Medical Diagnostic Ultrasound:

Imaging and interaction with tissue

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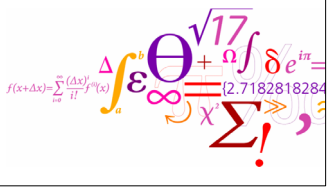


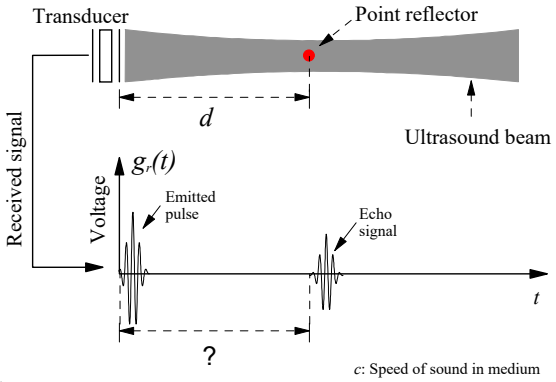
Content

- Imaging by the pulse-echo technique
  - A, M and B mode
  - Spatial resolution size
- Interaction with tissue
  - Plane waves
  - Transmission and reflection
  - Scattering
  - Attenuation
- Special issues
  - Speckle
  - Geometrical effects
  - Other effects (shadows)

Pulse-echo imaging

- Images consist of scan lines
- A scan line appears as a rectangular bar, or region, with a gray tone level proportional to the log of the envelope of the echo signal from the direction it represents

Basic principle in imaging
(pulse-echo mode)



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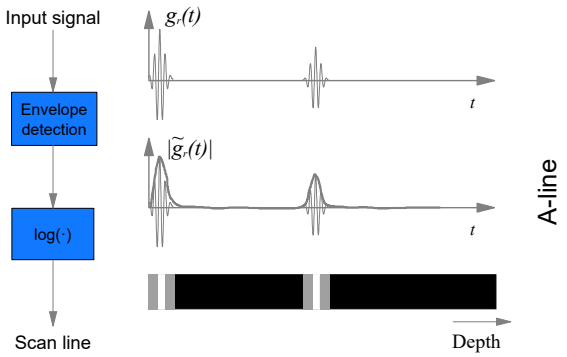
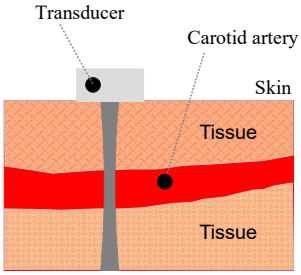
Creating one scan line

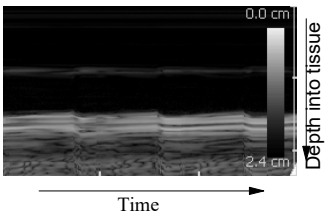


M-mode image of vessel wall

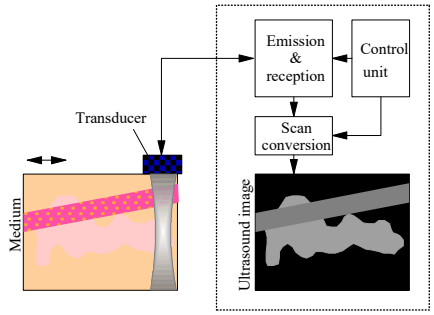
Measurement situation



M-mode image



Building the image with scan lines



Measurement situation Ultrasound system

Animation of B-mode imaging

Please see Webbook

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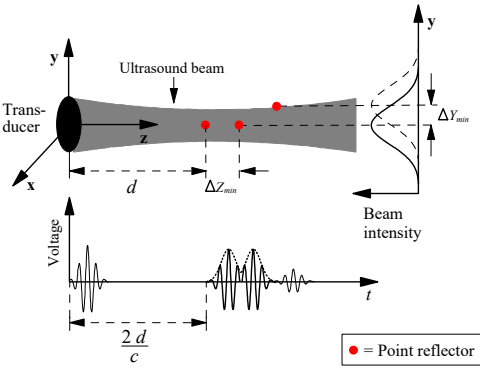
Spatial resolution size



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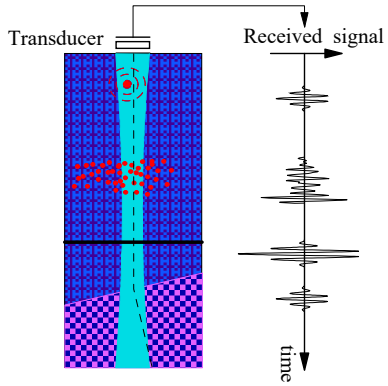
Ultrasound's interaction with tissue



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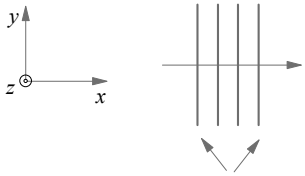
Plane waves



Propagation direction

At any given plane perpendicular to this picture, all acoustic parameters are constant.

