Neurosonology

Physics

Physics of sounds:

Sound:

- Audible sound is 20-20,000 Hz. Ultrasound is > 20KHz
- Acoustic variables: pressure – density – distance
- Sound is a longitudinal wave, particles move in same direction of the wave

7 parameters of sound waves:

- **Period**: time it takes for one cycle, determined by source, not affected by medium, can't be changed by sonographer
- **Frequency**: number of waves per second, determined by source, not affected by medium, can't be changed by sonographer. Typically range between 1-10MHz
  - Period x frequency = 1 or Period $\alpha \frac{1}{Frequency}$
- **Wavelength**: length of one wave in space. It is determined by both source and medium. It can't be changed by sonographer. Typically range from 0.1-0.8 mm in soft tissue.
  - **Wavelength =** $\frac{propagation\ speed\ (mm/us)}{Frequancy\ (MHz)}$ Wavelength $\alpha \frac{1}{Frequency}$
- **Propagation speed:** speed of sound propagation in a medium, units are mm/μs or m/s. It is a pure property of the medium, not related to sound source or can be changed by sonographer. It is determined by medium density and stiffness.
  - **Propagation speed** $\alpha \frac{Stiffness}{Density}$ remember S&S -> same direction
  - Propagation speed in soft tissue is 1540 m/s = 1.5 mm/μs
  - Propagation speed in air is 330m/s
  - Compressibility is opposite of stiffness, hence opposite of speed
  - Gases are not stiff -> low speed, bone is stiff and not very dense -> high speed
- **Amplitude, power and intensity:** all are measures of strength of sound waves, initially determined by sound source, not affected by medium, decrease as sound propagates and all can be changed by sonographer.
- **Amplitude**: strength of sound wave, it is the difference between average (not minimum) and maximum value of acoustic variable (pressure or density).
  - **Interference of waves**: In-phase waves augment (constructive interference) and out-phase waves reduce (destructive interference)
- **Power**: also strength of sound wave, units are watts.
  - Power α (Amplitude)^2 or power increases 9 times when amp triples
- **Intensity**: concentration of power in a sound beam. Units are watts/cm.

- Intensity = $\frac{power}{beam\ Area}$ or when power doubles, intensity doubles
- Intensity α (Amplitude)^2 If amplitude is quartered, intensity & power reduced to 1/16

- Period & frequency are fixed
- Propagation speed is a property of the medium only
- Wavelength depends on source (frequency) and medium
- Amp, power, intensity can be changed by sonographer. Power and intensity are related to amplitude squared

5 parameters of pulsed ultrasound:

- **Pulse duration:** time when pulse is on, determined only by source, can't be changed. It is related to number of cycles and periods of waves in the pulse. Short pulse will have few cycles and short periods (higher frequency). Shorter pulses produce higher quality images.
  - Ultrasound pulses are 2-3 cycles, Doppler pulses are 5-30 pulses
- **Pulse repetition period (PRP):** time from start on one pulse to start of next pulse. It can be changed by sonographer (changing listening time) while adjusting depth. Typically range from 100μs to 1ms.
  - PRP = pulse duration + listening duration.
- **Pulse repetition frequency (PRF):** number of pulses in a second. Also can be changed by adjusting depth.
  - ↑ depth → ↑ PRP and ↓ PRF
- **Duty factor:** percentage of time when pulse is on, no units, ranges from 0 to 1 or 0% to 100%. Also can be changed by adjusting depth. Typically ranges from 0.001 to 0.01, 1 in continuous wave US
  - **Duty factor =** $\frac{Pulse\ duration}{PRP}$ x 100
- **Spatial pulse length (SPL):** length of pulse in space (when pulse is on). It is related to source (cycles per pulse) and medium (wavelength)
  - **SPL = waves per pulse x wavelength**

- Pulse duration is fixed
- SPL is the only affected by medium
- PRP, PRF and duty factor are changed with adjusting depth

Intensity:

- Intensity is not same throughout the wave, it varies by time and location in the wave.
  - Temporal peak: maximum intensity at any point of time
  - Temporal average: average throughout all the time (transmitting and receiving)
  - **SPTP** (spatial peak temporal peak)

- **SATP** (spatial average temporal peak)
- **SPTA** (spatial peak temporal average)
- **SATA** (spatial average temporal average)

- Pulse-wave ultrasound is about time, holding and beaming. So another variable was introduced, that resulted in two more measurement
  - Pulse average: average for only when pulse is on

  - **SPPA** (Spatial peak pulse average)
  - **SAPA** (Spatial average pulse average)

  - Pulse average PA is always higher than Temporal average TA, because TA includes Off time.
  - SAPA value is between SATP and SATA
  - SPPA value is between SPTP and SPTA

- $\mathbf{I_m}$ is the average intensity during the most intense half cycle. Typically similar to SPTP (highest intensity)
- **Beam Uniformity Coefficient (SP/SA factor):** ratio that describes how uniform a wave is. Minimum is 1 (when both SP SA are same) with unlimited maximum.
  - **SP/SA factor =** Spatial peak intensity / spatial average intensity
- **Converting intensities:**
  - To convert spatial intensity, use SP/SA factor
    - SA = SP/BUC -> SATA = SPTA **/** (SP/SA)
  - To convert temporal intensity, use duty factor.
    - TA = PA x duty factor -> SPTA = SPPA **x** duty factor

Amplitude (Decibels):

- When we try to express the value for a variable that has an extremely wide range, we use logarithms.
  - 10 = log 1 1,000,000 = log 6 1billion = log 9
- Decibel is not actual value, rather it is used to express the change in value using logs. If above 10db, each 0 means 10 times increase. If below 10db, each 3dB means doubled one time:
  - 3dB = double 6dB = double double (4 times) 9dB = doubled 3 times (8 times)
  - 10dB = 10 times increase 20dB = 100 times 30db = 1000 times

Db	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Intensity	100%	79%	63%	**50%**	40%	32%	**25%**	20%	16%	13%	**10%**

Attenuation:

- Depends on distance traveled and frequency of sound.
- The greater the frequency the more the attenuation
- So we may choose lower frequency transducer to image deeper structures (same for TCD)
- Attenuation occurs through different mechanisms:
    - **Absorption**: directly related to frequency (increase with frequency)
    - **Reflection**: occurs at boundaries of media with different impedance
        - **Specular reflection**: if the boundary is smooth
        - **Scattering**: if the boundary is irregular, smaller than wavelength. It increases with increased frequency.
        - **Rayleigh scattering**: waves scatter in all directions when reflector is much smaller than wavelength. Occurs with red blood cells.

