

Ultrasound Physics Study Guide

An In-Depth Review by Dr. Alice Matthews

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*Based on Edelman, "Understanding Ultrasound Physics"
Formulas, plain English, analogies, and clinical applications.*

PART 1: THE SOUND WAVE

How Sound Travels

Think of sound like a crowd doing "the wave" at a stadium. Nobody in the crowd actually moves across the stadium. They just stand up and sit down. But the wave pattern travels from one end to the other. Sound works the same way: particles vibrate back and forth (compressions and rarefactions), and that vibration pattern moves through tissue.

Sound is a **mechanical, longitudinal wave**. It needs a medium (tissue, blood, bone) to travel through. It cannot travel through a vacuum.

Period and Frequency

$$T = \frac{1}{f} \quad f = \frac{1}{T}$$

What this means: Period (T) is how long one cycle takes. Frequency (f) is how many cycles happen per second. They are reciprocals. If you know one, flip it to get the other.

Analogy: Imagine a merry-go-round. If one full rotation takes 2 seconds (period = 2 s), then it completes half a rotation per second (frequency = 0.5 Hz). Speed up the ride so each rotation takes 0.5 seconds, and now you get 2 rotations per second. Shorter period = higher frequency. Always.

Application: You never adjust period or frequency during a scan. They are fixed by the transducer the moment you pick it up. But your choice of transducer (2 MHz vs. 10 MHz) determines everything downstream: wavelength, resolution, penetration.

Key values: - Diagnostic ultrasound: $f = 2 - 10$ MHz, $T = 0.1 - 0.5 \mu s$ - Ultrasound is any frequency above 20 kHz (above human hearing)

Wavelength

$$\lambda \text{ (mm)} = \frac{1.54}{f \text{ (MHz)}}$$

What this means: Wavelength (λ) is the physical length of one cycle of sound in tissue. Higher frequency = shorter wavelength. In soft tissue, divide 1.54 by the frequency and you have it.

Analogy: Picture ocean waves approaching a beach. A storm far offshore sends long, rolling swells (low frequency, long wavelength). A speedboat nearby creates short, choppy waves (high frequency, short wavelength). The water itself (the medium) is the same. What changes is the source.

Why this matters clinically: Wavelength determines your image detail. You cannot see anything smaller than the wavelength. A 5 MHz transducer has a wavelength of about 0.3 mm, so structures smaller than 0.3 mm will not be resolved. This is why superficial scanning uses high-frequency probes (short wavelength = finer detail) and deep scanning uses low-frequency probes (longer wavelength but better penetration).

Frequency	Wavelength	You would scan...
2 MHz	0.77 mm	Deep abdomen, obese patient
5 MHz	0.31 mm	Average abdomen, heart
10 MHz	0.15 mm	Thyroid, breast, superficial vessels

Unique fact: Wavelength is the only parameter determined by BOTH the source (frequency) AND the medium (speed of sound). Everything else is determined by one or the other, not both.

Propagation Speed

$$c = f \times \lambda$$

$$c_{\text{soft tissue}} = 1,540 \text{ m/s} = 1.54 \text{ mm}/\mu\text{s}$$

What this means: Sound speed depends entirely on the medium. It has nothing to do with the transducer. A 2 MHz probe and a 10 MHz probe both send sound through soft tissue at exactly 1,540 m/s. The transducer picks the frequency; the tissue picks the speed.

Analogy: Think of a highway with a speed limit. Cars of all colors (frequencies) travel at the same speed limit (propagation speed). A red car (high frequency) and a blue car (low frequency) both go 65 mph. The road (medium) determines the speed, not the car.

What controls speed?

Property	Effect on Speed	Memory Trick
Stiffness	↑ stiffness = ↑ speed	S and S go the Same direction
Density	↑ density = ↓ speed	D and S go Different directions

Analogy: Tap your knuckle on a wooden table (stiff), then on a pillow (soft). The “knock” sound travels through the table almost instantly because wood is stiff. The pillow absorbs it. Stiff = fast. Now compare a bowling ball (dense) to a basketball (light). The dense bowling ball actually resists transmitting vibration. Density slows things down.

