occurs, which is strong, but depends on the insonation angle. Quite contrary, if ultrasound hits a rough irregular surface or a structure which dimension is smaller than the wavelength of the ultrasound, scattering occurs. Scattered echoes are relatively weak, but independent of the insonation angle.

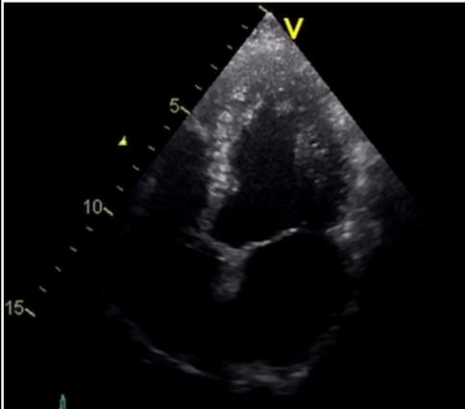
Attenuation

- Intensity of US decreases during propagation (attenuation)
- It depends on the
 - Distance
 - US frequency
 - Material (attenuation coefficient)



Energy of ultrasound decreases as it travels through body tissues. In most cases, **the main cause of attenuation is the conversion of the mechanical sound energy into heat (absorption)**. Attenuation of ultrasound energy depends on several factors, including path length, ultrasound frequency, and attenuation coefficient of the medium.

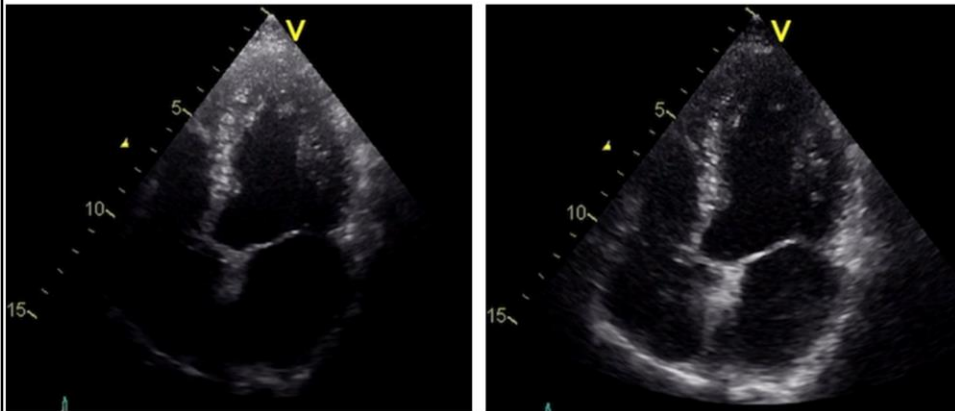
Attenuation → path length →
→ worse image quality in the deeper regions



<http://folk.ntnu.no/stoylen/strainrate/Ultrasound/>

Since ultrasound energy is attenuated with path length, attenuation results in worse image quality in the deeper regions.

TGC

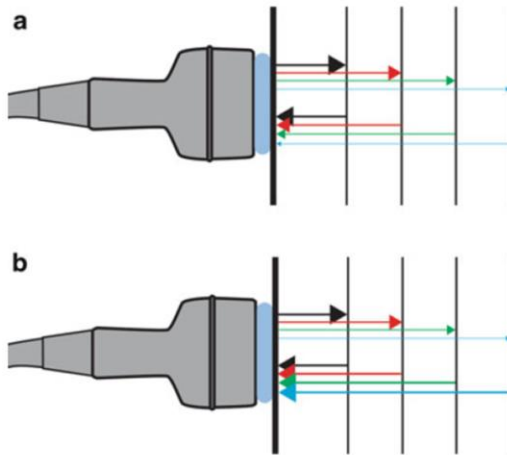


<http://folk.ntnu.no/stoylen/strainrate/Ultrasound/>

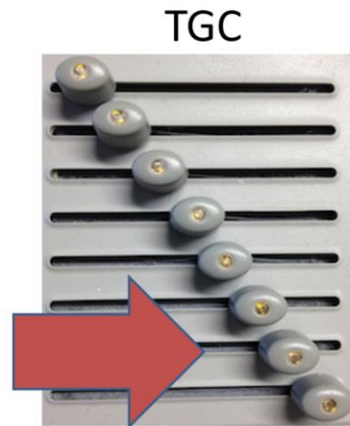
TGC allows to selectively amplify the attenuated waves by increasing the gain in the deeper regions

In order to brighten the deeper and thus the more attenuated area, the so called **time-gain compensation** can be used. Time-gain compensation allows to selectively amplify the attenuated waves by increasing the gain in the deeper regions.