- **Attenuation coefficient**: amount of attenuation per cm of tissue, units db/cm.
    - The higher the frequency the higher the attenuation coefficient
    - **Typically for soft tissue it is about half the frequency**. If 5MHz transducer, attenuation coefficient will be 2.5 db/cm
    - Attenuation coefficient is higher in bone (absorber) and lungs (scatterer)
- **Total attenuation** = attenuation coefficient x distance travelled

If US with frequency of 10MHz, starts with intensity of 20mW/cm, what is the intensity at 4cm?

- Attenuation coefficient for soft tissue = frequency/2 = 5dB/cm
- Total attenuation = coefficient x distance = 5 x 4 = 20dB
- 20dB = 100 decrease in intensity = 20mW/cm / 100 = 0.2 mW/cm at 4 cm depth

- **Penetration depth (Half value layer thickness)**: is the thickness at which half of intensity is lost, attenuation is -3 dB. Typically between 0.3-1cm
    - Penetration depth = $\frac{3}{Attenuation\ coeffecient\ (dB/cm)}$

What is the half value layer thickness (penetration depth) of 5MHz in soft tissue?

Attenuation coefficient in soft tissue = frequency / 2 = 2.5 dB/cm

Half value layer = 3/coefficient

t = 3/2.5 = 1.2 cm

Frequency (MHz)	**2**	**5**	**10**	**15**
Attenuation Coeff	1	2.5	5	7.5
Total Penetration (cm)	30	12	6	4

Impedance:

- Resistance to sound traveling through the medium. It is a characteristic of the medium only, represented by letter Z, units are Rayls. Typically 1.25-1.75 MRayls (million)
    - **Impedance = density x propagation speed**
    - Impedance is high in bone (dense and high propagation speed)
- Used to determine reflection. Refection occurs only between media of different impedance.

Reflection:

- **Types of reflection:**
    - **Specular reflection:** occurs at smooth surfaces
    - **No-specular reflection (scattering**): when surface is irregular with irregularities smaller than wavelength.
    - **Rayleigh scattering:** when sound is scattered in all directions, occurs with very small particles, smaller than wavelength as RBCs and intracellular particles.
- **Types of Incidence:**
    - Normal incidence: sound strikes surface at 90°
    - Oblique incidence: sound strikes surface at acute or obtuse angle
- **Intensity reflection coefficient**: percent of sound waves that is reflected
- **Intensity transmission coefficient**: percent of sound waves that pass through
    - **IRC + ITC always = 1**

- **Reflection at normal incidence depends on impedance**, strong reflection occur between soft tissue and bone. Near total between soft tissue and air.
    - IRC = $(\frac{Z2-Z1}{Z2+Z1})^2$
- **Reflection at oblique incidence, very complex, we can't predict if reflection will occur.**

Refraction:

- Change of direction of sound waves when pass from one medium to another
- Occurs only when there is **oblique incident** and **different propagation speeds**.

- Snell's law: $\frac{Sine\ transmission\ angle}{Sine\ incidence\ angle} = \frac{propagation\ speed\ medium\ 2}{propagation\ speed\ of\ medium\ 1}$

- If medium 2 speed > medium 1, transmission angle > incidence angle

Range equation:

- Process of calculating depth based on time-of-flight
- Sound travels 1 inch in 16 μs, 1 CM in 7.5 μs, go and return from 1 cm in 13μ**s**
- **Depth (mm) =** $\boldsymbol{Velocity\ x\ \frac{time-of-flight}{2}}$
- **Depth for soft tissue = 0.77 x time-of-flight**
    - 1CM = 13μs -> (13 x 0.77 = 10mm)

Physics of Transducers:

Anatomy:

- **Active element:** it a ferroelectric (Piezoelectric) material that vibrates when an electric current passes through it. (Piezoelectric effect)
    - **Curie temp:** temperature at which ferroelectric materials loses its piezoelectric properties
    - **Types of active elements:**
        - Natura: Quartz, tourmaline
        - Artificial: PZT (lead zirconate titanate), lead metaniobate, barium titanate
- **Damping material:**
    - Material attaches to the back of the active element to shorten its vibration.
    - Damping material is not used in continuous wave dopplers, they don't use pulses
    - Effects of damping material:
        - Shorter pulse duration
        - Shorter pulse length
            - -> increased picture quality (**improves resolution**)
        - Increases bandwidth (adds a range of frequencies)
            - -> decreases Quality factor
        - Reduces amplitude, **reduces efficiency and sensitivity** to see weak echoes.
- **Matching layer:**
    - A layer between active element and skin, aims to make a gradual step-wise decrease in impedance while sound moves towards the skin to avoid reflection
    - It has an impedance between that of PZT and the skin
    - Gel also has the same function, it has an impedance between matching layer and skin.

Transducer frequency:

- **Continuous wave**: frequency is same as electrical frequency used
- **Pulsed ultrasound:**
    - **PRF**: equals the frequency of electrical spikes that reach the PZT
    - **Frequency**: determined by PZT itself, the <u>thickness</u> and <u>propagation speed</u> in the crystal
        - PZT frequency in pulsed US = $\frac{Propagation\ speed\ (mm/us)}{thickness\ (mm) x\ 2}$
        - The thinner the crystal and more speed, the higher the frequency

Transducer bandwidth:

- PZT produces one frequency then damping material adds a band of frequencies
- Bandwidth is the difference between the lowest and highest frequencies
- If a 4Mhz transducer has a range of 2-5MHx, bandwidth is 3MHz.

- If a 5Mhz transducer has a bandwidth of 2.5, it can't work at 3 or 7Mhx (range is 3.75-6.25)
- Quality factor is used to express how pure the sound is
    - Quality factor = $\frac{resonat\ frequency}{bandwidth}$
- Diagnostic ultrasounds have lower quality factor compared with therapeutic ultrasound

Transducer sound beam:

- One may think of sound spreading away an all directions once it is produced by sound source. (Diffraction)
- In transducers, this doesn't happen, instead it will make an hour-glass pattern of sound beam because the tiny particles of PZT produce wavelets that interact with each other (destructive and constructive interference) producing this shape.

