chapter 1

Ultrasound Physics

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Definitions

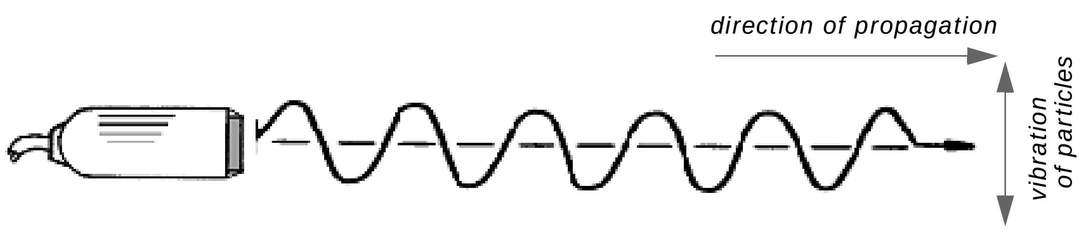
Sound creates images by sending short bursts into the body. Thus we are concerned with the interaction of sound & media.

Sound A type of wave that carries energy, not matter, from place to place.

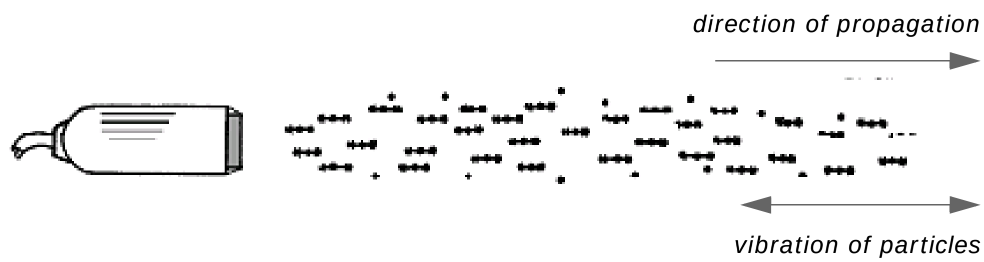
- Created by the vibration of a moving object. Rhythmical variations in pressure or density.
- Comprised of compressions (increases in pressure or density) and rarefactions (decreases in pressure or density).
- Sound must travel through a medium, cannot travel through a vacuum.
- Sound is a **mechanical, longitudinal** wave.

Waves

Transverse Wave Particles move in a perpendicular direction (right angles or 90^o) to the direction of the wave:



Longitudinal Wave Particles move in the *same direction* as the wave:



Parameters describe sound waves:

Period
Frequency

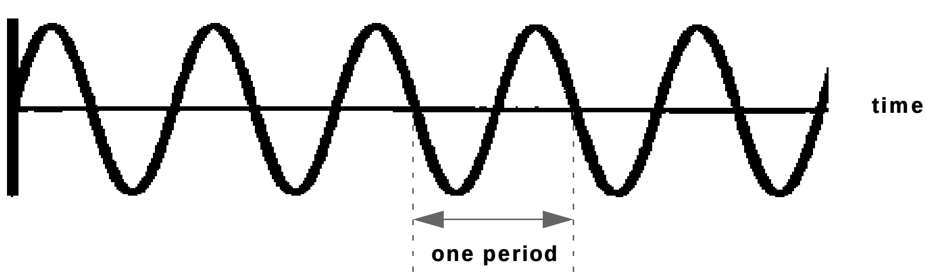
Speed

Bigness
(Amplitude, Power & Intensity)

Wavelength

Period

Definition	The time required to complete a single cycle.
Example	The period of the moon circling the earth is 28 days. The period of class in high school may be 50 minutes.
Units	μsecond—any unit of time
Typical Values	0.06 to 0.5μs
Determined By	Sound source
Changed by Sonographer	No



Frequency

Definition	The number of *certain events* that occur in a particular time duration. Simply, **the reciprocal of period.**
Units	per second, $\frac{1}{\text{second}}$, Hertz, Hz
Determined By	Sound source
Changed by Sonographer	No
***Ultra*sound**	A wave with a frequency exceeding 20,000Hz (20 kHz). This frequency is so high that it is not audible.
***Audible* Sound**	Heard by man, frequencies between 20Hz and 20,000Hz.
***Infra*sound**	Sound with frequencies less than 20Hz. This frequency is so low that it is not audible.
Typical Values	From 2MHz to 15MHz
Note	Frequency affects penetration and axial resolution (image quality.)

Intensity *(also power and amplitude)*

Definition	The concentration of energy in a sound beam.
Units	watts/square cm or watts/cm^2
Determined By	Sound source (initially)
Changed by Sonographer	Yes Intensity decreases as sound propagates through the body.

Wavelength

Definition The length or distance of a single cycle.

Similar to the length of a single boxcar in a long train.

Units mm - any unit of **length**

Determined By **Both** the source and the medium

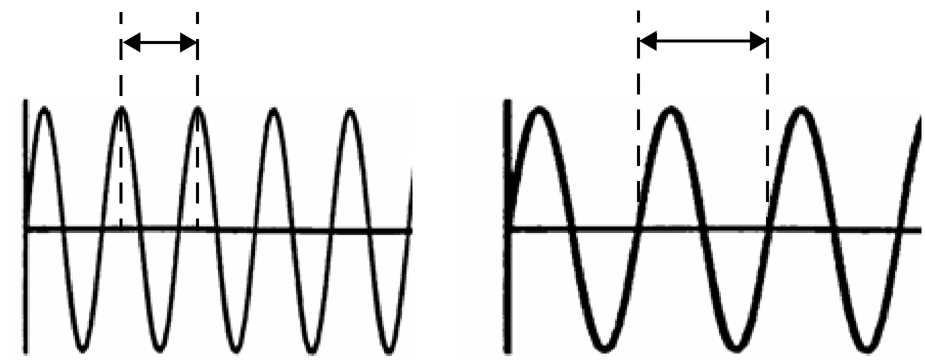
Changed by Sonographer No

Wavelength influences axial resolution (image quality).

