UniversitätsSpital Zürich

University of Zurich[UZH]

Physics of Clinical Ultrasound

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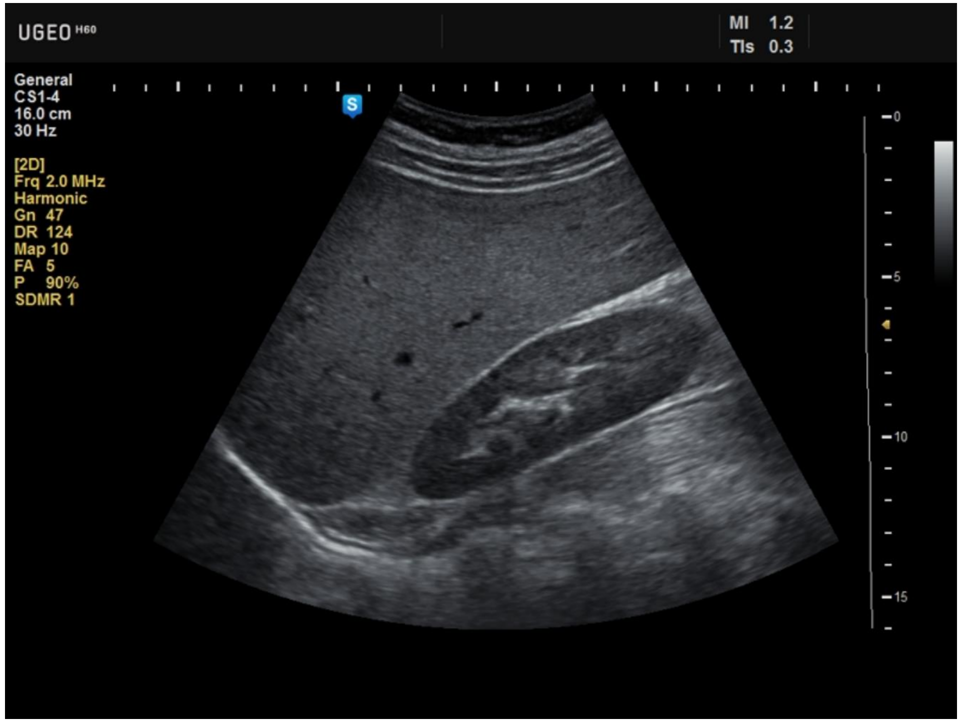
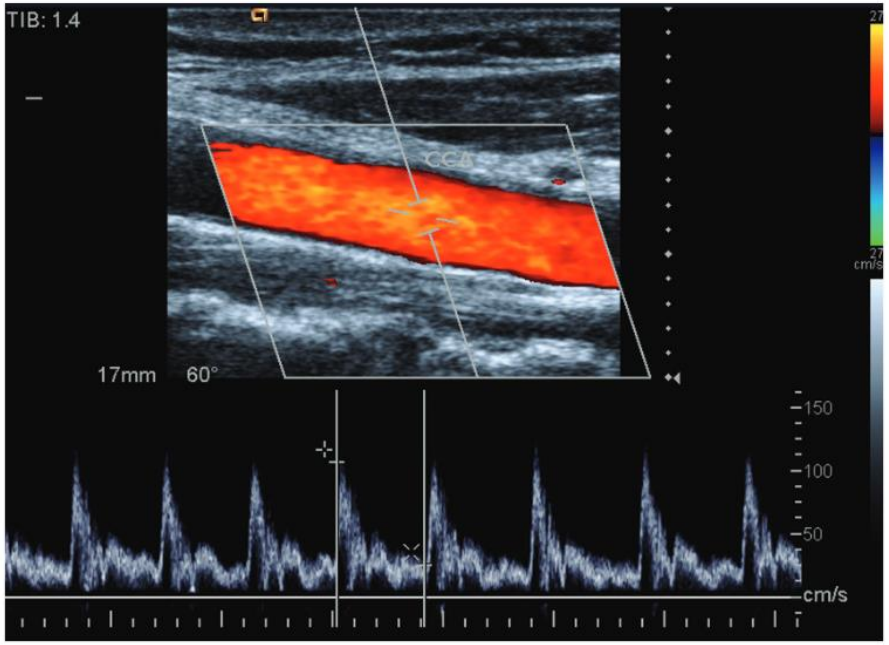
Institute of Diagnostic and Interventional Radiology

January 2021



UGEO H60
MI 1.2
TIs 0.3
General
CS1-4
16.0 cm
30 Hz
[2D]
Frq 2.0 MHz
Harmonic
Gn 47
DR 124
Map 10
FA 5
P 90%
SDMR 1



TIB: 1.4
17mm
60°
150
100
50
cm/s

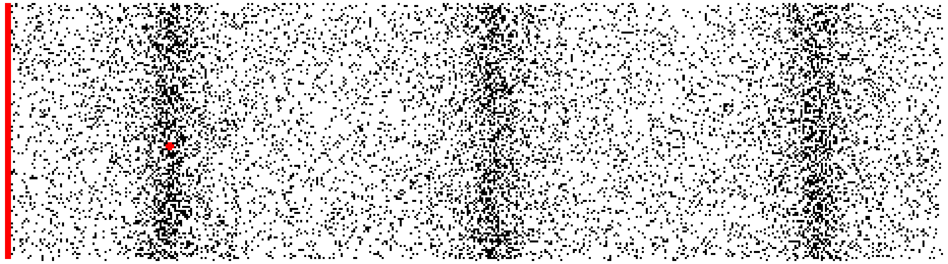
Wave physics: basics

Ultrasound waves

Mechanical waves: they need a medium to be propagated

Sound waves: Pressure field (compression and rarefaction)

<u>Longitudinal wave</u>: oscillations of particles along the propagation direction



Energy transfer without transferring matter

Ultrasound waves

Mechanical waves: they need a medium to be propagated

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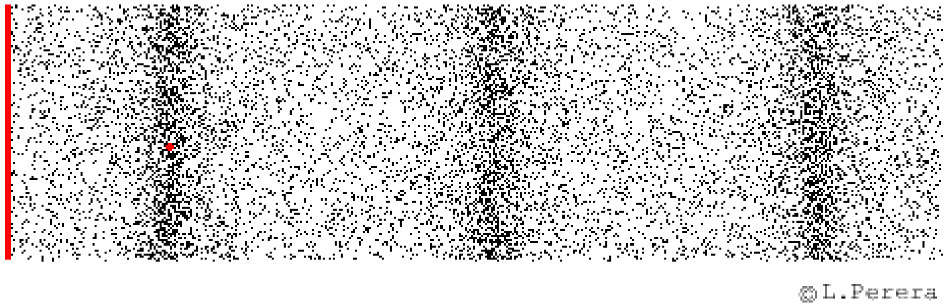
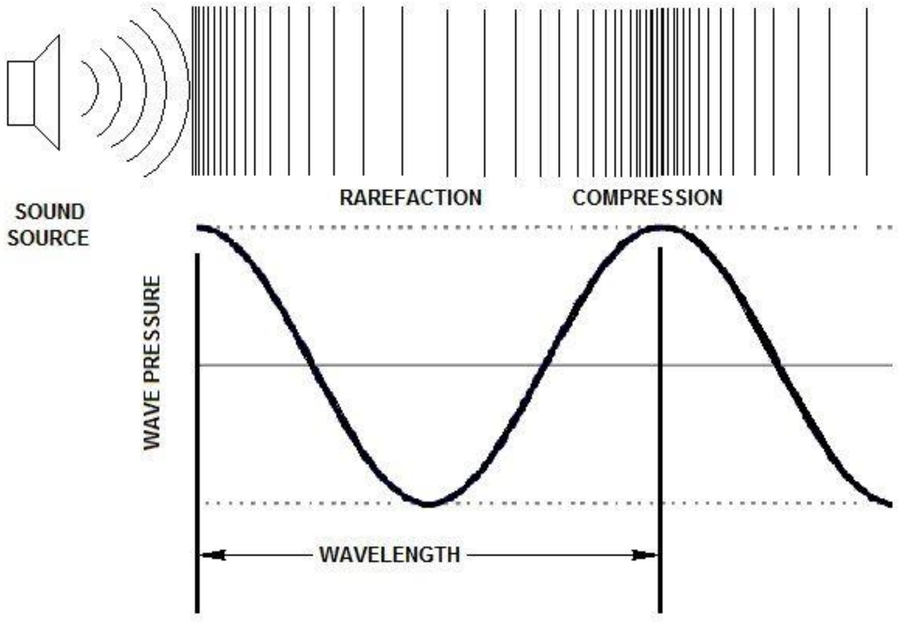


Energy transfer without transferring matter



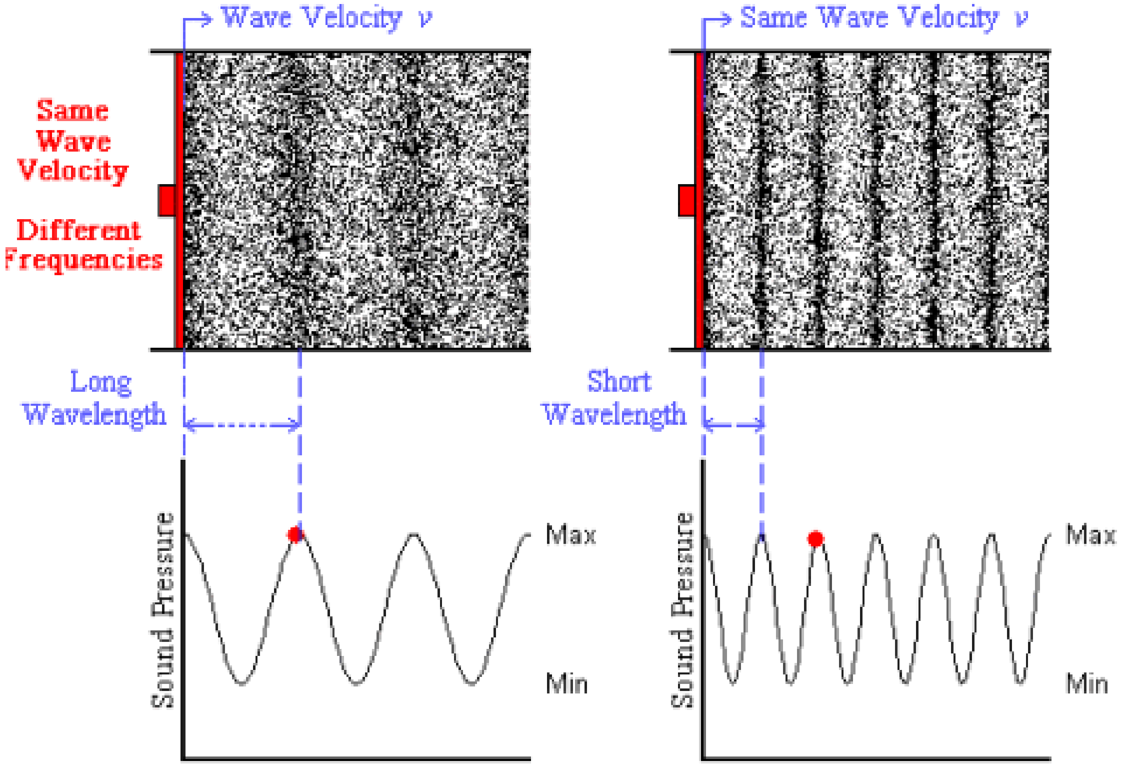
http://lossenderosstudio.com/rarefaction.jpg

Frequency, speed, and wavelength

Frequency (f): oscillation cycles per second (property of the source) [Hertz, Hz = 1/s]

Speed (c): The speed of propagation of sound waves (property of the medium) [m/s]

Wavelength (λ): Distance between two similar points on successive waves [m]



isvr

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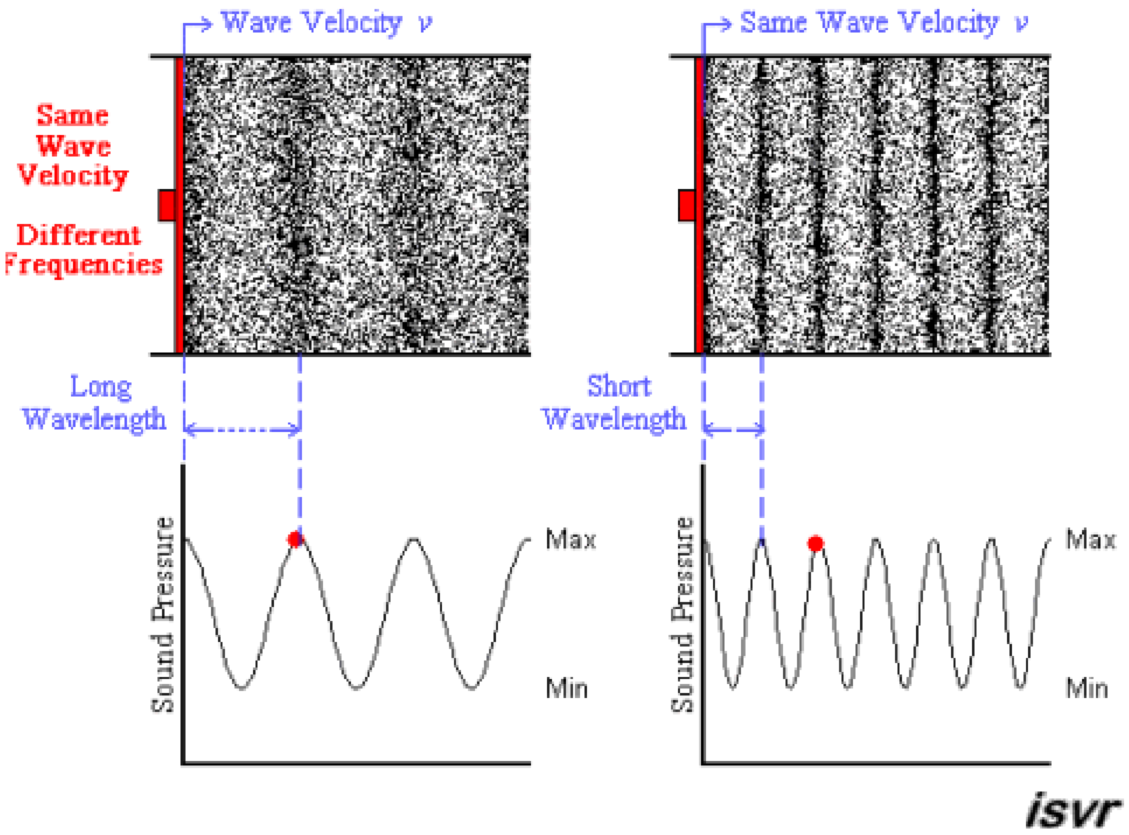
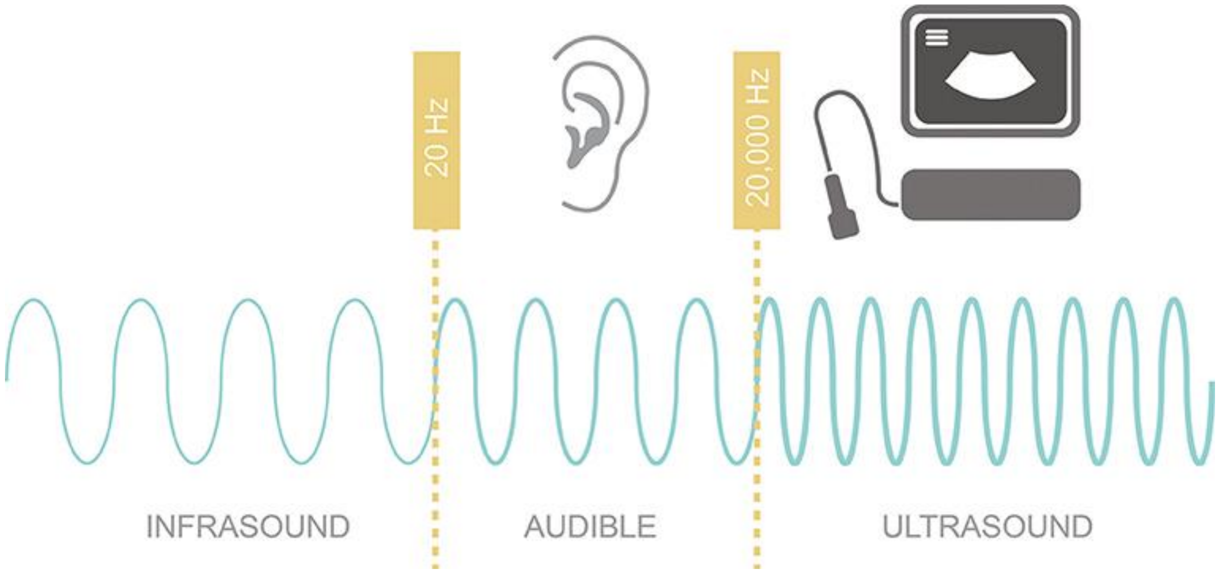
Wavelength (λ): Distance between two similar points on successive waves [m]