Attenuation of US depends on the depth



(a) As ultrasound waves enter tissues, they attenuate with depth from the surface. High-frequency waves attenuate more than those of low frequency.
(b) Time-gain compensation allows selective amplification of the weaker deep and intermediate returning echoes



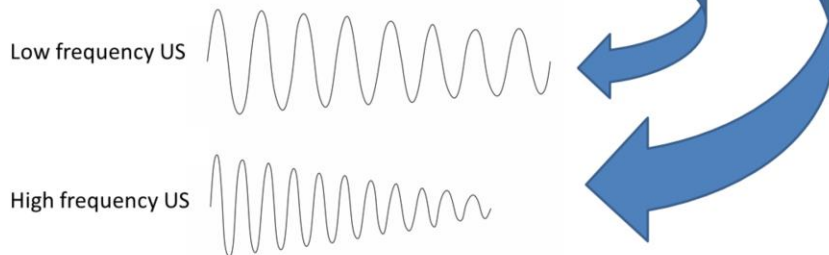
Selective amplification of the attenuated waves by increasing the gain in the deeper regions.

Time-gain compensation allows to selectively amplify the attenuated waves by increasing the gain in the deeper regions.

Attenuation of ultrasound depending on its frequency

High frequency ultrasound is attenuated more, limiting the penetration depth!

Low frequency ultrasound is attenuated less, therefore it penetrates deeper!



An important rule is that high-frequency ultrasound is attenuated more than low frequency ultrasound, limiting the penetration depth. The practical consequence of this phenomenon is that **deeper structures can be imaged with using low-frequency ultrasound, which is less attenuated, therefore penetrates deeper.**

Attenuation of US depending on the medium

Attenuation coefficient of some materials

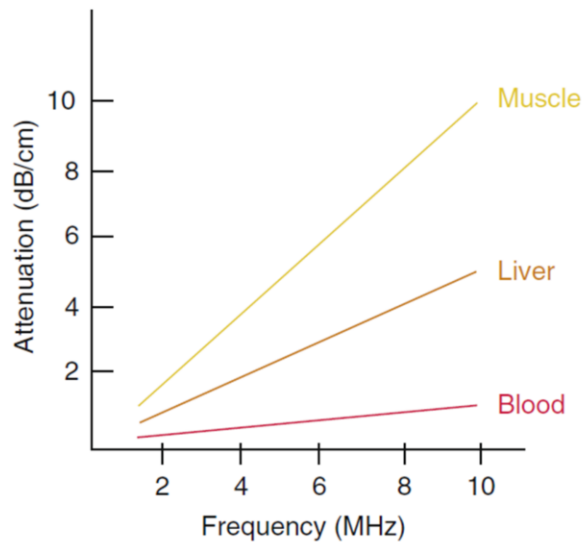
Attenuation coefficients for some biological materials at 1 MHz. The values at a higher frequency may be obtained approximately by multiplying by the frequency in MHz. (Note however that for water the value should be multiplied by the square of frequency.)

Material	Attenuation coefficient (dB cm ⁻¹)
Blood	0.2
Bone	10
Brain (adult)	0.8
Brain (infant)	0.3
Fat	0.6
Muscle	1.5
Water	0.002
Soft tissue average	0.7

Baumgartner RW, Handbook on neurovascular ultrasound

Attenuation coefficient, expressed as a decrease of ultrasound pressure amplitude in decibel in 1 cm distance, varies from tissue to tissue. Among the biological materials, the bone has the highest attenuation coefficient, which explains why the examination behind bony structures is so difficult.

Attenuation of ultrasound depends on its frequency and the medium



This figure shows the attenuation coefficients of different biological tissues at different US frequencies. It can be seen that the attenuation is frequency dependent: high frequency US is more attenuated than low frequency US.

GALL BLADDER; GALL STONE



<http://folk.ntnu.no/stoylen/strainrate/Ultrasound/>

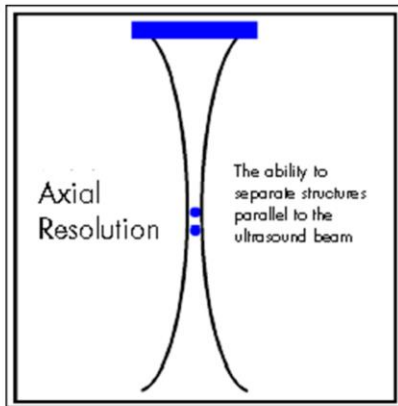
Behind a structure with low attenuation, the tissue appears denser (brighter) than the surrounding tissue. Behind the gall stone, which attenuates the ultrasound energy significantly, the tissue appears dark (acoustic shadow).

This figure shows an example of the effect of a little and a strong attenuation. A gall bladder can be seen with a gall stone. The bile fluid has low, while the gall stone has high attenuation coefficient compared to the surrounding tissue. Therefore behind the fluid with low attenuation the tissue appears brighter. Quite contrary, behind the gall stone, which attenuates the ultrasound energy significantly, the tissue appears dark (acoustic shadow).