The (complex) pressure is:

$\tilde{p}(x,t) = P_0 \exp(-j\,(2\pi f_0 t - 2\pi x/\lambda))$

where:

$\lambda = c/f_0$

and

f_0 = (CW) frequency of the wave

c = the speed of sound

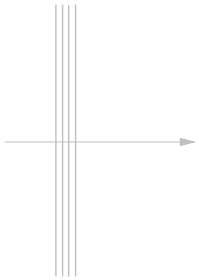
(Monochromatic) Plane waves

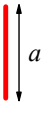
- Are mathematically easy to describe
- Only exist in theory
- Have one frequency and one direction
- "Behaves" as rays in the propagation direction
- Analogies to signal analysis:
  - A *plane wave* correspond to an *infinite tone signal*

Organization

Size matters!

Incident plane wave





a $a >> \lambda$ 1 Specular reflection

a $a \approx \lambda$ 3 Most real life

a $a << \lambda$ 2 Scattering

= Interface generating an echo. λ = wavelength

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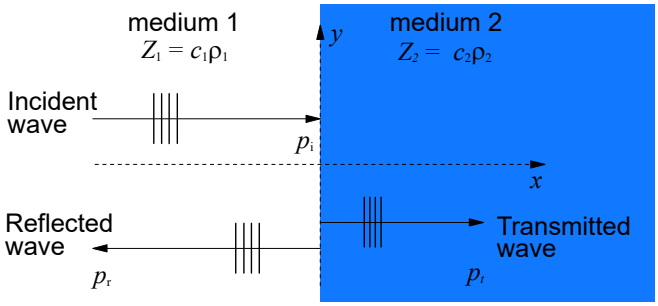
Transmission and reflection:

Normal incidence

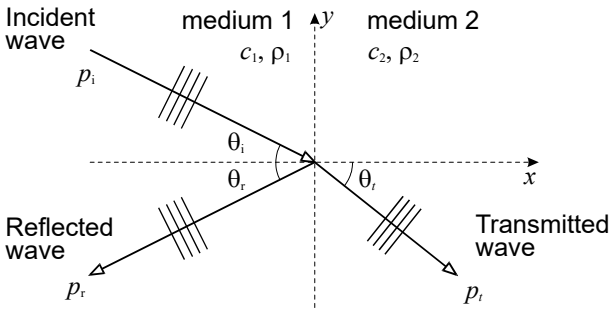


Z_1 = specific acoustic impedance.

$r_p = (Z_2\text{-}Z_1)/(Z_1+Z_2)$ = amplitude reflection coef. $-1 \le r_p \le 1$

Transmission and reflection:

Oblique incidence



θ_r and θ_t are governed by Snell's law (see notes)

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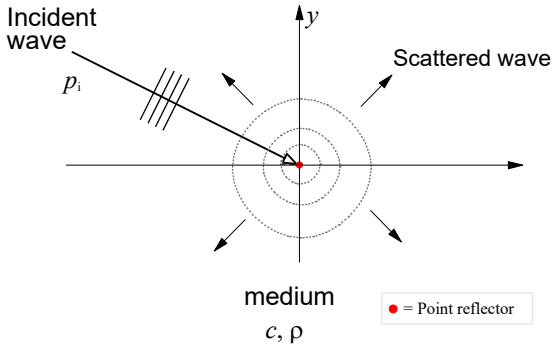
Scattering:



← Backscattering Forward scattering →

(relative to direction of incident wave)

Summarizing

Echoes in biological tissue are generated by a situation *in-between*:

- ***Specular reflection from infinitely large interfaces*** between materials of different acoustic impedance
- ***Scattering from infinitely small point targets*** with acoustic impedance different from the surroundings

Examples

Specular reflection from large interfaces:

-
-

Scattering from small point targets:

-
-

Echo from "structures":

-
-

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Attenuation (Kinsler & Frey):

1) Absorption (conversion of acoustic energy to heat):
   - Viscous losses
   - Heat conduction losses and
   - Molecular exchanges of energy
2) Losses due to scattering and reflection

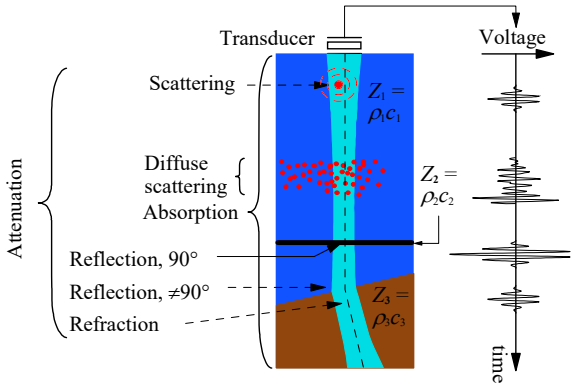
The intensity of the forward propagating wave:

$$I(z) = I(0)\exp(-\alpha z)$$

where α [m^{-1}] is the *attenuation coefficient* and z is distance traveled.

For typical tissue, the attenuation is 1 dB/cm/MHz

Ultrasound's interaction with tissue



Selected tissue parameters

Medium	Density (kgm^{-3})	Specific acoustic impedance ($kgm^{-2}s^{-1}$)
Air	1.2	0.4×10^3
Fat	0.92×10^3	1.33×10^6
Water	1.00×10^3	1.53×10^6
Kidney	1.04×10^3	1.62×10^6
Liver	1.06×10^3	1.66×10^6
Blood	1.06×10^3	1.66×10^6
Muscle	1.07×10^3	1.70×10^6
Bone	1.62×10^3	$4\text{-}7.5 \times 10^6$

- = Soft tissues

μ-Problem:

What is the amplitude reflection coefficient between blood and muscle (assuming normal incidence)?

μ-Solution:

The amplitude reflection coefficient between blood (Z_1) and muscle (Z_2):

$$r_p = (Z_2\text{-}Z_1)/(Z_1+Z_2)$$
$$= (1.7\text{-}1.66)/(1.66+1.7) = \_\_\_\_\_ \%$$

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Speckle

Many sub-resolvable scatterers are normally present in the ultrasound beam

⇒ random interference pattern between the echoes of the individual scatterers

⇒ Resulting echo signal might have a highly fluctuating amplitude

Show pulse_echo program

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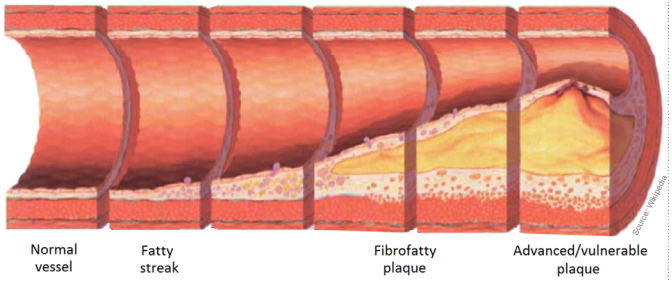
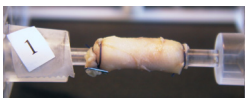
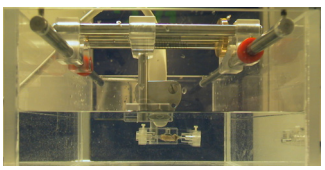
Atherosclerosis



Principle of measurement situation





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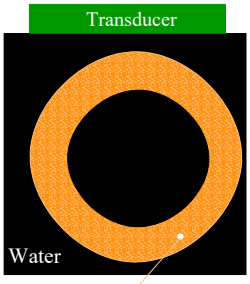
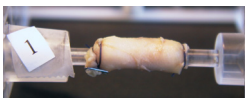
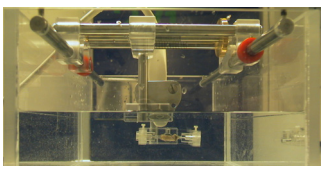
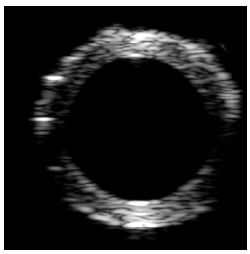