$$\boxed{\lambda = \frac{c}{f}}$$

Related to spatial resolution of ultrasound images



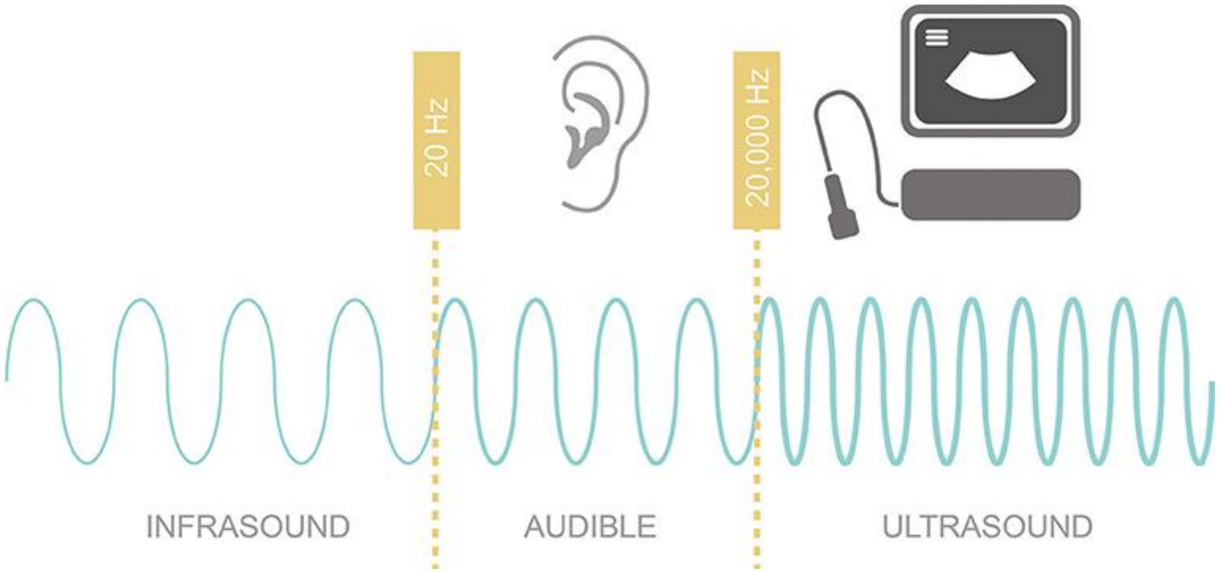
Some numbers



Most common in medical: 2–15 MHz

[El-Baba et al., 2020]

Some numbers



Material	c (m s^{-1})
Liver	1578
Kidney	1560
Amniotic fluid	1534
Fat	1430
Average tissue	1540
Water	1480
Bone	3190–3406
Air	333

[Hoskins et al., 2010]

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[El-Baba et al., 2020, Hoskins et al., 2010]

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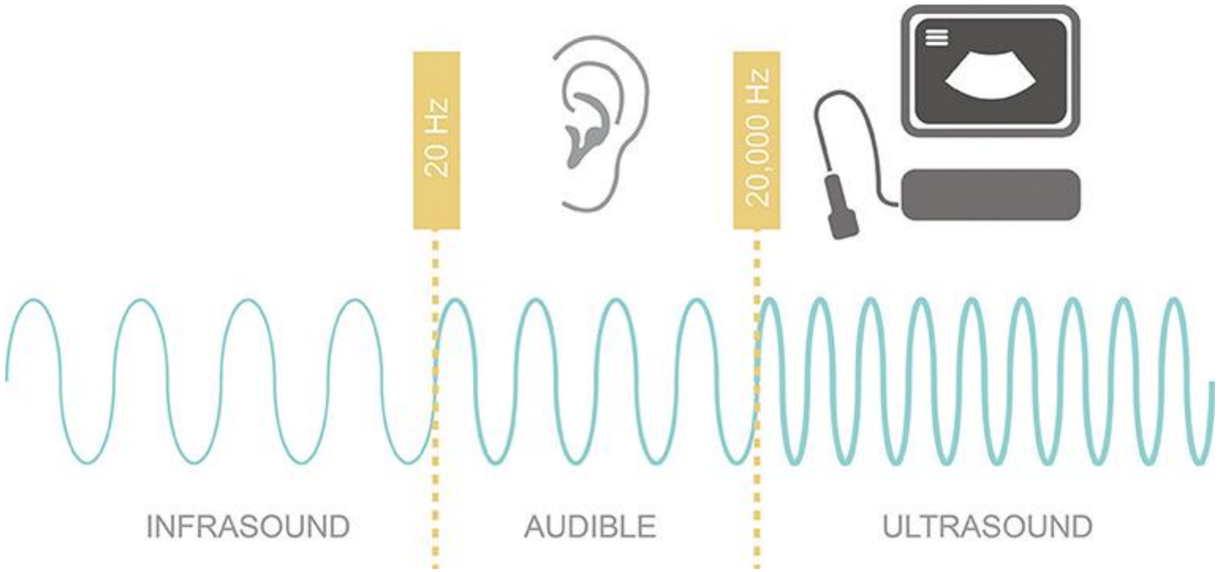

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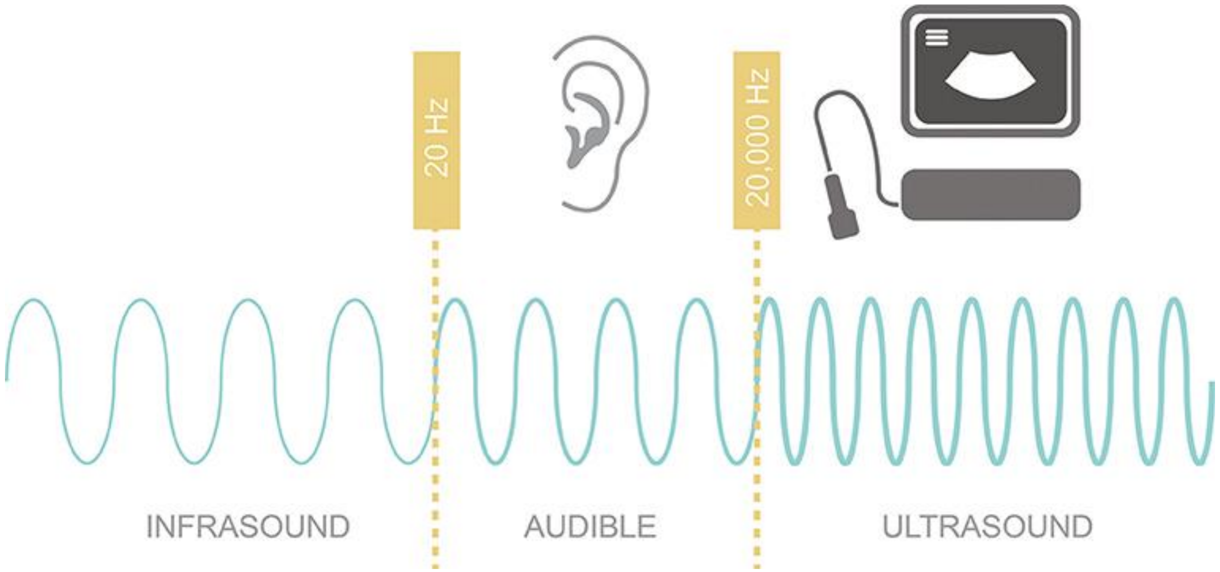

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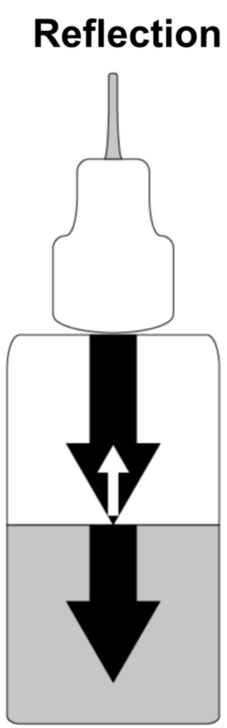
Most common in medical: 2–15 MHz → Wavelength: 0.1 – 0.8 mm

Ability to distinguish two closely spaced targets

[El-Baba et al., 2020, Hoskins et al., 2010]

Tissue interaction

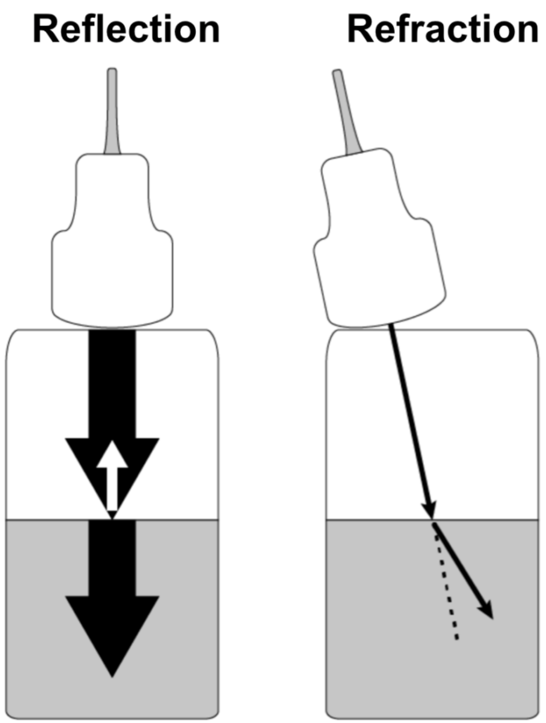


Change in acoustic impedance

$$z = \rho c$$

[density x speed]

Tissue interaction



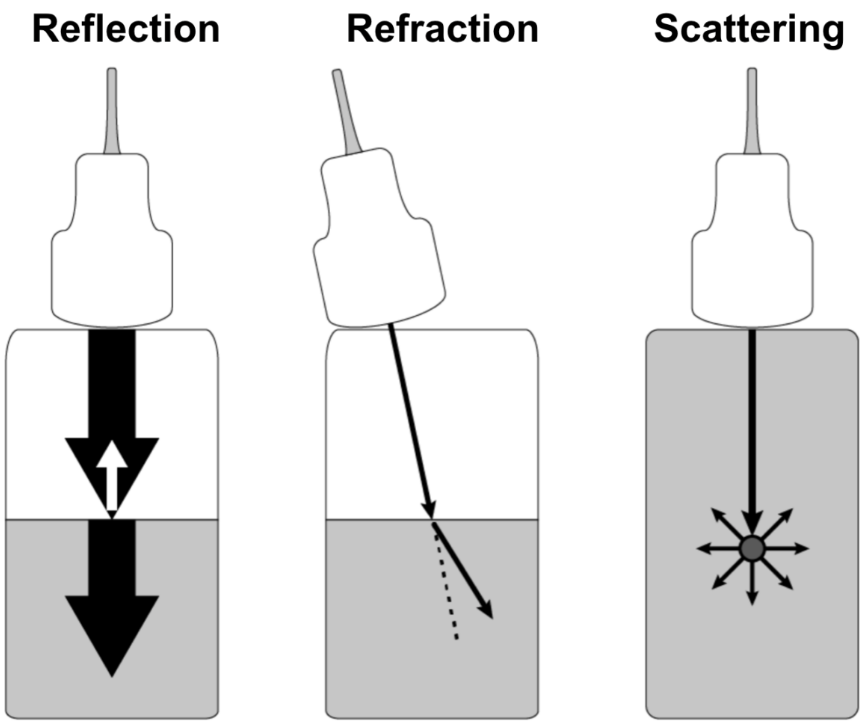
Change in acoustic impedance

$$z = \rho c$$

[density x speed]

[https://icurevisited.com/lus/]

