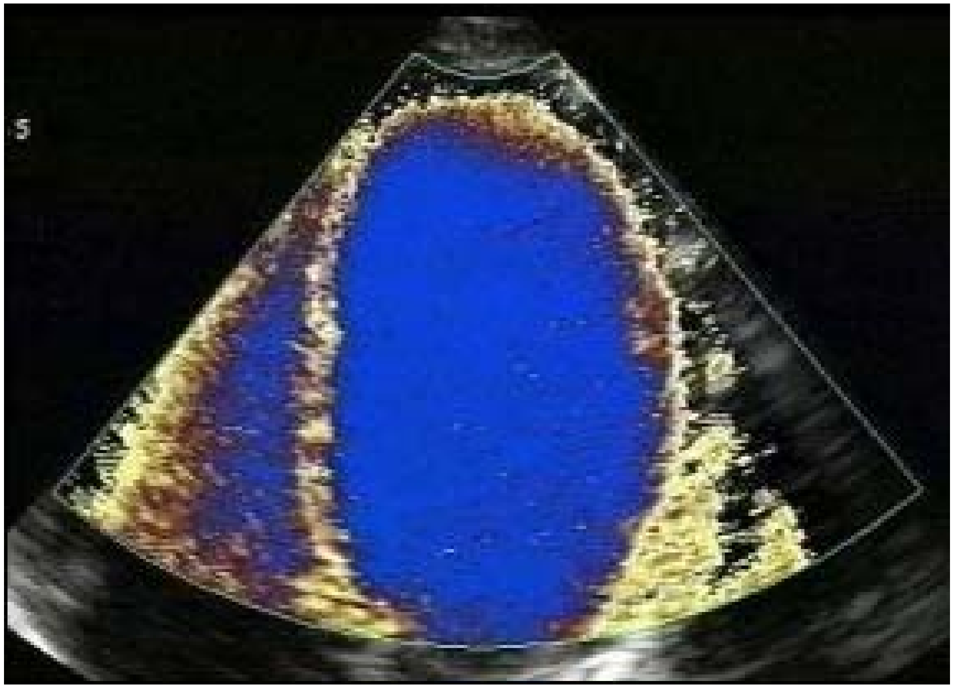
Medical Ultrasound

Contents:

- Physics of sound waves
- Ultrasound devices
- Signal processing
- Medical applications



Recommended book:
«Introduction to Medical Imaging»
Nadine Barrie Smith, Andrew Webb
Cambridge University Press, 2014

Based on lecture material from Prof. Urs Moser

Applications

Diagnostic:

• Echography (imaging tissue slices, > 30 frames/second))

• Doppler (measuring blood flow velocity)

• Bone densitometry

Frequency range: 1 to 50 MHz

Wavelength in tissue: 1 mm down to 0.03 mm

Intensity: temporal mean 100mW/cm^2 (eye 20mW/cm^2), pulsed: 10 W/cm^2

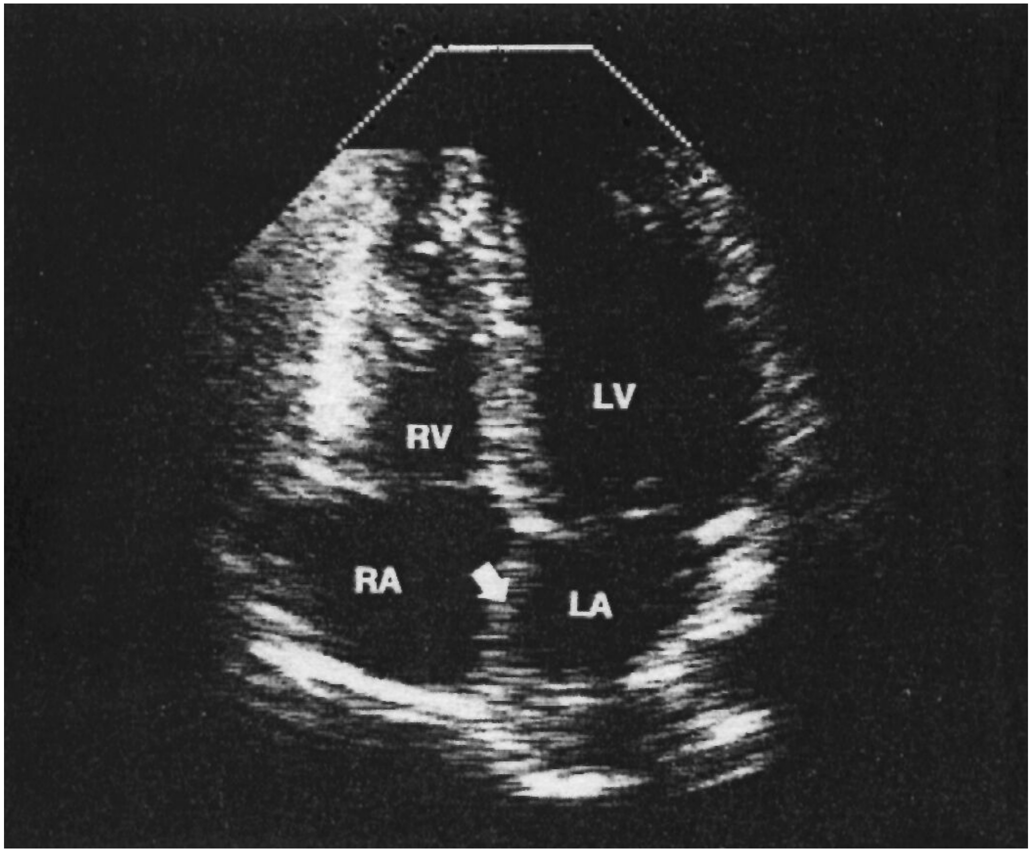
Therapeutic:

• Lithotripter (disintegration of kidney stones)

• Thermal therapy (ligaments, tendons etc.)

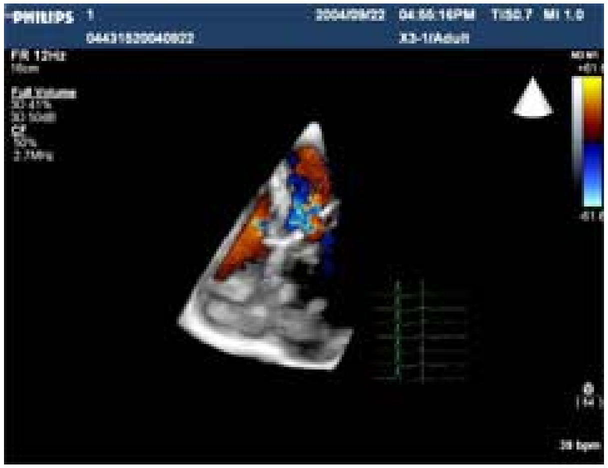
• Ultrasound surgery (e.g. in the deep brain)

Diagnostic Ultrasound: Cardiology



2D image

3D image



3D image + Doppler

Diagnostic Ultrasound : Vessels

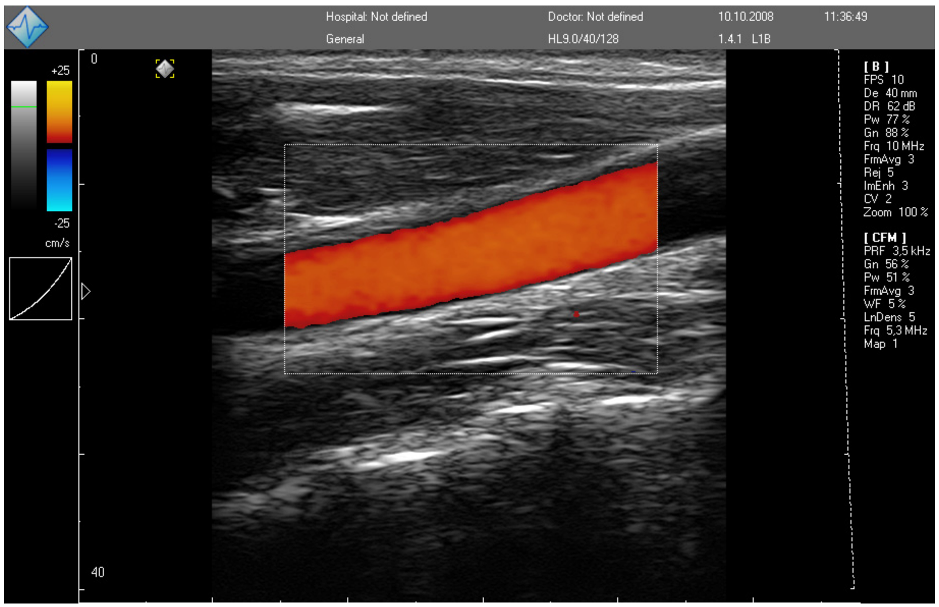
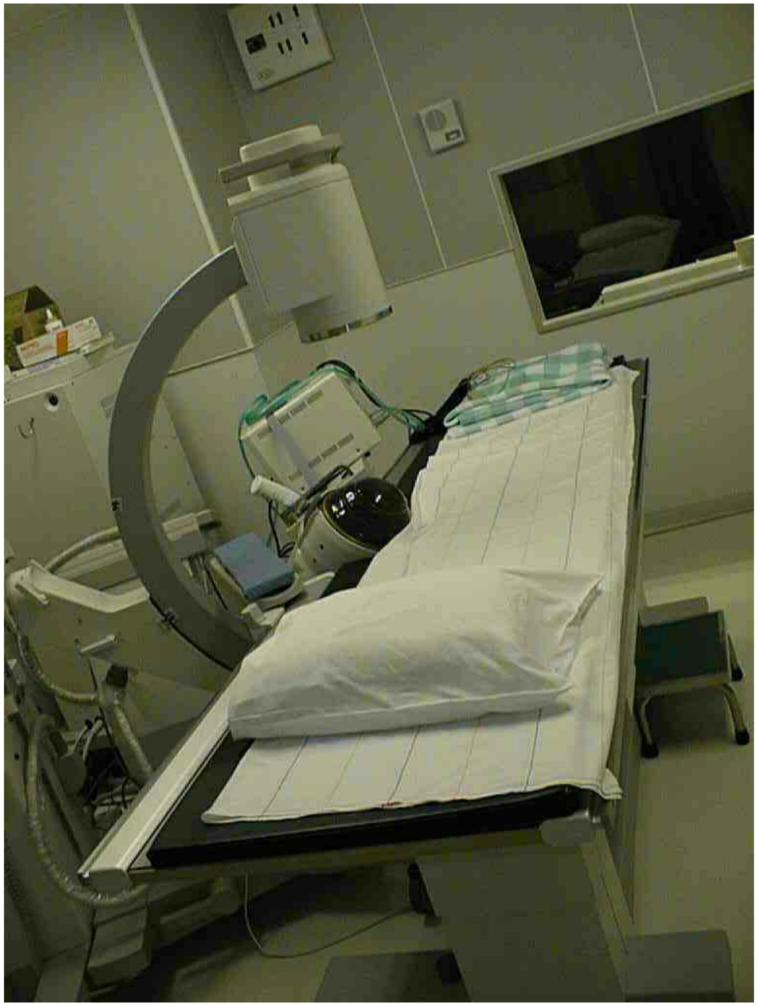


