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# Ultrasound Physics

## Basic Neurosonology Course

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## Disclosures

- **Financial**
  NovaSignal: design and run device clinical trials
- **Unapproved Use of Devices**
  None

## Clinical Ultrasound Physics

- **Ultrasound**
  - sound waves
  - acoustic variables & parameters
  - pulsed waves
  - sound in media
  - time of flight
  - sound beams
  - Doppler
- **Hemodynamics**
  - flow (laminar, turbulent)
  - energy
  - pressure-flow
  - Ohm's law/Hagen-Poiseuille
  - continuity of volume flowrate
  - stenosis
  - Bernoulli's principle

# Ultrasound



## Sound

- **sound is a mechanical, longitudinal wave**
- **requires a medium where molecules can be alternately "compressed" and "rarefied"**
- **what makes a wave "sound?"**
  - rhythmic oscillation of pressure, density or distance
- **how is sound described? Acoustic parameters**
  - period – time for 1 cycle (time)
  - frequency – number of cycles/time (Hz)
  - amplitude – Δmax/min and average (pressure, density or distance)
  - power – energy transfer, "work" (watts)
  - intensity – area in which power is distributed (watt/beam area)
  - wavelength – length of 1 cycle (length)
  - propagation speed – rate of travel through a medium (distance/time)
- **audible sound: 20 Hz – 20 kHz; ultrasound > 20 kHz**

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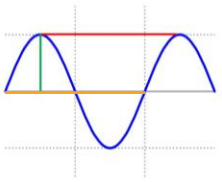
## Sound



Wavelength (λ)
Distance between identical points on consecutive waves

Amplitude
Distance between origin and crest (or trough)

Frequency (ν)
Number of waves that pass a point per unit time

Speed
= wavelength x frequency

Period
Time for 1 wave cycle (T)

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## Sound

- **"power" describes magnitude and energy transfer of a sound wave**
  power ∝ amplitude$^2$
- **"intensity" is that power distributed over an area**
  power (watt)/ area (cm$^2$)
- **period and wavelength* = 1/frequency**
- **period, frequency defined by source alone**
- **medium affects most parameters**
  amplitude, power, intensity
  wavelength uniquely affected by source and medium
- **propagation speed is determined by medium alone**
  speed ∝ stiffness; speed ∝ 1/density
- **average speed of sound in soft tissue: 1540 m/s or 1.54 mm/μs**

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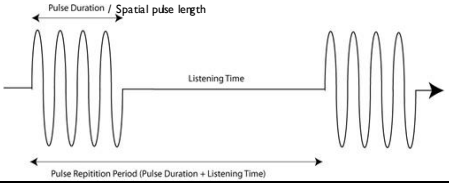
## Pulsed waves

- **pulsed waves are necessary to create images and for focal depth**
  continuous wave can provide Doppler data only
- **transmit/talking/"on" and receive/listening/"off"**
- **pulse repetition frequency = pulses/second (Hz)**



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## Pulsed waves

- **pulse duration is the number of cycles multiplied by the period**
  pulse duration = cycles*period; cycles/frequency
- **spatial pulse length is similar but the distance, not the time**
  SPL = cycles*wavelength; cycles/frequency;
  since wavelength can change in medium, so does SPL
- **pulse repetition period = pulse duration + listening time**
  increasing PRP → increased "depth of view"
- **pulse repetition frequency = pulses/second**
  PRP = 1/PRF
- **pulse duration, PRP and PRF set by the instrument, not medium**
- **duty factor = % time transmitting pulse = (pulse duration/PRP)*100**
  usually very low in imaging US (0.2%-0.5%)
  100% with CW Doppler

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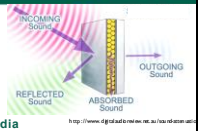
## Sound in Media




- **as sound travels through soft tissue it attenuates**
  attenuation = decrease in amplitude/power/intensity
  ∝ path length & frequency, measured in dB, comparing initial to reflected
- **attenuation is caused by**
  reflection, scattering, absorption
- **reflection happens when a pulse strikes a boundary between media**
  amount of reflection depends on the media on either side of the boundary, weakens the wave
  specular reflection = "clean" reflection off a smooth surface, diffuse reflection/backscatter = irregular
- **scattering**
  random redirection of sound in many directions, usually happens when the interface is small (≤λ)
  Rayleigh scattering = form of scattering when reflector is much smaller than λ, omnidirectional
  scatter ∝ frequency
- **absorption**
  amount of energy (heat or mechanical) lost to tissue, absorption ∝ frequency
- **"attenuation coefficient" is specific to medium, combines all 3 factors (dB/cm)**
  soft tissue attenuation coefficient = frequency/2