- **Focus**: the location where beam is narrowest
- **Focal length**: distance between transducer and focus
    - Depends on PZT diameter (or transducer aperture size) and frequency
    - **Larger crystal diameter and higher frequency (thin crystals) produce deeper focus**
    - Unfocused transducers, at 1 focal length the beam is half transducer diameter, at 2 focal length it is same transducer diameter.
- **Near Zone** (Fresnel): area between transducer and focus
- **Far zone**: area beyond the focus
- **Divergence:**
    - At deeper distances, beam will diverge.
    - Divergence is more pronounced with smaller diameter crystals

- **Crystal diameter**: large diameter causes deeper focus and less divergence in the far field
- **Crystal thickness**: the thinner the higher frequency and deeper focus

Transducer resolution:

- The shorter and narrower the pulse, the better the resolution
- **Longitudinal resolution (Axial, Radial, Depth):**
    - Ability to distinguish two structures that are inline with sound wave direction (front and back) as separate
    - The shorter the pulse, the better (smaller) longitudinal resolution
        - Longitudinal resolution = spatial pulse length / 2
    - It depends on sound source and medium
- **Lateral resolution (transverse, angular):**
    - Ability to distinguish two structures that are side be side as separate
    - The smaller the beam the better (smaller) the lateral resolution
        - Lateral resolution = beam diameter
- **Temporal resolution:**
    - Ability to determine position of moving structures.

    - It depends on frame rate.
    - a higher frame rate is limited by image resolution (number of lines) and if multi-focus is used (for better resolution at different depth) and the depth of image.

- Typically the longitudinal is better than the lateral resolution

Scan modes:

- A mode: plots depth against amplitude. Looks as Manhattan skylines
- B mode: plots depth and uses a gray scale to show amplitude. It is the usual gray-scale picture.
- C mode: constant depth mode, uses only specific gate of specific depth. Produces a slice of particular depth.
- M mode: motion mode, the only mode that plots motion.

Types of transducers:

- Steering is angling the sound beam, to make it at an angle, used for doppler and sor scanning larger sections than aperture size.
- Focusing is adjusting the focus to adapt to new depth
- Sequential means no steering and fixed focus
- Mechanical: the array can be tilted mechanically
- Phased array can do both electronically.

    - If focus can be adjusted, it is phased
    - If it has multi-focus, it is phased
    - If there is no moving parts, it is either sequential (no steering) or phased (electronic steering)

- **Linear**: sequential transducer, fixed focus, is good for near-field. Rectangular images.
- **Curved**: sequential transducer, fixed focus, is good for far-field (abdominal, transvaginal, rectal). Blunted sector shaped images.
- **Phased array**: steering is made electronically, focus can be adjusted, It has a small foot print , poor near field resolution, best used for cardiac, abdominal and brain. Sector shaped images.
- **Vector array**: combination of phased and linear sequential. Picture is trapezoid shape.

Receiver actions:

- **Amplification** (receiver gain or overall gain): too little, some signals will be dropped. Too much (saturated), all signals are bright.
- **Compensation**: (**Time gain compensation** or Swept gain compensation): same reflectors of different depth may show different signals due to more attenuation with deeper reflectors. Compensation will compensate deeper structures to have same intensity (brightness).

    - Problems with compensation affects deeper structures
- **Rejection** (threshold): reject very low noise signals
- **Compression**: to squeeze the signals into a smaller range to be showed on image.

Artifacts:

- **Acoustic speckle**:
    - Tissue appears more granular.
    - Caused by interaction between ultrasound wavelet and scattering of ultrasound within the tissue.
- **Slice thickness**:
    - causes small cysts to appear as filled-in or solids
    - beam is thick and will include tissues above and below the cyst causing it appear as gray not black from inside.
    - To overcome, decrease beam thickness by activating tissue harmonic imaging
- **Refraction**: structure appear at different location
- **Reverberation:**
    - Sound is trapped between two surfaces causing multiple reflections,
    - multiple equally spaced reflections due to sound trapped between two reflectors. Only first two reflectors are real.
- **Comet tail:**
    - reverberation from two reflectors that are very close**.**
    - Causes reverberations that are very close to each other, appear as comet tail
- **Mirror image**
- **Multipath**
- **Side lobes:** caused by single crystal transducers
- **Grating lobes:**
    - Duplicates structures lateral to true ones
    - caused by phased array transducers producing off axis waves. These off axis waves may cause reflectors outside the imaging area to appear on improper locations.
- **Shadowing** (after a reflector) **& Enhancement** (after a hypoechoic structure)
- **Propagation speed errors**
    - Displaces structures axially
    - Caused by fluid or fat tissues
- **Range ambiguity:**
    - Structures appear closer to the surface
    - During deeper imaging, when pulses get delayed and received with next pulse.
    - Prevented by reducing PRF (giving more time for returning echoes) in deeper scans
- **Aliasing in Doppler:**
    - Most common artifact with Doppler
    - Causes improper positioning of signals on the spectrum. Positive waves appear as negative.

    - Caused by exceeding Nyquist limit, not enough sampling rate. High velocities, sampling rate has to be high.
    - Corrected by increasing PRF, shifting the baseline or use transducer with lower frequency
    - Nyquist limit is the minimum number of sampling needed to avoid aliasing. Sampling rate has to be double the highest frequency.
- **Aliasing in color doppler:**
    - Same principle, caused by exceeding Nyquist limit
    - Will cause color to switch abruptly from highest velocity in one direction to highest velocity in opposite direction.
- Doppler range ambiguity:
    -

Ultrasound safety:

- **Ultrasound causes:**
    - **Heat:** SPTA < 100 mW/cm^2 have been shows as safe – thermal index < 2 is not harmful
        - **Thermal index:** power needed to raise tissue temp by 1 degree
    - **Mechanical:**
        - **Radiation force:** force exerted by sound beam on absorber
        - **Streaming:**
        - **Cavitation:** stable cavitation from bubbles changing their size with sound wave, collapsing cavitation when it is more severe change causing bubbles to rupture causing more injury.