Image of vessel with blood flow

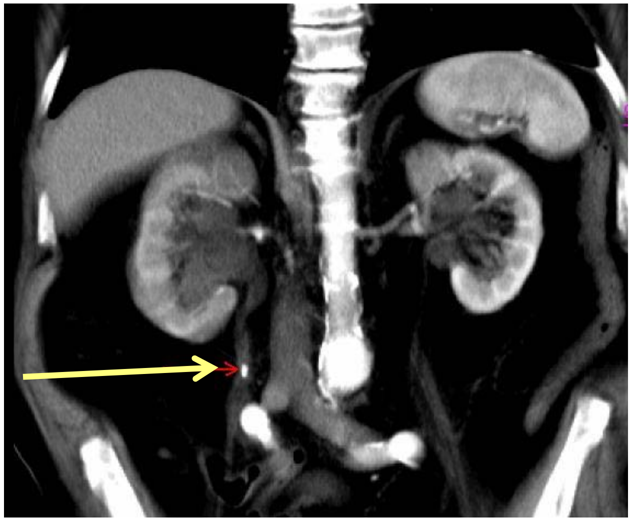
Vessel bifurcation

Therapeutic Ultrasound: Lithotripter



Lithotripsy device

Kidney stone
blocking ureter

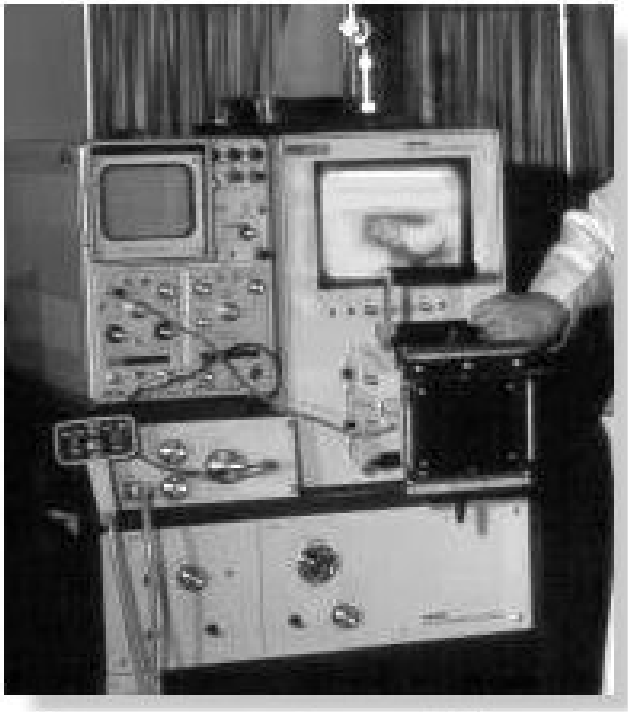


Kidney stone

History

1822	Daniel Coladon: Measures speed of sound in lake Geneva
1877	Lord Rayleigh: „The theory of sound“
1914	Langevin: first ultrasound generator using piezoelectric effect
1949	Ludwig, Struthers: detection of gall stones
1952	Howry: first slice images in water
1954	Edler, Hertz: adopt ultrasound cardiography
1957	Satomura: uses Doppler shift to detect heart beat
1958	Donald, Brown: 2D US diagnostics in obstetrics and inner medicine
1984	Baba: 3D ultrasound, fetal imaging
since	Continued development, powered by microelectronics

Development of Devices



about 1970

2005

2010: pocket device

Development of Devices

2017

(https://www.clarius.me)

Development of Image Quality

1970

1980

2D

2D FETAL PROFILE

1990

3D

3D FETAL PROFILE

1995

4D

4D FETAL PROFILE

2002

Clinical Applications

- Obstetrics/Gynaecology
- Cardiology (echocardiography, real-time imaging)
- Internal Medicine: liver, gall bladder, kidney etc.
- Musculoskeletal system: muscles, tendons, ligaments
- Breast imaging
- Urology: prostate
- Blood flow measurement (US Doppler)

Advantages and Drawbacks of Ultrasound

Advantages:

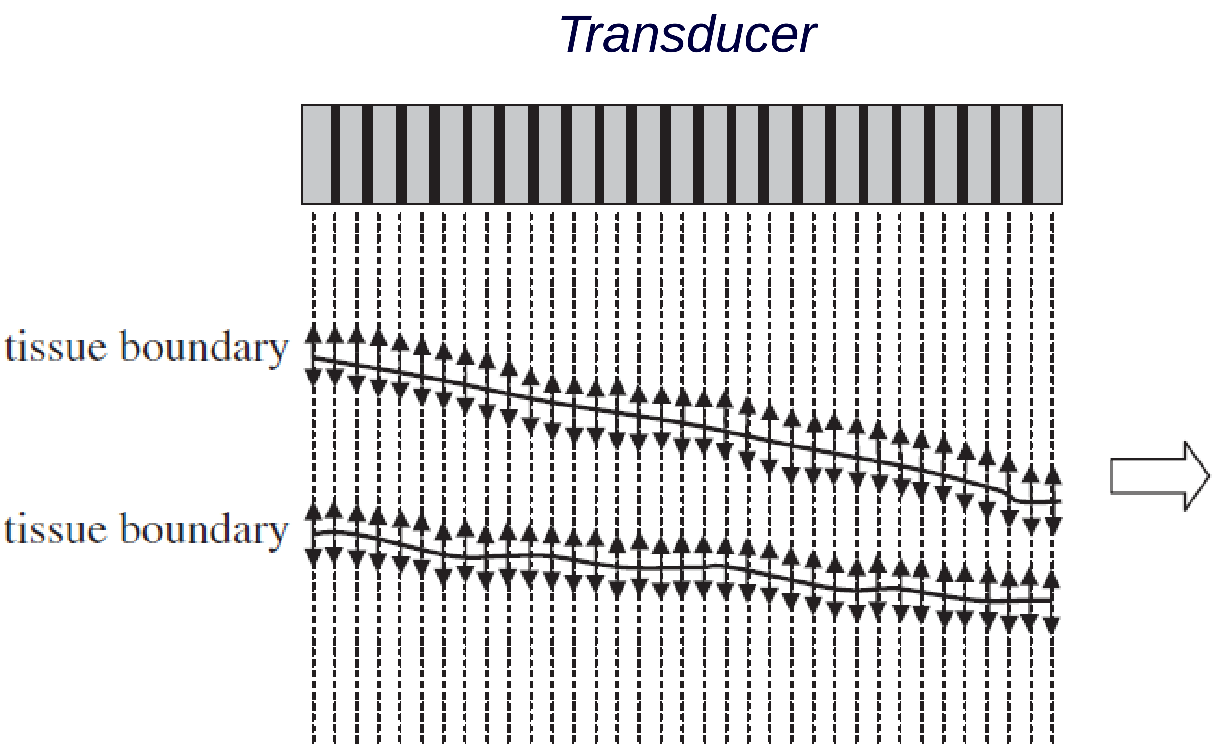
- small, mobile, bed-side
- patient-friendly
- real-time capability
- comparatively low costs
- no ionizing radiation

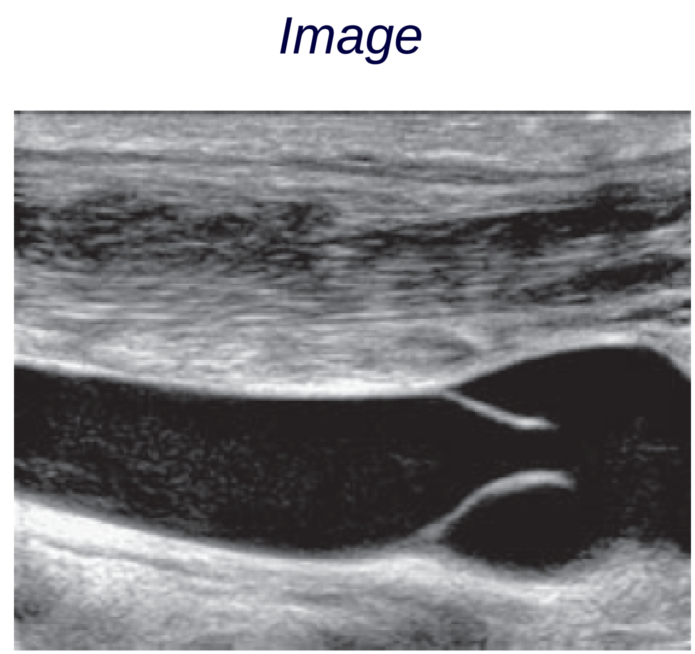
Drawbacks:

- moderate image quality, poor soft-tissue contrast
- need for ‚acoustic window‘
- substantial training required

Basic Principle of Ultrasound Imaging

Chapter 5.18

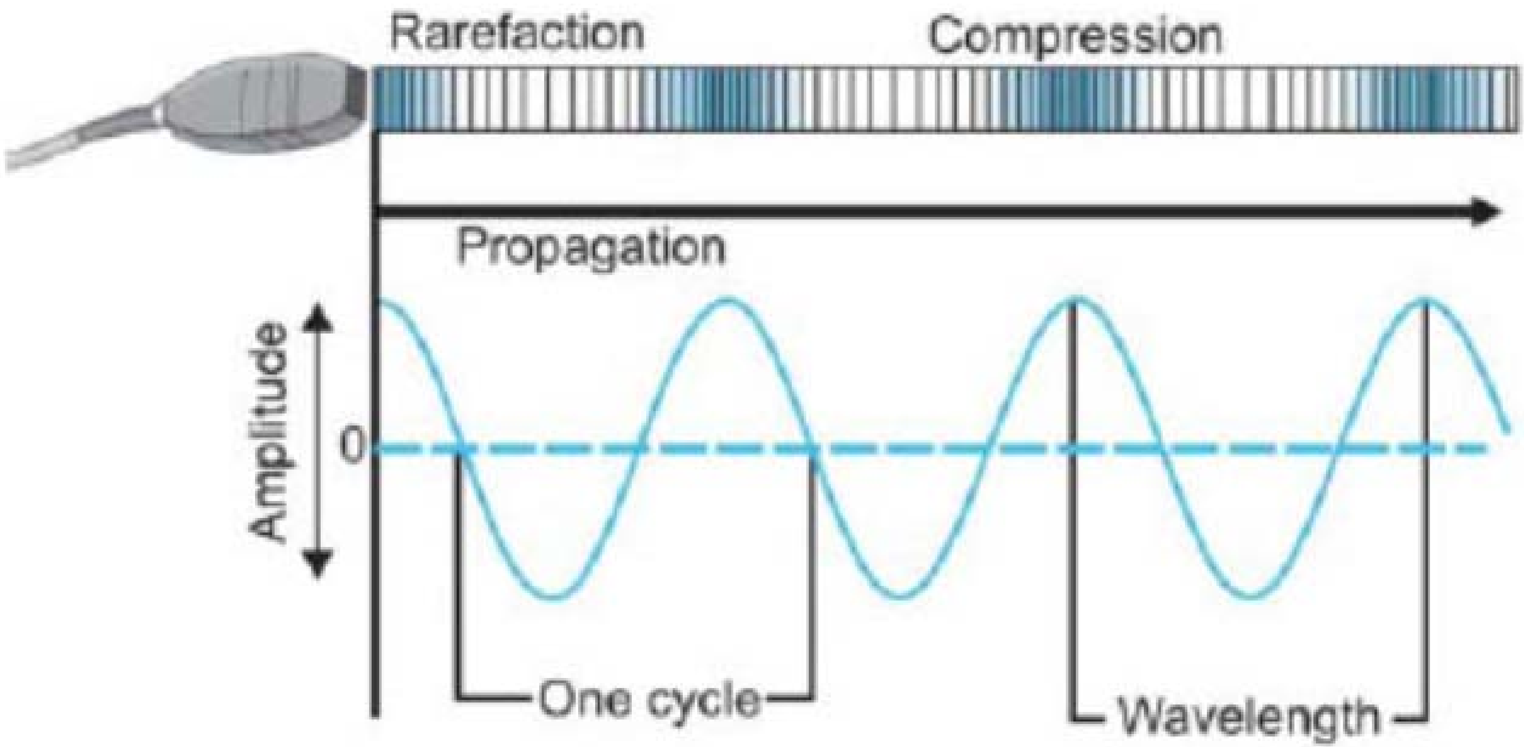




from Smith/Webb

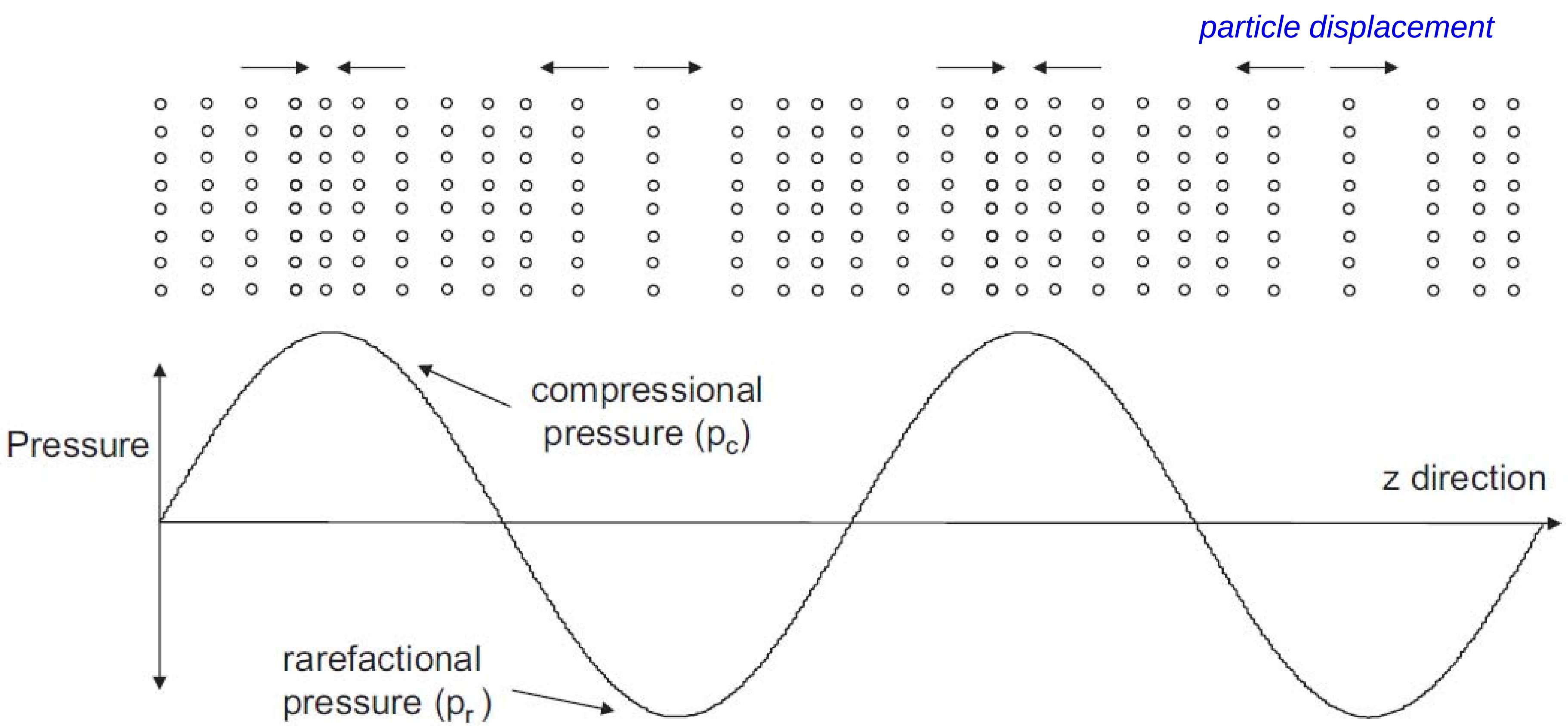
Ultrasonic Waves

Chapter 4.2



Ultrasound Propagation in Tissue

Longitudinal pressure wave $$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0$$