Typical Values 0.1–0.8 mm (in soft tissue)

Higher frequency also means shorter wavelength

Lower frequency also means longer wavelength.



Higher Frequency
Shorter Wavelength

Lower Frequency
Longer Wavelength

Wavelengths in Soft Tissue

- In soft tissue, sound with a frequency of 1 MHz has a wavelength of 1.54 mm.
- In soft tissue, sound with a frequency of 2 MHz has a wavelength of 0.77 mm.

Rule ***In soft tissue, divide 1.54 mm by frequency in MHz.***

$$\text{wavelength (mm)} = \frac{1.54\,\text{mm}}{\text{frequency (MHz)}}$$

Propagation Speed

Definition The rate that sound travels through a medium.

Units meters per second

Determined By *Medium* only - Density and stiffness

Note: All sound, regardless of the frequency, travels at the same speed through any specific medium. This means that sound with a frequency of 5MHz and sound with a frequency of 3MHz travel at the same propagation speed if they are traveling through the same medium.

Changed by Sonographer No

Typical Values

- Average speed of all sound (regardless of frequency) in *biologic* or "*soft tissue*:"

  1,540 m/s = 1.54 m/s = 1.54 mm/µs

- lung (air) << fat < soft tissue << bone
- ***General Rule:*** *gas (slower) < liquid < solid (faster)*

Tissue Type	Speed (m/s)
Air	330
Lung	300 - 1,200
Fat	1,450
Soft Tissue	1,540
Bone	2,000–4,000

Rule of Thumbs

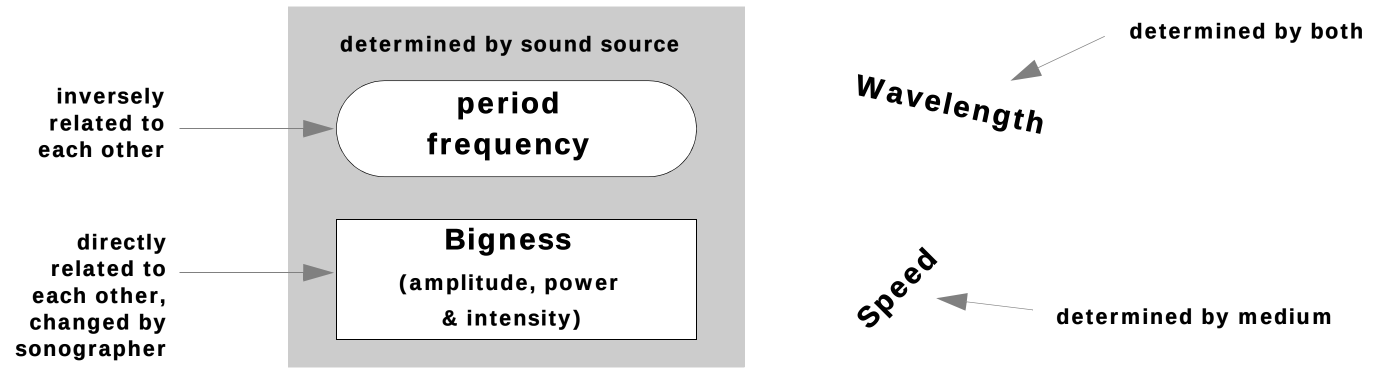
Stiffness is related to change in shape, 'squishability'

Density is related to weight

Stiffness and **S**peed — same direction

Density and **S**peed — opposite directions

The Skinny



Review 1

1. What are the units of:
   a. wavelength
   b. frequency
   c. intensity
   d. propagation speed
   e. period

2. Does the medium or the sound source determine these parameters?
   a. wavelength
   b. frequency
   c. intensity
   d. propagation speed
   e. period

3. (True or False) Sound is a transverse, mechanical wave.

4. (True or False) A wave with a frequency of 15,000 MHz is ultrasonic.

Answers

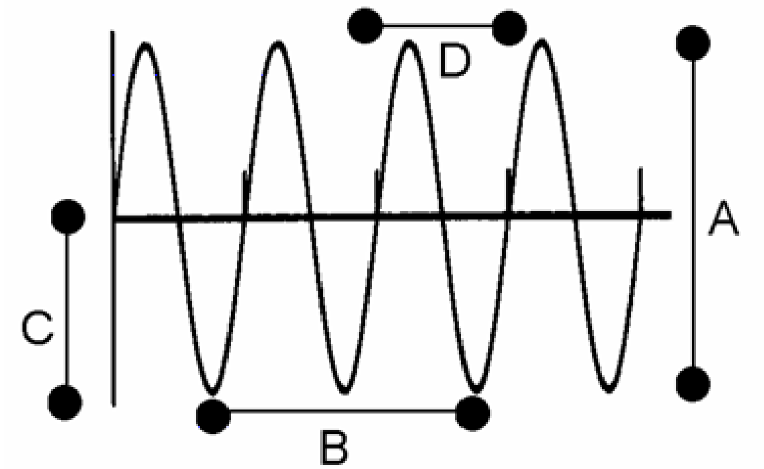
1a. millimeters
1b. Hertz
1c. Watts/cm^2
1d. meters/sec
1e. second

2a. both
2b. sound source
2c. sound source
2d. medium
2e. sound source

3. Sound is mechanical, but it is a longitudinal wave.

4 True. Ultrasound is defined as any wave with a frequency of greater than 20,000 Hertz.

Review 2



1. Which of the following best describes line B?
   a. amplitude
   b. peak-to-peak amplitude
   c. frequency
   d. wavelength
   e. none of the above

2. Which of the following best describes line D?
   a. amplitude
   b. peak-to-peak amplitude
   c. frequency
   d. wavelength
   e. none of the above

3. Which of the following best describes line D?
   a. amplitude
   b. peak-to-peak amplitude
   c. frequency
   d. period
   e. none of the above

4. Which of the lines above, A, B, C, or D, is most likely to be the reciprocal of frequency?

5. Which of the lines above, A, B, or C, is most likely to be determined by the source and the medium?

Answers

1. e
2. d
3. d
4. line D
5. line B

Review 3

1. A sound beam travels a total of 10 cm in 2 seconds. What is the speed of the sound in this medium?
   a. 10 cm/sec
   b. 2 cm/sec
   c. 5 cm/sec
   d. 0.2 cm/sec

2. (True or False) Propagation speed increases as frequency increases.