Clinical speed table (memorize the pattern, not every number):

Tissue	Speed	Memory Aid
Lung/Air	500 m/s (slowest)	Air is squishy, not stiff at all
Fat	1,450	Slightly below average
Soft tissue	1,540	THE number. Memorize this.
Blood	1,560	Slightly above average
Muscle	1,600	Denser but also stiffer
Bone	3,500 (fastest)	Extremely stiff

Why 1,540 matters: Your ultrasound machine assumes ALL tissue is soft tissue at 1,540 m/s. When it's wrong (like scanning through fat at 1,450 or bone at 3,500), the image places structures at the wrong depth. This is the source of **speed error artifacts**.

Amplitude, Power, and Intensity: "The Bigness Parameters"

These three all describe how "big" or "strong" the sound wave is. They are all directly related to each other.

Intensity

$$I = \frac{P}{\text{Area}} \quad I \propto A^2$$

What this means: Intensity is the concentration of energy in the beam. Power spread over a large area = low intensity. Power concentrated in a small area = high intensity.

Analogy: Imagine standing in the rain. If you hold a large beach umbrella, the rain (power) is spread over a wide area. You feel a gentle mist (low intensity). Now hold a tiny cocktail umbrella. The same rain now pelts your head. Same power, smaller area, higher intensity.

The squared relationship ($I \propto A^2$) is critical for board exams: - Double the amplitude → intensity increases $\times 4$ - Triple the amplitude → intensity increases $\times 9$ - Halve the amplitude → intensity drops to $\frac{1}{4}$

Application: When you turn up the "output power" knob on the machine, you are increasing amplitude, which increases intensity (and patient exposure). This is why ALARA matters. More output = more energy deposited in tissue.

The Master Relationship Table

Understanding which parameters are related. And which are NOT. Is one of the most tested concepts on board exams.

Pair	Relationship	Think of it as...
Frequency and Period	Inversely (reciprocals)	Fast merry-go-round = short ride time
Frequency and Wavelength	Inversely (same medium)	Choppy waves are short
Frequency and Speed	UNRELATED	All cars go the same speed limit
Amplitude and Intensity	Directly ($I \propto A^2$)	Louder speaker = more energy
Power and Intensity	Directly	More watts = more concentrated energy
Stiffness and Speed	Directly	Stiff materials carry sound fast
Density and Speed	Inversely	Dense materials resist vibration

PART 2: PULSED ULTRASOUND

Diagnostic ultrasound does not send continuous sound. It sends **short bursts (pulses)** and then listens for echoes. Think of it like sonar on a submarine: ping... listen... ping... listen.

Pulse Duration and Spatial Pulse Length

$$PD (\mu s) = n \times T \qquad SPL (\text{mm}) = n \times \lambda$$

What this means: Each pulse is a short train of cycles (typically 2-4 cycles). Pulse Duration measures the train in **time**. Spatial Pulse Length measures the train in **distance**.

Analogy: A freight train passes a crossing. You can describe it two ways: - "It took 30 seconds to pass" = Pulse Duration (time) - "It was 500 meters long" = Spatial Pulse Length (distance)

Same train, two measurements. One is a clock, one is a ruler.

	Pulse Duration	Spatial Pulse Length
Measures	Time	Distance
Units	μs	mm
Determined by	Source only	Both source and medium

Why SPL matters: SPL directly controls your axial resolution (image detail along the beam). Shorter pulse = better detail. This is why imaging transducers use damping to shorten the pulse.

PRP and PRF

$$PRP = \frac{1}{PRF}$$

What this means: PRP (Pulse Repetition Period) is the time from the start of one pulse to the start of the next. It includes both the transmit time AND the listening time. PRF (Pulse Repetition Frequency) is how many pulses are sent per second.

Analogy: Imagine you are standing at the edge of a canyon, shouting and listening for the echo. - You shout ("transmit"), then wait silently for the echo to return ("receive") - The time from one shout to the next shout = PRP - How many shouts per minute = PRF

If the canyon is deep (deep imaging), you have to wait longer for the echo, so your PRP is longer and your PRF is lower. If the canyon is shallow, echoes return quickly, you can shout more often, and PRF goes up.

This is adjustable by the sonographer. When you change imaging depth, you change PRP and PRF.