Doppler:

- Moving objects cause sound frequency to change
- **Doppler shift** = $\frac{2\ x\ reflector\ speed\ x\ incidentt\ frequency\ x\ cosine\ angle}{propagation\ speed + reflector\ speed}$
- **Velocity =** $\frac{77\ x\ Doppler\ shift}{Source\ frequency}$
- Doppler measured velocity is more accurate when in-line with direction of movement.
- **Actual Velocity** = measured velocity / cosine angle
    - Cosine of 0 and 180 is 1
    - Cosine of 45 is 0.7
    - Cosine of 90 is 0 -> no doppler signal
- **Types of doppler:**
    - **Continuous wave**: duty factor is 1, can measure very high velocities, produces a sound that is an estimate of speed, can't produce images, no gate.
    - **Pulsed wave doppler**: can produce image but limited max speed. We can identify the gate (depth) of interest by adjusting listening time.
        - Most important feature is identifying the tested location (gate)
        - Most limiting features: high velocities appear negative, called aliasing
- **Aliasing:**
        - Aliasing may occur only with pulsed wave, never with continuous doppler
        - Positive waves appear negative on screen.
        - **Nyquist limit**, is the velocity beyond which velocities are considered in negative direction.
            - **Nyquist limit = PRF / 2**
            - Since PRF change with depth, the shallower the depth, the higher the Nyquist limit, the deeper the smaller the limit the more aliasing.
        - To overcome aliasing:
            - Use transducer of low frequency
            - Try to use shallower depth
- **Doppler packets:**
    - Doppler sends packets of pulses to detect velocity, not just a single pulse.
    - The less packets, the less accurate, the more packets the less frame rate
    - Each packet produces a single velocity measurement.
    - Velocity mode: the average of velocities is shown (single number)
    - Variance mode: shows both average velocity and the variability
        - When flow is smooth, laminar, the variance in velocities is small, presented as yellow on variance map.
        - With turbulent flow, different velocities are picked, appears as green on variance map

Flow rate: flow of fluid in a long tube. Flow depends on pressure difference, viscosity and diameter

- Flow rate $\alpha \frac{Pressure\ difference}{Resistance}$
- Resistance $\alpha \frac{viscosity\ x\ tube\ length}{(Radius)4}$

Types of flow:

- Plug flow: all parts move as one unit, same velocity for all layers. Seen in spectral narrowing, in locations with severe stenosis.
- Laminar flow: flow in parallel lines, maximum speed at the center
- Disturbed flow: streamlines are not straight, as at bifurcation or focal stenosis.
- Turbulent flow: non-laminar flow chaotic speeds and directions

Bernoulli effect: As flow increase, pressure decrease. Pressure is reduced at stenosis compared with proximal and distal to stenosis which creates a pressure difference for the blood to accelerate at stenosis.

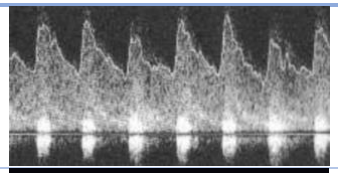
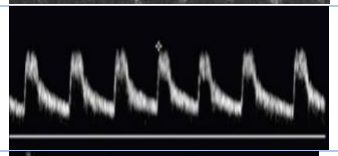
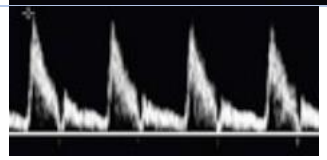
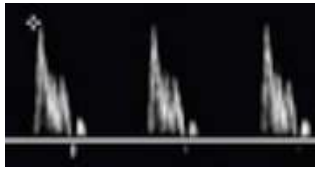
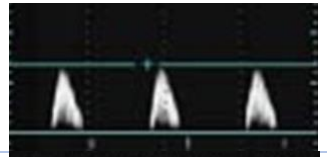
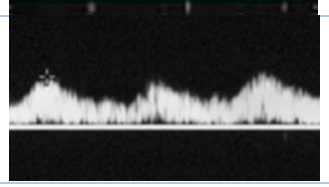
Spectral variations:

Spectrum size:

- The number of frequencies presented on the spectrum. If the spectrum is full, it means large variation in frequencies, variable speeds, turbulent flow or the sample volume is very large. Typically sample volume should be about 3mm, a the center of the vessel. If volume is large to include all the vessel diameter, it will bring all kinds of frequencies from slow laminar flow close to the vessel wall. With severe stenosis, all flow laminae will take high speed due to high pressure difference across the stenosis, causing spectral narrowing.

Distal Resistance:

- With high distal resistance, ED wave will decrease in size till it disappears.

Spectrum	Causes	
Spectral broadening	- Turbulent flow (after stenosis or large segment of irregular lumen) - Large sampling volume	
Spectral narrowing	- Severe stenosis - Very small sampling volume	
Distal resistance		  
Tardus-parvus wave	- Post severe stenosis	

Equations:

Wavelength (mm) = $\frac{Propagation\ speed\ (mm/\mu s)}{Frequency\ (MHz)}$	
Propagation speed α $\frac{Stiffness}{Compressibility\ (Density)}$	
Power α **(Amplitude)²**	Power increases 9 times when amp triples If amplitude is halved, power quartered
Intensity = $\frac{power}{beam\ Area}$ **Intensity** α **(Amplitude)²**	When power doubles, intensity doubles If amplitude is quartered, intensity & power reduced to 1/16
Duty factor = $\frac{Pulse\ duration}{PRP}$ **x 100**	
BUC (SP/SA factor) = SP/SA	1 is uniform, >1 is less uniform
TA = PA x duty factor	
Attenuation α **frequency**	Higher frequency attenuates more
Attenuation coefficient for soft tissue = frequency / 2	
Penetration depth = $\frac{3}{Attenuation\ coeffecient\ (dB/cm)}$	
Impedance = density x propagation speed	
Intensity reflection coef. = $(\frac{Z2-Z1}{Z2+Z1})^2$ ca	
Refraction Occurs only when there is oblique incident and different propagation speeds.	
Snell's law: $\frac{Sine\ transmission\ angle}{Sine\ incidence\ angle}$ **=** $\frac{propagation\ speed\ medium\ 2}{propagation\ speed\ of\ medium\ 1}$	
Depth (mm) = $Velocity\ x\ \frac{time-of-flight}{2}$	Depth for soft tissue = 0.77 x time-of-flight
PZT frequency in pulsed wave = $\frac{Propagation\ speed\ (mm/us)}{thickness\ (mm) x\ 2}$	
PZT frequency in continuous wave = electrical frequency	
Longitudinal resolution = spatial pulse length / 2	