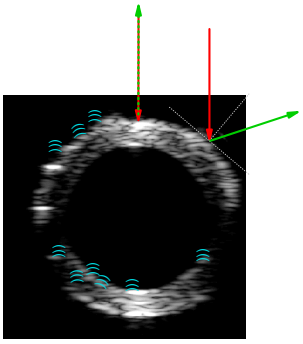




Conventional ultrasound image



Conventional ultrasound image

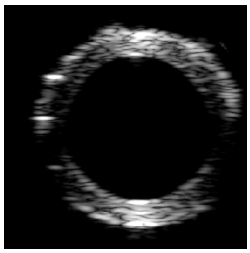


Specular reflection:
- Sound in "wrong" directions
- Phase cancellation at transducer surface

Scattering:
- Independent on angle

Interference:
- Provides the speckle pattern

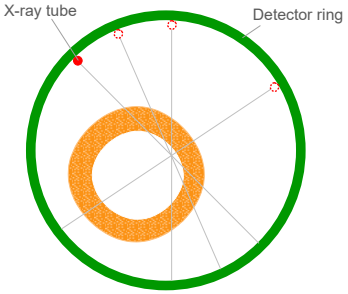
Conventional ultrasound image



Known tissue: ☺
Unknown tissue: 😐
Atherosclerosis: ☹

Comparison with CT

Recording of CT image



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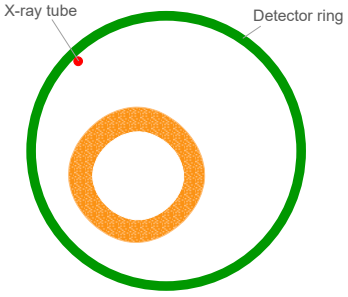
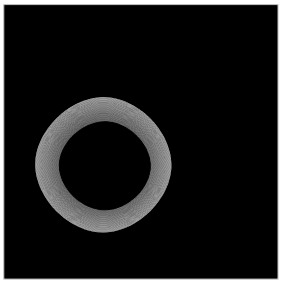
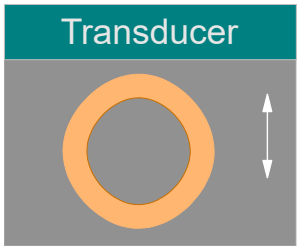


CT image



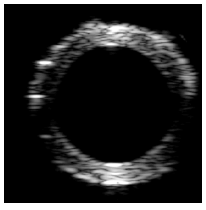
Conventional B-mode image

Measurement situation



$\theta_a = 0^o$

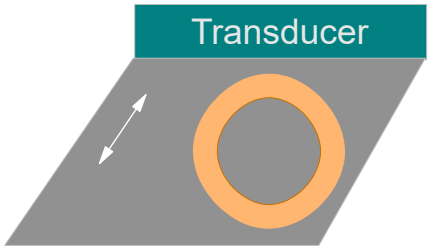
Corresponding image

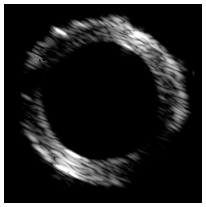


Spatial compounding (MACI)

Measurement situation

Corresponding image





$\theta_a = -25°$

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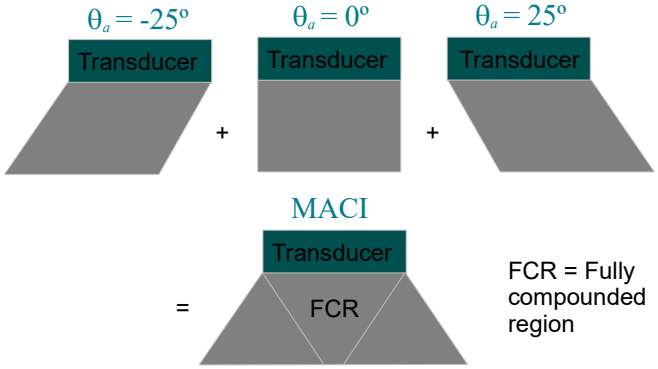
Spatial compounding (MACI)



FCR = Fully compounded region

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Conventional B-mode image

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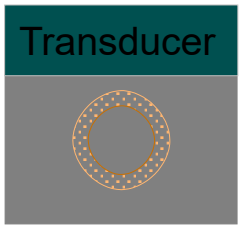