Tissue interaction



Change in acoustic impedance

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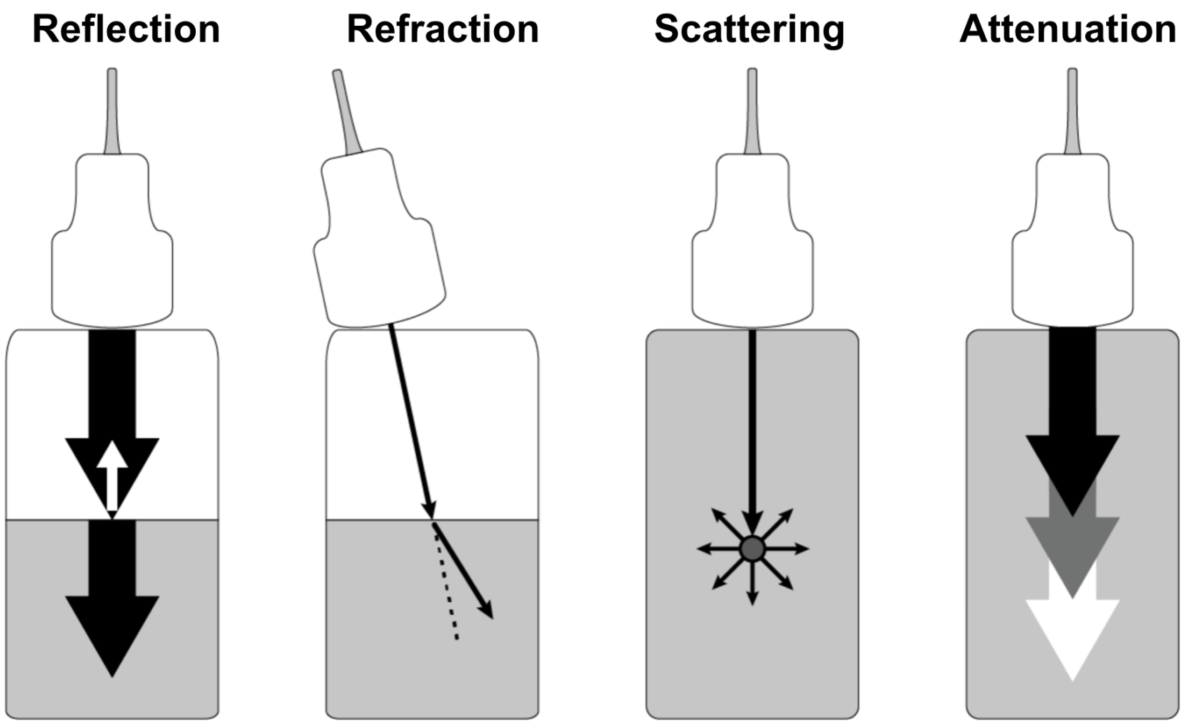
[density x speed]

Structures of size ≤ λ
(blood vessels)

[https://icurevisited.com/lus/]

Tissue interaction



Change in acoustic impedance

$$z = \rho c$$

[density x speed]

Structures of size ≤ λ
(blood vessels)

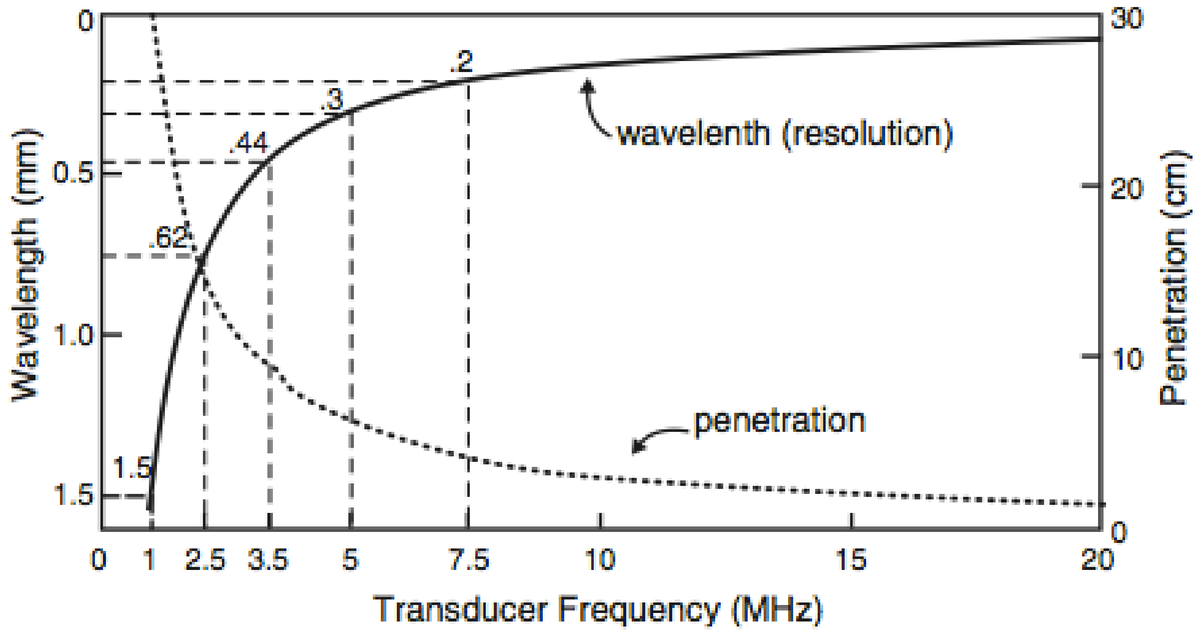
Absorption
(energy into heat)

[https://icurevisited.com/lus/]

Trade-off: resolution - penetration depth

Attenuation linear with frequency.

>> Tissues with higher water content: lower absorption
>> Tissues with higher protein content: higher absorption



[Lawrence, 2017]

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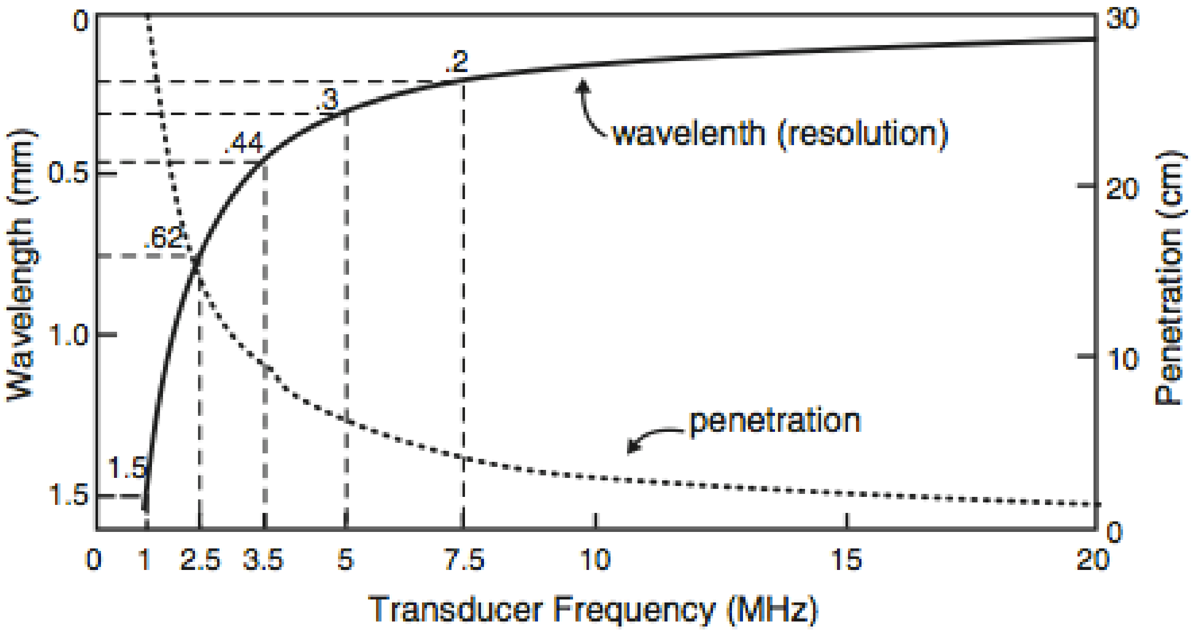


Higher frequency:
- **Shorter wavelength**
- **Better resolution**
- **Smaller penetration**

[Lawrence, 2017]

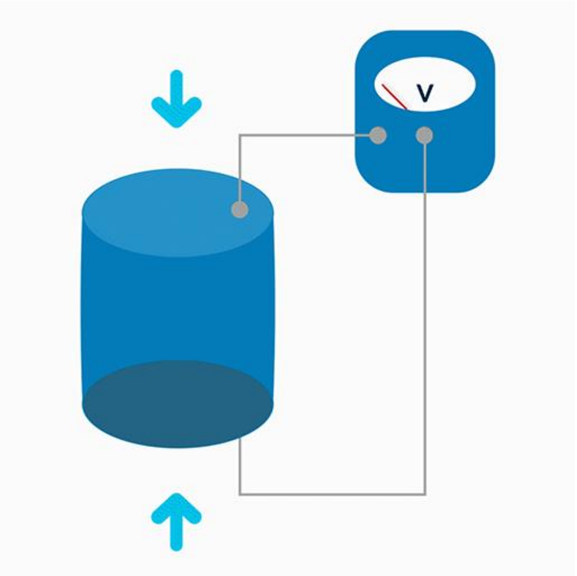
Image formation

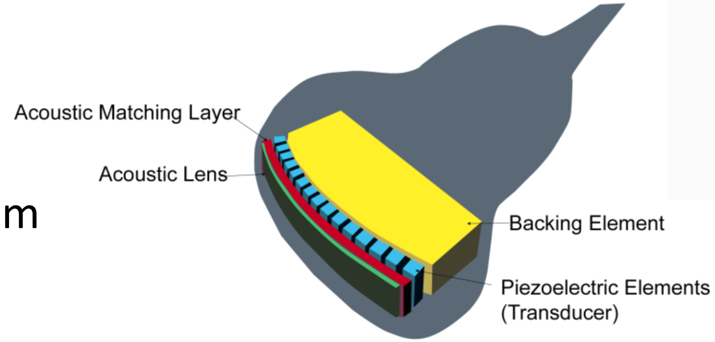
Source of ultrasound waves

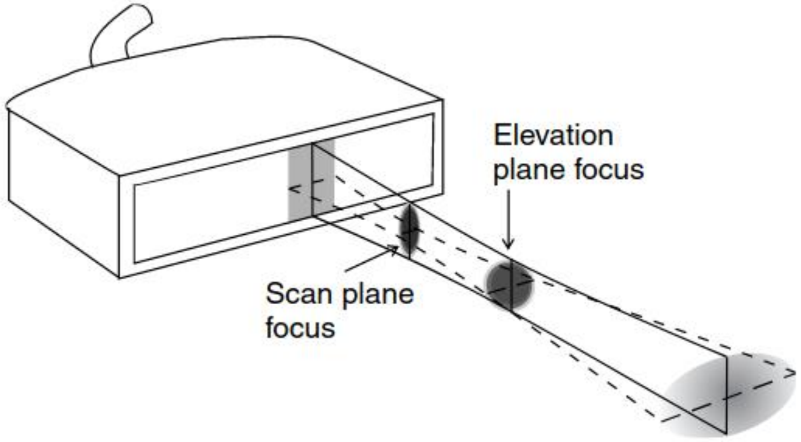
>> Transducers: Piezoelectric crystals **[electrical voltage ↔ mechanical pressure]**

>> US-probe: Typically, 128 transducer elements

>> Finite size transducer element - rectangular beam



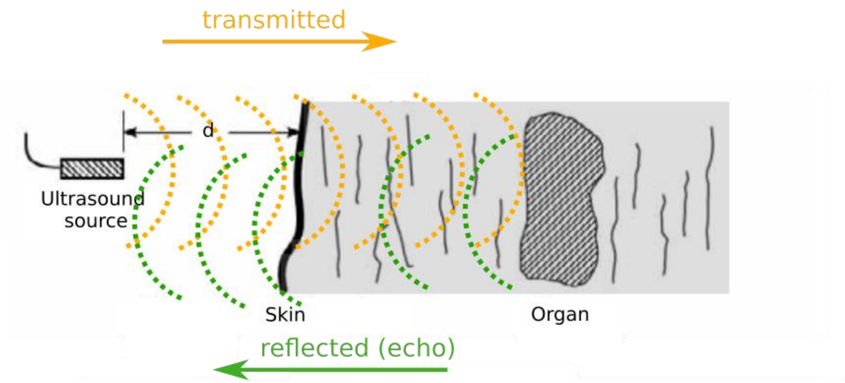




[Hoskins et al., 2010, https://onscale.com]

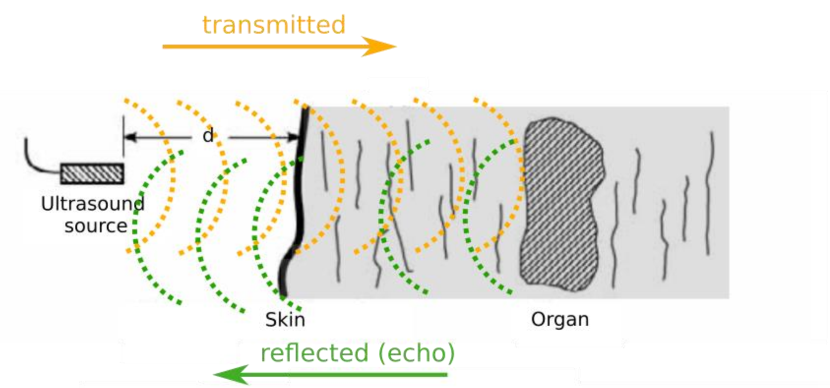
B-mode image formation

1 Ultrasound waves propagate through the tissue. Echoes occur with heterogeneities

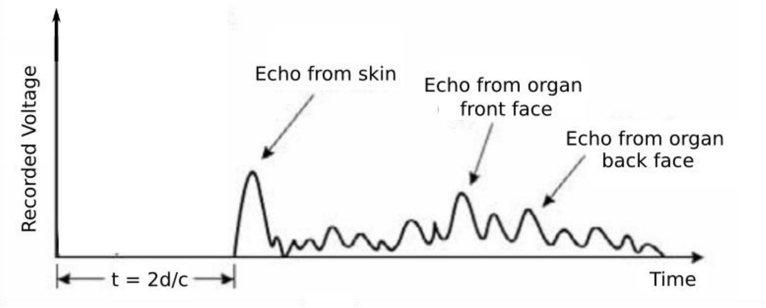


B-mode image formation

1 Ultrasound waves propagate through the tissue. Echoes occur with heterogeneities



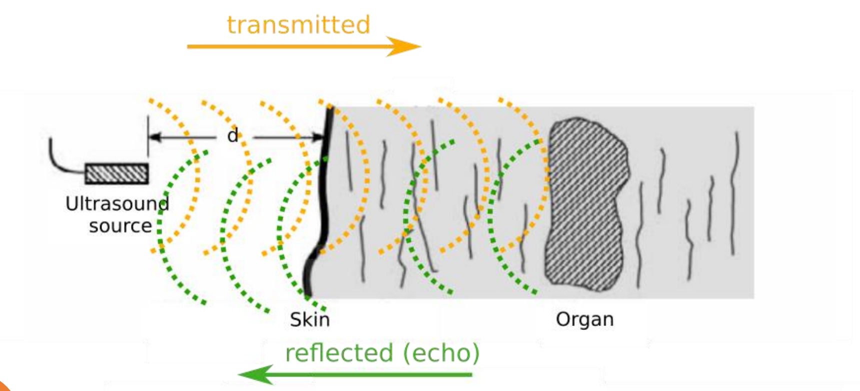
2 A-lines: Recorded signal (amplitude)



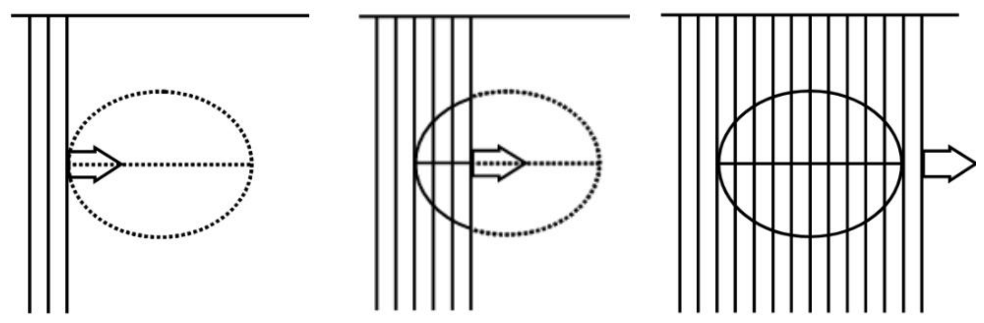
We assume constant velocity (c = 1540 m/s) and transform each time to a position in space.

