Medical Engineering - Imaging Systems

Ultra Sound

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Pattern Recognition Lab (CS 5)
SS 2021

Ultra Sound

Ultrasound Applications

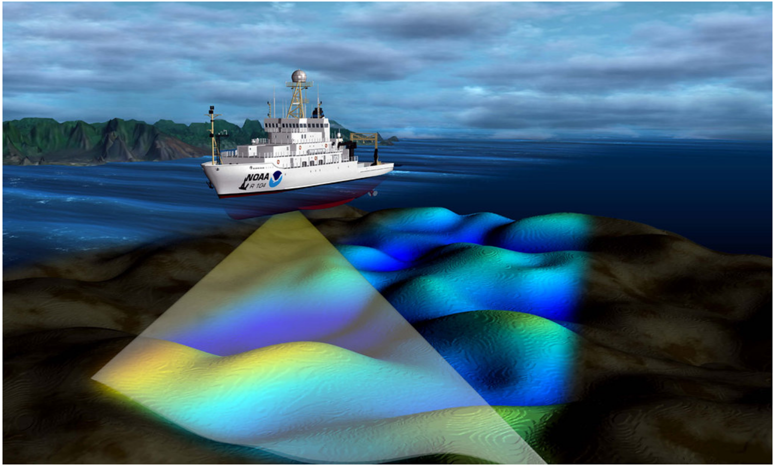
Ultrasound in Medicine

Physics of Sound Waves

Imaging Modes

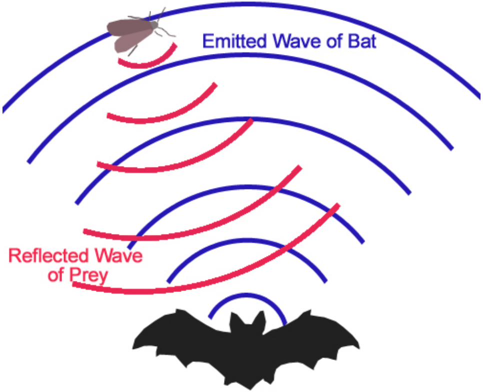
Safety in US Imaging

Ultrasound Applications: SONAR



Source: National Ocean Service

Ultrasound Applications: Echolocation



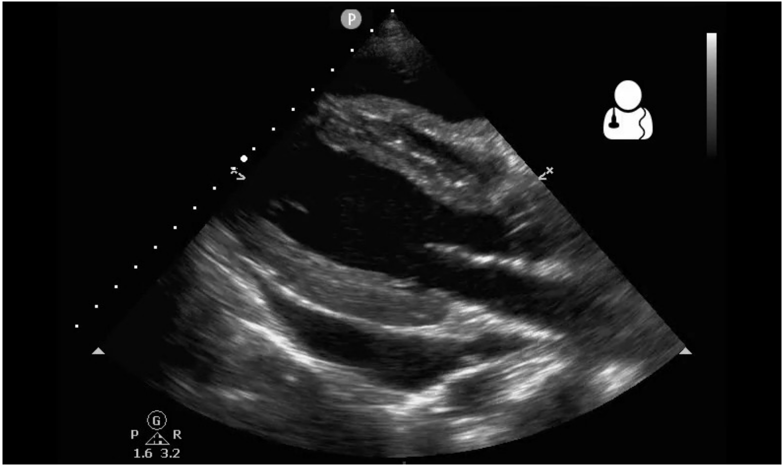
Source: By Shung `https://commons.wikimedia.org/w/index.php?curid=11999649`

Ultrasound Applications: Medical

Ultrasound Applications: Medical (cont.)

3D Ultrasound of fetuses. Source: [1]

Ultrasound Applications: Medical (cont.)



Ultrasound image of a beating heart (click for video).

Ultrasound Applications: Medical (cont.)

Applications of ultrasound in medicine

- Pregnancy
- Gynecology
- Gastrointestinal tract
- Heart
- Blood vessels (stenosis, aneurysms)
- Blood flow
- . . .

Ultra Sound

Ultrasound Imaging

Ultrasound (US) imaging (or ultrasonography)

- A medical imaging technique that uses high frequency sound waves and their echoes

→ similar to echolocation (bats, whales, dolphins) and SONAR (submarines)

Ultrasound Imaging (cont.)