RESOLUTION

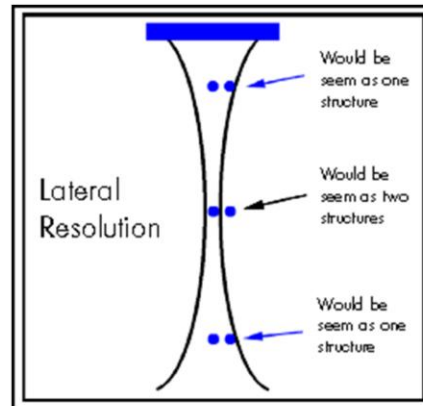
AXIAL RESOLUTION

- The ability to separate structures parallel to the ultrasound beam



LATERAL RESOLUTION

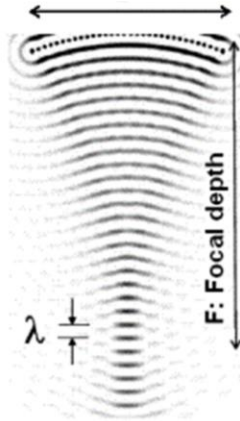
- The ability to separate structures perpendicular to the ultrasound beam



Axial resolution means the ability to discriminate between 2 points in the direction of the ultrasound beam, while lateral resolution refers to the ability to distinguish between two reflectors perpendicular to the beam.

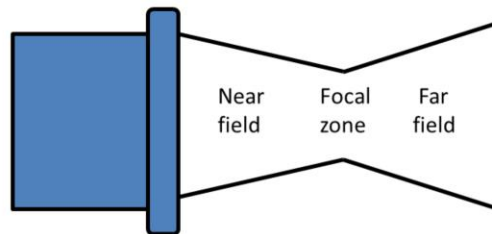
Axial resolution

Higher US frequency
Shorter wavelength
Better axial resolution



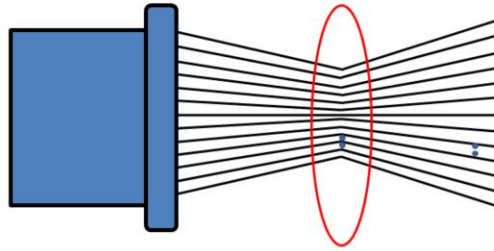
Axial resolution depends on the ultrasound frequency. Since shorter wavelength gives better axial resolution, application of high-frequency ultrasound is suggested for better image quality.

Lateral resolution



Concerning the lateral resolution, it should be noted that the emitted ultrasound does not maintain its linear shape, but becomes centrally narrowed with converging (near-field) and diverging (far-field) parts of the ultrasound beam. The narrowest point between these converging and diverging parts is called focal zone, where the lateral resolution is the best.