3. Medium 1 has a density of 9 and a stiffness of 6, while medium 2 has a density of 8 and a stiffness of 6. In which medium will sound travel slower?

4. Which of the following characteristics will create the fastest speed of sound?
   a. high density, high stiffness
   b. low density, high stiffness
   c. high density, low stiffness
   d. low density, low stiffness

Answers

1. c
2. False
3. Medium 1
4. b

chapter 2 Pulsed Sound

In diagnostic **imaging**, short **pulses** of acoustic energy are used to create anatomic images. ♥

Continuous wave sound cannot create anatomic images. CW is used for Doppler.

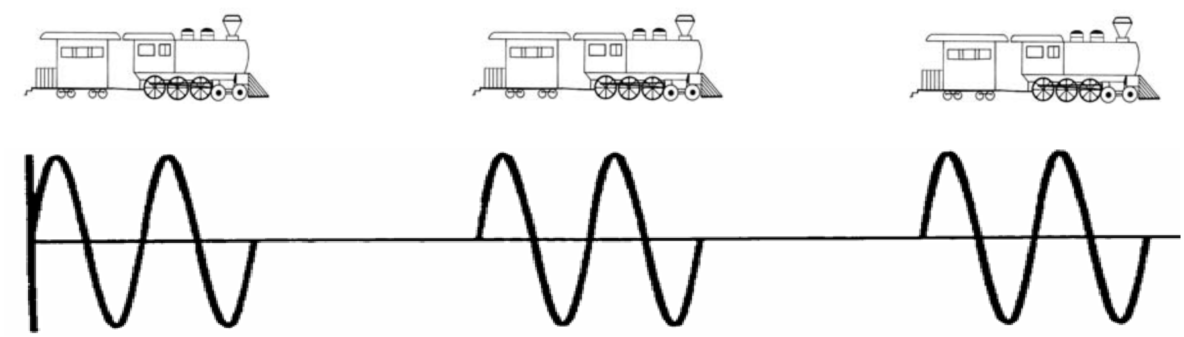
Definition A pulse is a collection of cycles that travel together.

Analogy Imagine a pulse as a train: although individual cycles (cars) create the pulse (train), the pulse moves as one.

A pulse *must* have a beginning and an end, otherwise the sound is continuous wave.

Two Components of Pulsed Ultrasound

1. the cycles ("on" or "transmit" time), and
2. the dead time ("off" or "receive" time)



Five Additional Parameters that Describe Pulsed Sound

Pulse Duration

Spatial Pulse Length

Pulse Repetition Period
PRF
Duty Factor

Note: Parameters describe the features of sound

Pulse Duration

Definition The time from the **start** of a pulse to the **end** of that pulse ♥, the **actual time** ♥ that the pulse is "on".

Units μsec — or any unit of time

Determined By Sound source

Pulse duration is determined by multiplying the **number of cycles** in the pulse and the **period** of each cycle.

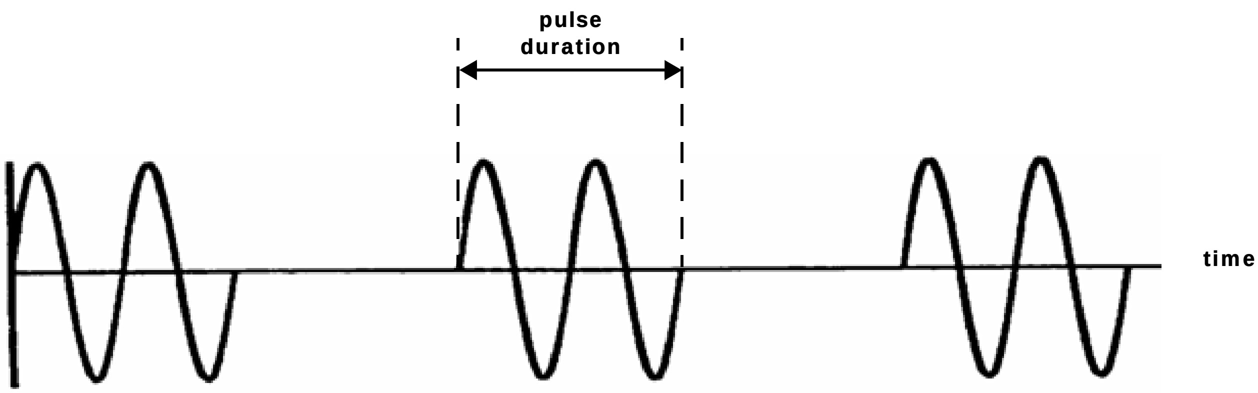
Changed by sonographer? No, pulse duration cannot be changed by sonographer. Pulse duration is a characteristic of each transducer. It does not change when sonographer alters imaging depth.

Typical Values In clinical imaging, pulse duration ranges from 0.5 to 3μs.

In clinical imaging, a pulse is comprised of 2–4 cycles. ♥

> Remember ♥
>
> A pulse is a pulse is a pulse;
>
> a transducer's talking time does not change.

Equation Pulse Duration (us) = # cycles in pulse × period (us)



Spatial Pulse Length

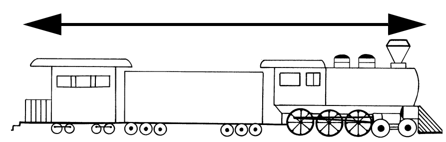
Definition The **length** or **distance** that an entire pulse occupies in space. The distance from the start to the end of one pulse.