B-mode image formation

1 Ultrasound waves propagate through the tissue. Echoes occur with heterogeneities



3 The image is built up line by line



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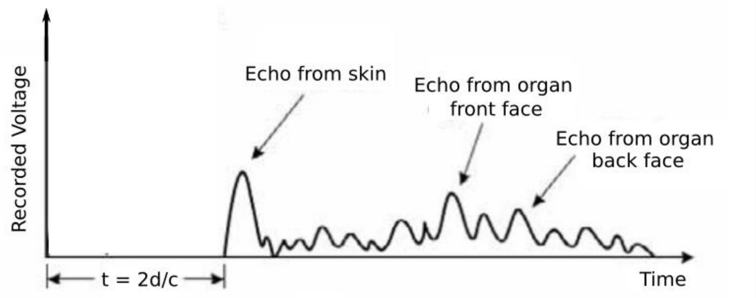
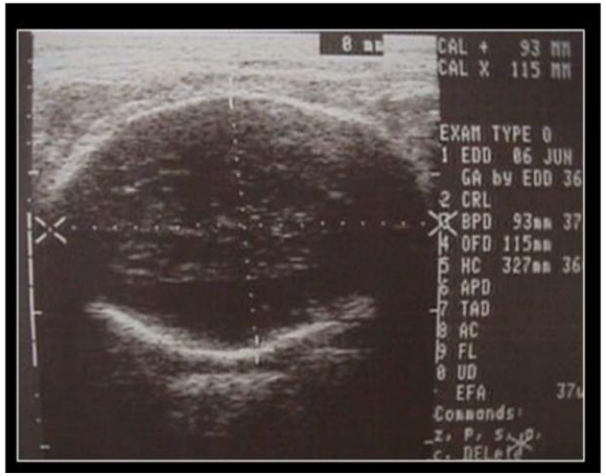


4 Final B-mode image (brightness)



We assume constant velocity (c = 1540 m/s) and transform each time to a position in space.

[Hoskins et al., 2010]

Image artifacts

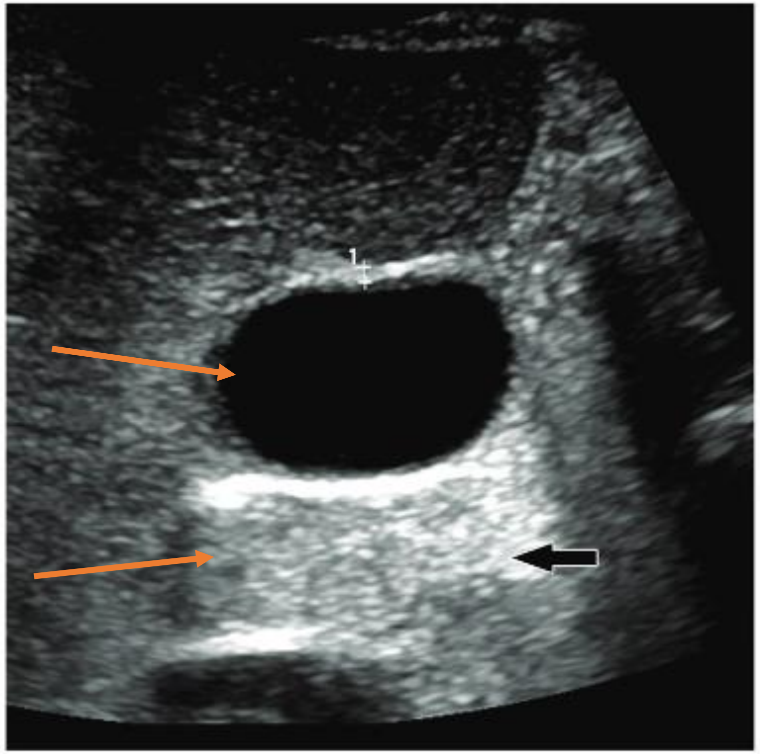
Underlying assumptions:
Uniform attenuation
Constant velocity
Single scattering

Attenuation and reflection artifacts

Increased through transmission

Less attenuating structure. Decreased acoustic impedance.

More transmission

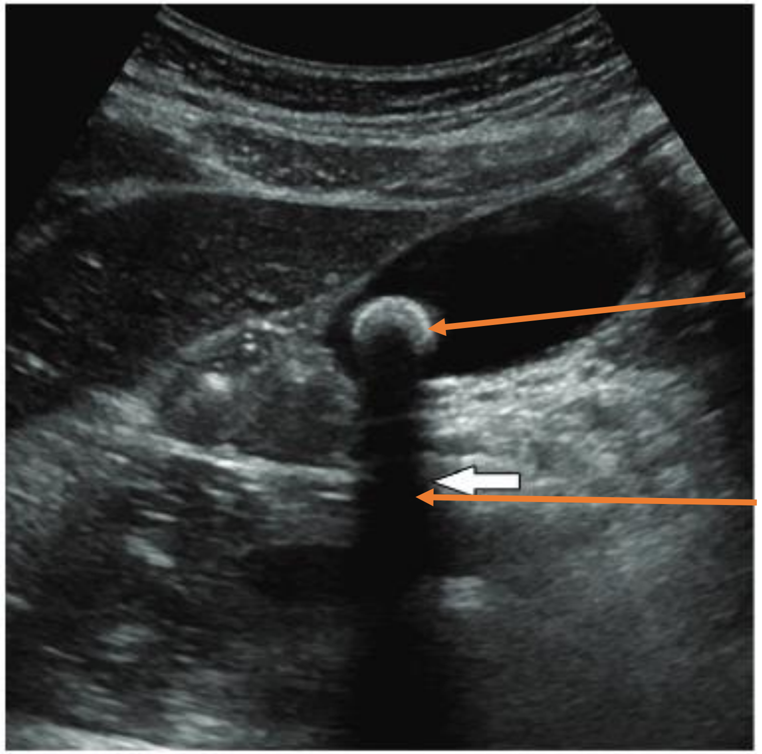


E.g., Cysts or veins

Acoustic shadowing

Strongly absorbing or reflecting structure. Increased acoustic impedance.

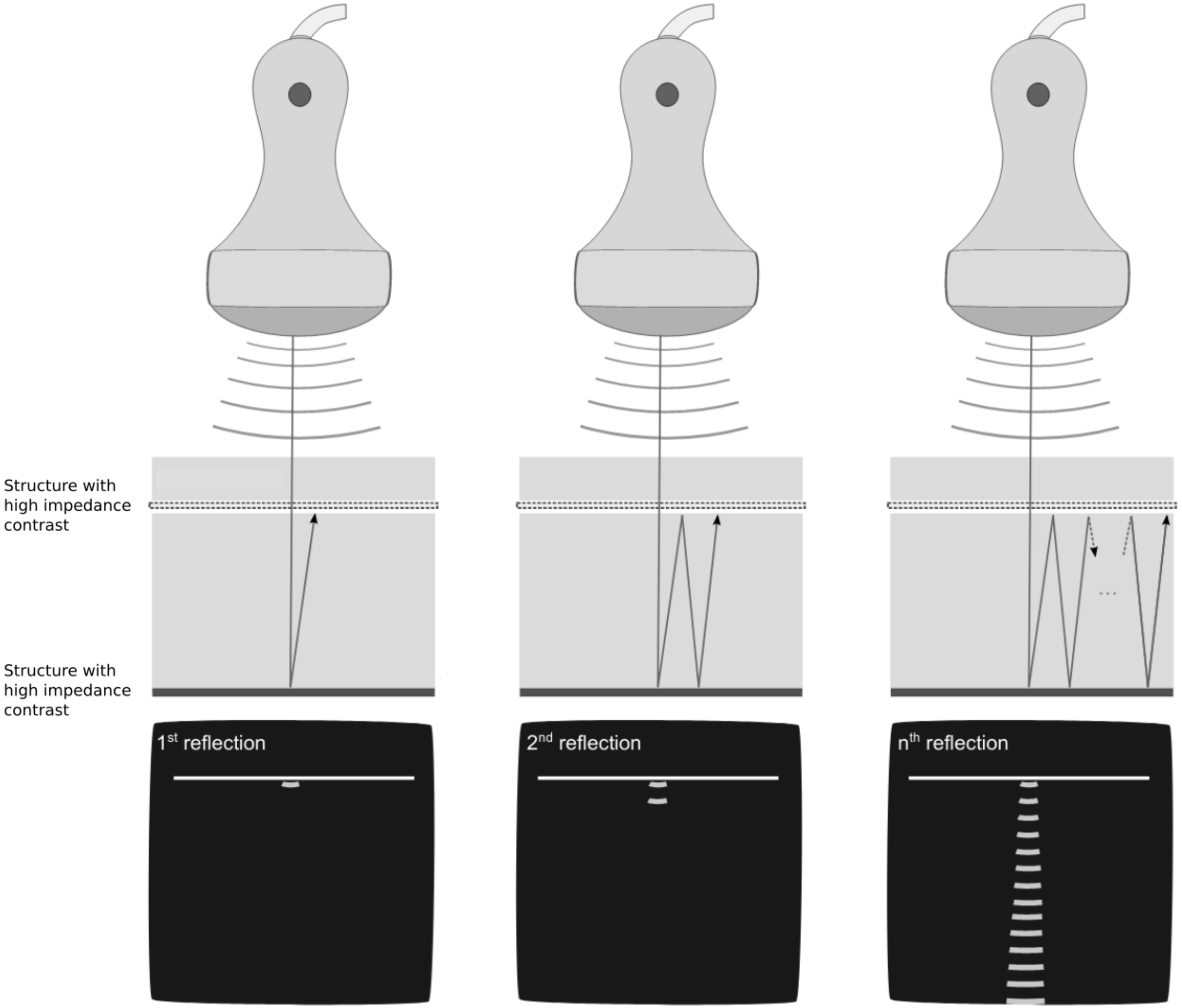
Little transmission



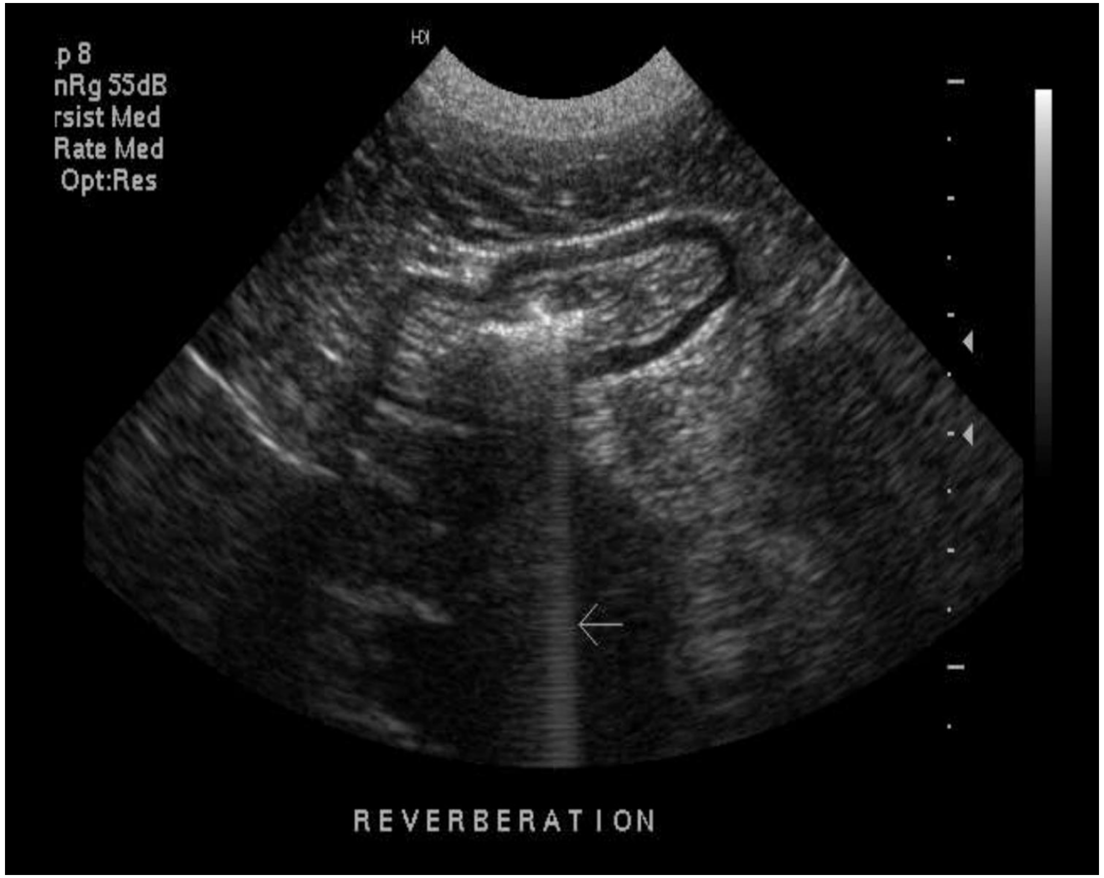
E.g., tumors, calcifications, or foreign bodies