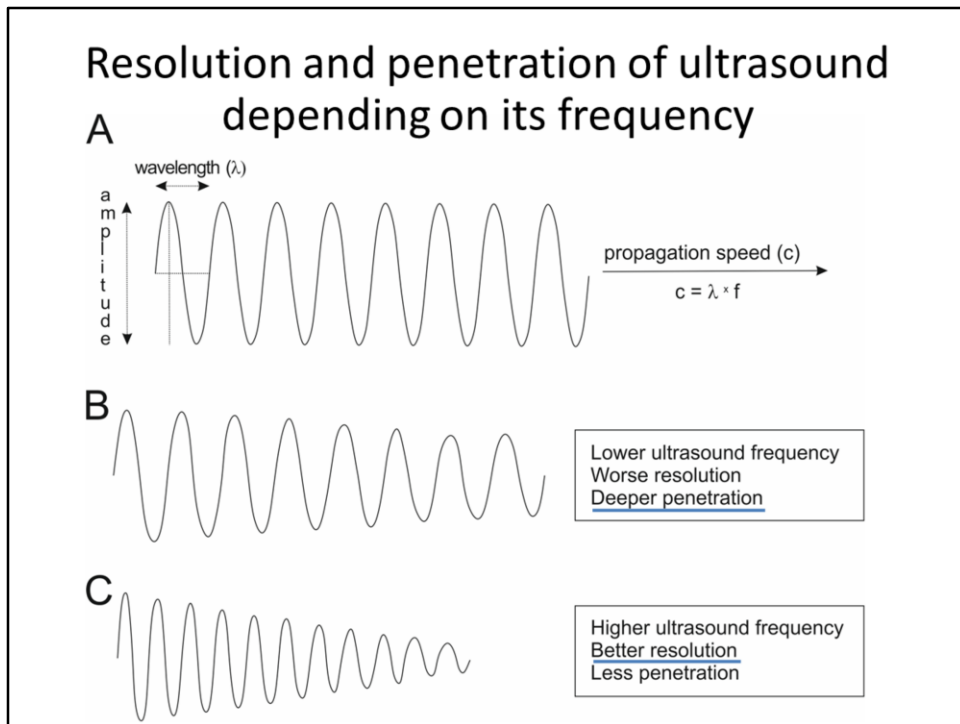
Lateral resolution



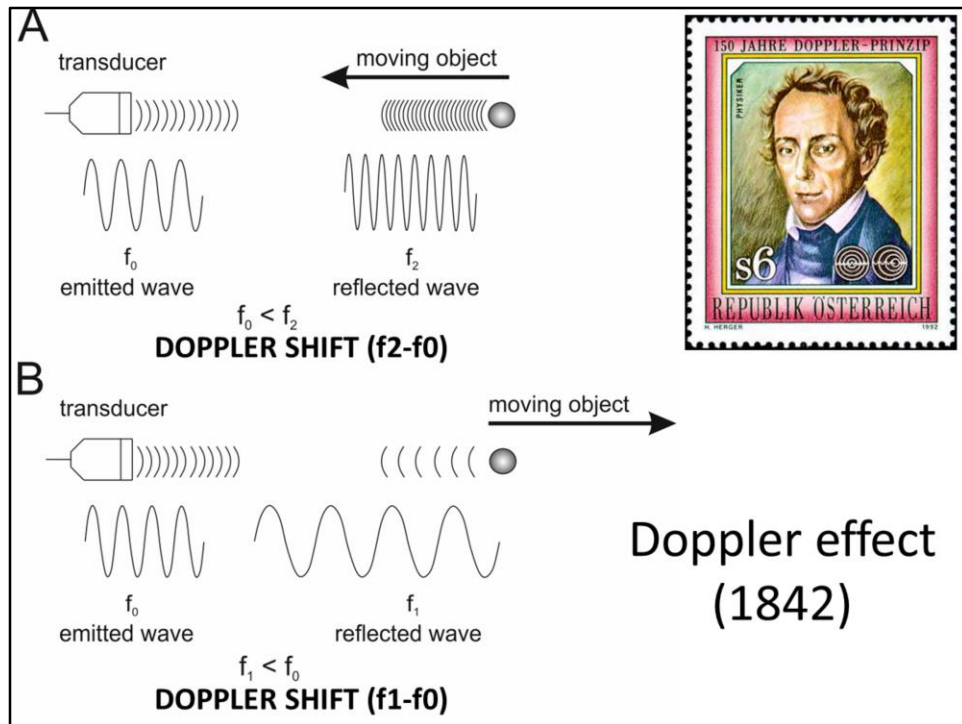
Lateral resolution can be improved by

- larger transducer surface,
- dynamic focusing
- multiple ultrasound beams, generating multiple focal zones.

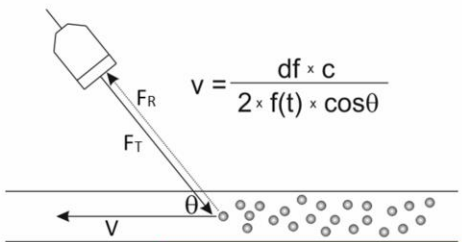
The ultrasound beams here are the most concentrated, therefore assures the best lateral resolution. Lateral resolution can be improved by larger transducer surface, as well as dynamic focusing and multiple ultrasound beams, generating multiple focal zones.



In summary, **low frequency US assures worse resolution but better penetration. In contrary, high frequency US results in better resolution but worse penetration** (high frequency is more attenuated!!!). In clinical practice, excellent resolution and deep penetration would be desired. However, because of the physics of ultrasound, both requirements cannot be fully met at the same time. For good axial resolution high-frequency ultrasound, for better penetration low-frequency ultrasound is required. **Therefore, the optimum ultrasound frequency should be chosen, which allows to visualize the structure of interest but also gives good resolution.**



The **Doppler effect** means that if the source of a wave moves towards the observer, the frequency will be higher, however, if the source of ultrasound moves away from the observer, the frequency will be lower than the emitted frequency. **The difference between the frequencies of the reflected echo and the emitted ultrasound is the Doppler shift.** The phenomenon was named after Christian Doppler and it is known as the Doppler effect.



$$V = \frac{df \times c}{2 \times f(t) \times \cos \theta}$$

$$\Delta F = (F_R - F_T) = \frac{2F_T V \cos \theta}{C}$$

Where: $V = \Delta F \, c / 2F_T \cos \theta$

$\Delta F \equiv$ Doppler shift frequency (the difference between the transmitted and received frequencies)

$F_T \equiv$ transmitted frequency

$F_R \equiv$ reflected frequency

$V \equiv$ velocity of the blood flow towards the transducer

$C \equiv$ velocity of sound in tissue

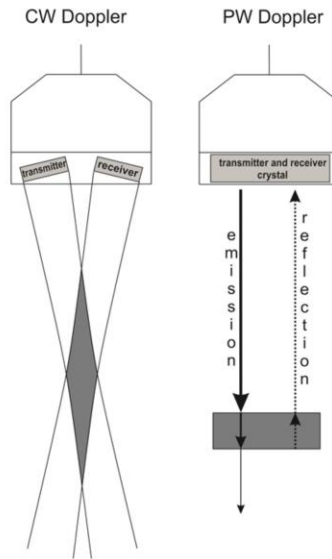
$\theta \equiv$ the angle between the sound beam and the direction of moving blood

The Doppler equation



According to the Doppler effect, moving blood cells change the ultrasound frequency. The **difference between the frequencies of the detected and transmitted waves (frequency shift or Doppler shift) is directly proportional to the velocity of the blood cells**. The Doppler shift, as well as the Doppler angle (the angle between the ultrasound beam and the flow vector) can be measured, the transmitted frequency and the propagation speed of the ultrasound are known, thus the Doppler equation can be used in the clinical routine to measure blood flow velocity.