Lateral resolution = beam diameter
Actual Velocity = measured velocity / cosine angle
Doppler shift = $\frac{2\,x\,reflector\ speed\ x\ incidentt\ frequency\ x\ cosine\ angle}{propagation\ speed + reflector\ speed}$
Nyquist limit = PRF / 2

Numbers:

Propagation speed:	Soft tissue = 1540 m/s Soft tissue = 1.5 mm/μs Sound moves 1cm in 7 μs	

Carotid & Vertebral ultrasound:

- **Unknown Branches of ICA:**
  - Caroticotympanic, in petrous portion
  - Vidian artery to pterygoid canal, in petrous portion
  - Meningohypophyseal trunk, cavernous portion
  - Inferolateral trunk to trigeminal ganglia, cavernous portion

- **Doppler Parameters:**

WAKE FOREST ICA STENOSIS CRITERIA			
STENOSIS	PSV	EDV	ICA/CCA
< 50%	< 140	< 40	< 2
50–69 %	> 140	< 100	2 – 3
70–99 %	> 140	> 100	> 3

WAKE FOREST POST STENT STENOSIS			
Revascularized artery will have higher velocities due to flow remodeling.			
50–69 %	175-299	--	--
70–99 %	> 300	> 140	> 3.8

US CONSORTIUM CRITERIA			
NORMAL	< 125	< 40	< 2
50-69%	125-230	40-100	2-4
70-99%	> 230	> 100	> 4
NEAR OCCLUSION	Low	Variable	Variable

  - PSV:
    - used to measure stenosis, PSV > 140 indicates > 50% stenosis. PSV > 140 and EDV > 100 indicates 70-99% stenosis
  - EDV:
    - Also used to measure stenosis, if EDV > 100 and PSV > 140 indicates stenosis > 70%
    - Decreased EDV indicates resistive waveform
  - ICA/CCA velocity ratio:
    - ICA highest PSV in ICA
    - CCA: distal CCA, 2-4 cm before the bulb
  - Side to side difference
    - Normal ratio between both sides is 0.7-1.3
  - Waveforms analysis

- **B-mode color flow:**
  - Stenosis:
    - NASCET = $\left(1 - \frac{d}{n}\right) x\ 100$ d is diseased narrow segment, n is normal distal segment.
    - ACAS/WUSH = $\left(1 - \frac{Minimum\ lumen\ diameter}{Carotid\ bulb}\right)$
    - 70% NASCET = 80% ACAS
    - DSA tend to underestimate stenosis
    - Stent stenosis: > 30% reduction in lumen diameter
  - Intima media thickness
  - Plaque size & characteristics
    - Longitudinal usually overestimates plaques, always check cross sections.
    - 1.1:2mm is mild – 2.1:4mm is moderate - > 4mm is large or severe
  - Dissection, aneurysm, thrombus
  - Slow flow:
    - Pulse doppler is more sensitive for low flow than B-mode
    - Slow flow may look as no flow on pulse doppler if PRF is low
    - On B-mode it may show as "spontaneous echo contrast"

CCA volume flow rate:
- Normal 200-400 ml/min
- Helps to differentiate true stenotic flow and increased flow for collateral hyperperfusion
- Case:
  - Right ICA severe stenosis, increased PSV in proximal Rt ICA (460), flow (118) – left ICA with PSV (200), flow (425). -→ Left ICA increased flow due to hyperemia
  - TCD will show Lt -> Rt cross flow
  - Lt ICA/CCA PSV ratio < 3 (both are hyperemic, not left ICA stenosis)

Reversed Robinhood Syndrome (Intracranial arterial steal):
- Hypercapnia causes paradoxical reduction in regional CBF within ischemic tissue and augmentation of CBF within normal tissue

Spectral broadening:
- Can be due to: large insonation angle, large sample volume > 3mm, large sample volume close to vessel wall or high gain settings.
- Typically spectral broadening is expected in TCDs due to large sample volume (usually 3 or more mm), and is not considered pathological.

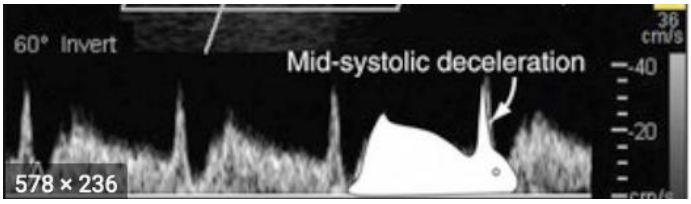
ICA occlusion findings:
- No flow signal
- High resistive stump waveform
- Distal ICA & MCA post-stenotic waveform

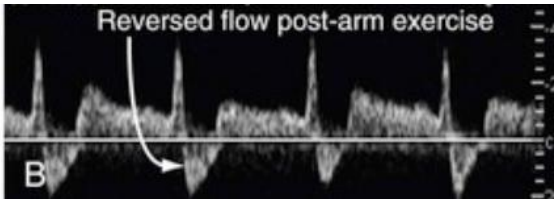
FMD:
- **Usually affect distal ICA, String of beads**
- **Long segment stenosis with increased velocities**

Vertebral arteries:

- **Numbers:**
  - Vertebral: V2: 40-50 cm/s intra-osseus. V1: 60 cm/s at origin
- **Subclavian steal:**
  - Systolic deceleration
  - Alternating flow/reversed flow at rest
- **Latent subclavian steal:**
  - Systolic flow deceleration
  - Second peak velocity

- **Hyperemia test:**
  - BP cuff inflated, ask patient to perform physical exercise
  - Increased metabolic demands causes vasodilatation
  - Release cuff, reversal will show on doppler





Transcranial Doppler:

- **Equation**: Reflector speed = $$\frac{\text{Doppler shift x propagation speed}}{2 \text{ x incident frequency x } \cos(\Theta)}$$

$$= \frac{770\ x\ new\ frequency}{Source\ frequency\ x\ \cos(\Theta)}$$

  - Propagation speed = 1540 m/s for soft tissue
  - Θ = angle of insonation, the larger the angle the greater is the error in measurement.
  - As angle of insonation increases, waveforms become blunted & ultimately disappear at 90 degree