[Baad et al., 2017]

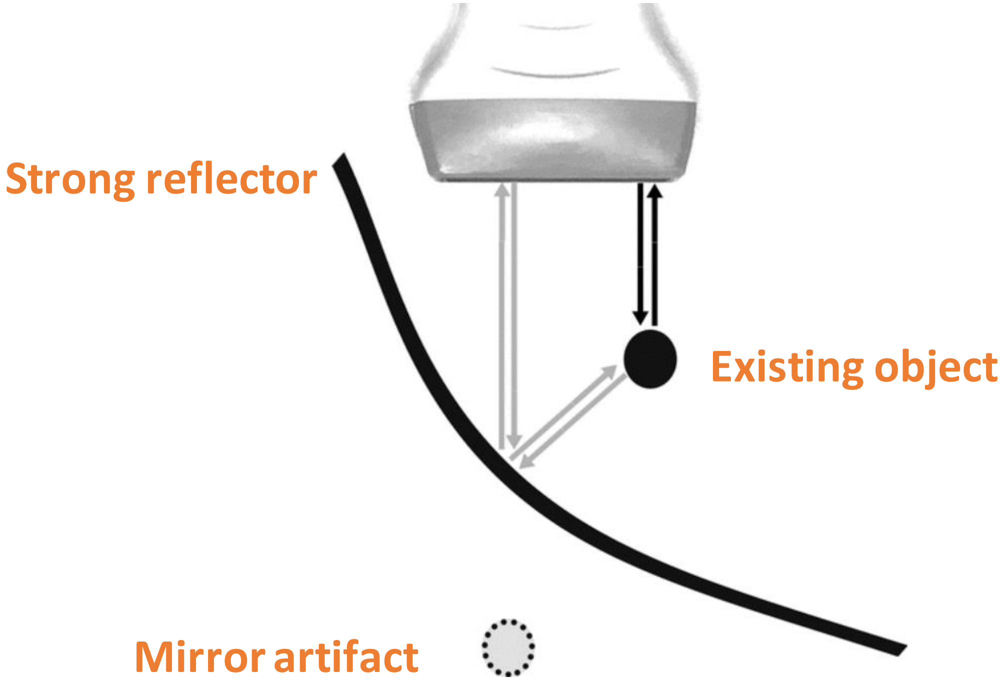
Reverberation artifact: comet tail



[Moshavegh et al., 2016]

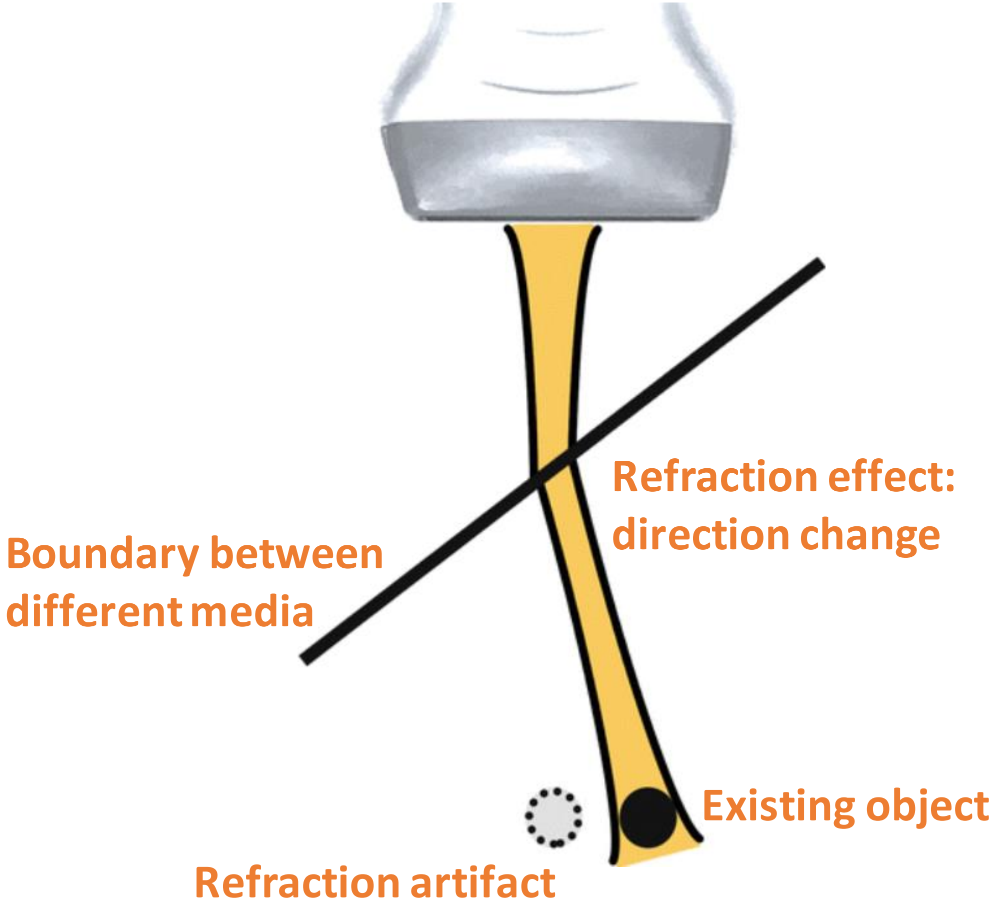


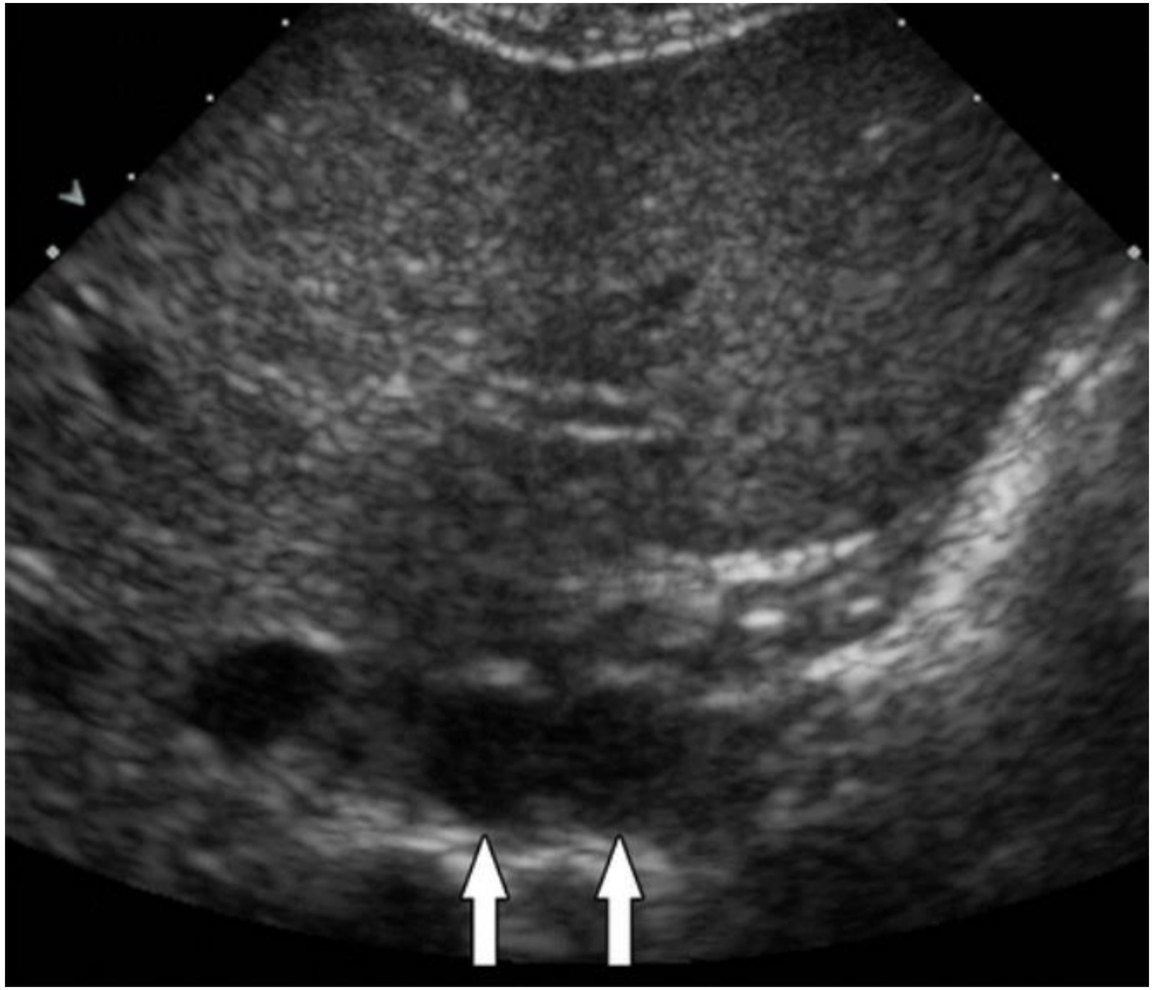
Mirror image artifact



[Baad et al., 2017]

Refraction artifact

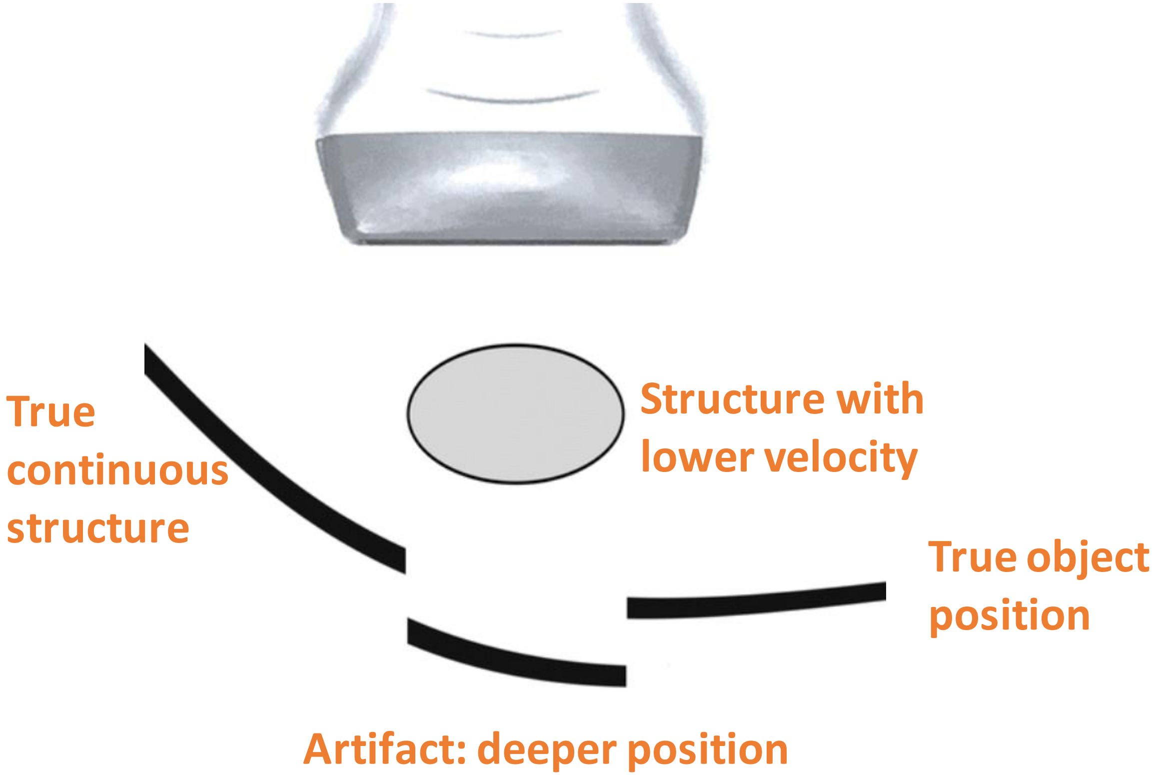


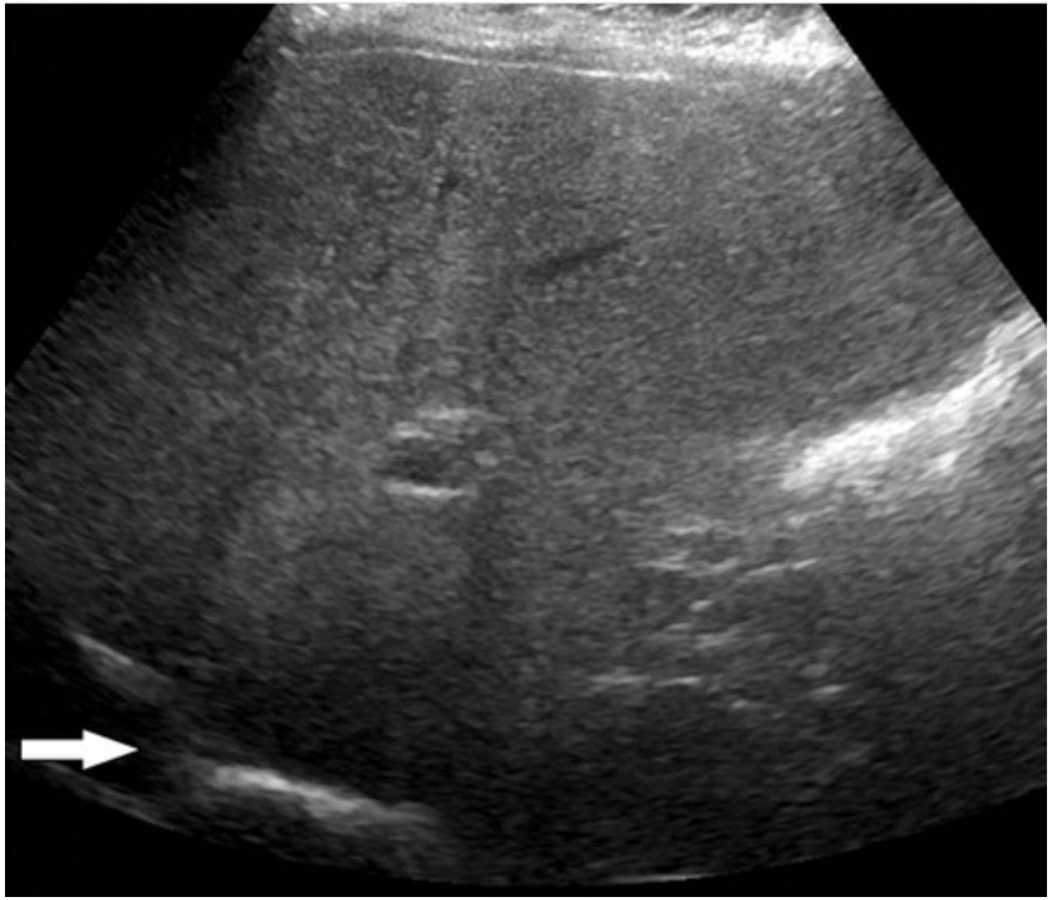


Duplicated

[Baad et al., 2017]