Acoustic spectrum

	Frequencies f	Examples
Infrasound	$0 \ldots 16$ Hz	Seismic waves
Audible sound	16 Hz ... 20 kHz	Music Human speech
Ultrasound	20 kHz and up	Bats Dolphins SONAR Acoustic microscopy Medical Imaging

$\rightarrow$ Medical ultrasound: $f \approx 1$ MHz ... 40 MHz

Historical Remarks

From discovery of underlying physical principles to first clinical scanner

1880: Discovery of piezoelectic effect
1920: Ultrasound-based distance measurement in water (SONAR)
1933: Therapeutic use of ultrasound
1952: First 2D pulse echo image
1953: Breast imaging using ultrasound
1957: Echocardiography using ultrasound motion mode (M-mode)
1957: Doppler imaging
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Ultra Sound

Sound Waves

Waves

- Spatially propagating, periodically repeating processes
- Distinction based on direction of propagation
  - Transverse waves
  - Longitudinal waves

Sound Waves

- Sound waves are longitudinal waves
- Caused by local periodic compression of matter
- In liquids and gases: only longitudinal waves possible

Sound Waves (cont.)

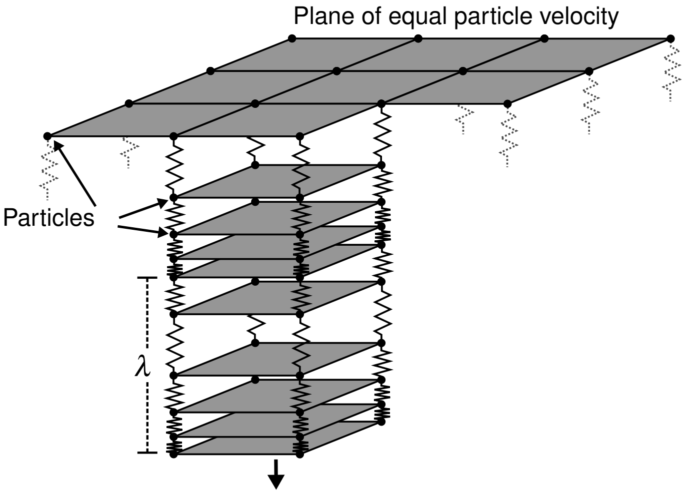
Sound waves can be characterized by

- Frequency f (Hz)
  - Oscillation count per second
- Sound velocity v ($\mathrm{m\,s^{-1}}$)
  - Independent of f
  - Varies with material properties (e.g. elasticity, density)
- Wavelength λ (m)
  - Distance between two oscillation maxima
- Intensity J ($\mathrm{W\,m^{-2}}$)
  - Acoustic power density

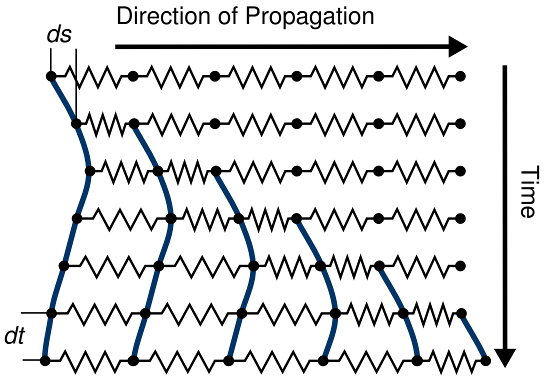
Fundamental wave equation:

$$\lambda = c/f$$

Sound Waves (cont.)



Sound Waves (cont.)



Mass-spring model of longitudinal wave

→ Sound velocity $v = \mathrm{d}s / \mathrm{d}t$

Sound Waves (cont.)

Acoustic impedance Z ($\mathrm{g\,cm^{-2}\,s^{-1}}$)

Z of a medium is determined by its material properties

$$Z = \sqrt{E \cdot D}$$

Z : Acoustic impedance
E : Tensile modulus (elasticity)
D : Density of medium

Sound Waves (cont.)

Sound velocity in, and impedance of various biological materials

Medium	v [m/s]	Z [g cm^{-2} s^{-1}]
Air	331	43
Fat	1470	$1.42 \cdot 10^5$
Water	1492	$1.48 \cdot 10^5$
Brain tissue	1530	$1.56 \cdot 10^5$
Muscles	1568	$1.63 \cdot 10^5$
Bones	3600	$6.12 \cdot 10^5$

Characteristics at Boundaries

At boundaries between two media, sound waves ...