from Smith/Webb

Key Quantities and Relationships

wave speed $$c = \frac{1}{\sqrt{\kappa\rho}}$$ κ = compressibility, ρ = mass density

pressure $$p = \rho\, c\, u_z$$ u_z = particle velocity

wave impedance $$Z = \frac{p}{u_z} = \rho\, c = \sqrt{\frac{\rho}{\kappa}}$$

wave intensity $$I = \frac{1}{2}\, p\, u_z$$

Acoustic Properties of Biological Tissue

as well as materials used for the transducer construction

Substance	Z [kg/m^{2}s]	ρ [g/cm^3]	c [m/s]
Water	$1.48 \cdot 10^6$	1.0	1480
Blood	$1.65 \cdot 10^6$	1.06	1560
Brain	$1.58 \cdot 10^6$	1.03	1530
Fat	$1.36 \cdot 10^6$	0.92	1476
Muscle	$1.66 \cdot 10^6$	1.06	1568
Bone	$6 \cdot 10^6$	1.3 -1.8	2800-4100
Air	400 (!)	0.0012	330
Epoxy	$3 \cdot 10^6$	1.2	2500
Plexiglass	$3.2 \cdot 10^6$	1.18	2730
PZT Ceramic	$29 \cdot 10^6$	7.65	3790
Steel	$39 \cdot 10^6$	7.7	5000

Reflection at Interfaces

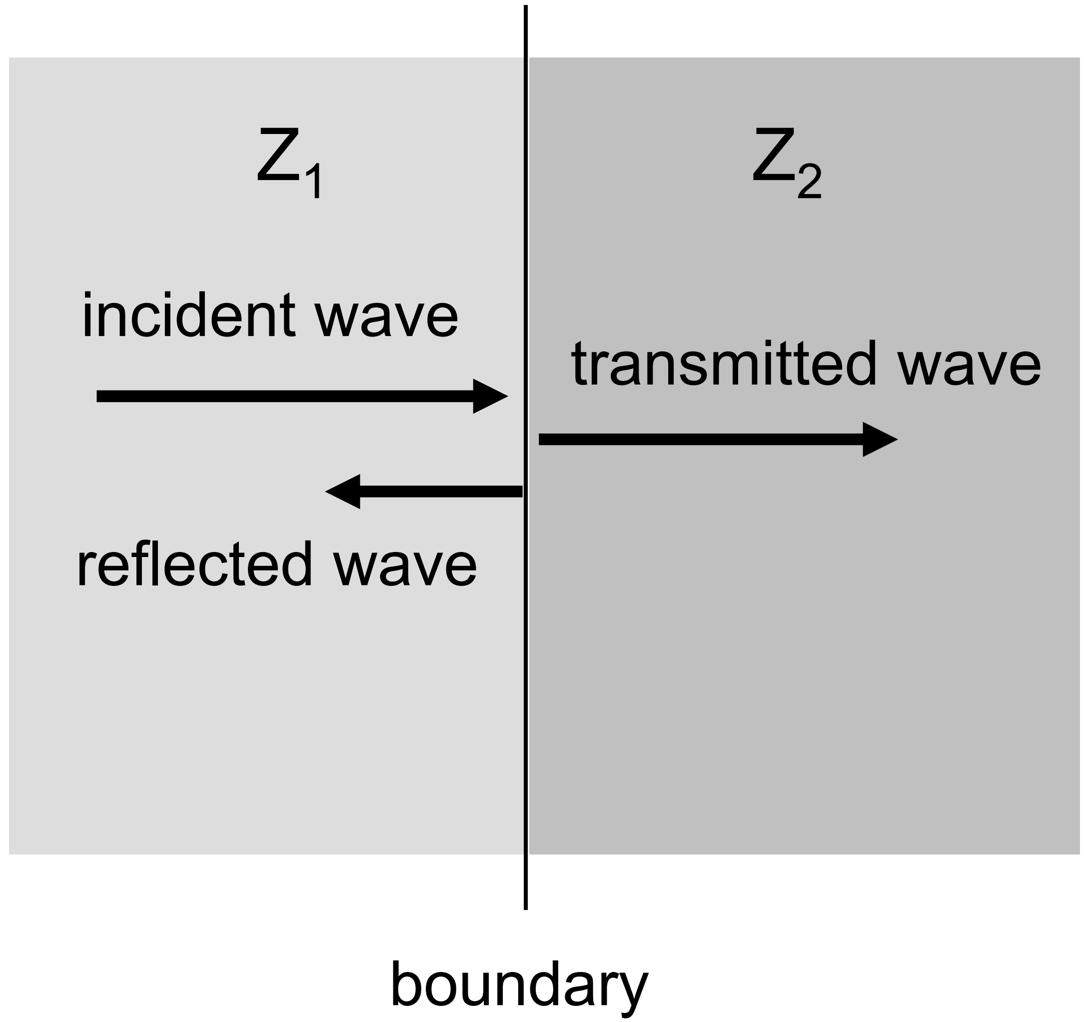
Chapter 4.3

Pressure reflection coefficient *r*

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

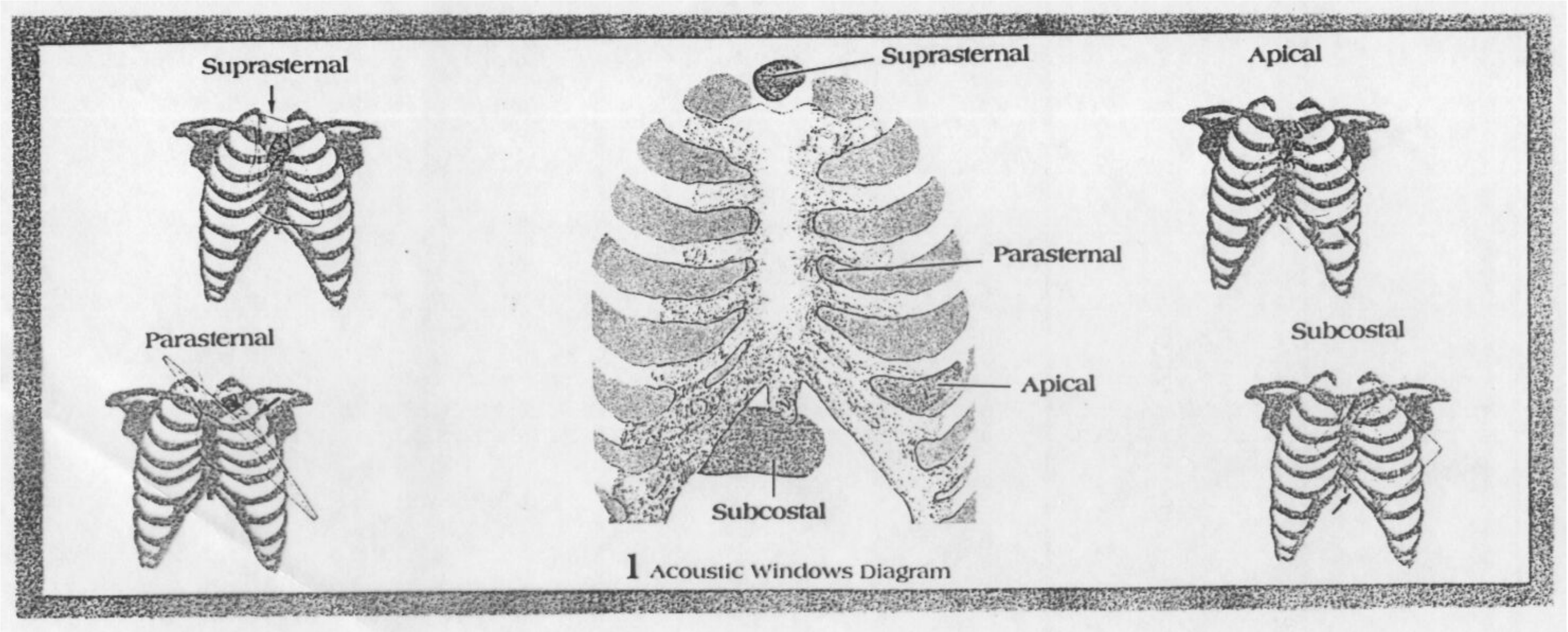
Pressure transmission coefficient *t*

$$t = \frac{2Z_2}{Z_2 + Z_1}$$



Acoustic Windows

Ultrasound is strongly absorbed in bones and is reflected nearly to 100% by tissue/air or air/tissue interfaces -> need for ‚acoustic windows‘