Critical distinction: PRF is NOT the same as frequency. Frequency describes cycles within a single pulse (millions per second, MHz). PRF describes how many pulses are sent per second (thousands per second, kHz). They are completely unrelated.

Duty Factor

$$DF = \frac{PD}{PRP} \times 100\%$$

What this means: What fraction of the time is the transducer actually transmitting? For imaging, it is transmitting less than 1% of the time and listening more than 99% of the time.

Analogy: Think of a lighthouse. The light flashes briefly, then goes dark for a long time, then flashes again. The duty factor is the percentage of time the light is actually on. For a typical imaging transducer, the duty factor is about 0.2-0.5%. It “flashes” for a tiny instant and “listens” for a comparatively enormous amount of time.

Continuous wave (CW) Doppler has a duty factor of 100%. Always transmitting, never stopping. This is why CW Doppler uses two crystals: one to transmit, one to receive.

PART 3: SOUND GETS WEAKER (ATTENUATION)

Decibels

dB Change	Intensity Change	Memory Trick
+3 dB	$\times 2$	3 = Double
+10 dB	$\times 10$	10 = Ten
-3 dB	$\times \frac{1}{2}$	
-10 dB	$\times \frac{1}{10}$	

What this means: Decibels are a shorthand for comparing two intensities. They are logarithmic (multiplicative, not additive) and relative (always comparing two values).

Analogy: Think of decibels like a scoring system for earthquakes (the Richter scale). A 6.0 earthquake is not “twice as strong” as a 3.0. It is 1,000 times stronger. Decibels work similarly: small dB numbers represent huge intensity changes. The trick is that +3 dB always means doubling, and +10 dB always means multiplying by 10. And you can stack them.

Stacking examples: - +6 dB = +3 + 3 = double, then double again = $\times 4$ - +20 dB = +10 + 10 = $\times 10$, then $\times 10 = \times 100$ - -9 dB = -3 - 3 - 3 = halve three times = $\times \frac{1}{8}$

Attenuation

$$\text{Total Attenuation (dB)} = \alpha \text{ (dB/cm)} \times d \text{ (cm)}$$

$$\alpha = \frac{f \text{ (MHz)}}{2} \quad (\text{soft tissue rule of thumb})$$

What this means: As sound travels through tissue, it gets weaker. The rate of weakening depends on the frequency and the type of tissue. Higher frequency = faster weakening. This is the fundamental trade-off in ultrasound: higher frequency gives better resolution but worse penetration.

Analogy: Imagine walking through a forest with a flashlight. A powerful, focused beam (high frequency) shows incredible detail on nearby trees but doesn’t reach very far. A dim, wide lantern (low frequency) illuminates less detail but you can see further into the woods. You pick the flashlight for close work and the lantern for distance.

The 0.5 rule: In soft tissue, every MHz of frequency costs you 0.5 dB per centimeter. So: - 2 MHz probe: loses 1 dB per cm - 5 MHz probe: loses 2.5 dB per cm - 10 MHz probe: loses 5 dB per cm

Example: A 5 MHz probe scanning 8 cm deep. Total round-trip path = 16 cm. Attenuation = $2.5 \text{ dB/cm} \times 16 \text{ cm} = 40 \text{ dB}$. That means the returning echo is $\frac{1}{10,000}$ as strong as the transmitted pulse. This is why TGC (time gain compensation) exists. To boost those deep, weakened signals back up.

Half-Value Layer

The distance sound travels to lose half its intensity (= 3 dB). Think of it as “how far can this frequency reasonably penetrate?”

- High frequency in a highly attenuating medium = thin HVL (poor penetration)
 - Low frequency in a weakly attenuating medium = thick HVL (great penetration)
-

Acoustic Impedance

$$Z = \rho \times c$$

What this means: Impedance is a tissue property that determines how much sound reflects at a boundary. It combines density (ρ) and speed (c). You never measure it directly. It is calculated.

Analogy: Think of impedance as “acoustic hardness.” When you throw a ball at a wall (high impedance), most of the energy bounces back. When you throw a ball into a curtain (low impedance), most energy passes through. Now imagine throwing a ball from one room into another through a doorway. If both rooms have the same “hardness,” the ball passes through easily (no reflection). If the second room has a very different hardness, the ball bounces back.