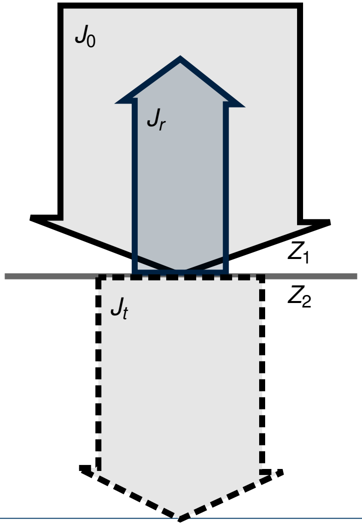
- ... are partially reflected
  $\rightarrow$ Reflection coefficient

$$R = \frac{J_r}{J_0} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

- ... and partially transmitted
  $\rightarrow$ Transmission coefficient

$$T = \frac{J_t}{J_0} = \frac{4 \cdot Z_1 \cdot Z_2}{(Z_1 + Z_2)^2}$$

$\Rightarrow$ Holds for perpendicular incidence



$\rightarrow$ J_0, J_r, J_t: Acoustic intensities $[\mathrm{W\,m^{-2}}]$

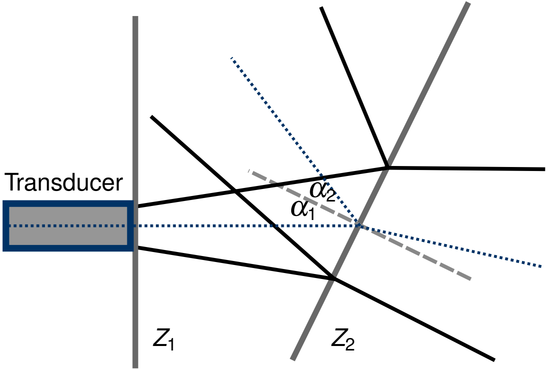
Characteristics at Boundaries (cont.)

Reflectivity at boundaries between various materials

Material 1	Material 2	Reflected portion
Brain	Skull bone	43.5 %
Fat	Muscle	1 %
Fat	Kidney	0.6 %
Muscle	Blood	0.1 %
Soft tissue	Water	0.25 %
Soft tissue	Air	99.9 %

Characteristics at Boundaries (cont.)

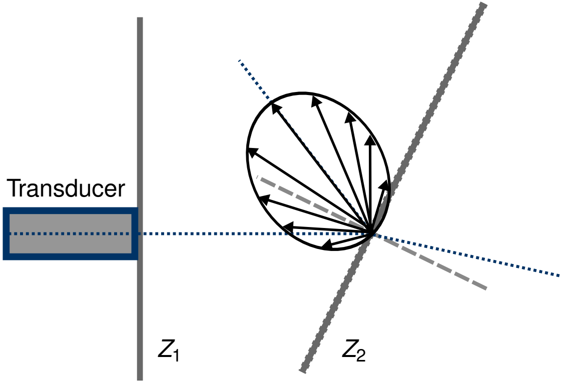
Reflection of sound waves at smooth surfaces (angles α_1, α_2)



$$\alpha_1 = \alpha_2$$

Characteristics at Boundaries (cont.)

Diffuse reflection at rough boundaries

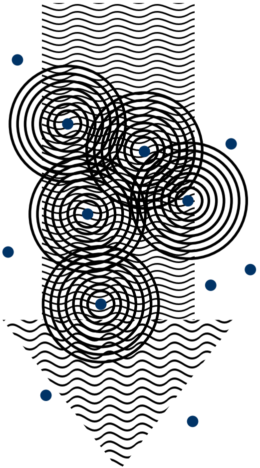


$\rightarrow$ Width of reflection cone increases with decreasing λ and increasing roughness

Characteristics at Boundaries (cont.)

Small inhomogeneities (size: *a*) in the material cause scattering of the waves.

- $a \gg \lambda$: Geometric range (high scattering)
  $\rightarrow$ Vessels
- $a \approx \lambda$: Stochastic range (medium scattering)
  $\rightarrow$ Liver
- $a \ll \lambda$: Rayleigh range (low scattering)
  $\rightarrow$ Blood



Characteristics at Boundaries (cont.)

Reflection

- Reflection defines borders in ultrasound images
- Large portions of the incident intensity can be reflected

  $\rightarrow$ especially at borders of materials with large difference in impedance

Scattering ...