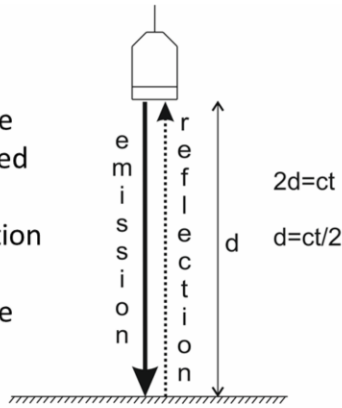
CW and PW Doppler



Based on the function of pizeletric crystal, 2 Doppler systems are known. In the continuous wave Doppler one crystal continuously emits ultrasound and an another crystal continuously detects the reflected echo. In the PW system, however the same crystal emits ultrasound and detects the reflected echoes.

Advantage of PW Doppler over CW Doppler

t: time interval between the emission of the ultrasound pulse and the reception of the reflected echo
c: speed of ultrasound propagation
 → the distance between the transducer and the target can be calculated!



If:

$c=1540 \text{ m/s}$, time delay $=52 \mu\text{s} (=0.000052 \text{ s})$

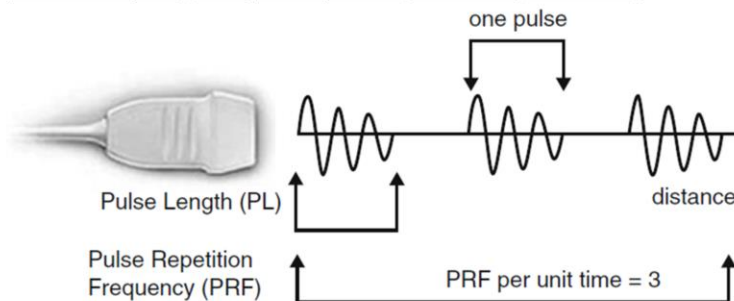
→ $d=1540 \text{ m/s} \times 0.000052 \text{ s} / 2=0.04 \text{ m} (4 \text{ cm})$

The PW Doppler system allows **to measure or control the time interval between US emission and echo reception**, thus it makes possible to determine the distance between the US source and the target.

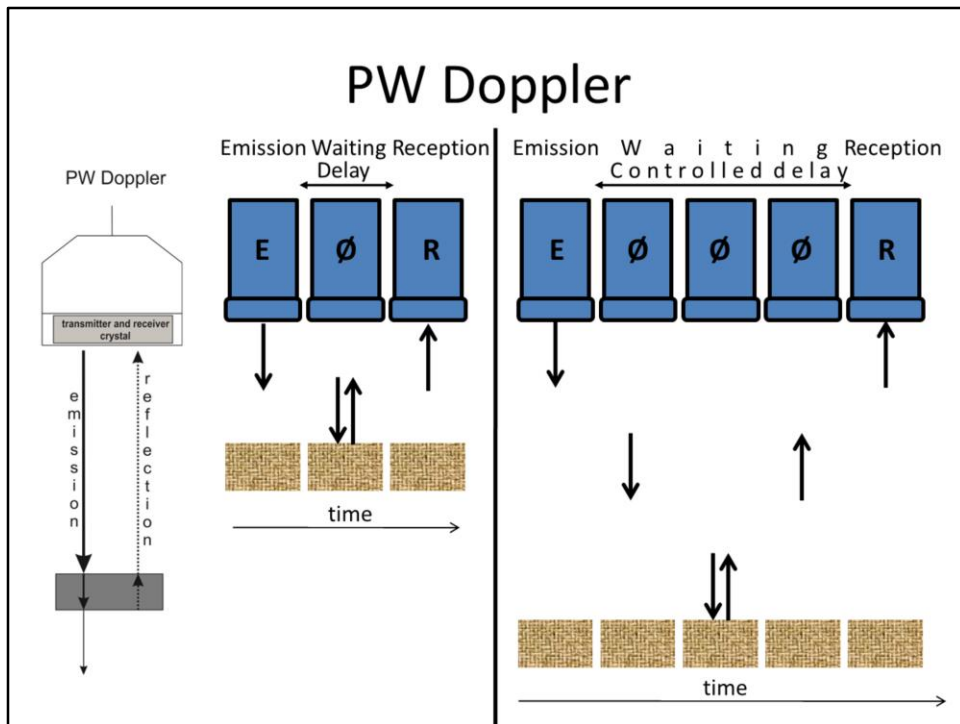
PW Doppler

Pulse Repetition Frequency (SCALE)

- Ultrasound waves are generated in short pulses that usually consist of two or three cycles of the same frequency
- Number of pulses transmitted in a second: PRF
- PRF in medical imaging devices is between 1-10 kHz
- **PRF=sampling frequency=sample rate (SCALE!!!)**