The reflection formula:

$$IRC (\%) = \left[\frac{Z_2 - Z_1}{\frac{Z_2 + Z_1}{2}} \right]^2 \times 100$$

When impedances are similar (soft tissue to soft tissue): reflection is tiny (< 1%), almost all sound passes through. This is good. We need sound to reach deep structures.

When impedances are very different (soft tissue to bone, soft tissue to air): reflection is massive. This is why:
- We use **gel** between the transducer and skin (removes air gap) - **Lung** and **bowel gas** block ultrasound (huge impedance mismatch with surrounding tissue) - **Bone** creates strong reflections and shadows

Snell's Law (Refraction)

$$\frac{\sin \theta_t}{\sin \theta_i} = \frac{c_2}{c_1}$$

What this means: When sound crosses from one medium to another at an angle AND the two media have different speeds, the beam bends. This is refraction.

Analogy: Picture a car driving from pavement onto a sandy beach at an angle. The right tires hit the sand first and slow down, while the left tires are still on pavement going fast. The car turns (refracts) toward the sand side. If the car hit the sand straight on (perpendicular), it would slow down but not turn.

Two conditions are required for refraction: 1. Oblique incidence (sound hits at an angle, not straight on) 2. Different propagation speeds in the two media

Clinical relevance: Refraction creates **position artifacts**. Structures appear shifted from their true location because the beam bent as it passed through tissue boundaries.

PART 4: FINDING DEPTH (THE RANGE EQUATION)

$$d \text{ (mm)} = \frac{1.54 \times t \text{ (}\mu\text{s)}}{2}$$

What this means: The machine sends a pulse and times how long until the echo returns. Since it knows the speed (1.54 mm/ μ s in soft tissue), it calculates the depth. The division by 2 accounts for the round trip. Sound goes TO the reflector and BACK.

Analogy: You stand at the edge of a canyon and clap your hands. You hear the echo 4 seconds later. Sound travels at about 340 m/s in air. Total distance = $340 \times 4 = 1,360$ meters. But that is the round trip, so the canyon wall is 680 meters away. The ultrasound machine does this calculation thousands of times per second, for every pulse.

The 13-Microsecond Rule

$$13 \mu\text{s} = 1 \text{ cm of depth in soft tissue}$$

What this means: For every 13 microseconds of round-trip time, the reflector is 1 cm deeper. This is the most practical shortcut in ultrasound physics.

Quick math: Imaging 10 cm deep? The machine needs $10 \times 13 = 130 \mu\text{s}$ before it can send the next pulse. That constrains how fast it can image (PRF and frame rate).

How Depth Controls Everything Downstream

$$PRP = d \times 13 \mu\text{s/cm} \quad PRF = \frac{77,000}{d \text{ (cm)}}$$

Application: This is why deeper imaging = slower frame rates. At 20 cm depth, each pulse needs 260 μs to return. At 100 lines per frame, that is 26 ms per frame = about 38 frames/sec. Go to 30 cm, and frame rate drops further. This is the unavoidable physics constraint that limits real-time imaging.

PART 5: IMAGE QUALITY

Axial Resolution

$$AR = \frac{SPL}{2}$$

What this means: Axial resolution is the ability to distinguish two structures that lie along the beam's path (one deeper than the other). It equals half the spatial pulse length. Shorter pulse = better resolution.

Analogy: Imagine you are dropping pebbles into a pond one at a time. Each pebble creates a ring of ripples. If the rings are long and spread out (long SPL), two pebbles dropped close together will have overlapping rings. You cannot tell them apart. If the rings are short and tight (short SPL), you can distinguish two closely spaced pebbles.

What makes axial resolution better: - Higher frequency (shorter wavelength = shorter pulse) - Fewer cycles per pulse (damped transducer) - These are fixed by the transducer. The sonographer cannot adjust axial resolution

Typical values: 0.1 - 1.0 mm. **Lower numbers = better.**

Memory aid for synonyms (LARRD): Longitudinal, rAnge, Radial, Depth. These all mean axial resolution.

Lateral Resolution

$$LR = \text{beam diameter at that depth}$$

What this means: Lateral resolution is the ability to distinguish two structures that lie side by side (perpendicular to the beam). It equals the beam width. Narrower beam = better lateral resolution.