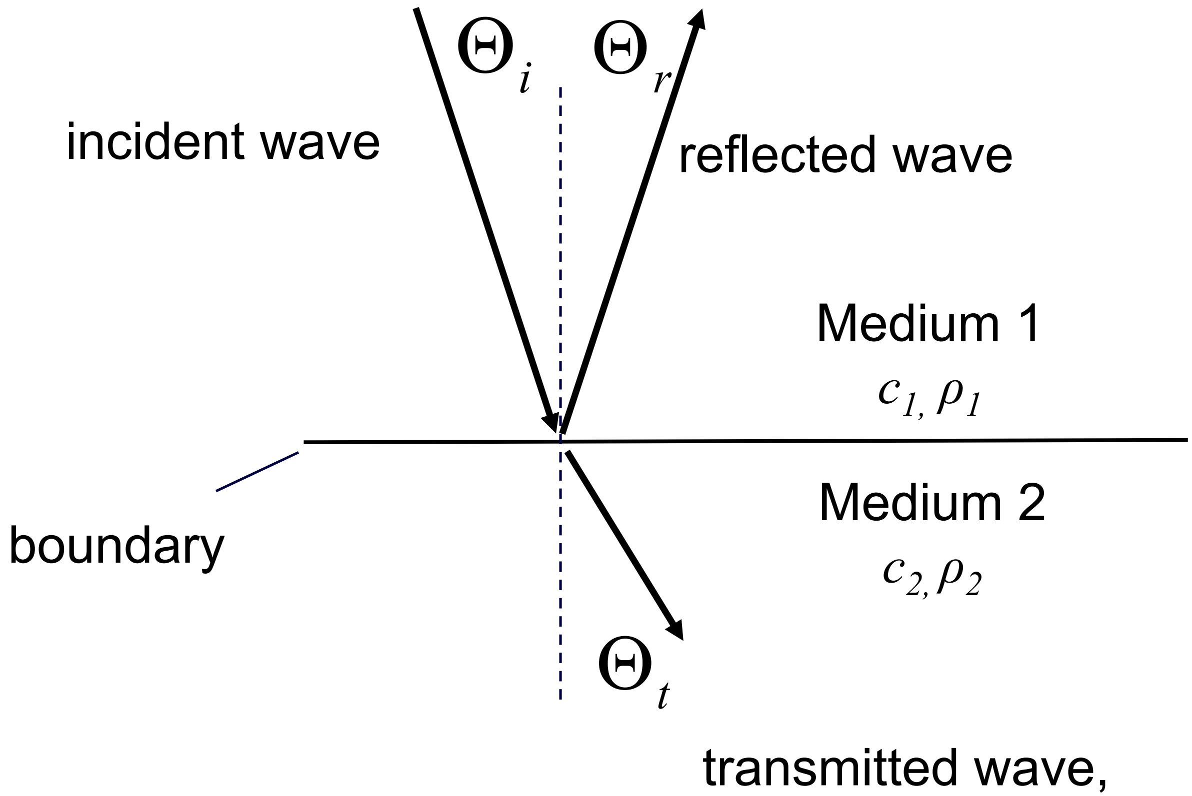


Acoustic windows for cardiac imaging

Refraction of Transmitted Waves

$$\Theta_i = \Theta_r$$

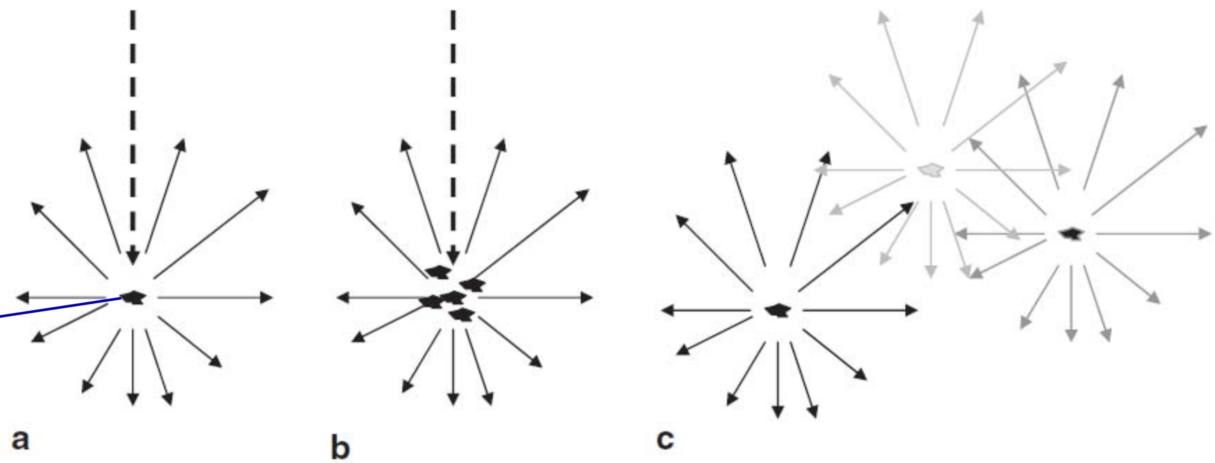
$$\frac{\sin \Theta_i}{\sin \Theta_t} = \frac{c_1}{c_2}$$



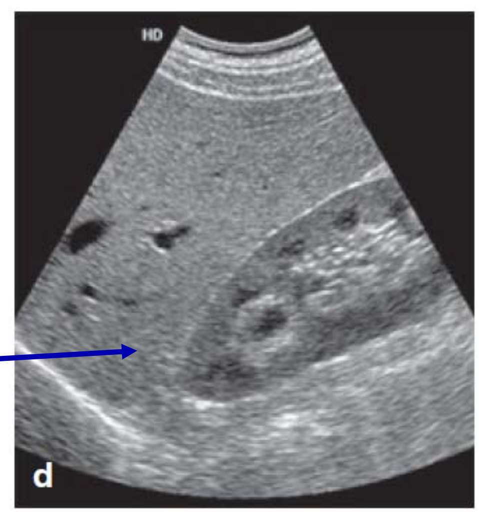
In general the effect of refraction is negligible, i.e. $\Theta_i \approx \Theta_t$

Rayleigh Scattering by Small Structures

Rayleigh
scattering



Speckles produced by
constructive interference



from Smith/Webb

Attenuation

Absorption (conversion to heat), scattering cause attenuation.

In homogeneous tissue pressure decreases exponentially:

$$p(z) = p_0\, e^{-\alpha z}$$

z: distance in cm

p_0: pressure amplitude at z=0

α : damping factor

Decibel notation: $$\alpha_0 = 20 \log\left[\frac{p_0}{p(z)}\right]\frac{1}{z} = 8.686\,\alpha\,[dB/cm]$$

Attenuation in Biological Tissue

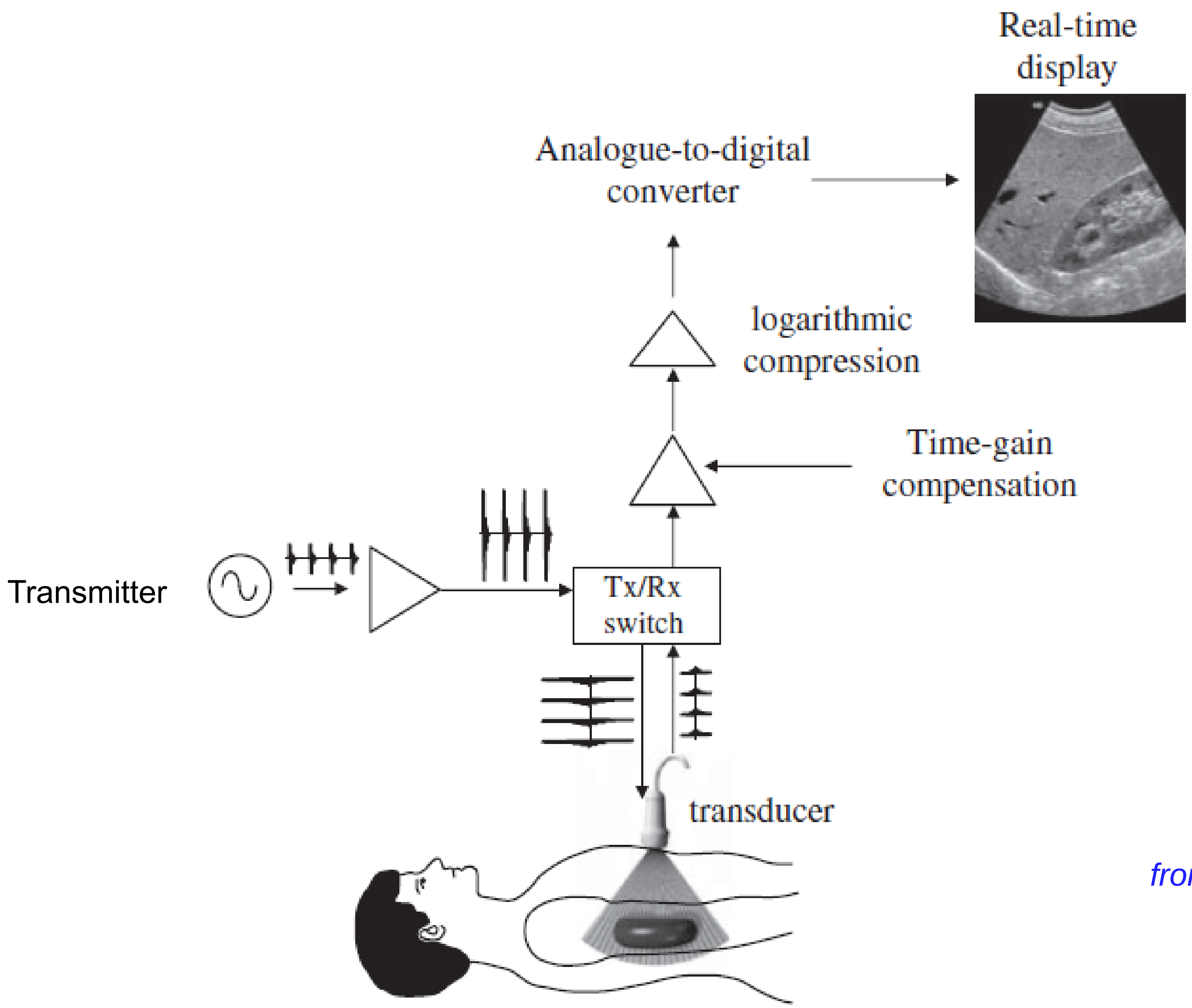
The attenuation increases exponentially with frequency, therefore the attenuation measure in ‘dB’ is roughly proportional to frequency:

Attenuation measure / frequency	[dB/(cm MHz)]
kidney, brain	ca. 1.0
liver	0.8 - 1.3
skeletal muscle	1.5 - 2.2
fat	ca. 0.5
bone	ca. 13

For a given penetration depth, the sound frequency is limited due to strong increase of the attenuation with frequency.

Example: A 5 MHz sound wave is attenuated in kidney by 5 dB per cm.

Instrumentation

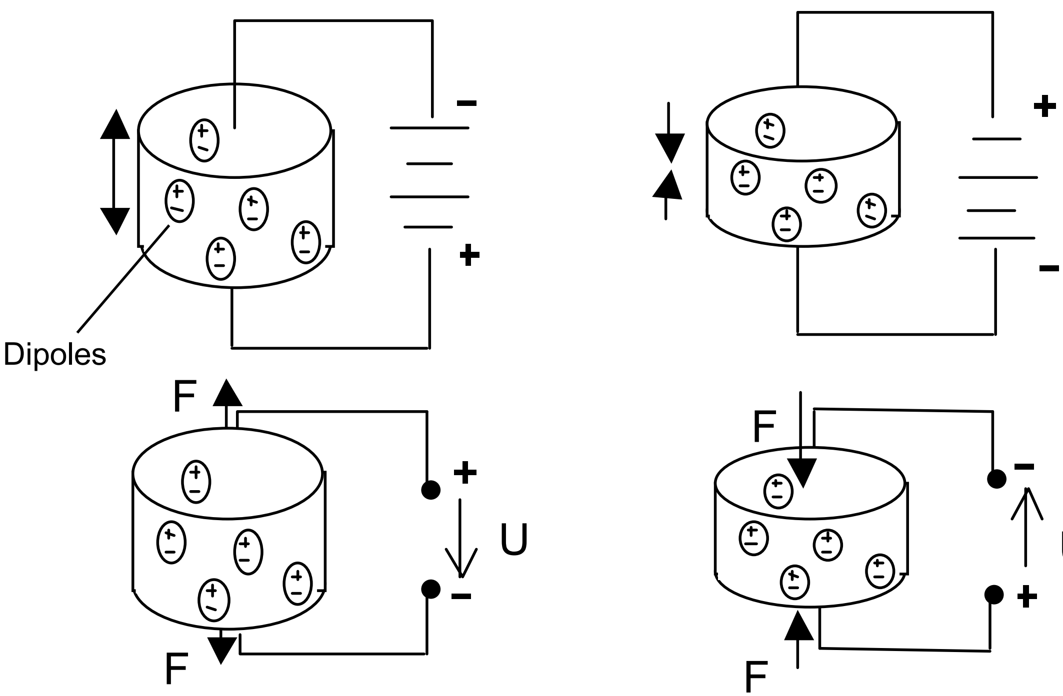


from Smith/Webb

Ultrasound Converter (Transducer)

Chapter 4.6

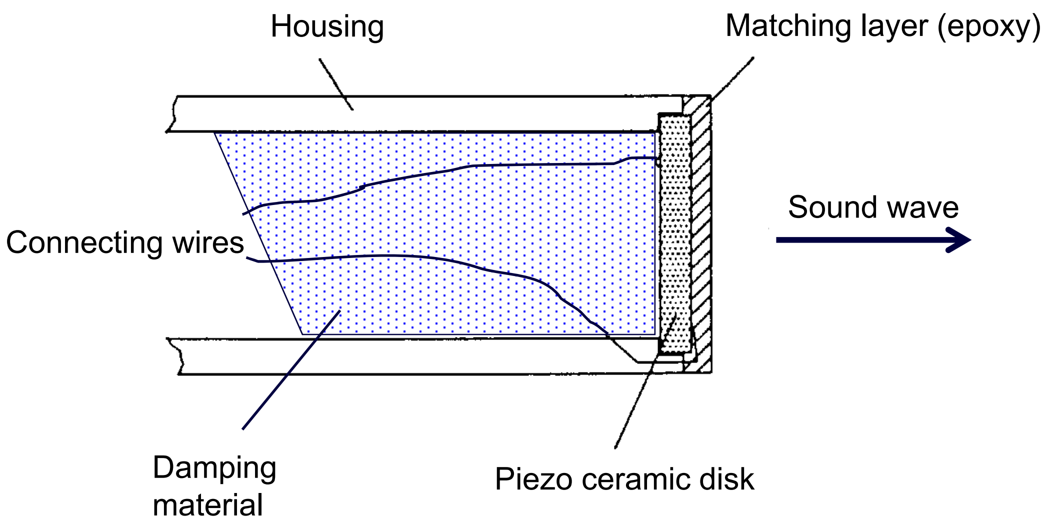
Piezoelectric effect:

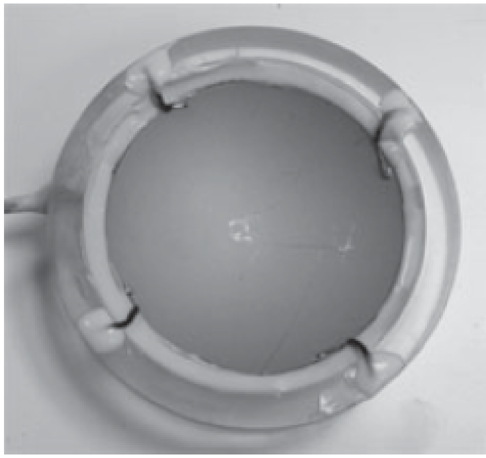


Applied voltage produces force (transmit)

Applied force produces voltage (receive)

Single Element Transducer

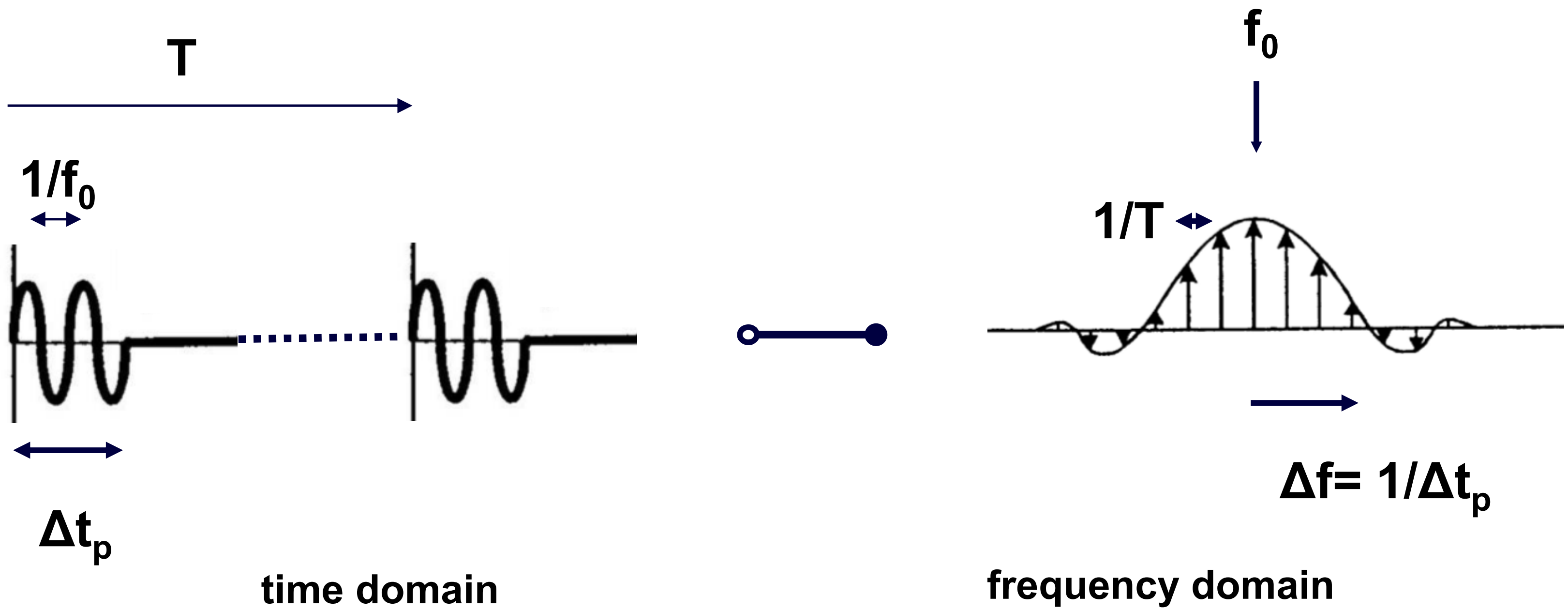




from Smith/Webb

Pulsed Excitation

- A pulse contains not a single frequency, but a spectrum of width $\Delta f \sim 1/\Delta t_p$
- Pulsed excitation is what enables <u>resolution in axial direction</u>



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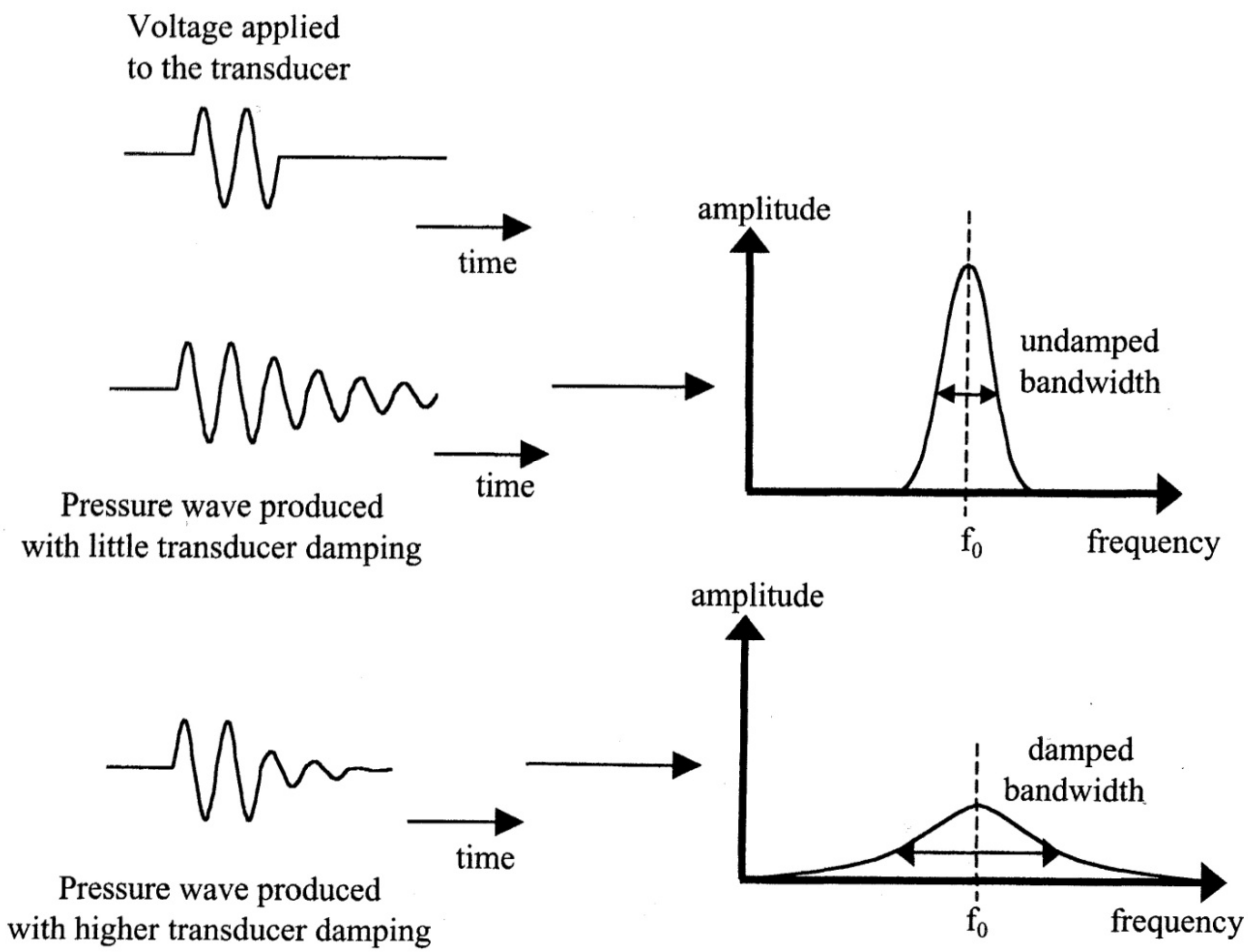
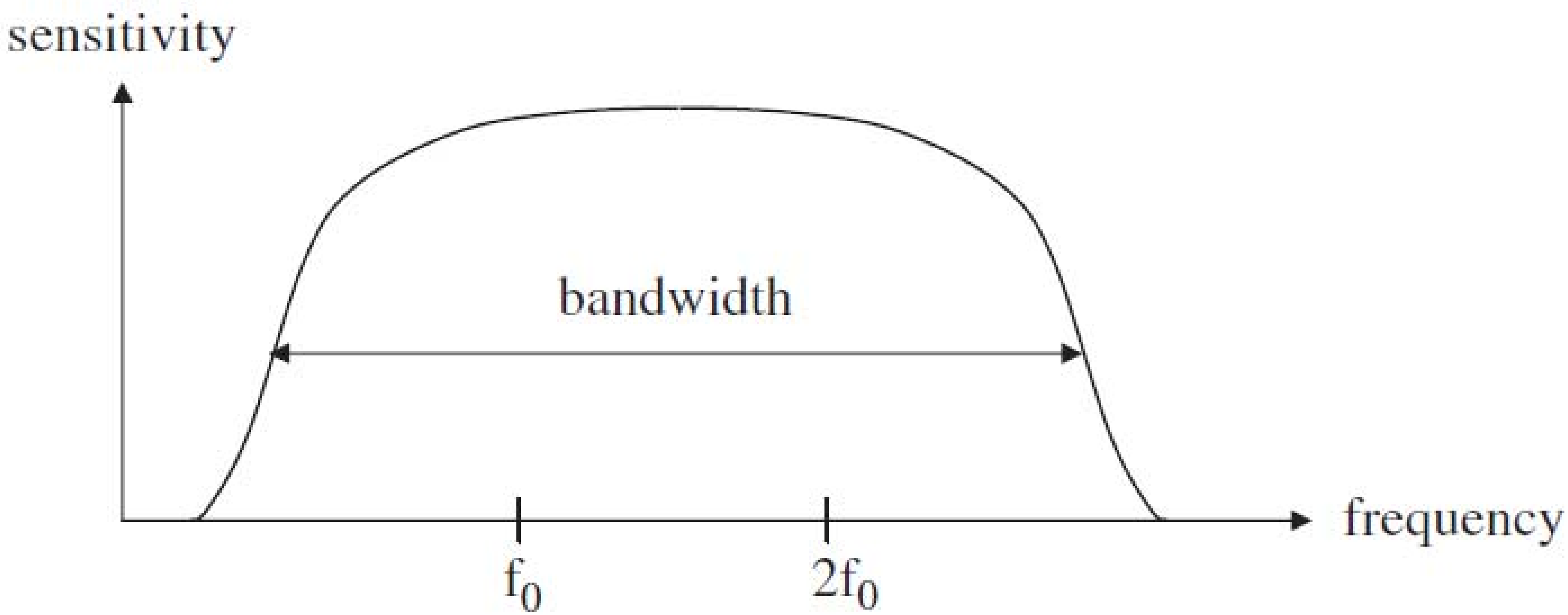
Damping



High transducer bandwidth required for short pulses

from Smith/Webb

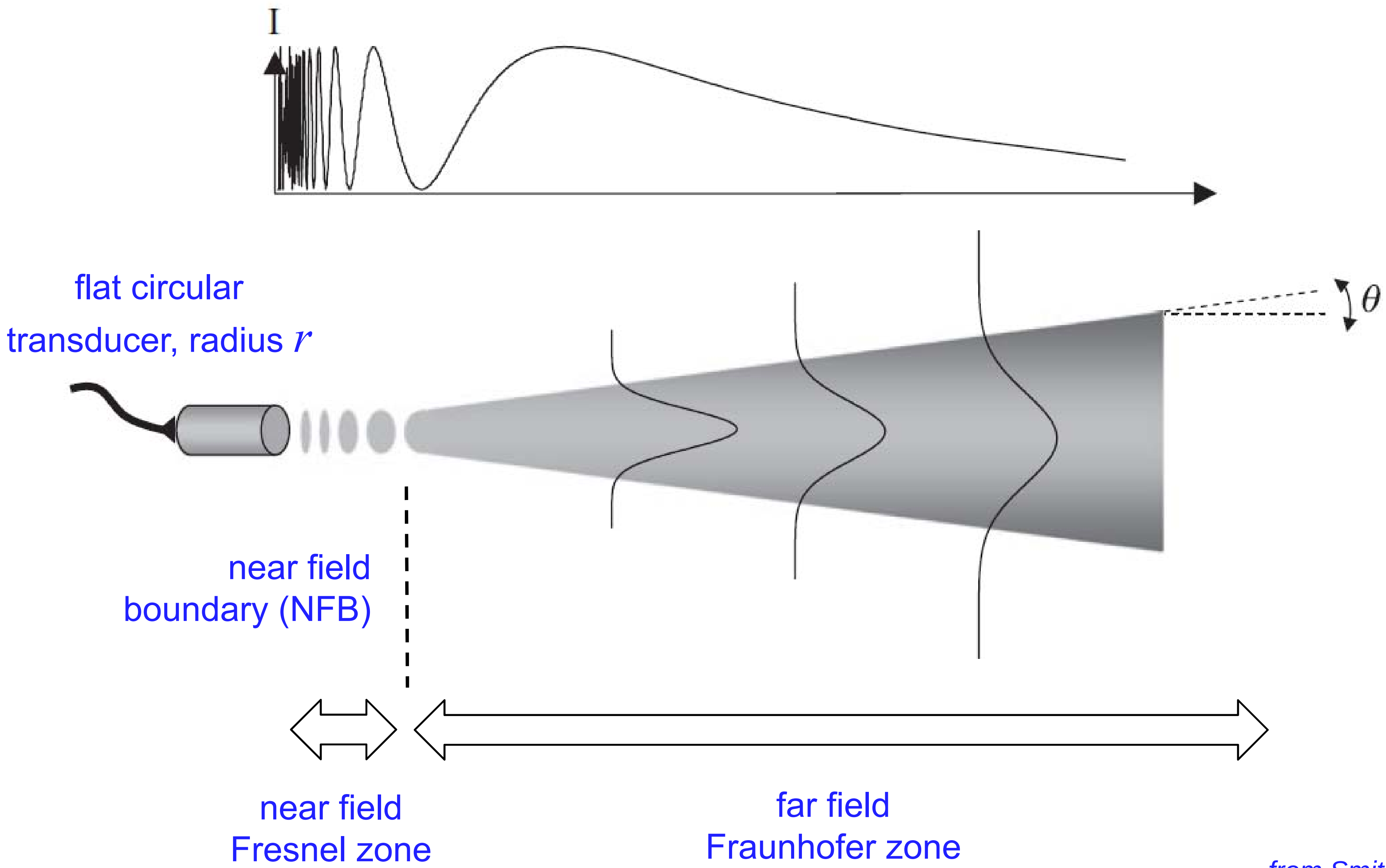
Broadband Transducer



Bandwidth can be larger than f_0 !