- ... adds to reflective response
- ... generates speckle noise

  $\rightarrow$ especially for inhomogeneities with $a \approx \lambda$ (geometric range)

Attenuation

Exponential law of attenuation

$$J(x) = J_0 \cdot \exp\left(-\mu \cdot x\right) \tag{1}$$

$\Rightarrow$ Acoustic intensity J decreases with increasing penetration depth (x)

Attenuation coefficient μ [dB]

- Attenuation that occurs with each cm the sound wave travels in a medium
- Depends on material (tissue type) and ultrasound frequency f
- Consists of absorption μ_a and scattering μ_s part: $\mu = \mu_a + \mu_s$
- Absorption leads to heating of tissue

Attenuation (cont.)

Maximum penetration depth for various frequencies *f*

f [MHz]	Max. depth [cm]	Typical Applications
1	50	*n/a*
3.5	15	Fetus, liver, heart, kidney
5	10	Brain
7.5	7	Prostate
10	5	Pancreas (intraoperative)
20	1.2	Eye, skin
40	0.6	Intravascular

$\Rightarrow$ For high maximum penetration depth, small frequencies are necessary.

$\Rightarrow$ Resolution decreases with decreasing frequency

$\Rightarrow$ more later . . .

Transducers

Ultrasound transducers . . .

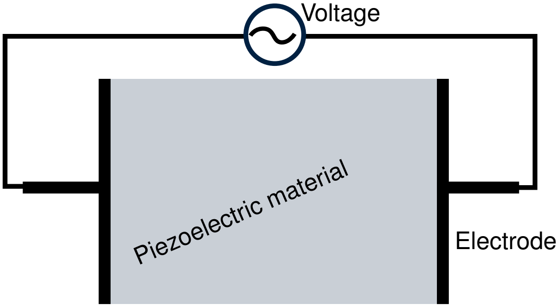
- . . . send and receive ultrasound waves (and their echoes)
- . . . convert mechanical energy into electrical energy and vice versa
- . . . make use of the piezoelectric effect

Source: Medical Imaging Systems [1]

Transducers (cont.)

Piezoelectric effect

- Mechanical pressure (*piezo* (gr.)) is converted to electric polarization
  $\rightarrow$ Electric voltage is generated (measurable using two electrodes)
- Electric field causes stretching of piezoelectric material
  $\rightarrow$ Can be used to generate sound waves



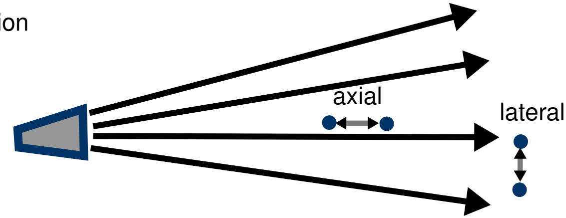
Spatial Resolution

Lateral resolution

- Minimal distance perpendicular to US beam to distinguish two points
- Affected by beam width and depth of imaging

Axial resolution

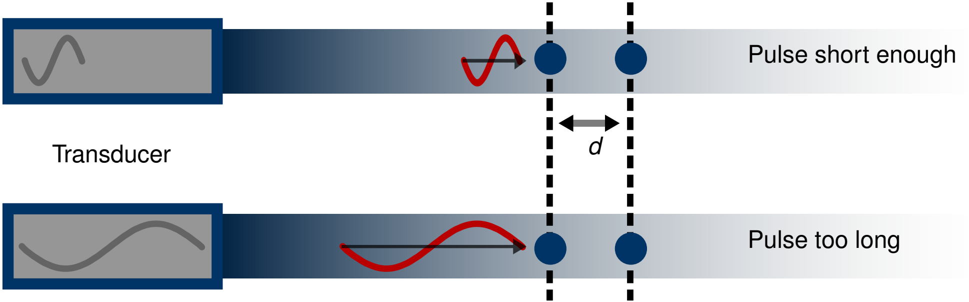
- Resolution in direction parallel to US beam
- Does not change with depth
- Also known as longitudinal or azimuthal resolution



Spatial Resolution (cont.)

Axial resolution (cont.)