- **Factors that affect TCD velocities:**
  - Age & sex: TCD velocities tend to get slower with age, small difference between premenopausal women and men
  - Viscosity & hematocrit: inversely related to velocity. Drop 10% of hematocrit will increase velocity by 20%
  - Blood pressure: despite autoregulation, increase BP increases TCD velocities
  - CO2 pressure
- **TCD machines:**
  - Non-duplex and duplex (transcranial color coded duplex TCCD)
  - TCD shows the anatomy in B-mode besides the spectral doppler. It also allows to measure angle of insonation to correct flow velocities.
  - Probe is 2MHz, higher frequency usual US probes can't penetrate the skull
- **TCD Windows:**
  - Transtemporal
  - Transorbital
  - Suboccipital
  - Submandibular
- **Clinical use:**
  - SAH for vasospasm

	Mean MCA	**MCA/ICA LR**
Normal	< 120	< 3
Moderate Vasospasm	120-150	3 – 6
Severe vasospasm	150-200	> 6
Critical vasospasm	> 200	> 6

  - Collateral flow
  - Vasodilatory reserve

- Sickle cell disease:
  - Vmean > 200 will benefit from transfusion to lower HBS < 30% (STOP trial)
  - STOP trial: kids with increased Vmean > 200 allocated to periodic transfusion to lower HBS < 30% had less risk of stroke (92% risk reduction). Over 8 year period, 5 fold decrease in the rate of stroke.
    - Technique: Use TAMV (time averaged mean velocity) not PSV
    - Inadequate TCD: to be adequate both MCA and BIF (bifurcation) have to be captured
    - Normal: TAMV < 170 in all segments
    - Conditional: TAMV 170-200
    - Abnormal: TAMV > 200
    - If inadequate: repeat the study, if still inadequate you may get MRI/MRA
    - If normal: repeat annually till age of 16
    - If conditional: repeat in 2 weeks to 2 months
    - If abnormal: either transfuse or repeat in 2 weeks
  - STOPII trial: tried to see if we can stop TCDs after 30 months of transfusions, it stopped early due to increased incidence of stroke in the group that stopped TCD
  - **Guidelines, NHLBI TCD recommendations 2014**:
    - Typically screening start at age of 2 and continues till age of 16
    - Refer to transfusion expert if TCD is abnormal (>200) or conditional (170-200)
- Micro-emboli detection
  - Depends on backscatter seen with emboli, gaseous > solid
  - Used in patients with carotid stenosis, MI, Afib & mechanical valves
  - CARESS trial: Clopidogrel and Aspirin for Reduction of Emboli in Symptomatic Carotid Stenosis. Repeating TCD at day 7 after treatment showed reduction of microemboli with dual antiplatelets
- Cerebral circulatory arrest
  - Make sure SBP > 70 during the procedure
  - With increased ICP, initially waves are more spiked, then diastolic component is lost, then flow reversal in diastole.
  - The retrograde oscillatory diastolic flow along with systolic spikes are characteristic for circulatory arrest
  - Sensitivity 96%, specificity 100%
- Research for: cerebral autoregulation, neurovascular coupling (functional hyperemia), Intraoperative TCD

- **Parameters:**
  - **Peak systolic velocity and EDV**
    - EDV is typically 25-50% of PSV
  - **Mean velocity:**
    - **MV =** $\frac{PV+3EDV}{3} = EDV + \frac{PV-EDV}{3}$

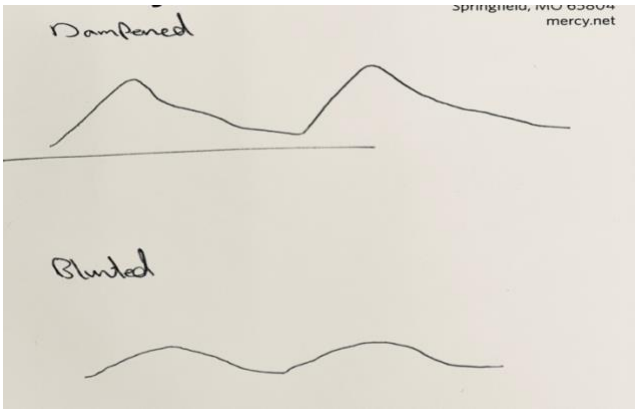
        - MV is the average of the edge frequency over the cardiac cycle
        - Varies between laboratories
        - Wake Forest: MCA 40-80 ACA 35-60 ICA 40-70 PCA 30-55 BA 25-60 VA 25-50
        - MCA vasospasm: Mild 80-120 Moderate 120-200 Severe >200
        - Sickle cell disease:
            - Hemolysis causes low hemoglobin and increased velocities. Sickle cells also irritate arteries and cause vaso-occlusion.
            - increased Vmean > 200 is associated with increased risk for ischemic stroke
    - **Lindegaard ratio (LR):**
        - ratio between Vmean of MCA to ICA
        - Used to differentiate hyperemia from vasospasm
        - Hyperemia will increase Vmean in both MCA and ICA
        - LR < 3 is normal or mild spasm, 3-6 is moderate spasm, > 6 severe spasm
        - LR > 6 indicates preferential increased MCA > ICA

    - **Pulsatility Index (PI):**
        - PI = $\frac{PV-EDV}{Mean}$
        - Normal values 0.6-1.2 (Except in OA is > 1.2)
        - TCD can only measure proximal vessel velocities, can't see distal vessels.
        - Increased PI indicates increased distal resistance
        - Rounded waveform has low PI, peaked waveform has high PI
        - Isolated one artery with increased PI, can be focal stenosis, compare with baseline PI to determine if increased from baseline.
        - Diffuse increase in PI may indicate diffuse spasm or increased ICP
    - **Resistive Index (RI) :**
        - RI = $\frac{PV-EDV}{Peak}$
        - A measure for <u>downstream</u> resistance
        - Normal value: < 0.75
    - **Flow Acceleration (FA):**
        - FA = $\frac{PV-EDV}{\Delta t}$
        - A measure for <u>upstream</u> systolic flow
        - Low FA indicates increased upstream resistance as in severe proximal ICA stenosis, aortic stenosis

- **Conditions:**
    - **Cerebral artery stenosis:**
        - Mild stenosis:
            - ↑ PSV – no change in doppler pattern
        - Moderate stenosis:
            - ↑↑ PSV