Analogy: Imagine painting a fence with a thick roller vs. a thin brush. The thick roller cannot paint fine details. Adjacent pickets blur together. The thin brush can distinguish each one. The beam width is your “brush width.”

Key difference from axial: Lateral resolution CHANGES with depth (the beam is narrow at the focus and wide in the far field). Axial resolution stays the same at all depths. This is why axial resolution is always better than lateral resolution.

What makes lateral resolution better: - Focusing (narrows the beam at a specific depth) - Higher frequency (tighter beam) - Larger transducer aperture

Memory aid for synonyms (LATA): Lateral, Angular, Transverse, Azimuthal.

Frame Rate and Temporal Resolution

$$\text{Frame Rate} = \frac{1}{T_{\text{frame}}} \quad T_{\text{frame}} = \text{Pulses per Frame} \times PRP$$

$$PRF = \text{Lines per Frame} \times \text{Frame Rate}$$

What this means: Frame rate is how many complete images the machine produces per second. Higher frame rate = smoother real-time motion = better temporal resolution.

Analogy: Think of a flip book. If you draw 30 pages per second, the animation looks smooth (high frame rate). If you only draw 5 pages per second, the motion looks choppy (low frame rate). Each “page” in ultrasound is one frame, and each frame requires many pulses (one per scan line). If each pulse takes a long time to return (deep imaging), you can draw fewer pages per second.

What DECREASES frame rate (worse temporal resolution):

Factor	Why
Deeper imaging	Each pulse takes longer to return
More focal zones	More pulses per scan line
Wider sector	More scan lines per frame
Higher line density	More scan lines per frame

Clinical tip: For fast-moving structures (heart valves, fetal heart), you need high frame rate. Narrow the sector, use single focus, and keep depth as shallow as possible.

PART 6: TRANSDUCERS

Transducer Frequency

$$f = \frac{c_{PZT}}{2 \times \text{thickness}}$$

What this means: A transducer's frequency is determined by the thickness of its piezoelectric crystal. Thinner crystal = higher frequency. The crystal is always cut to be exactly half a wavelength thick.

Analogy: Think of a guitar string. A short, thin string vibrates at a high pitch (high frequency). A long, thick string vibrates at a low pitch. The PZT crystal works the same way. Its physical dimensions set the "pitch" of the sound it produces.

Quality Factor (Q)

$$Q = \frac{f_{\text{main}}}{\text{Bandwidth}}$$

What this means: Q-factor describes how "pure" the transducer's output is. A high-Q transducer produces a very narrow range of frequencies (like a tuning fork). A low-Q transducer produces a wide range (like a drumbeat).

	Imaging Transducers	CW/Therapeutic
Q-factor	Low	High
Bandwidth	Wide	Narrow
Pulse	Short (good for imaging)	Long (continuous)
Damping	Heavy	None

Clinical application: Imaging needs short pulses (low Q) for good axial resolution. CW Doppler needs a pure frequency (high Q) for accurate velocity measurement.

Beam Shape and Focusing

$$NZL = \frac{D^2 \times f}{61.6}$$

What this means: The near zone length (NZL) is the distance from the transducer to the natural focal point. A larger transducer or higher frequency pushes the focus deeper.

Analogy: Think of a flashlight. A large reflector (large diameter) produces a beam that stays focused further into the distance. A small penlight diverges quickly. Similarly, a large transducer aperture keeps the beam narrow for a longer distance.

Beam width at key points:

Location	Width	Image Quality
At the transducer face	$= D$ (full diameter)	Moderate
At the focus	$= \frac{D}{2}$ (half diameter)	Best
Beyond $2 \times NZL$	$> D$ (diverging)	Worst

PART 7: INSTRUMENTATION

The Receiver Chain

The returning echoes are incredibly weak. The receiver processes them in five steps (memorize this order):

1. **Amplification:** Turns up the overall volume (like a master volume knob)

2. **Compensation (TGC):** Boosts deep echoes more than shallow ones (like an equalizer)
3. **Compression:** Squeezes the huge range of echo strengths into a displayable range
4. **Demodulation:** Cleans up the signal (rectification + smoothing)
5. **Reject:** Removes the weakest signals (noise filter)

ALARA and the Output Power vs. Gain Decision

As Low As Reasonably Achievable

The rule: If your image is too dark, increase **receiver gain first** (free. No added patient exposure). Only increase output power as a last resort (adds patient exposure).