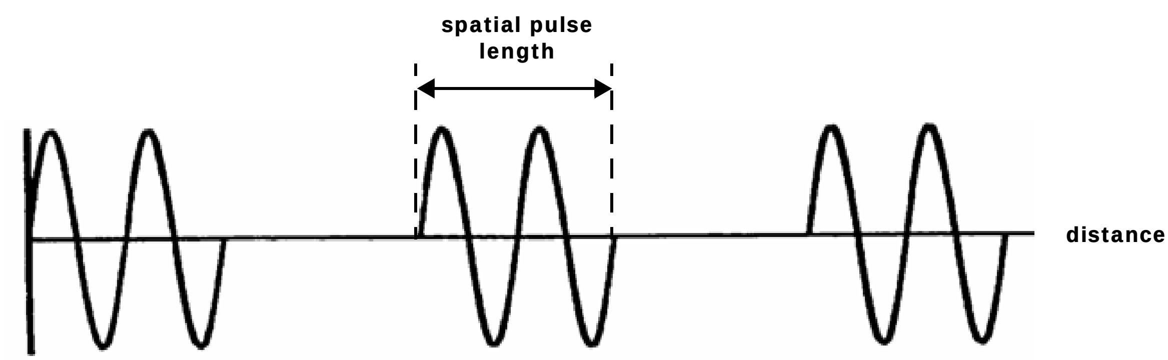
Units mm — any unit of distance

Determined By **Both** the source and the medium. Since wavelength is determined by both the source & medium, so too is the spatial pulse length.

Changed by sonographer? No, cannot be changed by the sonographer.

Example For SPL, think of a train (the pulse), made up of cars (individual cycles). The overall length of our imaginary train from the front of the locomotive to the end of the caboose.





Typical Values 0.1 to 1 mm.

Note SPL determines axial resolution.

Shorter pulses create higher quality images.

Equation Spatial Pulse Length (mm) = # of cycles $\times$ wavelength (mm)

Pulse Repetition Period

Definition Pulse repetition period (PRP) is the time from the *start* of one pulse to the *start* of the next pulse♥. It includes one pulse duration and one “listening time.”

Units msec — or any unit of time

Determined By Sound source

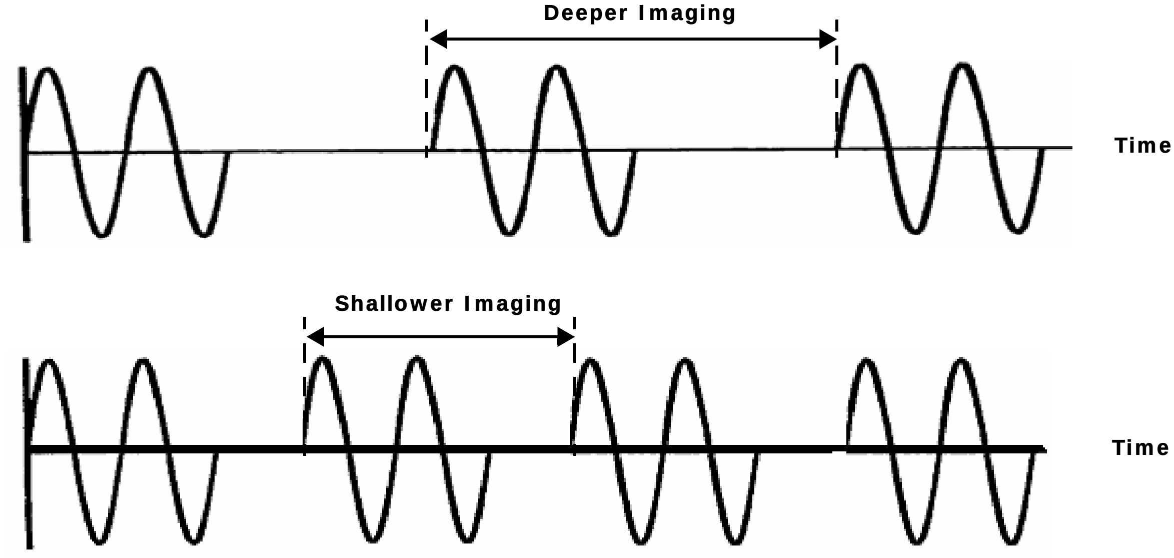
Changed by sonographer? Yes, PRP can be changed by the sonographer.

When adjusting the depth of view, the operator changes only the “listening time”, never the pulse duration. Deeper imaging is associated with longer PRP.

Typical Values In clinical imaging, the PR period ranges from 100µs to 1 ms.

Hint PRP is determined by the imaging depth.

Note: In reality, the listening time is hundreds of times longer than the talking time (pulse duration).



As PR period increases, imaging depth increases. ♥
As PR period decreases, imaging depth decreases.

Remember

A pulse is a pulse is a pulse!

The sonographer changes *only* the listening time between pulses.

PRF

Definition — **PRF** is the number of **pulses** created by the system in one second.

Units — Hertz, Hz, per second

Determined By — Sound source

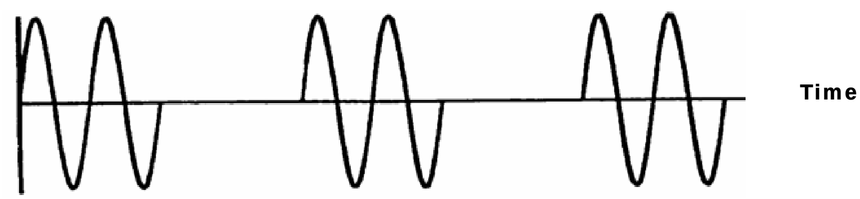
Changed by sonographer? — Yes

Typical values — In clinical imaging, from 1,000–10,000 Hz (1-10 kHz) ♥

Notes

- *The PRF is determined by imaging depth.*
- As imaging depth increases, PRF decreases (inverse relationship). ♥
- Since depth of view is changed by the sonographer, the sonographer changes the PRF. The operator actually adjusts the pulse repetition period, thereby changing the PRF.

Shallow image, higher PRF
Deep image, lower PRF



Relationship

- Pulse repetition period and PRF are **reciprocals** (inverse relationship-when one parameter goes up, the other goes down). Therefore, pulse repetition period also depends upon imaging depth.