        - Spectral broadening
        - ↑ EDV
        - Post-stenotic depression of PSV
        - Turbulent flow

- **Abnormal waveforms:**
    - Absent: no flow detectable
    - Minimal signal:
        - flow signal present but no end diastolic flow
        - PI > 1.2
    - Blunted signal:
        - Delayed acceleration
        - Stetp-wise Maximum velocity arrival in mid-late systole
        - Focal ↓ MFV
        - PI < 1.2
    - Dampened signal:
        - Turbulent flow
        - Normal flow acceleration
        - ↓ MFV
        - Any PI



- **Collateral patterns:**
    - ACA reversal:
        - Reversed flow in ipsilateral A1
        - ↑ velocity in contralateral ACA
        - Contralateral ACA velocity > MCA by at least 25%
    - PCOM reversal: (blood from PCA through PCOM to MCA and ACA)
        - ↑ PCA velocity
        - PCA > MCA

- ECA to ICA collaterals:
  - Reversed ophthalmic
  - ↓ PI in ophthalmic (Internalization of OA)
- Signs of ICA stenosis: any one of the following has 95% sensitivity for 70% ICA stenosis
  - Reversed flow in ipsilateral OA
  - Reversed flow in ipsilateral ACA
  - ↑ velocity > 80 in contralateral ACA
  - No doppler signal in ipsilateral OA or bifurcation

- **Predictors of vasospasm in SAH:**
  - Rise in velocity > 20 cm/s/day between days 3-7
  - > 25% velocity rise per day

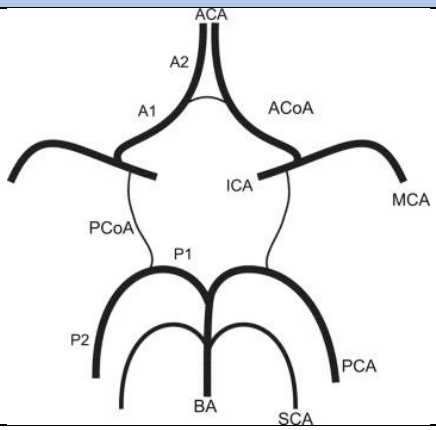
CRITERIA FOR NORMAL TCD

ARTERY	Depth	Direction	MVF Adult	MVF Kids
MCA (M1-M2)	40-65	Towards	< 80	< 170
ACA (A1)	62-75	Away	< 80	< 150
ICA SIPHON	60-64	↔	< 70	< 130
OA	50-62	Towards	Variable	
PCA	60-68	↔	< 50	< 100
BA	80-100	Away	< 60	< 100
VA	45-80	Away	< 50	< 80

Extracranial carotid system	Wake-Forest Criteria 2020	
Right	**Left**	**Comments**
CCA volume flow _____ml /min CCA ___ plaque (mild/mod/large) ICA velocity _____cm/s ICA stenosis _____ % stenosis ICA ____ plaque (mild/mod/large) ECA velocity _____cm/s ECA: <50% / > 50 % stenosis BIF: velocity _____cm/s BIF stenosis _____% stenosis BIF ____ plaque (mild/mod/large) VA: Forward flow. Yes /No	CCA volume flow _____ml /min CCA ___ plaque (mild/mod/large) ICA velocity _____cm/s ICA stenosis _____ % stenosis ICA ____ plaque (mild/mod/large) ECA velocity _____cm/s ECA: <50% / > 50 % stenosis BIF: velocity _____cm/s BIF stenosis _____% stenosis BIF ____ plaque (mild/mod/large) VA: Forward flow. Yes /No	**Plaque Category Measurement** Normal < 1.1 mm Minimal / Mild 1.1 – 2.0 mm Moderate 2.1 – 4.0 mm Large / Severe > 4.0 mm **ECA:** If ICA < 70%, ≥ 140 cm/s suggests 50% or greater in ECA If ICA ≥ 70%, then cut point increased to 200 cm/s **CCA Volume Flow:** Normally 300 cc/m +/- 100. Lower with advanced age Side difference of 50% also suggests stenosis/collateral flow

% Stenosis	PSV	EDV	ICA:CCA
< 50%	< 140 cm/s	<40 cm/s	< 2.0
50-69%	> 140 cm/s	< 100 cm/s	2.0 – 3.0
70-99%	> 140 cm/s	> 100 cm/s	> 3.0

STENT			
% Stenosis	**PSV**	**EDV**	**ICA:CCA**
50-69%	175-299	----	----
≥ 70%	≥300	≥140	≥3.8

Transcranial Findings *Depth /Mean Velocity / Pulsatility Index*	*Normal Mean Velocity Ranges* *MCA 40-80 PCA 30-55 VA 25-50 ACA 35-60 ICA 40-70 BA 25-60*	
Right	**Left**	
MCA ACA Terminal ICA OA IC siphon PCA VA **Basilar**	MCA ACA Terminal ICA OA IC siphon PCA VA	
Normal Sharp upstroke, stepwise deceleration, robust diastole <30% side to side difference MCA>ACA>Siphon>PCA>BA **High resistance:** Sharp upstroke, Low EDV, no EDV, normal to decreased velocity, high PI **Post-Stenotic:** Decreased upslope, low peak velocity (tardus parvus), decreased PI **Minimal:** Systolic spikes, Absent EDV Decreased velocity	**Pulsatility Index (PSV –EDV/MFV):** Normal range 0.6-1.2 **Vasospasm** **CO2 reactivity:** Expect 30-50% increased MCA MFV 20-30% mild reduction; 10-20 moderate; <10% severe	**PEARLS** • Identify systole –diastole • Systole- sharpness flow acceleration • End diastole consistent with expected resistance? • Waveform shape transition from proximal to distal • Symmetry with the contralateral segment • Systemic factors (fever, anemia, hypotension, etc.) • Explain the waveform appearance: – Technical factor – Systemic condition – Focal lesion – Resistance

Mean MCA	MCA/ICA	Category
< 80	< 3	Normal
80-120	< 3	Mild
120-200	3-6	Moderate
> 200	> 6	Severe

AHMED KORIESH

Sample TCD reports:

Sickle Cell Disease:

VASC LAB TRANSCRANIAL DOPPLER COMP
Performed: **5/4/2017 1:55 PM** Status: **Final result** Visible to patient: **Yes (MyChart)** [redacted]

Details

Reading Physician	Reading Date	Result Priority
[redacted]	5/4/2017	

Narrative

Bilateral: Sickle cell disease.
The bilateral intracranial internal carotid, middle, anterior and posterior cerebral arteries were examined with the duplex scanner. The intracranial vertebral arteries and basilar artery were also examined.
The arteries are patent with flow in the normal directions.
In the right hemisphere, the maximum middle cerebral flow velocity measures 138 cm/sec with a mean velocity of 91 cm/sec, and a calculated right hemispheric ratio of 1.92.
In the left hemisphere, the maximum middle cerebral flow velocity measures 137 cm/sec with a mean velocity of 86 cm/sec, and a calculated left hemispheric ratio of 2.57.