from Smith/Webb

Beam Geometry



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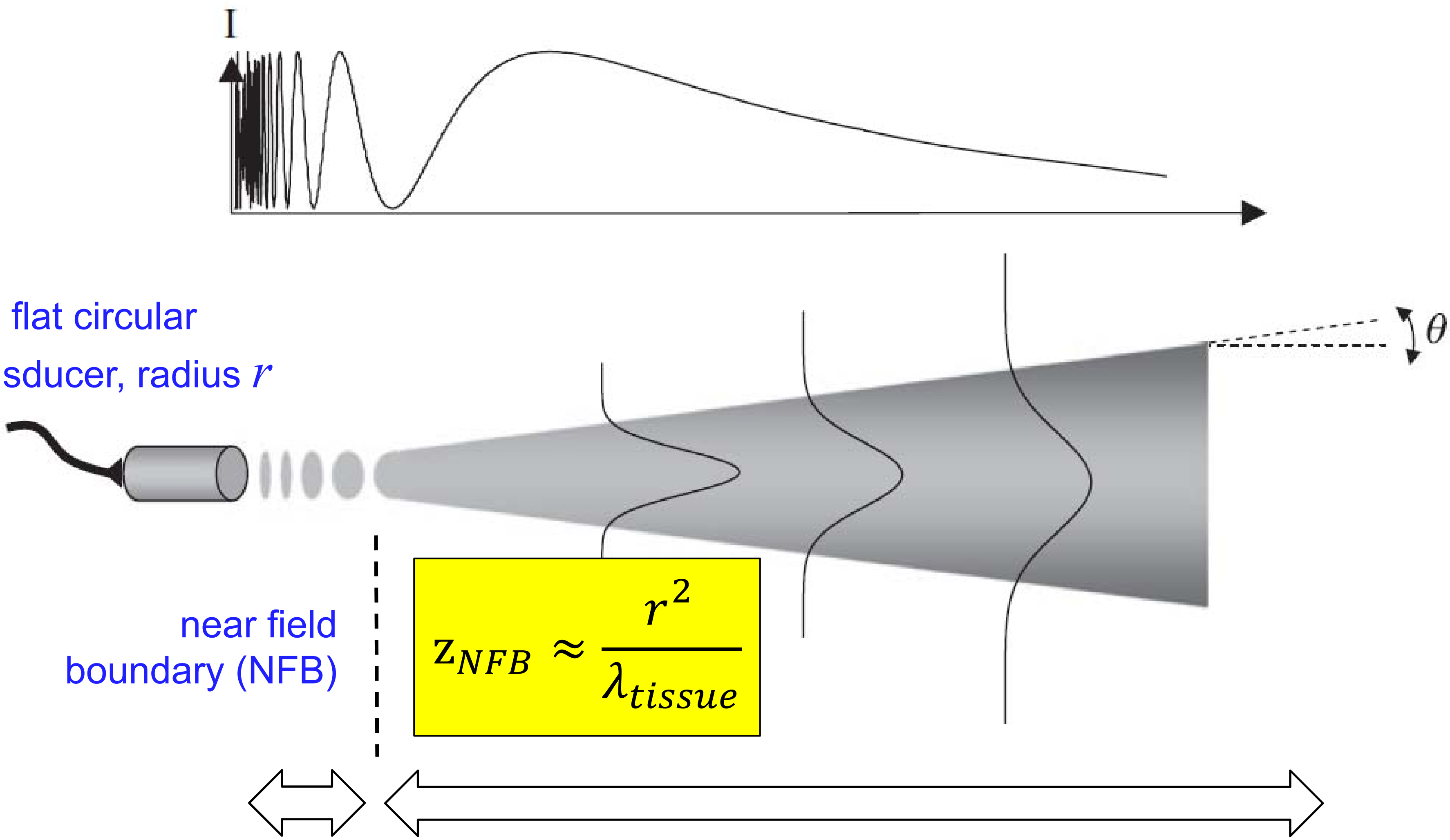
Beam Geometry



flat circular transducer, radius r

near field boundary (NFB)

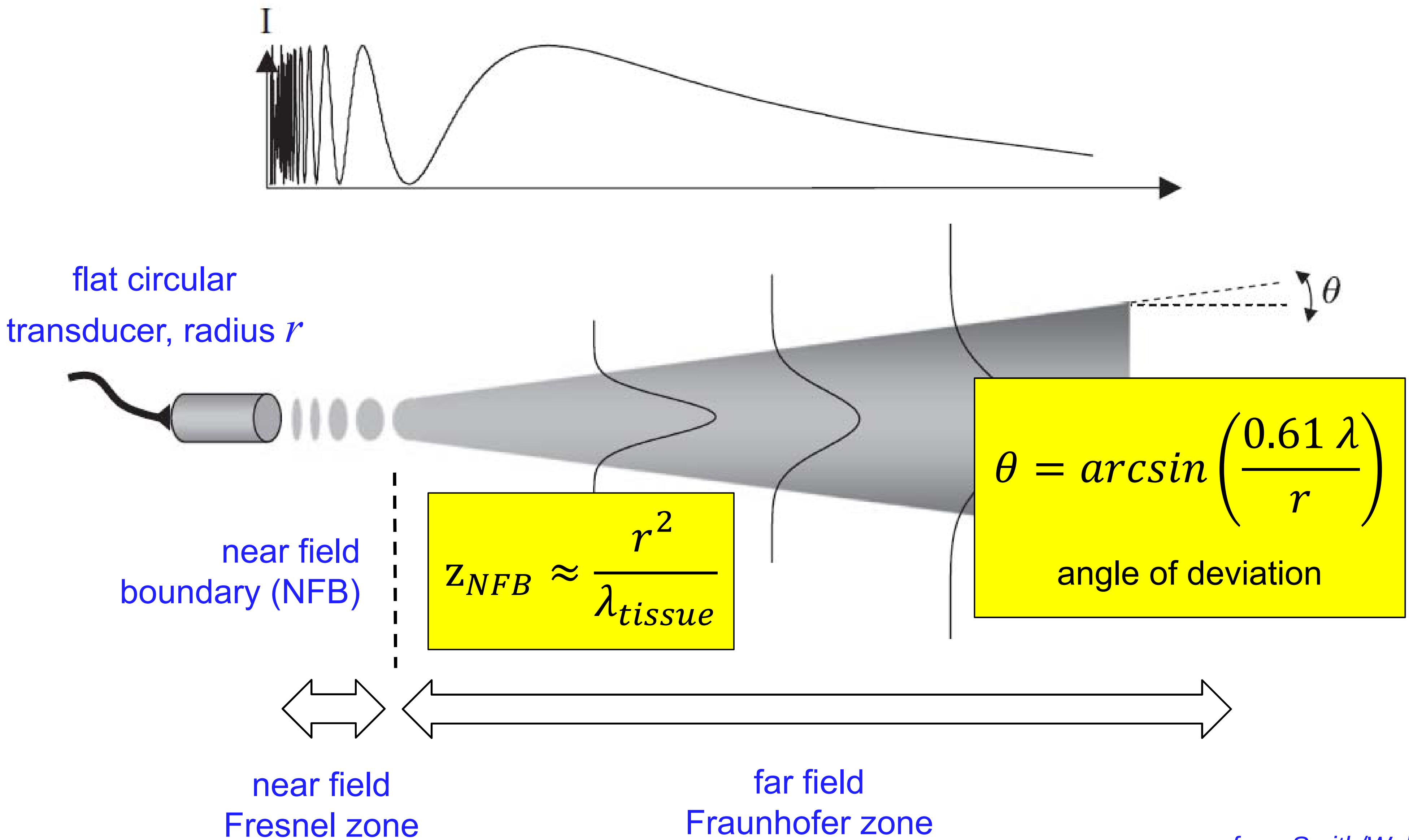
$$z_{NFB} \approx \frac{r^2}{\lambda_{tissue}}$$

near field
Fresnel zone

far field
Fraunhofer zone

from Smith/Webb

Beam Geometry



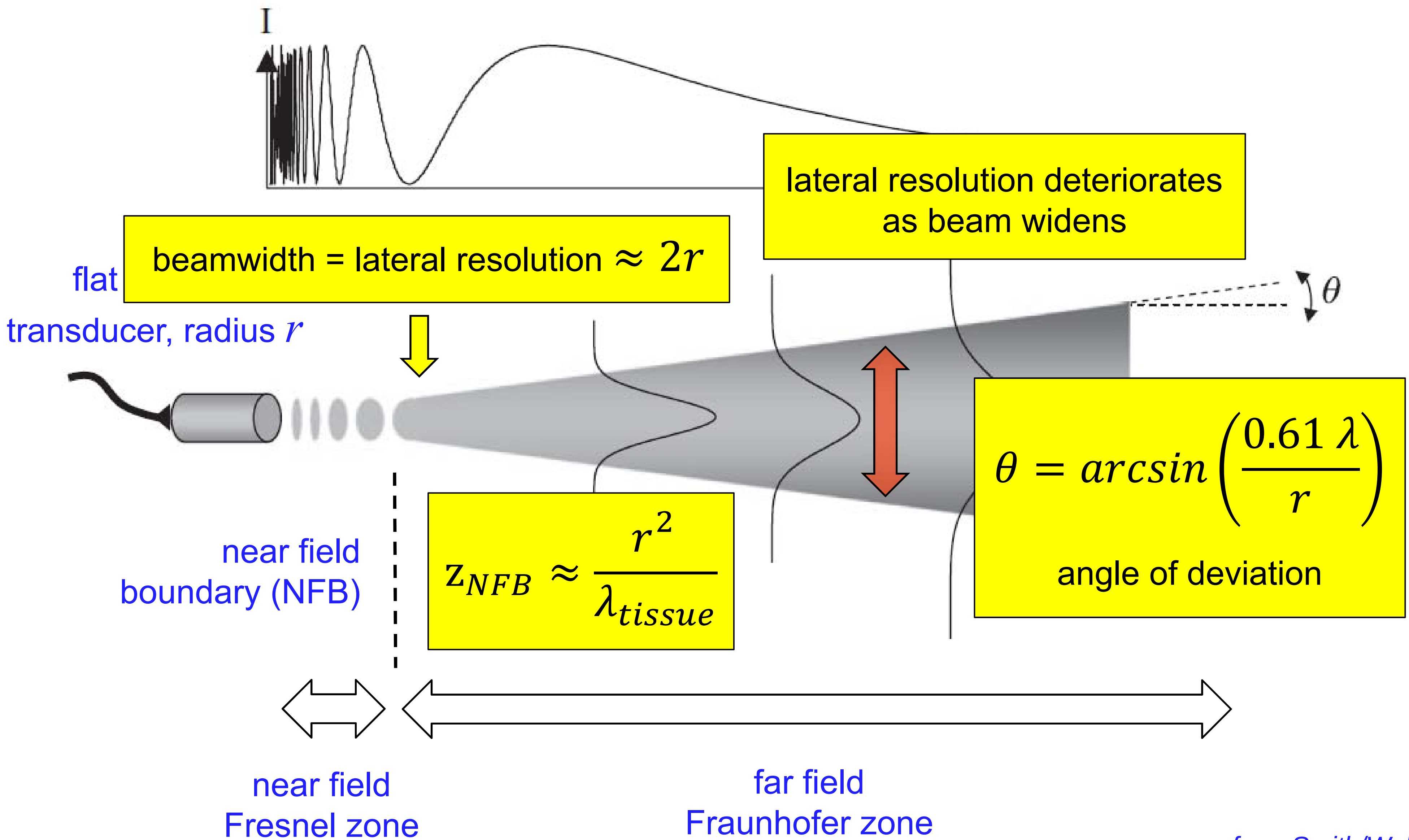
$$z_{NFB} \approx \frac{r^2}{\lambda_{tissue}}$$