Equation

$$\text{pulse repetition period (sec)} \times \text{pulse repetition frequency (Hz)} = 1$$

HINTS — **PRF** means **pulse repetition frequency**.

PRF is determined only by imaging depth.

PRF is <u>not</u> related to frequency.

Duty Factor

Definition The **percentage** or **fraction** of time that the system transmits sound.

Units Unitless!

Factors & coefficients are unitless (one exception)!

- » Maximum = 1.0 or 100%, continuous wave.
- » Minimum = 0.0 or 0%, the system is off.

Determined By Sound source

Changed by sonographer? Yes, can be changed by the sonographer when imaging depth is changed.

Typical values From 0.1% to 1% *or* 0.001 to 0.01 (little talking, lots of listening) ♥

Shallow image, higher duty factor
Deep image, lower duty factor

Duty factor always has a small value. With deeper imaging, the duty factor is even smaller.

Note An **imaging** system must use pulsed ultrasound. Therefore, the duty factor must be between 0% and 100% (or 0 and 1), typically less than 1%. CW sound cannot create anatomical images. ♥

♥ Very Important Concept

Terms That Have the Same Meaning♥	
shallow imaging	deep imaging
high pulse repetition frequency (PRF)	low pulse repetition frequency (PRF)
high duty factor	low duty factor
short pulse repetition period	long pulse repetition period

Hint: Tap your fingers.

Parameters that Describe Both Pulsed and Continuous Waves

Period	Frequency
Wavelength	Propagation Speed

Continuous and pulsed sound are both comprised of cycles. Therefore, any parameter that describes a cycle describes both PW and CW sound.

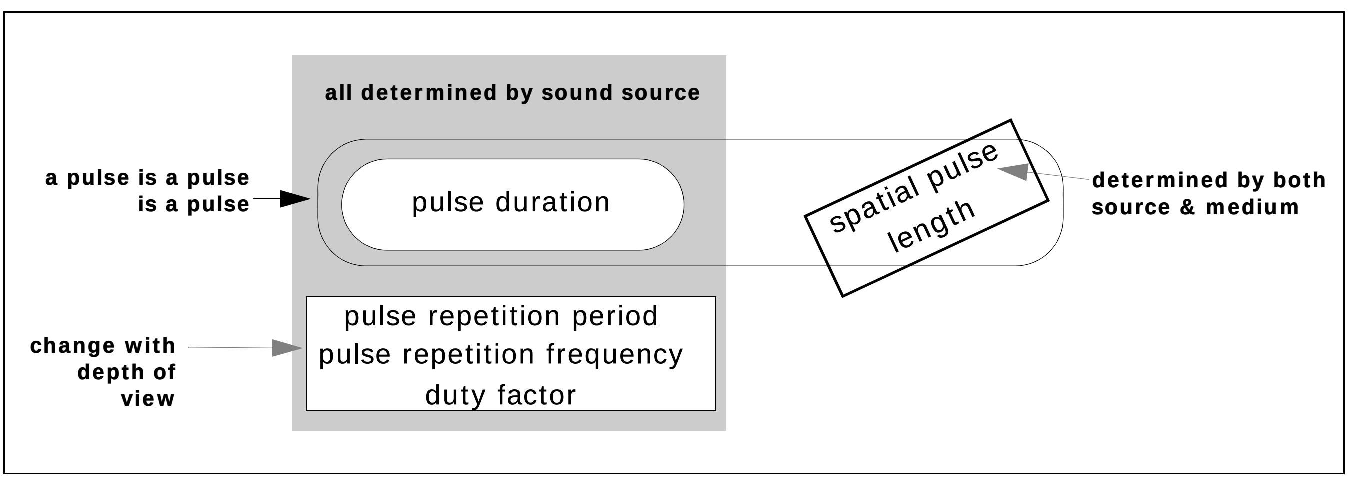
Parameters of Pulsed Waves

Parameter	Basic Units	Units	Adjustable	Determined By	Typical Values
pulse duration	time	µs	no	source	0.5–3.0 µsec
spatial pulse length	distance	mm	no	source & medium	0.1–1.0 mm
pulse repetition period	time	ms	yes	source	0.1–1.0 ms
PRF	1/time	1/sec, Hz	yes	source	1–10 kHz
duty factor	none	none	yes	source	less than 1%

By adjusting the imaging depth, the operator changes the ***pulse repetition period***, ***PRF***, and ***duty factor***.

The ***pulse duration*** and ***spatial pulse length*** are characteristics of the pulse itself and are inherent in the transducer design. They are not changed by sonographer.

The Skinny II



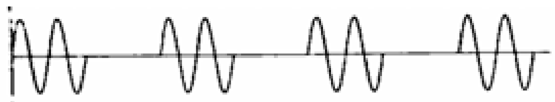
Review 1—Pulsed Waves

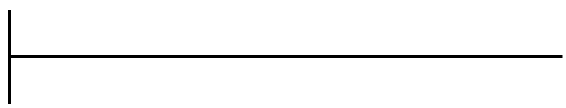
1. ____________ is the time from the start of a pulse to the end of that pulse.

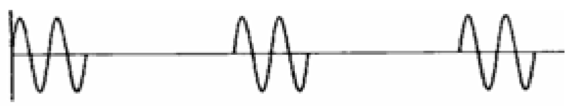
2. ____________ is the time from the start of a pulse to the start of the next pulse.

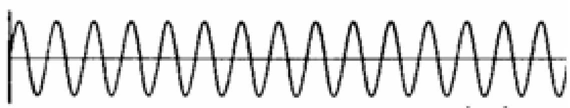
3. Pulse repetition frequency is the reciprocal of ___.