Conclusions: Transcranial Doppler evaluation without evidence for vasospasm. The middle cerebral artery velocities are below the potential threshold values indicating increased risk of stroke in patients with sickle cell disease.
The study does not indicate increased stroke risk in a patient with sickle cell disease.

- Correctly examines ICA, MCA, ACA, PCA and basilar (**and vertebral**)
- Reports mean velocities. Assume this is the TAMMV?
- Reports and interprets only the MCA, **no mention of ICA velocities**

Sample Report—UW

EXAMINATION: US Intracranial Doppler Complete

DATE: 08/03/2016

COMPARISON: Ultrasound May 5, 2015

TECHNIQUE: Color and spectral Doppler interrogation was performed of the intracranial arteries. Time average mean of the maximum velocities of the intracranial arteries were obtained and are reported below.

FINDINGS:

RIGHT:

Right middle cerebral artery velocities of 158,160,159 cm/sec at a depth of 3.4,3.9,4.4 cm.
Previous maximum velocity measured 133 cm/s at a depth of 4.7 cm.

Right anterior cerebral artery: 63 cm/sec
Right terminal internal carotid artery: 104 cm/sec
Right posterior cerebral artery: 35 cm/sec
Right vertebral artery: 51 cm/sec

LEFT:

Left middle cerebral artery velocities of 173,154,148 cm/sec at a depth of 3.5,4.0,4.5. Previous maximum velocity measured 140 cm/s at a depth of 3.3 cm.

Left anterior cerebral artery: 70 cm/sec
Left terminal internal carotid artery: 126 cm/sec
Left posterior cerebral artery: 121 cm/sec
Left vertebral artery: 77 cm/sec

Basilar artery: 108,80,69 cm/sec

IMPRESSION:

The time average mean of the maximum velocities in the left MCA are conditionally elevated at 173 cm/s.

Overall, an excellent study and format

Reports TAMMV

Correctly examines ICA, MCA, ACA, PCA and basilar.

Vertebral arteries reported, but not part of STOP

Sample Report—Oakland

Transcranial Doppler Report

Location: outpatient

Indication for Procedure: This is a transcranial Doppler study for a 3 y.o. 6 m.o. male who has Hemoglobin S-S disease.

Procedural Notes: Annual screening TCD for a child with SCD on hydroxyurea.

Right Arterial System		Left Arterial System	
RMCA:	137 cm/sec	LMCA:	127 cm/sec
RdICA:	92 cm/sec	LdICA:	68.5 cm/sec
BIF:	121 cm/sec	BIF:	112 cm/sec
RACA:	-95.5 cm/sec	LACA:	-84.7 cm/sec
RPCA:	112 cm/sec	LPCA:	105 cm/sec

Fails to indicate that velocities are TAMMV

Interpretation: Normal study

Return Visit: 1 year

Reports fails to include the basilar velocities, even though they are obtained.

Sample Report—Nevada[1]

TRANSCRANIAL DOPPLER EVALUATION OF THE MIDDLE CEREBRAL ARTERIES

CLINICAL HISTORY:
History of sickle cell disease. Currently off of penicillin and aspirin.

TECHNIQUE:
Time average maximum mean velocities (TAMMX) of the middle cerebral arteries were obtained.

COMPARISON:
None.

Reports the TAMMV

FINDINGS:
Right middle cerebral artery:
Proximal: 102-103 cm/sec.
Mid: 75-85 cm/sec.
Distal: 55-81 cm/sec.
Right posterior cerebral artery: 77-82 cm/s.
Right anterior cerebral artery: 55-70 cm/s.
Left middle cerebral artery:
Proximal: 55-66 cm/sec.
Mid: 90-102 cm/sec.
Distal: 97-109 cm/sec.
Left posterior cerebral artery: 64-86 cm/s.
Left anterior cerebral artery: 43-50 cm/s.
There is low resistance waveform without evidence of flow reversal. Preserved systolic upstrokes is seen throughout.
(TAMMX is classified as follows:
Normal: velocities less than 170 cm/s
Conditional: at least one velocity 170-199 cm/s
Abnormal: at least one velocity > 200 cm/s)

Correctly examines MCA, ACA, PCA. **Fails to examine the ICA and basilar.**

IMPRESSION:
Time average mean maximum velocities of the middle cerebral arteries are within normal proposed limits. Continued followup in 6-12 months is suggested.

Sample Report—Nevada[2]

EXAMS: 004945400 US DOP TRANSCRANIAL COM

REASON FOR EXAM: SICKLE CELL DISEASE

CPT CODE: 93886

PROCEDURE: Doppler Transcranial Complete.

DATE: 10/31/2016 10:18 AM

COMPARISON: September 24, 2015

HISTORY: Sickle Cell disease

FINDINGS: Transcranial doppler was performed through transtemporal and suboccipital windows. The results are in mean velocity (cm/sec).

LEFT:
MCA: 144.
ACA: 115.
VERTEBRAL: 104.
BASILAR: 113.
PCA: 114.

RIGHT:
MCA: 108.
ACA: 60.
VERTEBRAL: 75
PCA: 74.

IMPRESSION: Velocities remain within normal range. Followup study is recommended in one year.

The study is considered normal if all mean velocities are less than 170 cm/s, conditional for velocities between 170 and 200 cm/s, and abnormal if the mean velocity is greater than 200 cm/s.

Reports mean velocities. Assume TAMMV?

Correctly examines MCA, ACA, PCA and basilar. **Fails to examine the ICA.**

Vertebral arteries reported, but not part of STOP