Analogy: You are listening to a quiet radio station. You have two knobs: one turns up the radio's broadcast power (output power), and one turns up the volume on your speakers (receiver gain). Turning up the speaker amplifies everything equally. Both the music and the static. Turning up the broadcast power actually makes the music louder relative to the static (better signal-to-noise ratio) but uses more electricity (patient exposure). ALARA says: turn up your speakers first.

	Output Power	Receiver Gain
Brightness	Changes	Changes
Signal-to-Noise	Improves	No change
Patient exposure	Increases	No change
ALARA: too dark?	Increase SECOND	Increase FIRST
ALARA: too bright?	Decrease FIRST	Decrease second

Dynamic Range and Compression

$$DR \text{ (dB)} = 20 \times (\text{zeros in voltage ratio})$$

What this means: Dynamic range is the ratio between the strongest and weakest signals the system can handle. A wide dynamic range displays many shades of gray (subtle tissue differences). A narrow dynamic range displays fewer shades (higher contrast, more black-and-white).

Analogy: Think of a camera's exposure range. A professional camera (wide dynamic range) captures detail in both shadows and highlights. You see subtle differences everywhere. A cheap security camera (narrow dynamic range) shows everything as either bright white or dark black. High contrast but no subtlety.

The imaging chain progressively compresses dynamic range:

Stage	Dynamic Range
Returning echoes	120 dB (1,000,000,000,000 : 1 intensity range)
After receiver	100-120 dB
Scan converter	40-50 dB
Display	20-30 dB

PART 8: DOPPLER

The Doppler Effect

$$f_d = \frac{2 v f_t \cos \theta}{c}$$

What this means: When sound bounces off moving blood cells, the frequency of the echo changes. Blood moving toward the transducer returns a higher frequency; blood moving away returns a lower frequency. The amount of shift depends on four things: blood velocity, transducer frequency, the angle between beam and flow, and the speed of sound.

Analogy: Stand next to a road and listen to an ambulance. As it approaches, the siren sounds higher pitched. As it passes and moves away, the pitch drops. The faster the ambulance, the bigger the pitch change. This is the Doppler effect. In ultrasound, the “ambulance” is a red blood cell, the “siren” is the transmitted frequency, and the pitch change is the Doppler shift.

Why the factor of 2? The sound hits the blood cell (first Doppler shift) and then bounces back to the transducer (second Doppler shift). Two encounters, two shifts.

The Angle Problem

$$v_{\text{measured}} = v_{\text{true}} \times \cos \theta$$

What this means: The Doppler equation includes $\cos \theta$, which means the angle between the beam and the blood flow direction changes what you measure.

Angle	$\cos \theta$	What You See
0° (parallel, toward)	1.0	100% of true velocity
60°	0.5	Only 50% of true velocity
90° (perpendicular)	0.0	ZERO. No signal at all.

Clinical rule: Always keep the Doppler angle below 60°. At 60°, you are already losing half the velocity. At 90°, you get nothing. This is why you angle-correct in spectral Doppler and why you steer the color box.

Analogy: Imagine standing by a highway with a speed gun. If you point it straight down the road (parallel to traffic), you read the true speed. If you point it at an angle, you read a lower speed. If you point it perpendicular to traffic, the cars appear stationary. Zero reading. Same physics, same problem.

Nyquist Limit and Aliasing

$$f_{\text{Nyquist}} = \frac{\text{PRF}}{2}$$

What this means: Pulsed Doppler can only measure velocities up to the Nyquist limit. Beyond that, the signal “wraps around” (aliasing). High velocities appear as flow in the opposite direction.

Analogy: Watch a helicopter blade or car wheel on video. At low RPM, you see the blade spinning forward. As it speeds up, there is a point where the blade appears to stop, then appears to spin backwards. That is aliasing. The video’s frame rate (like PRF) cannot keep up with the motion. The solution: either increase the frame rate (increase PRF) or use a different method (CW Doppler, which never aliases because it is always “watching”).