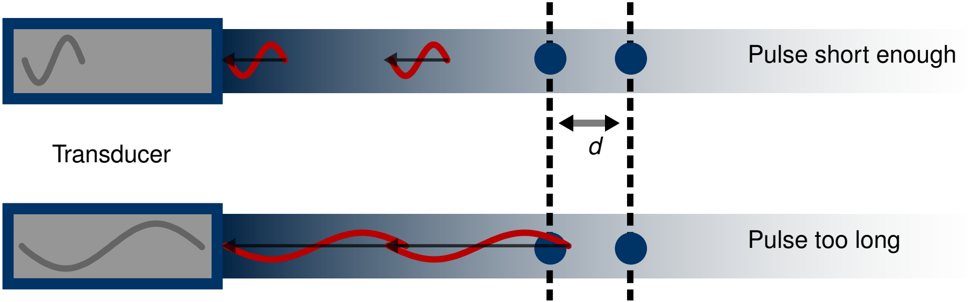
- Shortest pulse: single wave



Spatial Resolution (cont.)

Axial resolution (cont.)

- Shortest pulse: single wave



$\rightarrow$ Two distinguishable echoes are generated only if $d > \lambda/2$.
$\rightarrow$ Resolution decreases when λ increases (frequency $f = c/\lambda$).

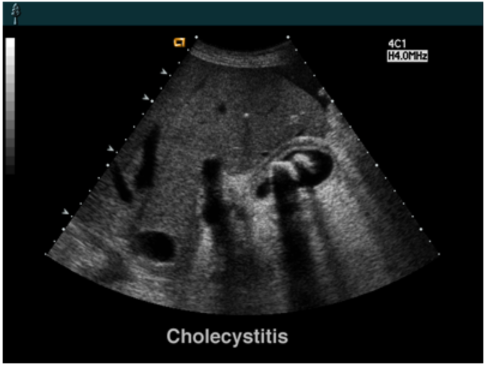
Spatial Resolution (cont.)

Frequency trade-off

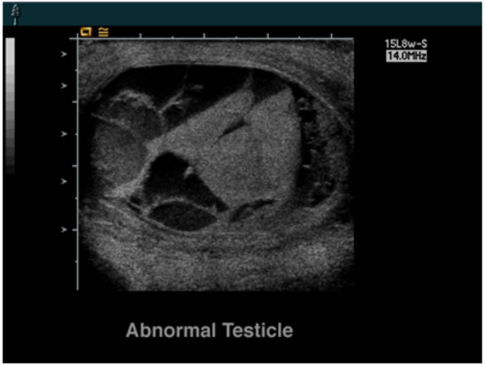
- Transducer frequency is directly related to resolution
    - High frequency $\rightarrow$ high resolution
    - Low frequency $\rightarrow$ low resolution
- However, it is also directly related to attenuation
    - High frequency $\rightarrow$ high attenuation
    - Low frequency $\rightarrow$ low attenuation
- High frequency $\rightarrow$ low penetration depth with high resolution
- Low frequency $\rightarrow$ deep penetration with low resolution

Spatial Resolution (cont.)

Frequency trade-off (cont.)



$f = 4$ MHz.



$f = 14$ MHz.

Ultra Sound

Imaging Modes

Most common US imaging modes

- A-mode
- B-mode
- M-mode
- Doppler mode
  - Pulse wave Doppler
  - Continuous wave Doppler
  - Spectral Doppler
  - Color Doppler

Imaging Modes (cont.)

A-mode

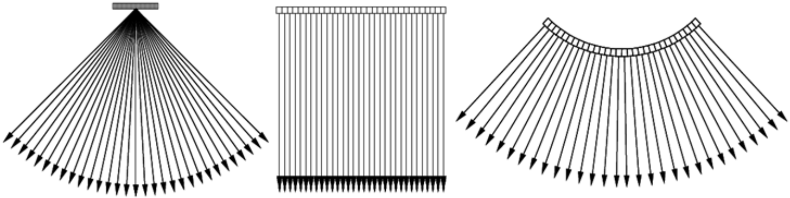
- **A**mplitude-mode
- Single transducer scans on a line through the body (1D)
- Depth: time required for US beam to hit boundary and reflect signal
- Reflected signal strength can be measured (amplitude)
- Echoes are plotted on screen as function of depth

$\rightarrow$ Simplest scanning method.

Imaging Modes (cont.)