$$\theta = arcsin\left(\frac{0.61\,\lambda}{r}\right)$$

angle of deviation

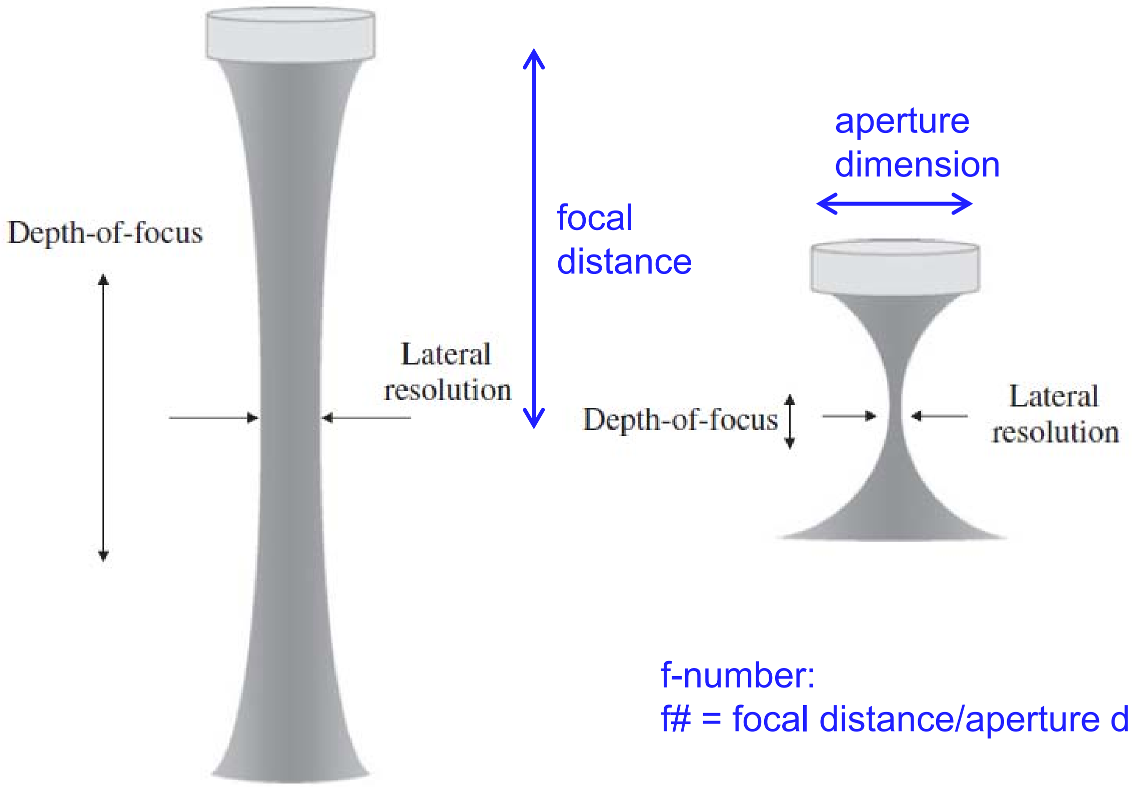
from Smith/Webb

Beam Geometry



from Smith/Webb

Focusing with an Acoustic Lens



f-number:
f# = focal distance/aperture dimension

Strong focusing: good lateral resolution but short focal depth

Weak focusing: medium lateral resolution, longer focal depth

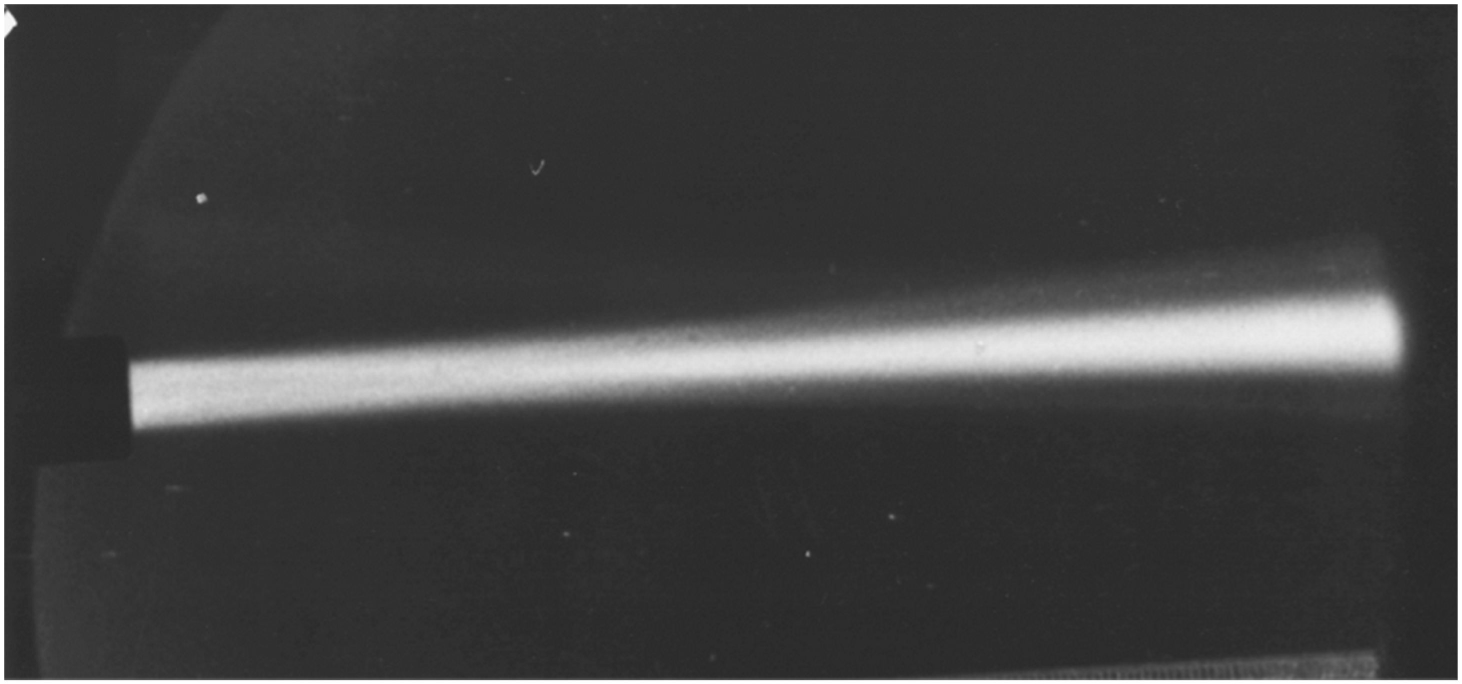
from Smith/Webb

Schlieren Imaging

https://www.youtube.com/watch?v=mLp_rSBztel

Harvard Natural Sciences Lecture Demonstrations

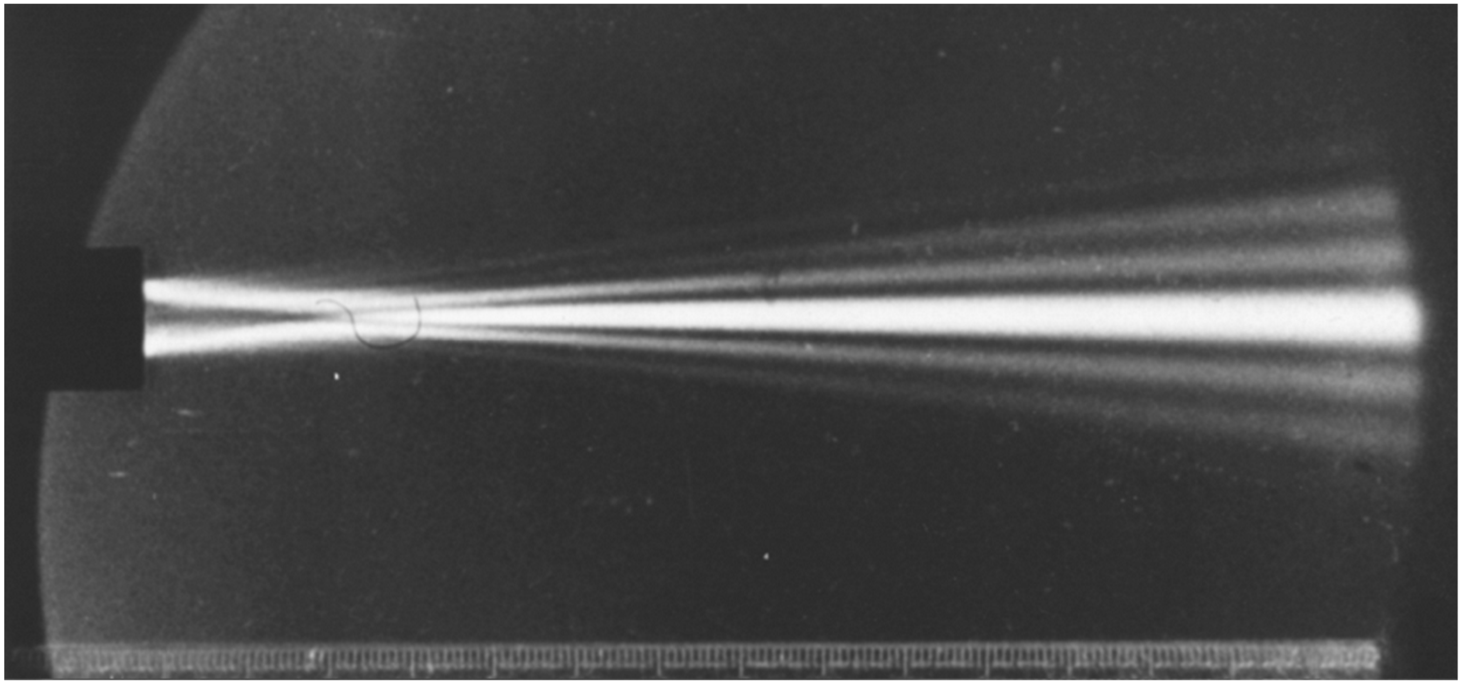
Beam Geometry



Ultrasound beam in water tank

Schlieren picture

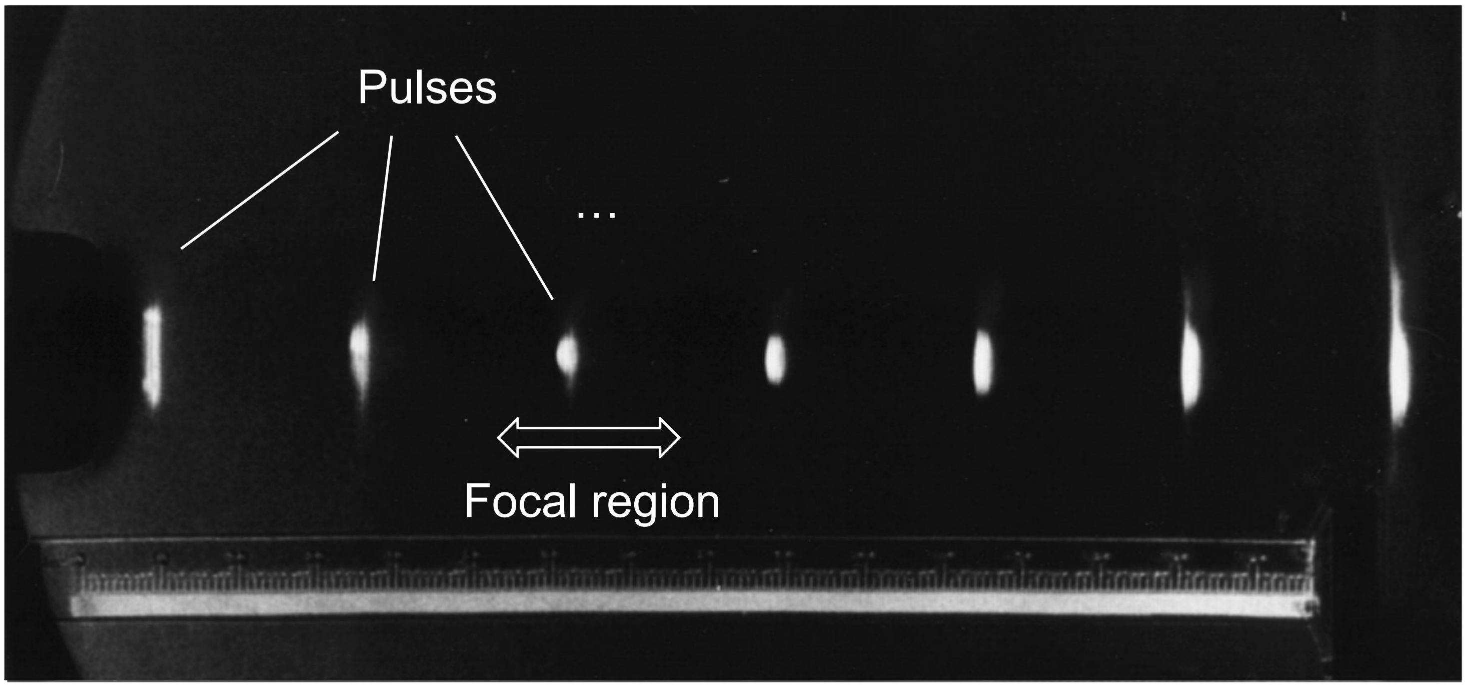
Beam Geometry



Focused ultrasound beam in water tank

Schlieren picture

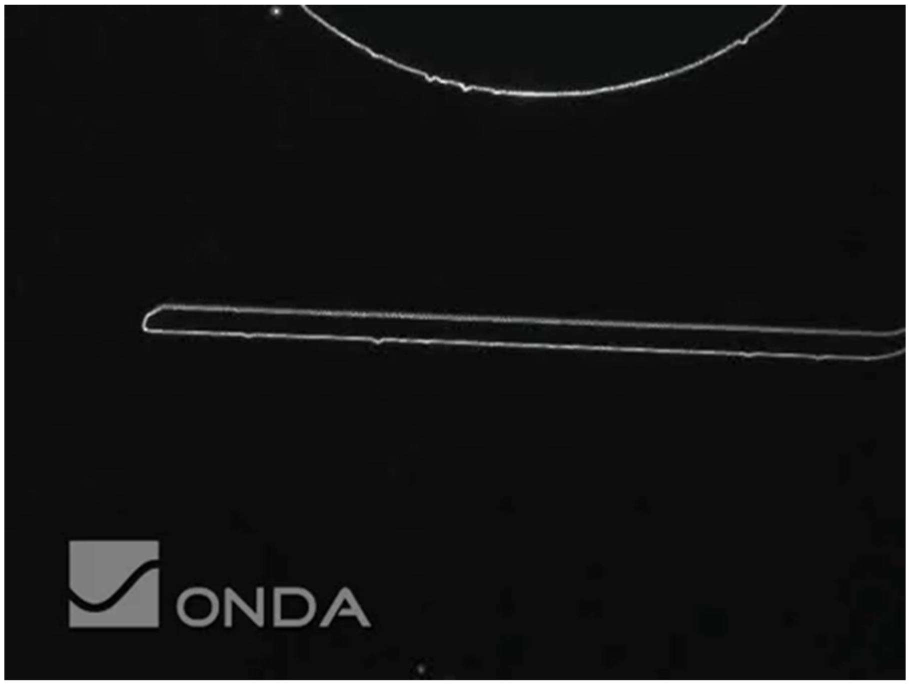
Beam Geometry



Focused and pulsed ultrasound beam in water tank

Schlieren picture

Propagation, Reflection, Focusing, Attenuation



https://www.youtube.com/watch?v=PPBKjSRTwqs

ONDA Corporation

https://www.youtube.com/watch?v=jBEV3IRPNJY

ONDA Corporation