4. What is the duty factor of the following 4 signals? *(To determine a duty factor, use one transmit and receive time, then determine the ratio.)*

a


b


c


d


5. Which pattern in question #4 indicate a system with a superficial imaging depth?

6. Which pattern in question #4 indicate a system with the deepest imaging depth?

7. Which two patterns in #4 identify an ultrasound system that cannot create an image of anatomy?

8. When changing the imaging depth, which of the following parameters does the operator also change? (more than one may be correct)
   a. PRF (pulse repetition frequency)
   b. duty factor
   c. propagation speed
   d. pulse repetition period
   e. amplitude
   f. spatial pulse length

9. The speed of a 5MHz continuous wave is 1.8km/sec. The wave is then pulsed with a duty factor of 0.5. What is the new propagation speed?

10. Arrange the following from shortest to longest.
    a. pulse duration
    b. period
    c. pulse repetition period
    d. listening time

Answers

1. Pulse Duration is the time from the start of a pulse to the end of that pulse.

2. Pulse Repetition Period is the time from the start of a pulse to the start of the next pulse.

3. Pulse repetition frequency is the reciprocal of Pulse Repetition Period.

4.
   a. 0.5, the system is talking half of the time and listening half of the time.

   b. 0.0, the system is not transmitting.

   c. 0.333, the system is transmitting 1/3 of the time.

   d. 1.0, the system is transmitting all of the time.

5. Choice A has the shallowest imaging depth because the pulse repetition period is the shortest. The pulse repetition frequency is the highest.

6. Choice C has the deepest imaging depth because the pulse repetition period is the longest. The pulse repetition frequency is the lowest.

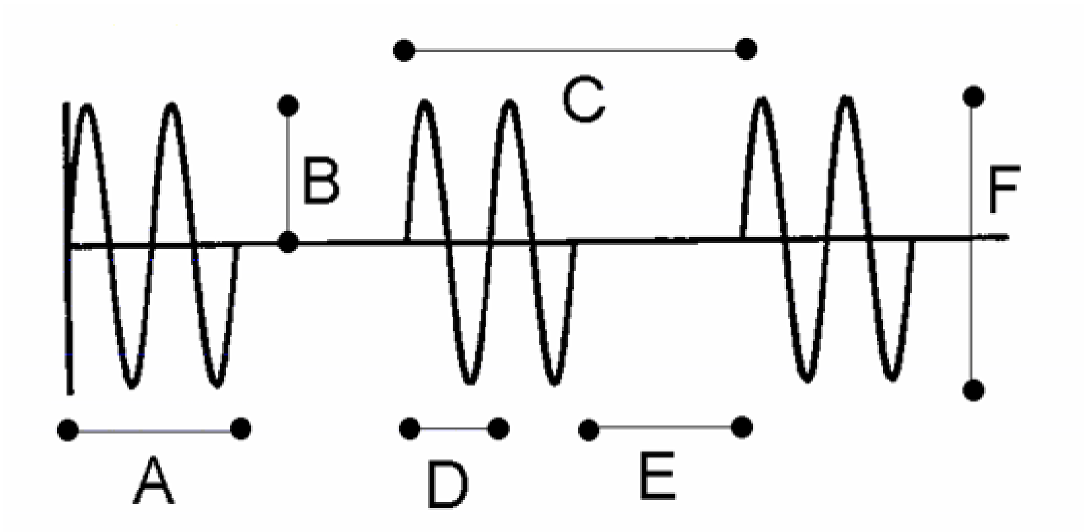
7. System D cannot perform imaging because it produces a continuous ultrasound beam. Only pulsed ultrasound systems can create an image of anatomy. Additionally, system B cannot perform imaging because it does not produce acoustic waves.

8.
   a.pulse repetition frequency
   b.duty factor
   d. pulse repetition period

9. The propagation speed for pulsed and continuous US is the same and depends only upon the medium through which the sound travels. The new propagation speed is exactly the same as the old propagation speed, 1.8km/sec.

10. From shortest time to longest time:
    b, a, d, c

Review 2—Pulsed Waves



1. Which of the following best describes line A?
   a. frequency
   b. pulse repetition period
   c. period
   d. pulse duration
   e. duty factor
   f. amplitude

2. Which of the following best describes line B?
   a. frequency
   b. pulse repetition period
   c. period
   d. pulse duration
   e. duty factor
   f. amplitude

3. Which of the following best describes line C?
   a. frequency
   b. pulse repetition period
   c. period
   d. pulse duration
   e. duty factor
   f. amplitude

4. Which of the following best describes line D?
   a. frequency
   b. pulse repetition period
   c. period
   d. pulse duration
   e. duty factor
   f. amplitude

5. Which of the following best describes line E?
   a. frequency
   b. pulse repetition period
   c. period
   d. listening time
   e. peak-to-peak amplitude
   f. amplitude

6. Which of the following best describes line F?
   a. frequency
   b. peak-to-peak amplitude
   c. period
   d. pulse duration
   e. duty factor
   f. amplitude

7. Which of the following best describes line A?
   a. frequency
   b. pulse repetition period
   c. period
   d. spatial pulse length
   e. duty factor
   f. amplitude

8. Which of the following best describes line D?
   a. frequency
   b. pulse repetition period
   c. wavelength
   d. pulse duration
   e. duty factor
   f. amplitude

Answers

1. d 2. f 3. b 4. c 5. d 6. b 7. d 8. c

Review 3—Pulsed Waves

1. A sonographer adjusts the depth of view of an ultrasound scan from 8cm to 16cm. What happens to each of the following parameters? Do they increase, decrease or remain the same?
   a. period
   b. frequency
   c. wavelength
   d. speed
   e. amplitude (initial)
   f. power (initial)
   g. intensity (initial)
   h. pulse duration
   i. PRF
   j. duty factor
   k. spatial pulse length
   l. pulse repetition period

2. A sonographer is using a 3MHz transducer and changes to a 6MHz transducer. The imaging depth remains unchanged. What will happen to each of the following parameters? Do they increase, decrease or remain the same?
   a. period
   b. frequency
   c. wavelength
   d. speed
   e. amplitude (initial)
   f. power (initial)
   g. intensity (initial)
   h. PRF
   i. pulse repetition period