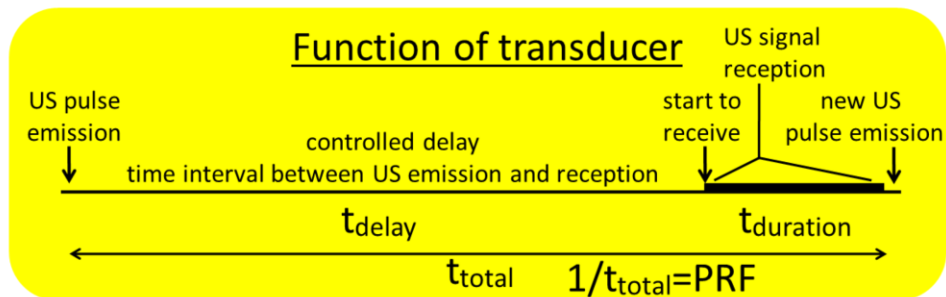


In PW mode ultrasound waves are generated in pulses that usually consist of two or three cycles of the same frequency. The number of pulses transmitted in a second is known as the pulse repetition frequency (PRF). **The PRF in medical US devices is between 1-10 kHz.** It means that 1000 -10 000 US pulses are sent in a second. The transmitted ultrasound pulses serve for measurement, data collection, therefore **the pulse repetition frequency is equivalent to the sampling frequency.**



Let's examine the function of a PW Doppler transducer. As it was mentioned **in the PW system the same crystal emits US and detects or receives US signals**. It means that the piezoelectric crystal at first emits US pulse. After the US pulse is emitted, the crystal switches to receiving mode, but only after a certain time period. This time interval between US emission and echo reception can be controlled. Certainly if the crystal switches to receiving mode after a short period, it will detect US signals returning from the superficial regions. However, if the crystal switches to receiving mode after a longer time interval, the crystal will detect US signals returning from the deeper regions. **This is the main advantage of the PW system: this mode is site specific, in other words it is able to differentiate structures being at different depth.** It is easy to understand that the **duration of reception will define the thickness of the sample volume (SV)**. If the receiver is opened for longer time period, this will receive echoes from a larger SV, however if it is opened for a short period, that is closed early, it will receive echoes from a small SV.

Time-based gating in PW Doppler mode



- $t_{\text{delay}} \rightarrow$ **insonation depth**, $t_{\text{duration}} \rightarrow$ **sample volume**
- The next US pulse can only be emitted after return of the reflected signal
- **PRF (frequency of pulse transmission) cannot be increased above a certain value!!!**
- **Insonation of a deeper structure $\rightarrow$ lower PRF limit**

This is the so-called time-based gating technique. The time delay between US pulse emission and echo reception, as it was demonstrated, determines the insonation depth, while the duration of reception will define the SV. **It is easy to understand that the new pulse cannot be sent before the arrival of the reflected echo. It means that the PRF is limited, it cannot be increased above a certain limit. Especially not if a deeper structure is insonated, because US signal, echo returns back to the transducer significantly later, therefore the new US pulse can also be emitted later.**

Disadvantage of PW Doppler compared with CW Doppler

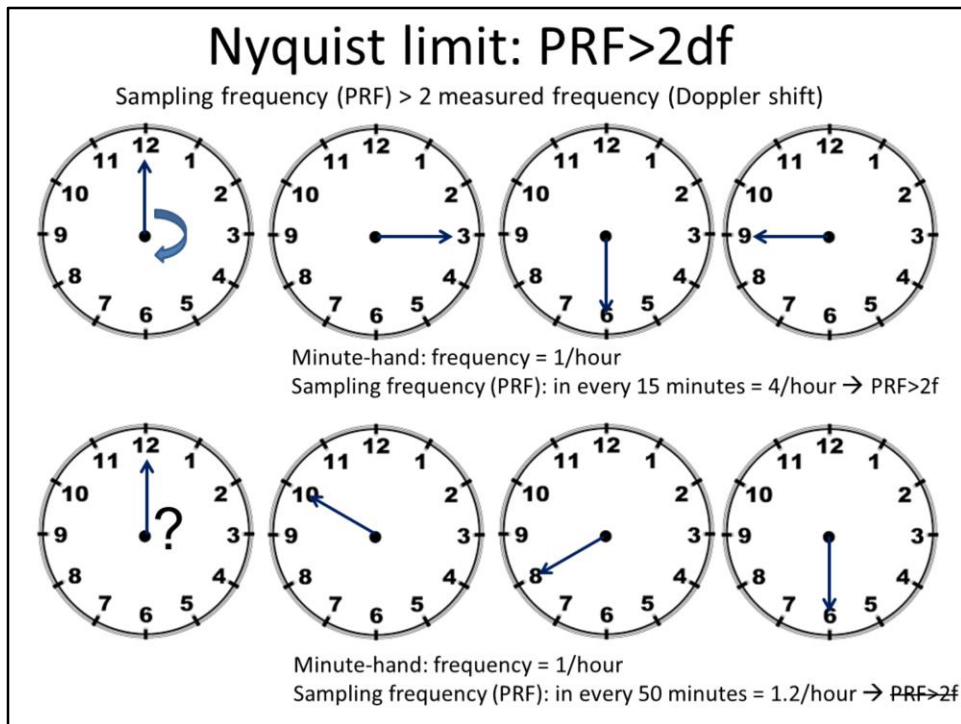
- **Detection of high Doppler shift (high flow velocity) is not always possible (especially not from deeper tissue) by PW Doppler**

The advantage of the PW Doppler is that it is site specific. However, there is a disadvantage, too. Namely, very high flow velocity cannot be determined by the PW system.