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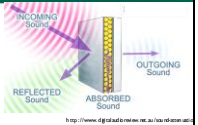
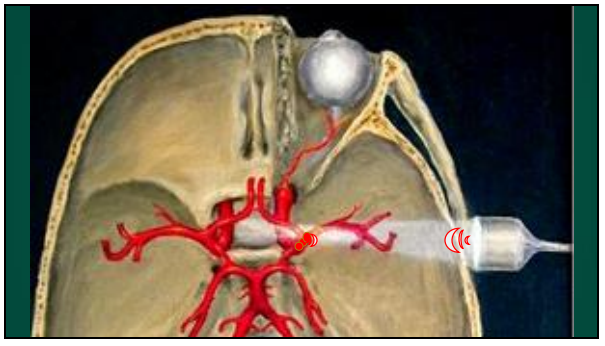
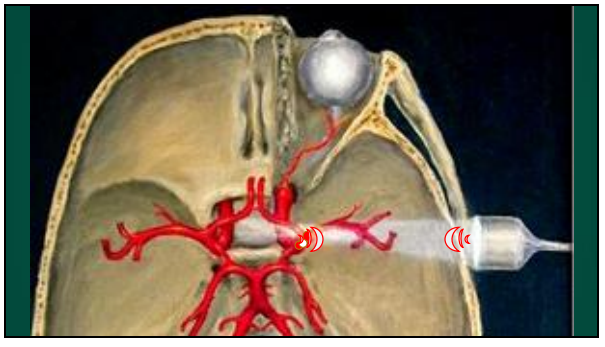
## Sound in Media




- **reflection is the basis of diagnostic ultrasound**
- **amount of reflection vs transmission influenced by impedance**
  impedance (z) = resistance to sound traveling = density x prop. speed
  reflection depends on the difference in impedance between two media
- **conservation of energy at the boundary**
  incident energy = reflected + transmitted
  intensity reflection coefficient (IRC) is the % of energy reflected when sound strikes boundary between media
  IRC (normal) = $(z_2-z_1/z_2+z_1)^2$; smaller differences will make fractions, large differences will ~1
  intensity transmission coefficient (ITC) = (transmitted/incident)*100 = 1-IRC
- **oblique incidence**
  cannot as easily predict or measure reflection or transmission
  refraction = "bend" of transmitted wave; happens when oblique and wave travels at different speeds in media





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## Time of Flight

- **echo must go to depth x and return the same distance x**
- **time of flight (TOF)**
  - go there and back (2x) at the prop. speed of the medium
  - soft tissue: 2x / 1.54 = TOF or depth x = 1.54(TOF)/2
- **increase TOF – and depth – by increasing PRP on the instrument**
- **as TOF and depth increase, PRF is decreased**
  - number of pulse repetitions possible in one second decreases as we ask the echo to go further
  - PRF = prop. speed/2*depth
  - important for Doppler sampling

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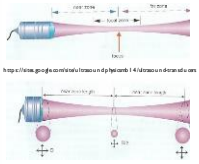
## Sound Beams

- **width of beam changes as sound travels**
- **starts as width of transducer, narrows at focal length, then diverges again**
  cross sectional diameter of beam at focus = ½ transducer cross section
- **focal depth ∝ probe diameter & frequency**
  "bad physics" of higher frequency → deeper focus; smaller elements to compensate



https://sites.google.com/site/ultrasonicphysicsmb14/ultrasound-beam-structure



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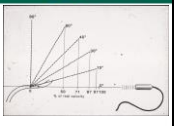
## Doppler

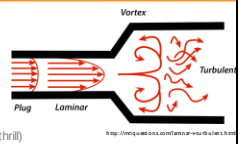


- **the shift in frequency that occurs when the sound source and receiver are in motion relative to one another**
  source moving toward receiver = positive shift
  source moving away from receiver = negative shift
- **instrument "demodulates" the shift frequency from the carrier frequency of the probe**
  carrier freq = 2MHz; received frequency is 2.003 MHz; instrument filters out the 2MHz so we can hear the 3 KHz shift (within the range of audible sound)
- **Doppler equation**
  Doppler shift = (2*velocity*transducer frequency*cosθ)/prop. speed
  any angle other than 0° or 180° is a fraction of the true velocity
- **sampling limit**
  accurate sampling of velocity depends on the PRF
  Nyquist Limit is the highest Doppler shift that can be accurately measured
  Nyquist Limit = PRF/2

# Hemodynamics

## Flow

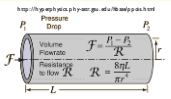
- **Laminar flow**
  streamlines are aligned and parallel layers traveling at an individual speed, physiologic
- **Turbulent flow**
  streamlines are obliterated and chaotic, pathological
  flow energy is converted into sound (bruit) or mechanical (thrill)
- **Flow happens because of energy gradients**
  All things move from high to low; systole gives blood energy
  the total energy at any one point is kinetic (mass*velocity) + potential (pressure) energy
- **Energy loss**
  viscosity – overcoming "stickiness," driven by hematocrit
  friction – blood "rubbing" against endothelium generating heat or mechanical energy
  inertia – tendency to resist changes in velocity (Newton's 1st law)

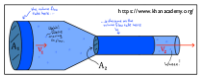





## Flow

- **simplified pressure-flow dynamic**
  pressure gradient = flow x resistance
  essentially Ohm's law: voltage = current x resistance
- **less simplified: Poiseuille's law**
  *laminar, straight pipe, no acceleration, Newtonian/incompressible
- **continuity of volume flow rate**
  velocity increases in stenosis
- **Bernoulli's principle**
  conservation of energy: with steady flow, the sum of the energy (kinetic and potential) is the same
  if kinetic energy is rising mid-stenosis due to continuity, potential energy must decrease (potential → kinetic)
  pressure energy rises again in the post-stenotic region as blood decelerates (kinetic → potential)



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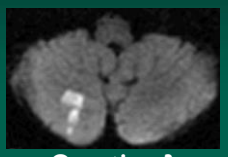

**Questions?**
**Ask in the Chat or email:**
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