Axial Resolution

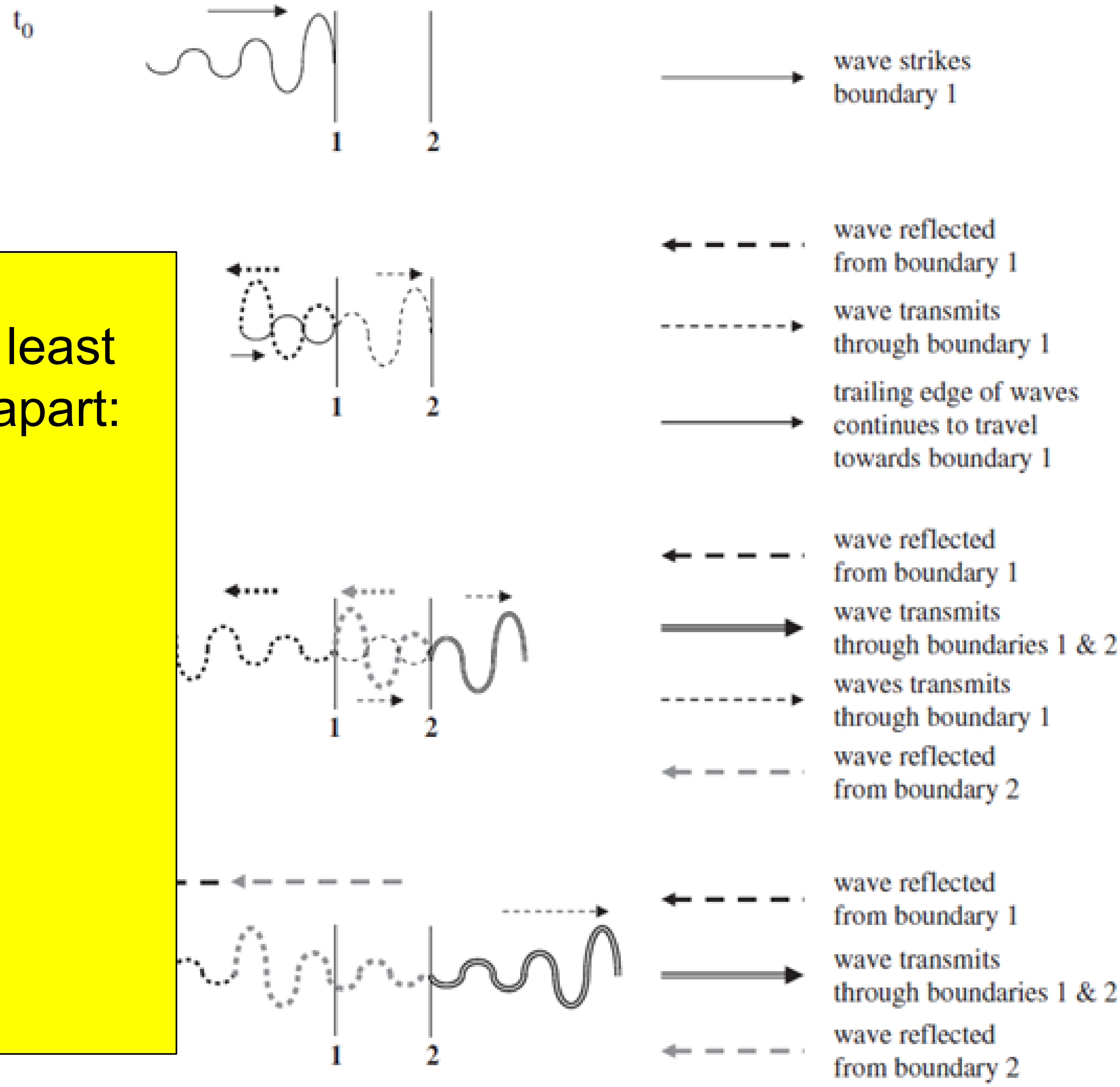
Features must be at least half the pulse width apart:

$$\Delta z = \frac{p_d\, c}{2}$$

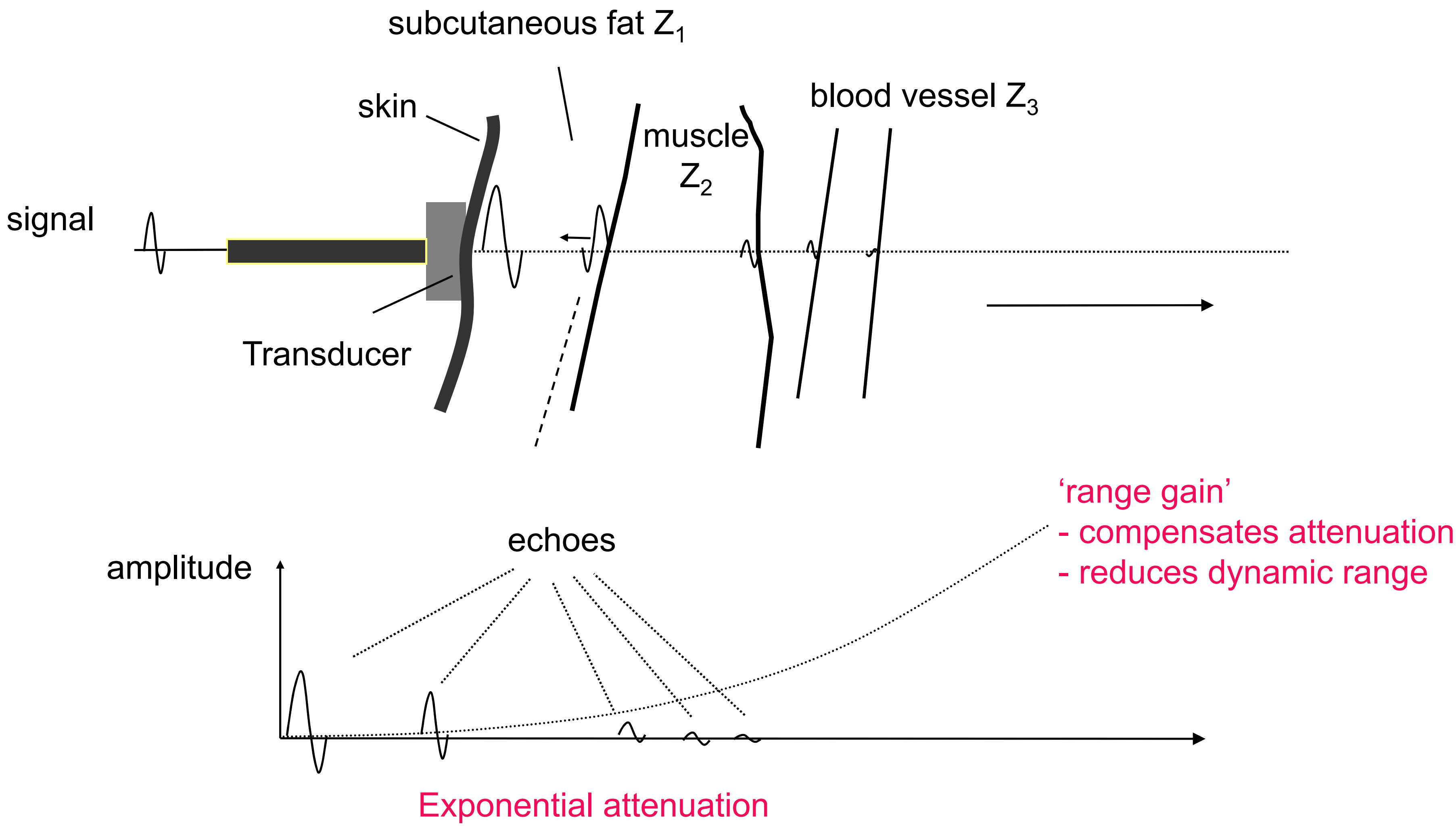
p_d = pulse duration

c = wave speed

implies $\Delta z \geq \frac{\lambda}{2}$



Range Gain


subcutaneous fat Z_1
skin
blood vessel Z_3
muscle
Z_2
signal
Transducer
'range gain'
- compensates attenuation
- reduces dynamic range
echoes
amplitude
Exponential attenuation

SNR in Ultrasound Devices

Example.: frequency 3.5MHz, mean attenuation measure 1dB/cm/MHz, penetration: 15cm

--> Attenuation

$$2\text{x}15\text{cm x } 3.5\text{MHz x } 1\text{dB/(cm MHz)} = 105 \text{ dB (!)}$$

Maximum dynamic range:

Transmitted peak pulse power 10W

Thermal noise of the transducer at bandwidth B=1 MHz and T=310°K:

$$P_N = k\,T\,B = 4.3 \times 10^{-15}\text{ W} \qquad \text{k: Boltzmann constant, } 1.38 \cdot 10^{-23}\text{J/K}$$

--> dynamic range: 154 dB

S/N: dynamic range – attenuation in tissue – loss due to low reflection coefficient (e.g. 3%)

$$S/N = 154 - 105 - 30 = 19 \text{ dB}$$