Disadvantage of PW Doppler compared with CW Doppler

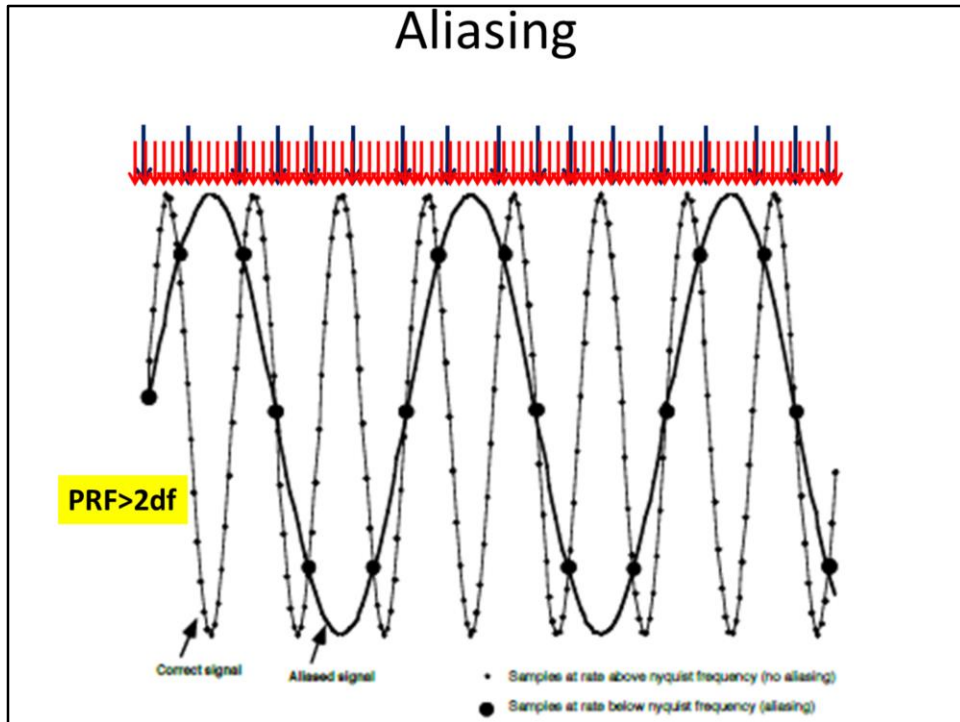
- Detection of high Doppler shift (high flow velocity) is not always possible (especially not from deeper tissue) by PW Doppler
 - High flow velocity → high Doppler shift frequency
- 
- Measurement of high Doppler shift frequency requires higher PRF → **Nyquist limit**: the sampling rate (PRF) should be more than double of the Doppler shift frequency ($PRF > 2df \rightarrow PRF/2 > df$)
 - PRF cannot be increased above a certain limit

It is well known that high flow velocity results in high Doppler shift. It is also known that correct measurement of higher Doppler shift requires higher PRF (in the practice we have to increase the scale). This is because of the so-called Nyquist limit, which says that the Doppler shift can only be measured correctly, if this is not more than half of the PRF, in other words, the PRF should be more than double of the Doppler shift. It is a general rule: the sampling frequency should be more than double than the measured frequency.