Speed of sound artifact





[Baad et al., 2017]

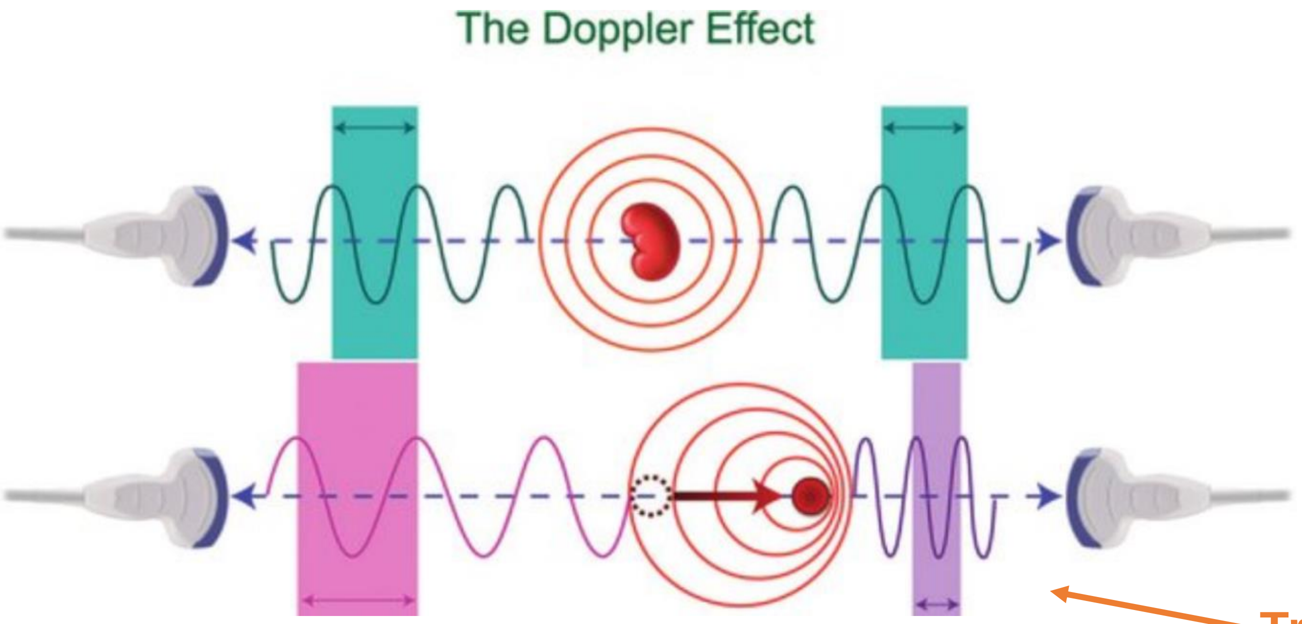
Doppler Ultrasound

It is primarily used to study blood flow
and myocardial motion

Doppler effect

Used to detect the motion of blood and tissue

Doppler effect: change in observed frequency compared to the emitted frequency due to the relative motion between the observer and the source.

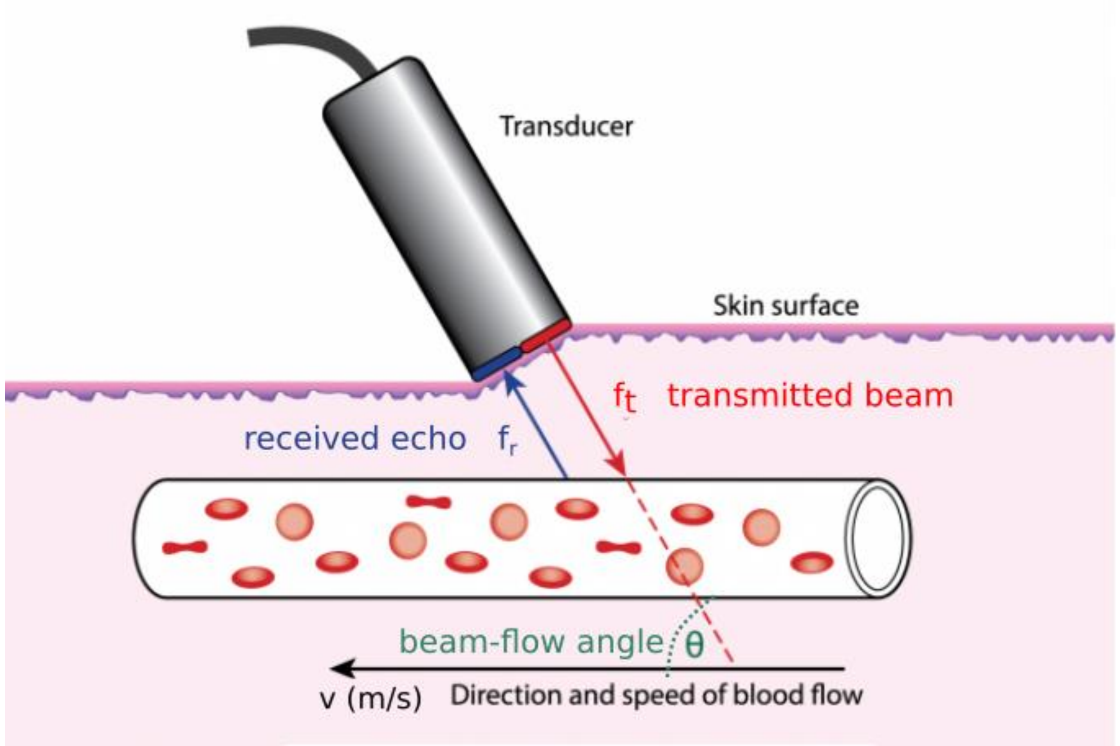


Traveling towards US probe: increased frequency

Moving away from US probe: decreased frequency

[Kaproth-Joslin, 2015]

Doppler Shift frequency (f_d)



[Turns, 2011]

Angle between US beam and direction blood flow

Velocity of blood flow

$$f_d = f_r - f_t = \frac{2 f_t v \cos\theta}{c}$$

Received frequency

Tissue speed of sound (1540 m/s)

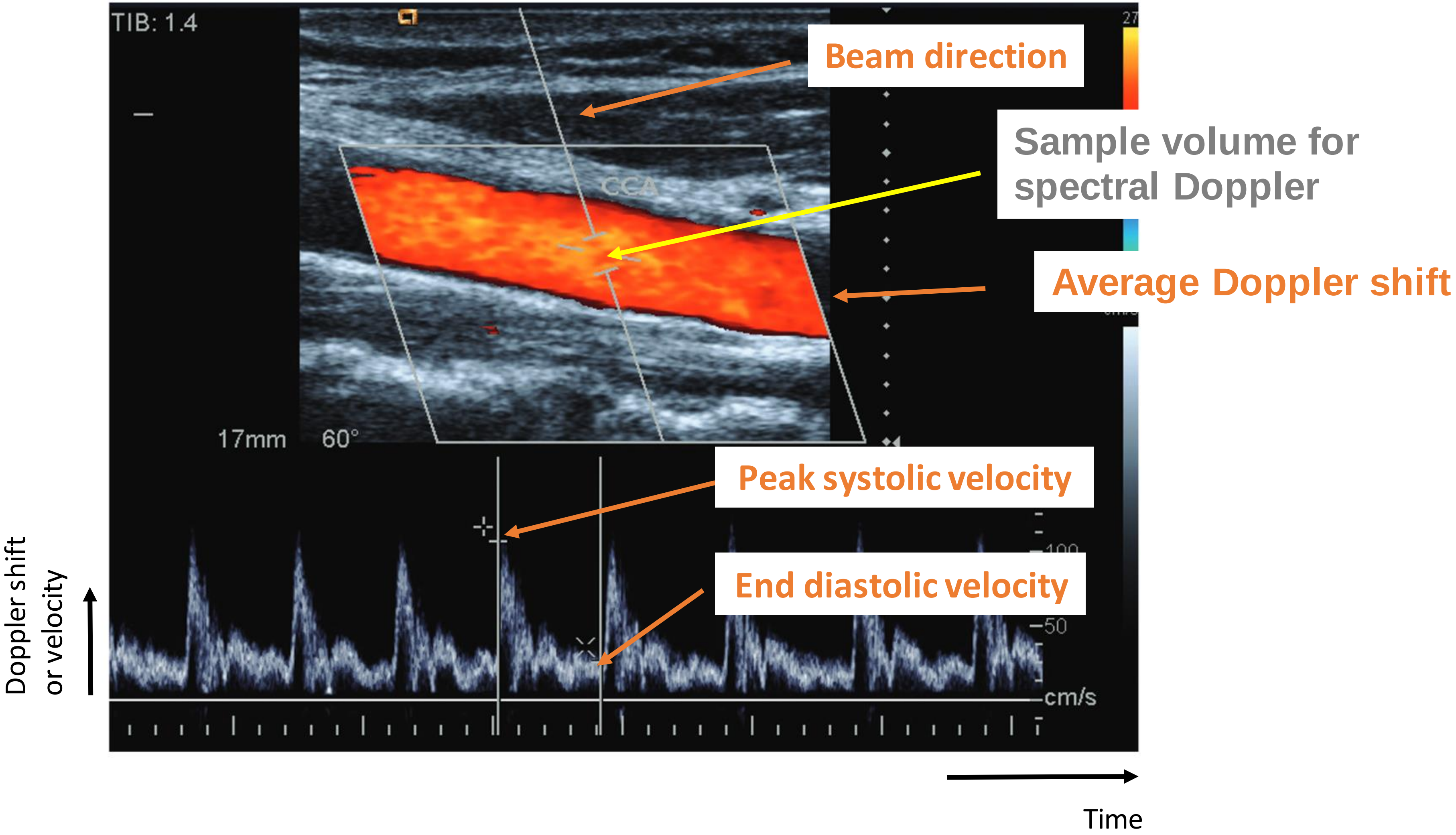
Transmitted frequency

Color Doppler

Presence of blood flow within a large area of the tissue.

Spectral Doppler

Changes in velocity over time within a single small area.

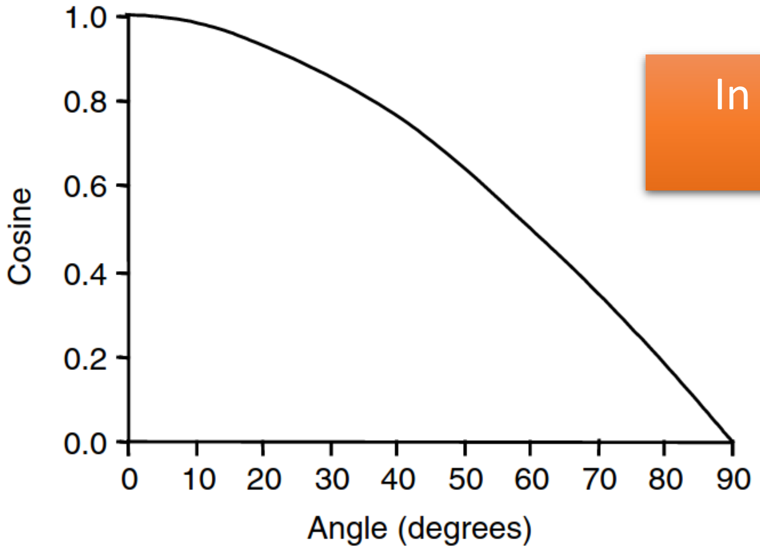


[Hoskins et al., 2010]