3. A sonographer is using a 3Mhz transducer and increases the output power in order to visualize structures that are positioned deeper in the patient. No other controls are adjusted. What happens to each of the following parameters. Do they increase, decrease or remain the same?
   a. period
   b. frequency
   c. wavelength
   d. speed
   e. amplitude (initial)
   f. power (initial)
   g. intensity (initial)
   h. pulse duration
   i. PRF
   j. duty factor
   k. spatial pulse length
   l. pulse repetition period

4. What is the duty factor of a 7 MHz continuous wave sound beam at a depth of 10 cm?

Answers

1a. remains same
1b. remains same
1c. remains same
1d. remains same
1e. remains same
1f. remains same
1g. remains same
1h. remains same
1i. decreases
1j. decreases
1k. remains same
1l. increases

2a. decreases
2b. increases
2c. decreases
2d. remains same
2e. remains same
2f. remains same
2g. remains same
2h. remains same
2i. remains same

3a. remains same
3b. remains same
3c. remains same
3d. remains same
3e. increases
3f. increases
3g. increases
3h. remains same
3i. remains same
3j. remains same
3k. remains same
3l. remains same

4. 1.0 The duty factor of continuous wave sound is always 1.

chapter 3

Range Equation

Ultrasound systems measure "*time-of-flight*" and relate that measurement to distance traveled.

Since the average speed of US in soft tissue (**1.54 km/sec**) is known, the time-of-flight and distance that US travels in the body are directly related.

Time-of-flight

The time needed for a pulse to travel **to and from** the transducer and the reflector is called:

» **go-return time** or **time-of-flight**

When time-of-flight is known, we can determine the distance.

When one reflector is twice as deep as another reflector, the pulse's time-of-flight is doubled for the deeper reflector. In other words, the time-of-flight will be increased by a factor of two.

Equations

$$\text{distance to boundary (mm)} = \frac{\text{go-return time } (\mu s) \times \text{speed } (mm/\mu s)}{2}$$

In soft tissue:

$$\text{distance to boundary (mm)} = \text{time } (\mu s) \times 0.77 \ \frac{mm}{\mu s}$$

The 13 Microsecond Rule

- *In soft tissue, every 13µs of go-return time means the reflector is 1cm deeper in the body.*

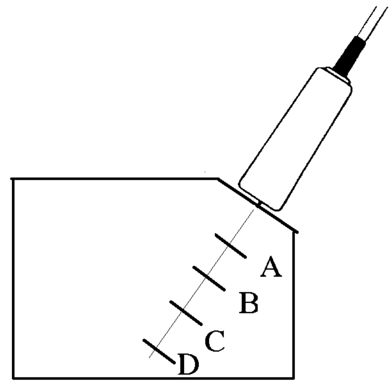
Note

On the exam, pay attention to the subtle difference in the words *depth* and *distance*.

Time-of-Flight	Reflector Depth	Total Distance Traveled
13 µs	1 cm	2 cm
26 µs	2 cm	4 cm
52 µs	4 cm	8 cm
130 µs	10 cm	20 cm

Examples

1. A sound pulse is produced by a transducer and travels in an ultrasound phantom. It travels from the transducer to pin "D", reflects off of it and returns to the transducer in 130 μsecs. How deep is pin "D"?
2. A sound pulse emitted from a transducer travels in an ultrasound phantom, reflects off of pin "A", and returns to the transducers in 52 μsecs. How deep is pin "A"?



Solution

In an ultrasound phantom, the speed of sound is the same as that in soft tissue, 1.54mm/μs. Each 13 μsec means the reflector is 1cm deeper:

1. In 130μsec, the reflector, pin D, is located **10 cm** from the transducer.
2. In a 52μsec go-return time, the pin is **4 cm deep** in the phantom.

Concept

The important lesson is that if we know the speed of US in soft tissue (or in any medium), then there exists a fixed, invariable relationship between **time-of-flight** and **distance**. This is how pulsed ultrasound systems measure distance in biologic media.

chapter 4

Resolutions and 2-D Imaging

Resolution

The ability to image accurately (*accuracy*, not merely *quality*)

Axial Resolution

The ability to distinguish two structures that are close to each other **front to back**, **parallel to**, or **along** the beam's main axis.

Synonyms

- **L**ongitudinal
- **A**xial
- **R**ange, **R**adial
- **D**epth

LARRD resolution.

Units

mm, cm — all units of distance

The shorter the pulse, the better the LARRD resolution.

Axial resolution = half of the pulse length. Short pulses create more accurate images.

Changed by sonographer

No, a new transducer is needed to change LARRD resolution.

Note

"Short pulse" means a short spatial pulse length *or* a short pulse duration.

Transducers are designed by the manufacturers to have few cycles per pulse, so that the numerical LARRD resolution is low and the image accuracy is superior.

Typical Values

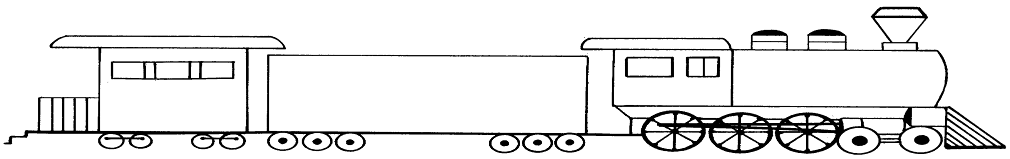
0.05–0.5 mm

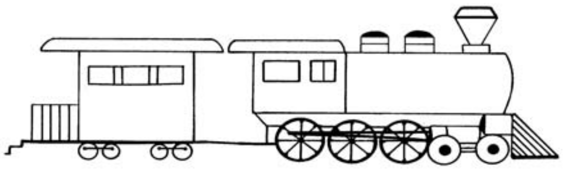
Equation

$$\text{LARRD resolution (mm)} = \frac{\text{spatial pulse length (mm)}}{2}$$

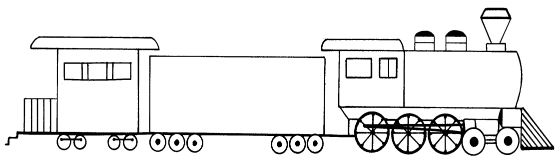
Note

Axial resolution is identical throughout an image.