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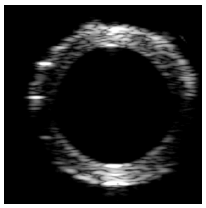

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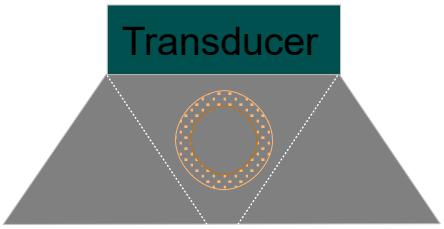
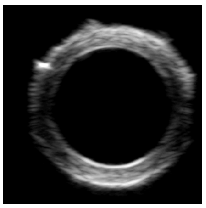


Compound image
(-25°, -15°, -5°, 5°, 15°, 25°)



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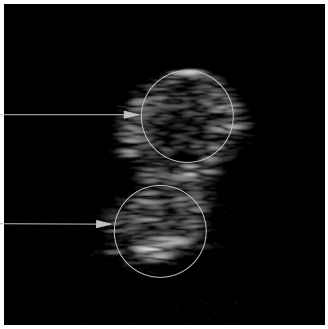
B-mode image of *in vitro* Carotid plaque



0° image

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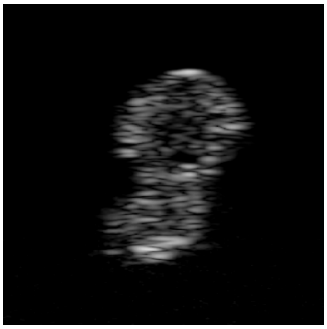
B-mode image of *in vitro* Carotid plaque



0° image

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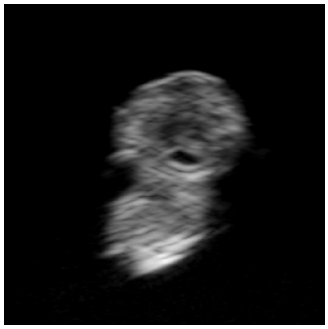
Compound image of *in vitro* Carotid plaque



Average of 7 single-angle images

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Angle-dependence

- Modelling
- Measurements (rough surfaces)

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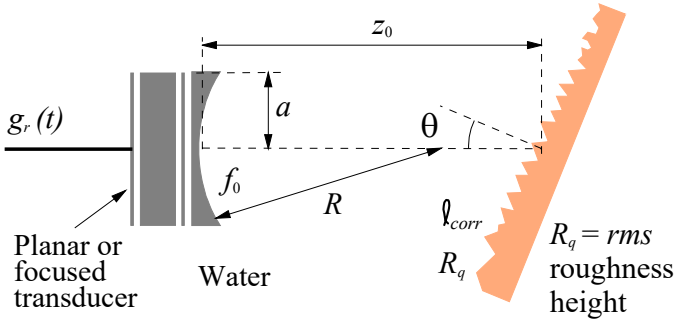
Simplified measurement set-up



$$E(\theta, z_0, R_q) = \int |\tilde{g}_r(t, \theta, z_0, R_q)|^2 \, dt$$

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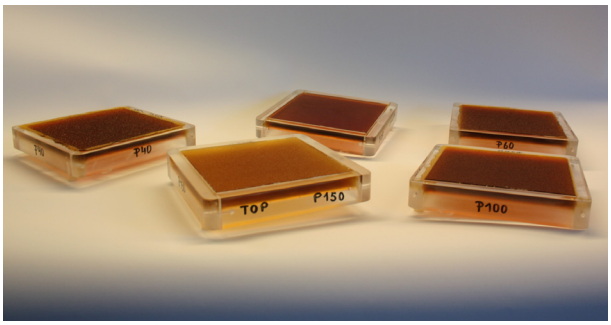
Rough surfaces



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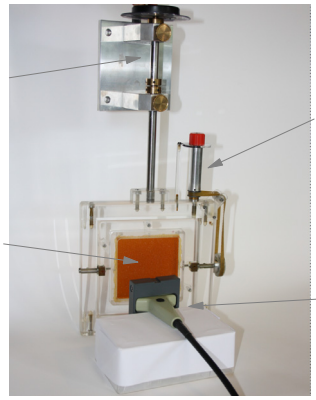
Dual-angle rotation holder