Some numbers

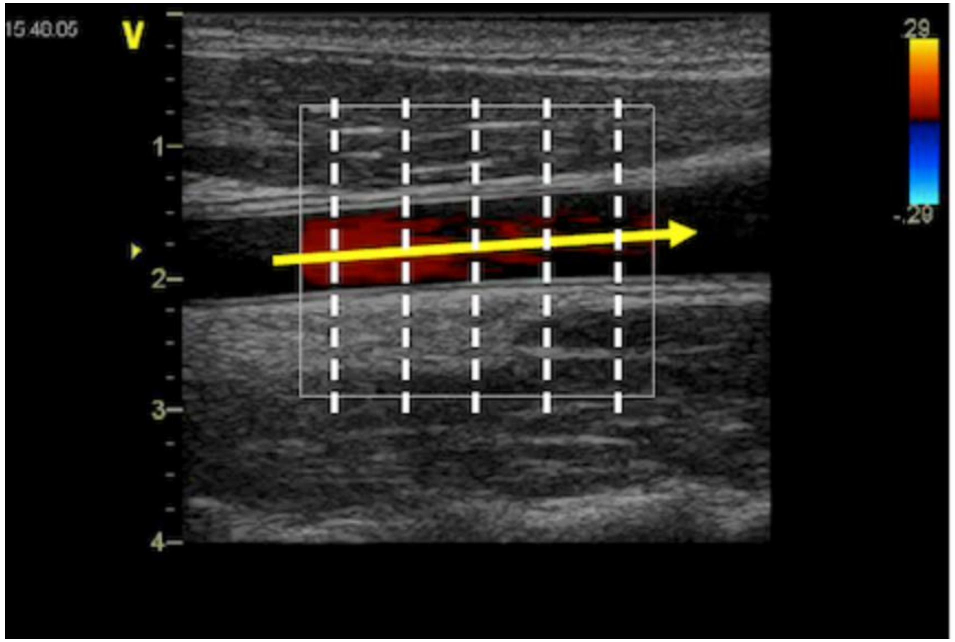
$$f_d = \frac{2 f_t v \cos\theta}{c}$$

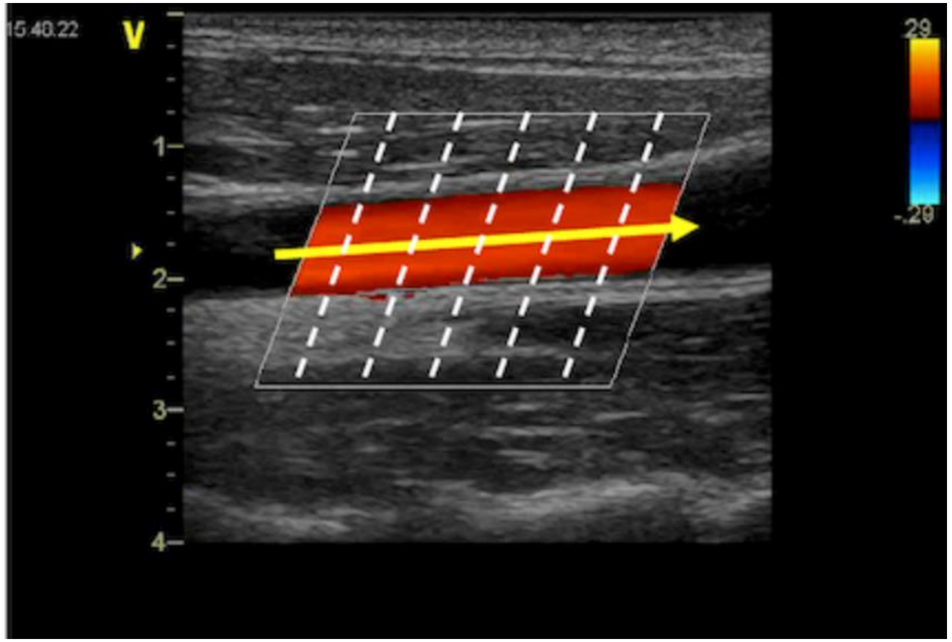
Ideal situation



Complete loss of flow

In practice: Do not use angles > 60º





[Source: Asbjorn Støylen]

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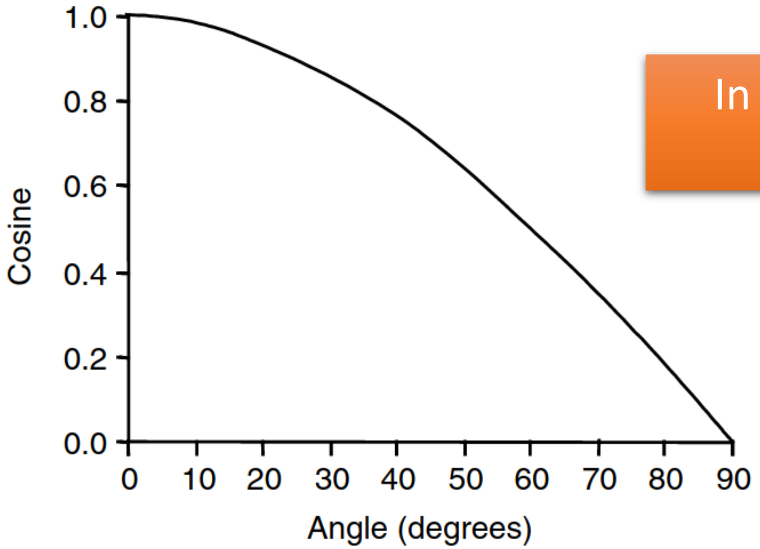

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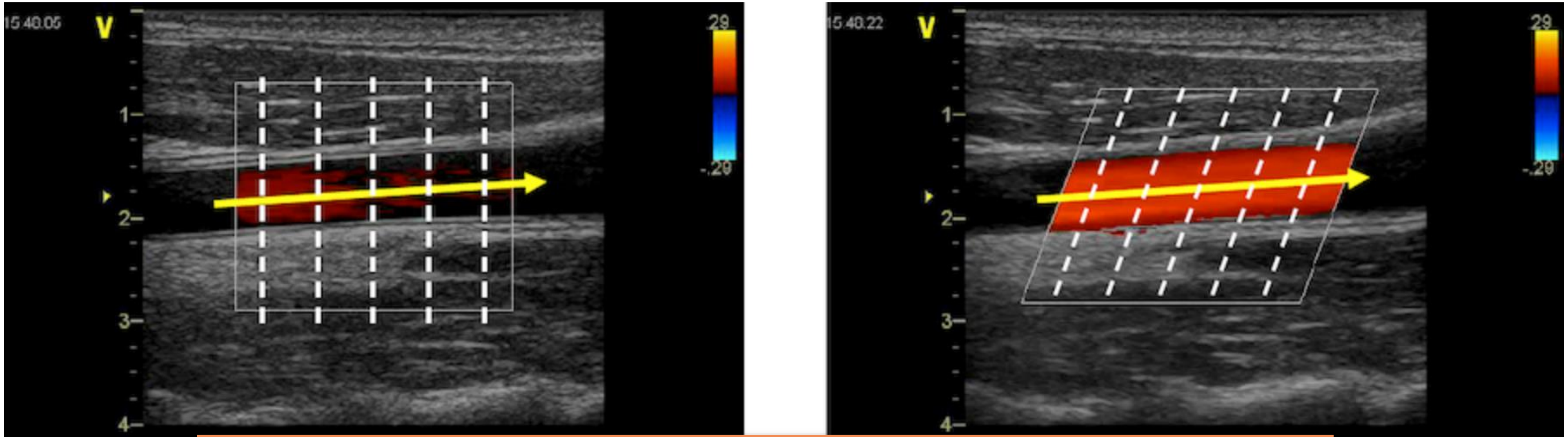

Typical color scale: BART rule – blue away, red towards

[Source: Asbjorn Støylen]

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Postdoctoral researcher

Institute of Diagnostic and Interventional Radiology

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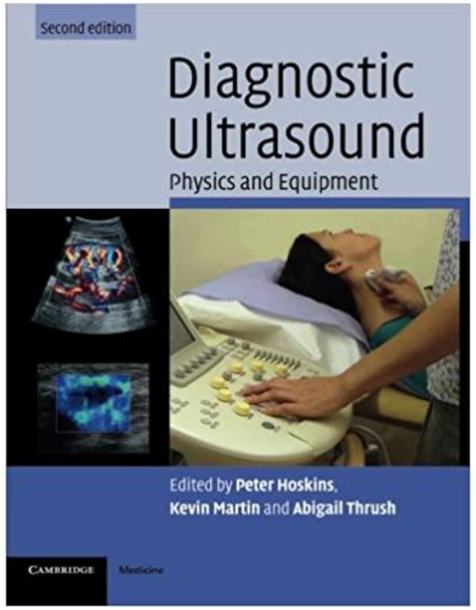
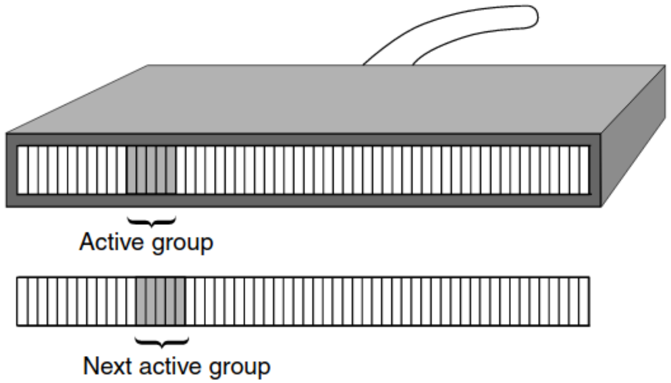
References:



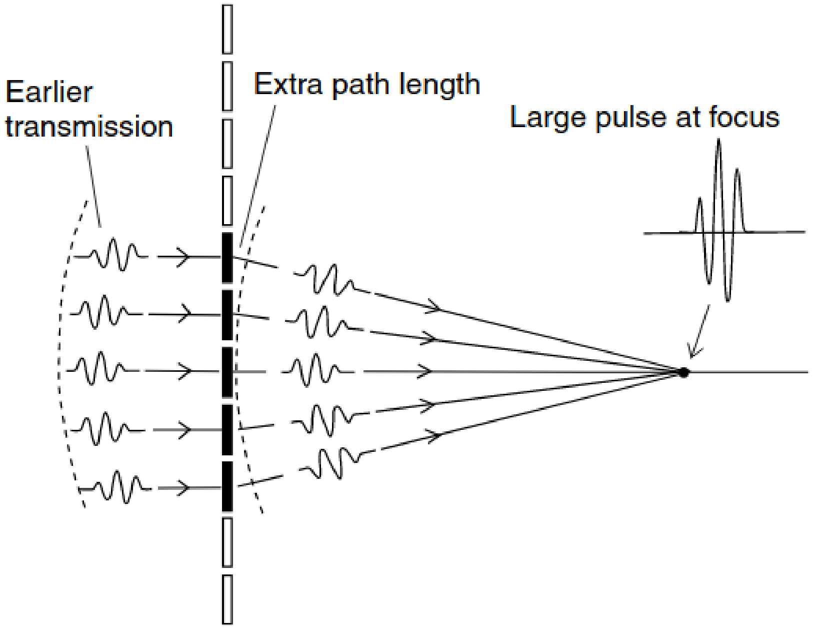
Source of ultrasound waves

Spatial resolution: Focusing

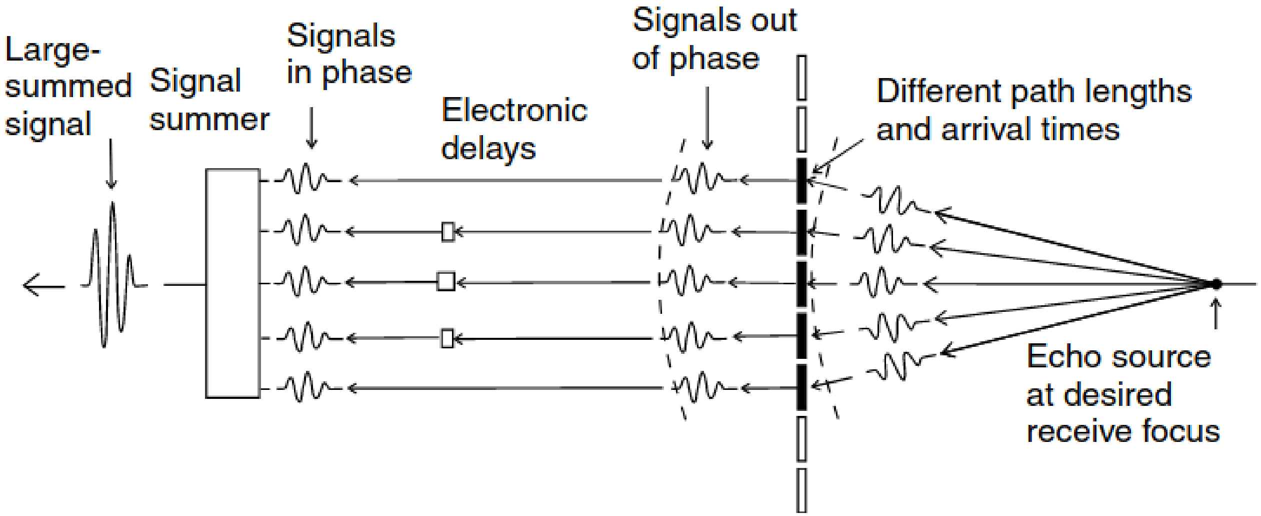
Adjusting the focusing point to improve lateral resolution