B-mode

- **B**rightness-mode (or 2D mode): spatially encoded echo amplitude
- Time required for echo: position
- Amplitude: image brightness
- Uses array of transducers to generate 2D images

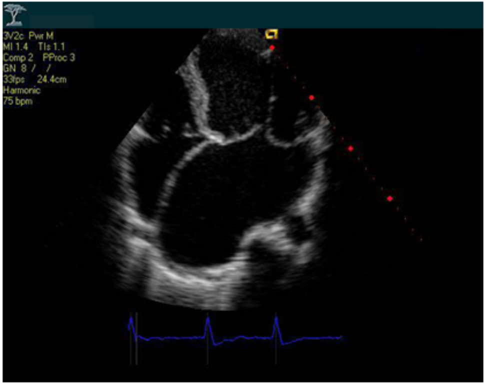


Left to right: sector probe, linear array, curved array.

→ Most common scanning method.

Imaging Modes (cont.)

B-mode (cont.)

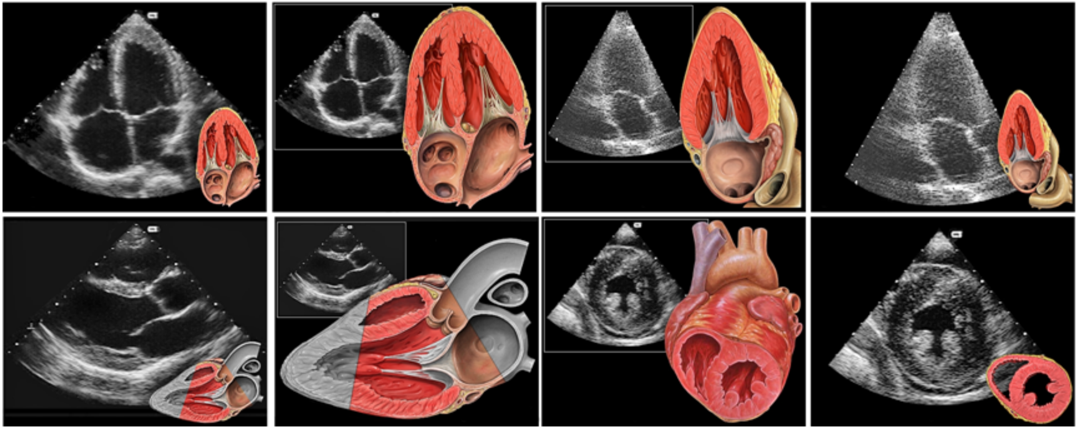


Heart with enlarged atrium (sector probe)

Liver with large tumor (curved array)

Imaging Modes (cont.)

B-mode (cont.)



Various views of the heart

Source: Patrick J. Lynch (`http://wikipedia.org/`)

Imaging Modes (cont.)

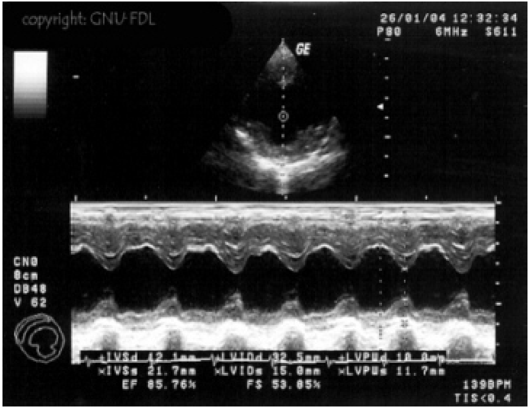
M-mode

- **M**otion-mode
- Pulses are emitted in quick succession (same probe position)
- Either an A-mode or a B-mode image is taken each time
- Time-dependent organ movement relative to the probe can be measured
  $\rightarrow$ velocity of specific organ structures

$\rightarrow$ Example: Cardiac (echocardiography) wall movement analysis.

Imaging Modes (cont.)

M-mode (cont.)



Combined B- and M-mode visualization of dog heart

Source: `http://wikipedia.org/`

Imaging Modes (cont.)

Doppler ultrasonography

- Enables visualization of blood flow (velocity)
- Continuous wave (CW) Doppler
  $\rightarrow$ Half of transducer array emits, half detects pulses (simultaneously)
  $\rightarrow$ No distance information
- Pulsed Wave (PW) Doppler
  $\rightarrow$ Pulse-based
  $\rightarrow$ Distance information is obtained (time-gating)

$\rightarrow$ Makes use of the Doppler effect.

Imaging Modes (cont.)