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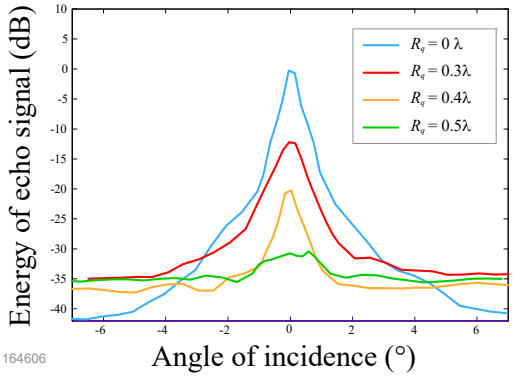
Energy of received signal, $E(\theta, z_0, R_q)$

(5 MHz planar transducer, a = 12.7 mm, z_0 = 70.4 mm)

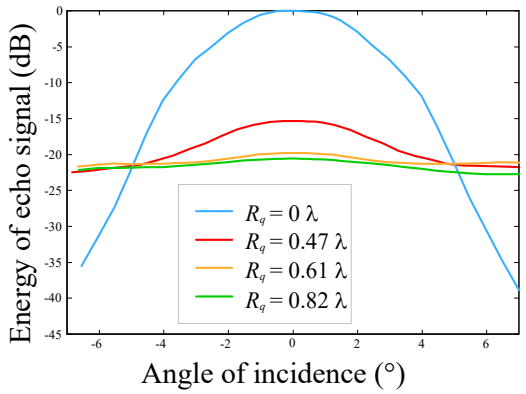


Serial: 164606

BME Health Technology

Energy of received signal, $E(\theta, z_0, R_q)$

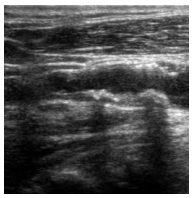
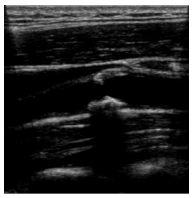
(7.5 MHz focused transducer, a = 6.35 mm R = 58.5 mm, z_0 = 58.5 mm)



Content

- Imaging by the pulse-echo technique
  - A, M and B mode
  - Spatial resolution size
- Interaction with tissue
  - Plane waves
  - Transmission and reflection
  - Scattering
  - Attenuation
- Special issues
  - Speckle
  - Geometrical effects
  - Other effects (shadows)

Shadows

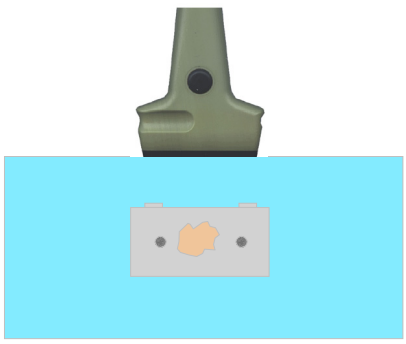




N. Endrup, CADIUS, 2005

Images of atherosclerotic Carotid plaque causing shadows

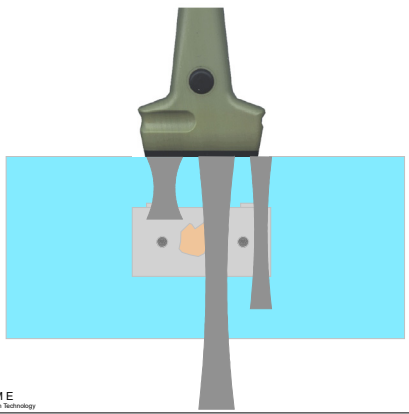
Measurements in this course

Measurements in this course



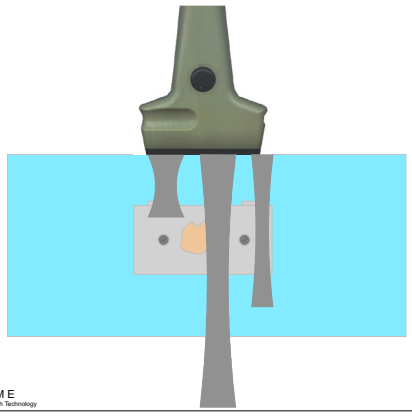
- Before recording:

Measurements in this course



- Before recording:
  - Depth of image
  - Transmit focal point

Measurements in this course



- Before recording:
  - Depth of image
  - Transmit focal point
- After recording:
  - Note transducer frequency
  - Are pixels quadratic in size?
  - How to find axis?