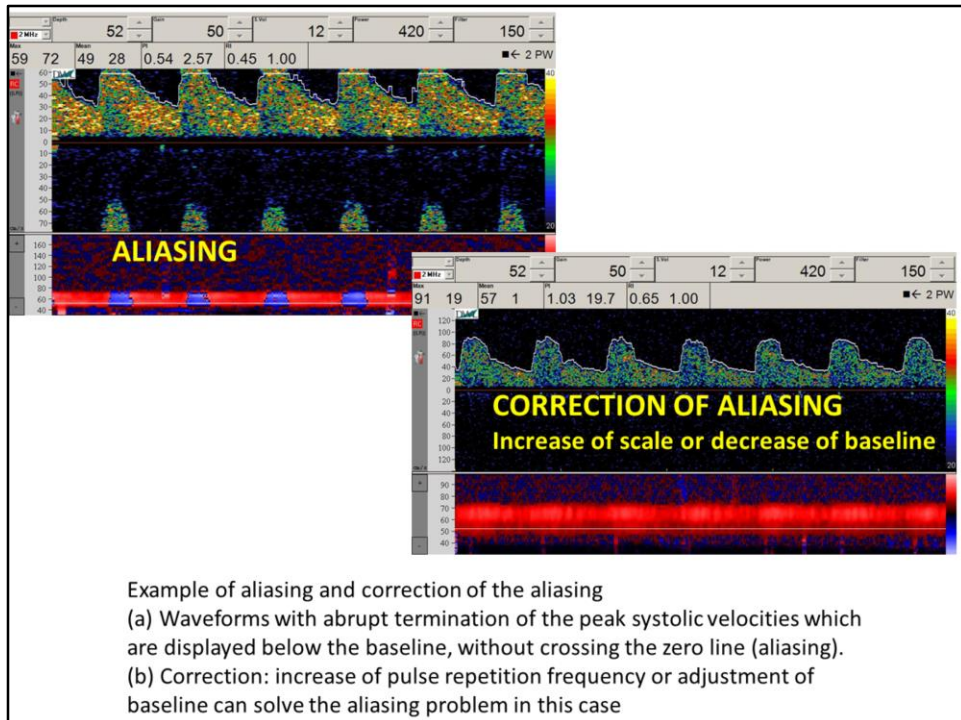


Let's see what happens if the sampling frequency is less than double of the measured frequency. There is a clock. The minute hand goes around in an hour, so the frequency is 1/hour. If the sampling frequency is more than 2/hour, let's say 4/hour, we can detect the direction and the velocity of the minute hand. But see the lower figure! Here, seemingly the minute hand is going to the wrong direction. Why? Because the sampling frequency is less than double of the measured frequency. In this case data were only collected in every 50 minutes, that is 1.2/hour. This is below the Nyquist limit. In this case the direction and the velocity of the minute hand cannot be determined correctly. This example explains the aliasing phenomenon.

Aliasing



A example can be seen here. **The sinus curve with thin line demonstrates the Doppler shift.** If the measurement frequency (sampling rate) is high (red arrows), the Doppler shift can be measured correctly. However, if the sampling rate (longer, blue arrows) is lower than the double of the Doppler shift, correct measurement is not possible any more. (See the sine curve determined by the large dots)

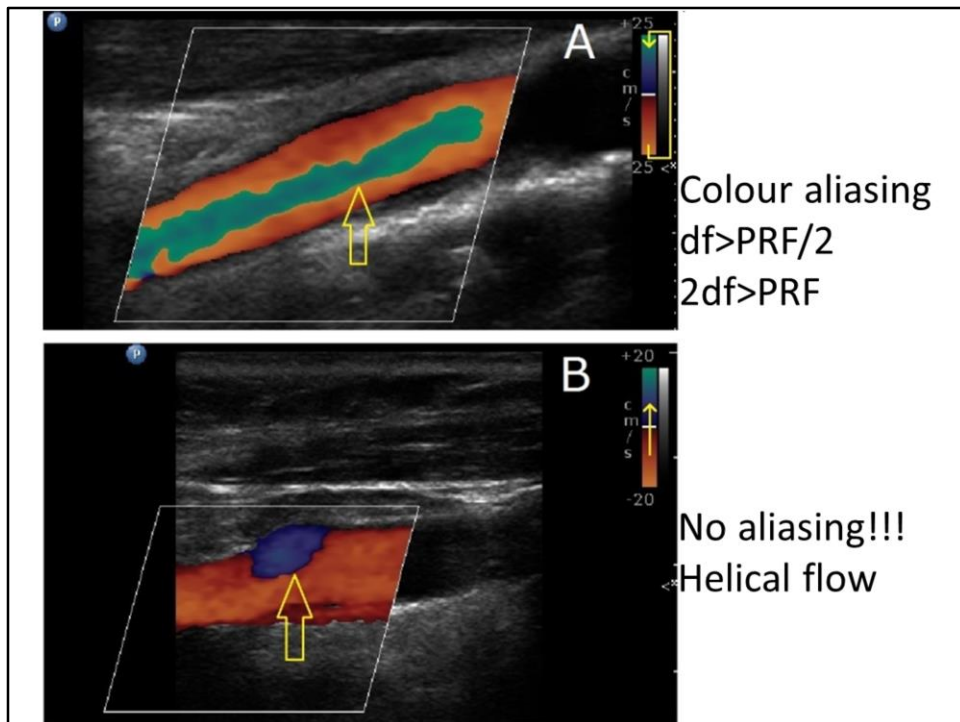


In the clinical practice spectral aliasing can be seen as an abrupt termination of the peak systolic velocities which are displayed below the baseline. Aliasing can be avoided by increasing the PRF, or adjusting the baseline. Certainly, if the peak systolic flow velocity is too high (500-600 cm/s), it may happen that the PRF cannot be increased further, and the very high flow velocity cannot be measured.

Aliasing is more likely if

- The PRF is low
 - The flow velocity is high
 - The object is in the deeper region → the echo requires longer time to return to the transducer → PRF cannot be increased above a certain limit
- 
- CW Doppler

Aliasing is more likely if the PRF is low, the flow velocity is high, or when the object of interest is in the deeper region. In this case the echo requires longer time to return to the transducer, therefore the PRF cannot be increased above a certain limit. In contrast with the PW Doppler, there is no velocity limit when CW Doppler is used, because in the continuous mode one crystal only emits US pulses while another crystal always receives the reflected or scattered echoes. However, the main disadvantage of the CW Doppler is that it is not site specific.



Since colour flow map is based on flow velocity measured by pulsed-wave technology, aliasing occurs if the frequency shift is higher than half of the PRF. Low PRF value and high flow velocity especially in the deeper regions increase the probability of **aliasing** that can be recognized in colour flow map as an **apparent flow reversal**: colour changes from the maximum velocity in one flow direction to the maximum velocity in the opposite direction without crossing the zero line. In the lower figure one colour changes to other colour with crossing the zero line, indicating a **real flow reversal**.

THE END