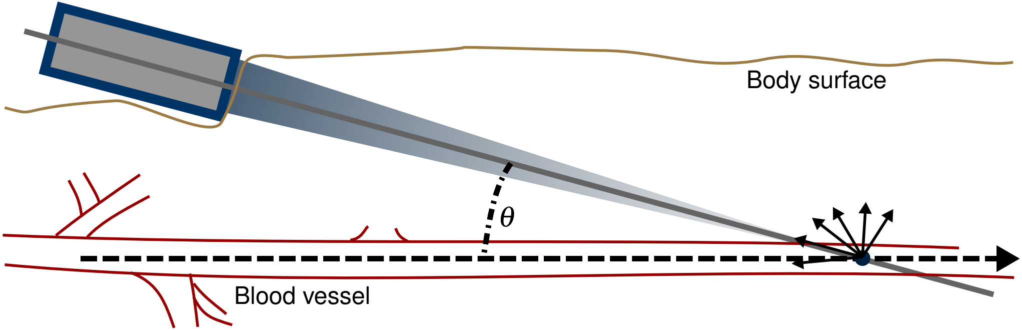
Doppler ultrasonography (cont.) – Doppler effect

- Change in wave frequency by relative movement between source and observer
- Characteristic frequency shifts appear → proportional to velocity
- Named after Christian Johann Doppler (∗1803, † 1853)
- Examples
  - Siren of ambulance
  - Astronomical red-shift
  - Blood flow

Imaging Modes (cont.)

Doppler ultrasonography (cont.)

- Doppler effect in US blood flow imaging
  - Source: Moving blood cells (through scattering of US wave)
  - Observer: US transducer
  - Doppler angle θ (between blood and sound direction) $\rightarrow$ the smaller the better



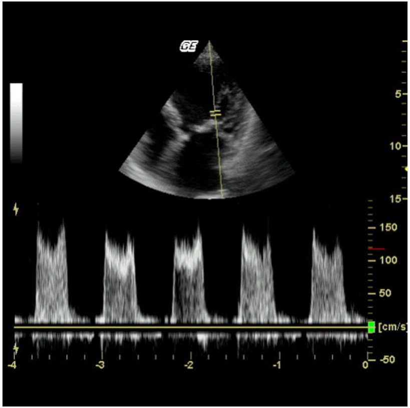
Imaging Modes (cont.)

Doppler ultrasonography (cont.)

- Spectral Doppler
  → Visualize spectrum of blood speeds
- Color Doppler
  → Color-coded overlay on top of B-mode image

Imaging Modes (cont.)

Doppler ultrasonography (cont.)

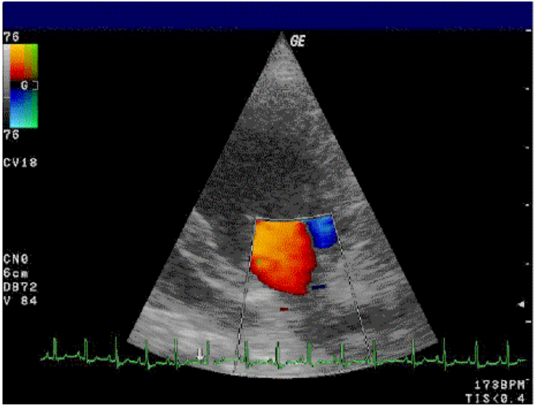


Spectral doppler.

Source: http://gehealthcare.com/

Imaging Modes (cont.)

Doppler ultrasonography (cont.)



Mitral valve insufficiency (dog heart), color doppler

Source: http://wikipedia.org/

Imaging Modes (cont.)

Dimensionality of acquired images

- 1D $\rightarrow$ A- or M-mode
- 2D $\rightarrow$ many B-mode scan lines (e.g. linear/curved transducer array)
- 3D $\rightarrow$ several 2D images at different angles combined into single volume
- 4D $\rightarrow$ 3D + time

Ultra Sound

Ultrasound Applications

Ultrasound in Medicine

Physics of Sound Waves

Imaging Modes

Safety in US Imaging

Safety in US Imaging

US waves are not ionizing, however they can harm the body . . .

- . . . through heating
  $\rightarrow$ locally, proportional to absorbed acoustic intensity (J)
- . . . through cavitation
  $\rightarrow$ emerging gas bubbles in low pressure phase of sound wave
  $\rightarrow$ collapse at high pressure phase

$\rightarrow$ Acoustic intensities for medical diagnostics rather low
$\rightarrow$ harmless, it is even used during pregnancy

Therapeutical use of ultrasound

- Break up gallstones and kidney stones
- Heat and destroy diseased or cancerous tissue