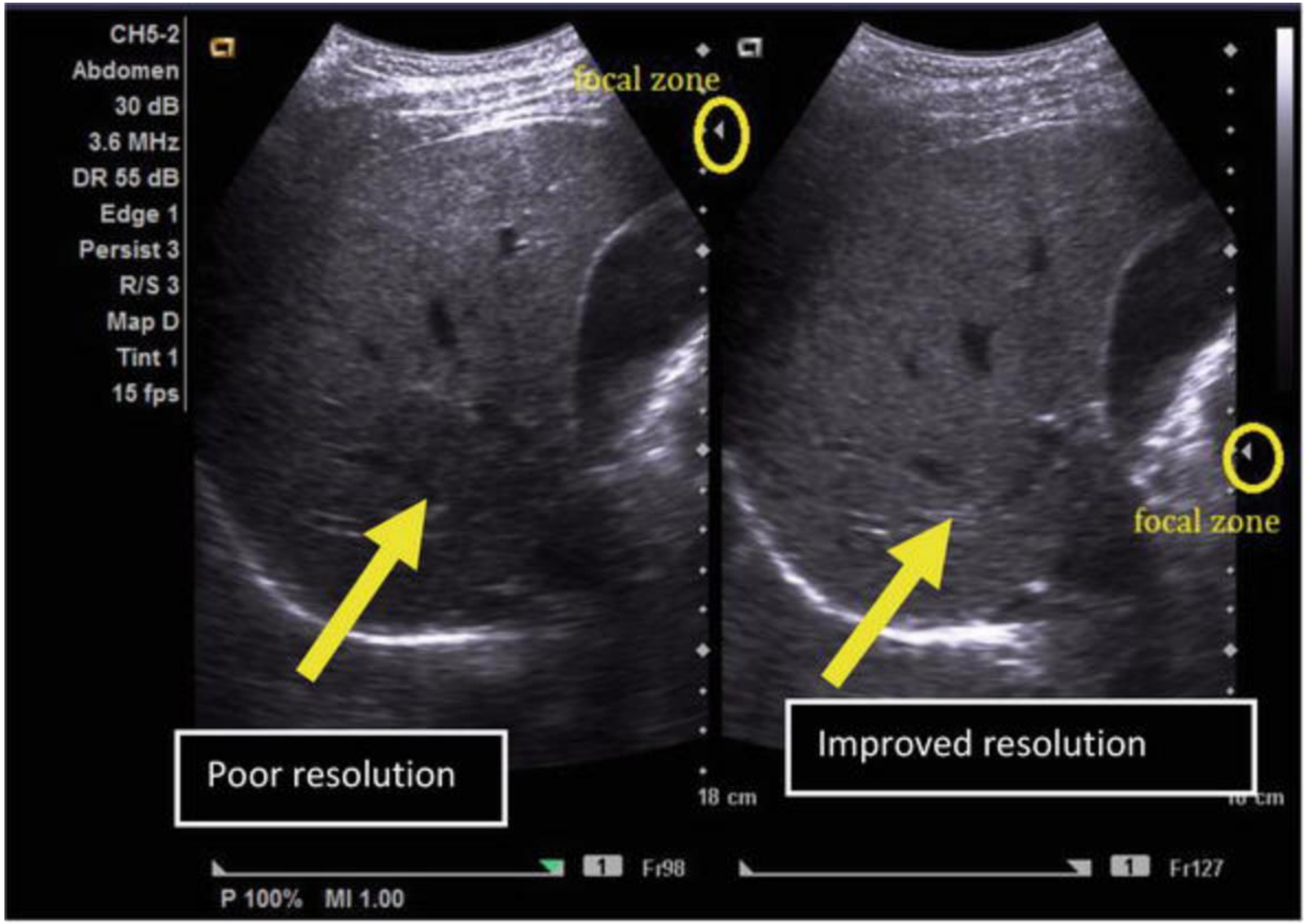
Focusing in transmission



Focusing in reception

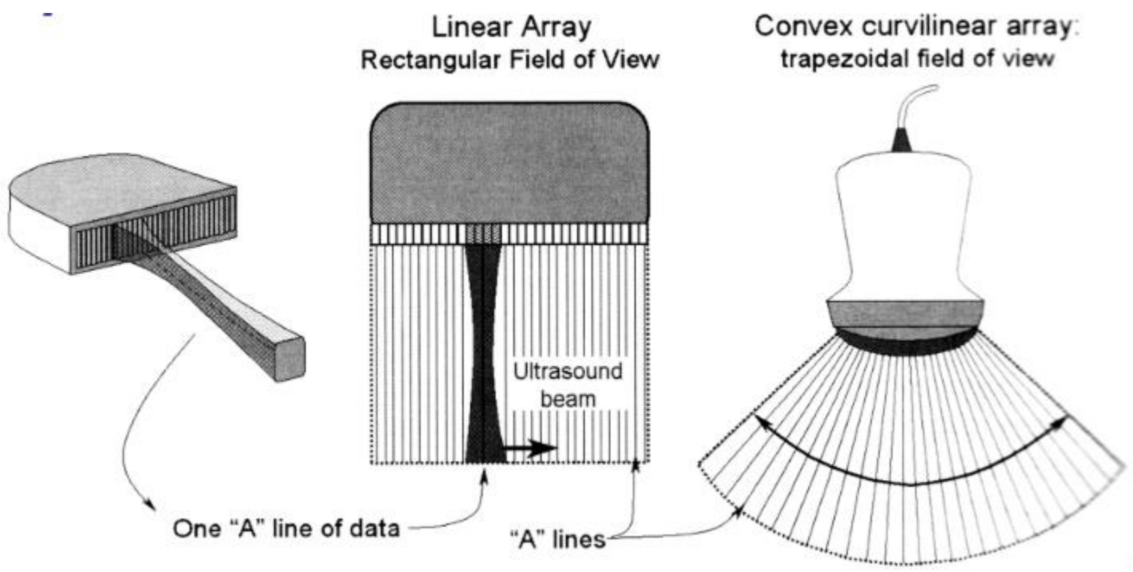


[Hoskins et al., 2010]



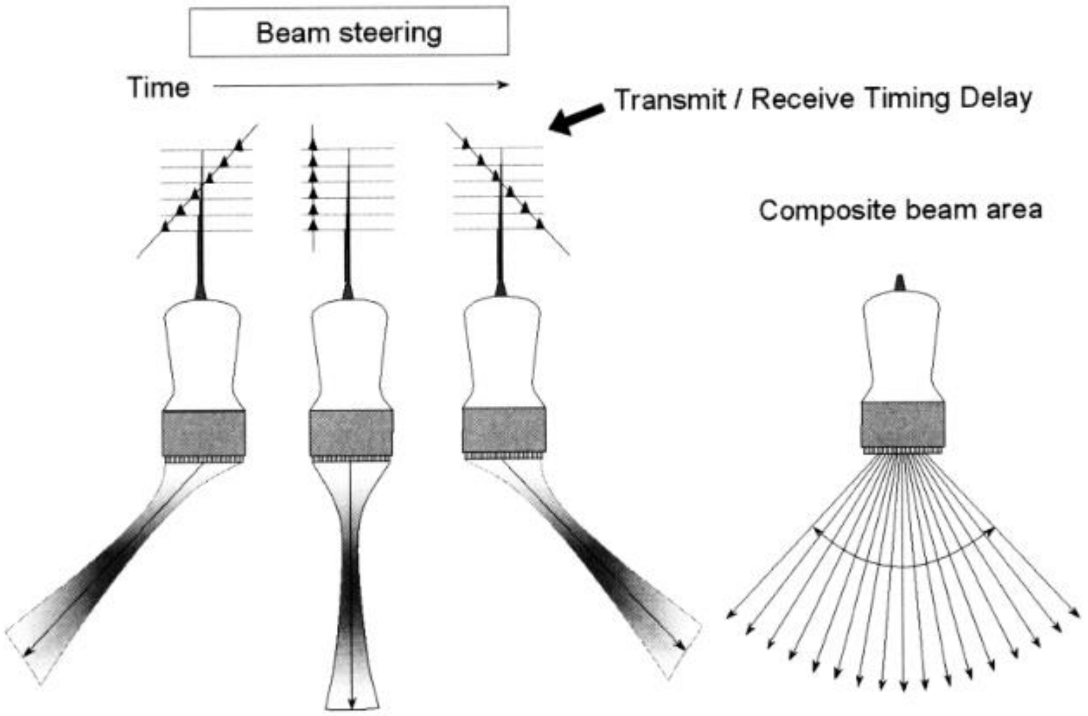
[Amo-Wiafe and Badu-Peprah, 2018]

Transducer arrays – field of view



~15 to 20 adjacent elements simultaneously activated

Phased array



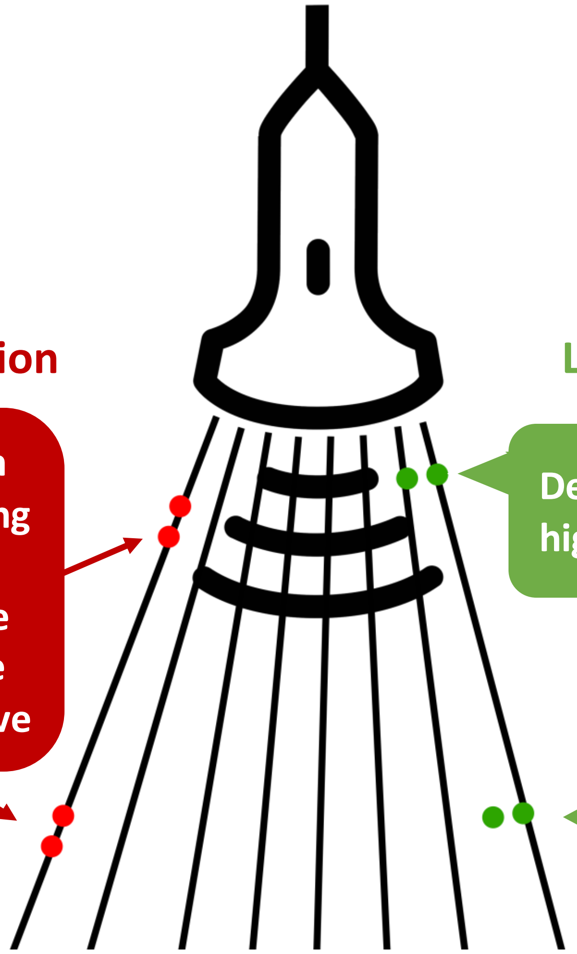
All transducer elements simultaneously activated

[Hoskins et al., 2010]

Resolution versus depth

Axial resolution

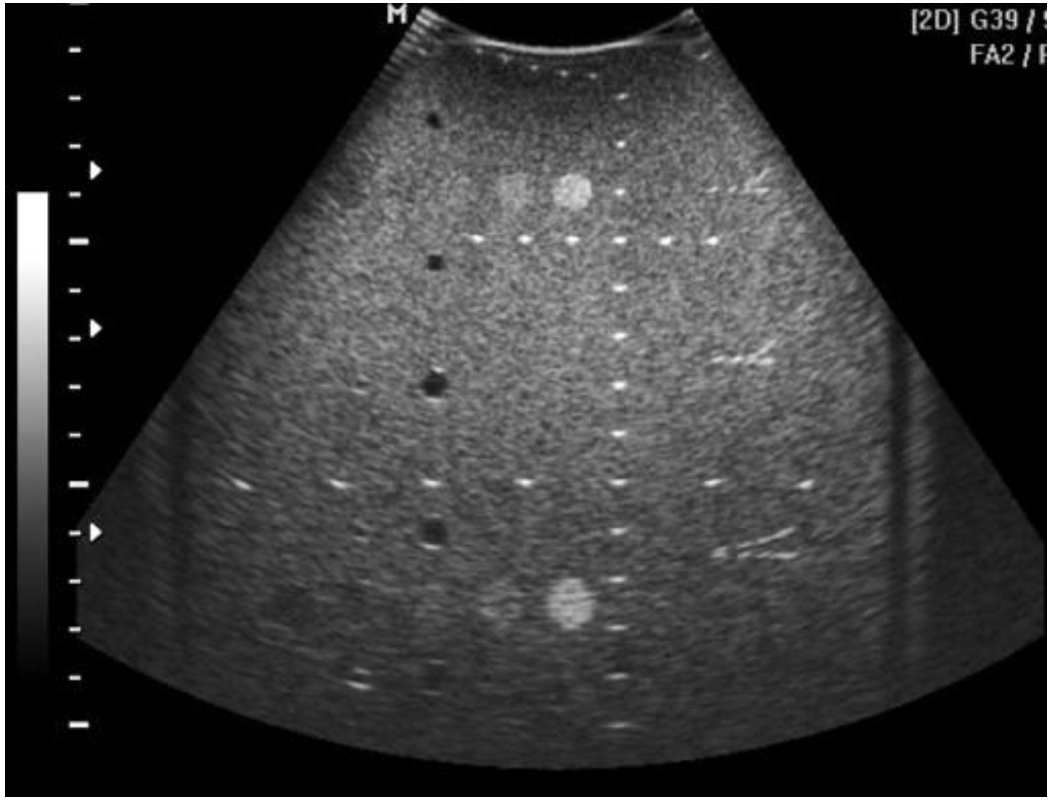
Axial resolution is constant along the beam. It depends on the frequecy of the ultrasound wave



Lateral resolution

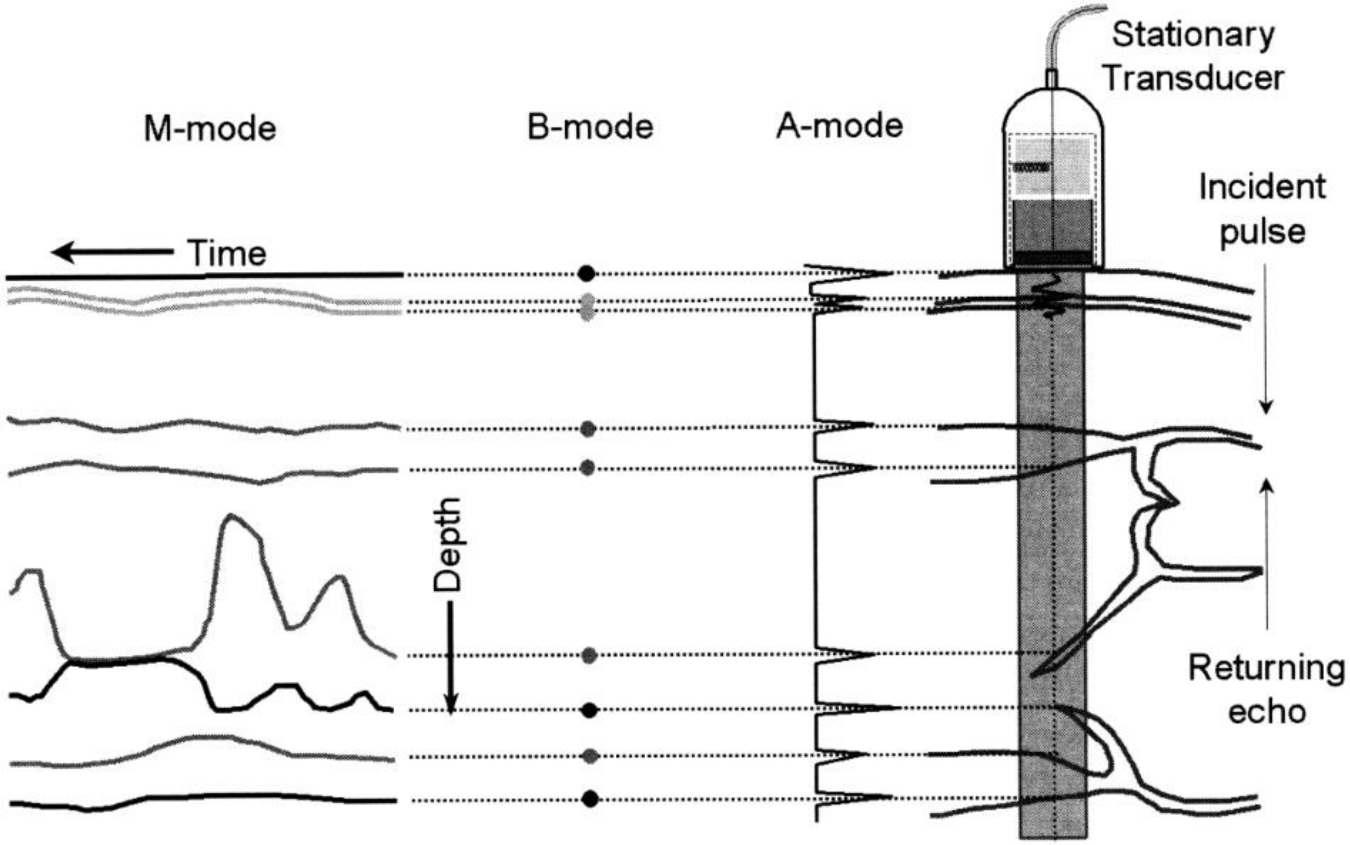
Dense beam region, high lateral resolution

Beams diverge and lateral resolution decreases



[https://www.cirsinc.com/]

A-, B-, M-mode



[Motion] [Brightness] [Amplitude]