Five ways to reduce aliasing: 1. Increase scale (increase PRF) 2. Lower frequency transducer (smaller shifts for same velocity) 3. Shallower sample volume (allows higher PRF) 4. Switch to CW Doppler (eliminates aliasing completely) 5. Baseline shift (cosmetic only. Moves the display, not the physics)

Key fact: CW Doppler NEVER aliases. The trade-off is that CW has no depth selectivity. It measures everything along the beam.

Resistivity and Pulsatility Indices

$$RI = \frac{V_{\max} - V_{\min}}{V_{\max}} \quad \quad PI = \frac{V_{\max} - V_{\min}}{V_{\text{mean}}}$$

What these mean: Both describe the “shape” of the arterial waveform. How much the velocity changes between systole and diastole. High resistance vessels (like peripheral arteries) have a big difference between systolic and diastolic flow. Low resistance vessels (like the internal carotid or renal artery) maintain flow throughout the cardiac cycle.

Analogy: Think of a garden hose. If you kink the hose downstream (high resistance), the flow surges when you squeeze the nozzle and drops to almost nothing when you let go. Big RI. If the hose is wide open (low resistance), flow is steady regardless of how hard you squeeze. Low RI.

Clinical advantage: Both RI and PI are **ratios**, so Doppler angle errors cancel out. You do not need to angle-correct for these indices.

PART 9: ARTIFACTS

The Six Assumptions

Every ultrasound image is based on assumptions. When reality violates an assumption, you get an artifact.

Assumption	What Happens When Violated	Artifact
Sound travels in straight lines	Beam bends at tissue interfaces	Refraction artifact
Sound goes directly to a reflector and back	Multiple bounces	Reverberation, comet tail
Sound travels at 1,540 m/s	Speed mismatch	Range error (too deep or too shallow)
Echoes come from the main beam only	Side/grating lobes reflect	Side lobe artifact
The imaging plane is thin	Beam has width in elevation	Slice thickness artifact
Echo strength = tissue character	Strong reflectors dominate	Shadowing, enhancement

Speed Error

$$c_{\text{actual}} > 1,540 \implies \text{structure placed TOO SHALLOW}$$

$$c_{\text{actual}} < 1,540 \implies \text{structure placed TOO DEEP}$$

Analogy: Your GPS says it takes 30 minutes to drive somewhere at 60 mph. If you actually drive 80 mph, you arrive early (the GPS overestimated the time/distance). If you drive 40 mph, you arrive late. The ultrasound

machine “assumes 1,540 mph.” If tissue is faster, the echo returns sooner than expected, and the machine places it too shallow.

PART 10: SAFETY

Thermal Index (TI) and Mechanical Index (MI)

TI = predictor of temperature increase (unitless)

$$MI = \frac{P_{\text{neg}}}{\sqrt{f}}$$

TI estimates how much the tissue could heat up. Higher TI = more heating risk. There are three versions: - **TIS**: soft tissue (default) - **TIB**: bone at the focus (biggest concern in OB. Fetal bone) - **TIC**: cranial bone near the transducer (transcranial Doppler)

MI estimates the likelihood of mechanical damage (cavitation. Tiny bubble formation and collapse). Higher MI = more cavitation risk.

Analogy: Think of a microwave oven. TI is like the power setting (how hot will the food get?). MI is like whether the food might “pop” or explode (like a grape in a microwave). Both are concerns, but different types of damage.

Safety thresholds: - No confirmed bioeffects below 2°C rise for exposures under 50 hours - Fetal concerns begin at 39°C (2° above normal body temperature of 37°C)

ALARA in practice: Use the lowest output power that produces a diagnostic image. Minimize scan time. Pay attention to the TI and MI displays on the screen.

MASTER CONSTANTS (Quick Reference)

Constant	Value	When You Use It
Speed in soft tissue	1,540 m/s = 1.54 mm/ μ s	Every depth calculation
Wavelength at 1 MHz	1.54 mm	Quick wavelength estimation
Attenuation in soft tissue	0.5 dB/cm/MHz	Penetration calculations
13- μ s rule	13 μ s per cm depth	PRF and frame rate
+3 dB	Intensity doubles	Decibel problems
+10 dB	Intensity $\times 10$	Decibel problems
Normal body temp	37°C	Bioeffects thresholds
Doppler shift range	20 Hz - 20 kHz	Falls in audible range

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