Less ringing (fewer cycles)

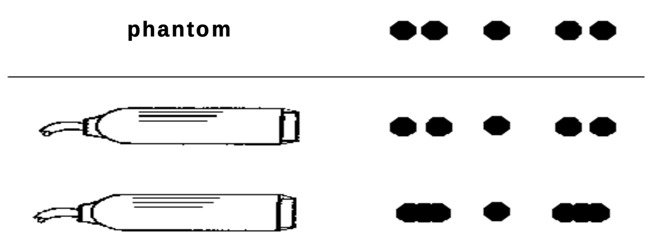


Higher frequency (shorter wavelength)

LARRD resolution improves with:

- **Less ringing**, fewer cycles in pulse (fewer cars in the train)
- **Higher frequency** sound (each car in the train is shorter), shorter wavelength (each car is shorter).
- *changing either of these factors requires a new transducer*

Example



HINT If you encounter a **numerical question**,
axial resolution is *best* in transducers with the highest frequency and the fewest numbers of cycles per pulse,
axial resolution is *worst* in transducers with the lowest frequency and the largest number of cycles/pulse.

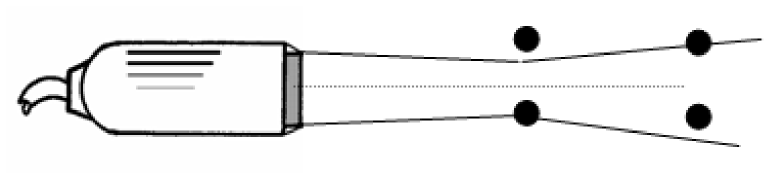
Lateral Resolution

Definition the minimum distance that two structures are separated by **side-to-side** or **perpendicular to the sound beam** that produces two distinct echoes.

approximately equal to the sound beam's diameter

Synonyms **L**ateral **A**ngular **T**ransverse **A**zimuthal

LATA resolution.



Units mm, all units of length

smaller number, more accurate image

Note Since the beam diameter varies with depth, the lateral resolution also varies with depth.

The lateral resolution is best at the focus or one near zone length (focal depth) from the transducer because the sound beam is narrowest at that point.

Note When two side-by-side structures are closer together than the beam width, only one wide reflection is seen on the image.

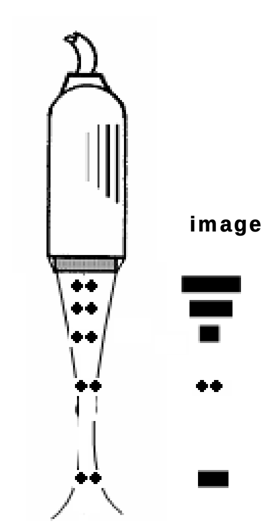
Note **LATA** resolution is usually not as good as **LARRD** resolution because US pulses are wider than they are short.

Hint

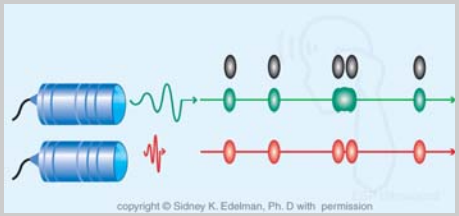
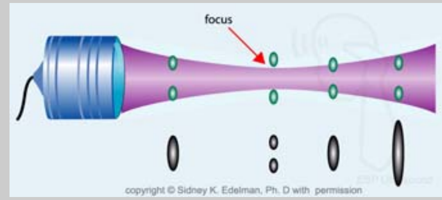
Lateral resolution is equal to beam diameter.

Lateral resolution at a variety of depths can be assessed with a test phantom by measuring the width of a reflection created by a pin in the phantom.

Wider reflections at depths further away from the focus exhibit poor lateral resolution.ψ

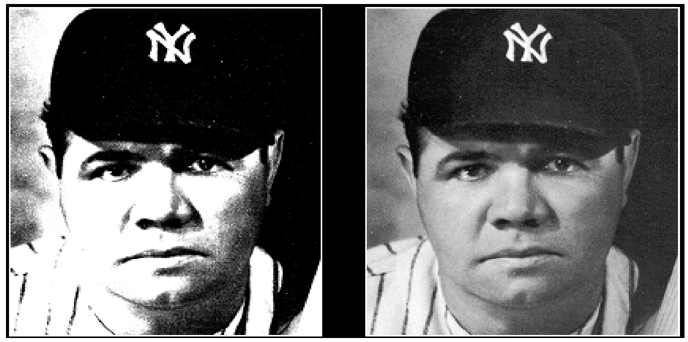


Comparison of Lateral & Axial Resolution

	AXIAL	LATERAL
		
Orientation	Front-to-back parallel to beam	Side-by-side perpendicular to beam
Mnemonic	LARRD	LATA
Determined by	Pulse length	Beam width
Best with:	shortest pulse highest frequency & fewest cycles	narrowest beam
Changes	same at all depths, does not change	changes with depth, best at focus
In Near Field, best with	shortest pulse	smallest diameter crystal
In Far Field, best with	shortest pulse	largest diameter & highest frequency (least divergence)

Contrast Resolution

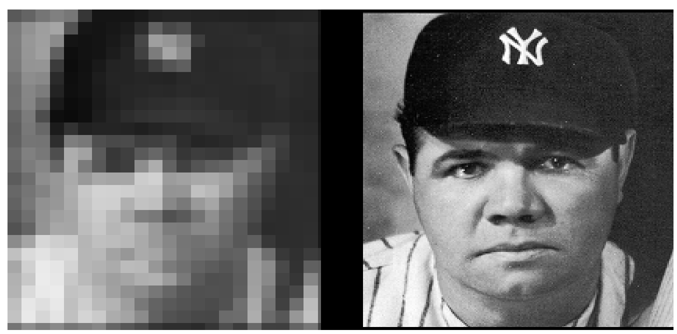
seeing different gray shades in an image



few gray shades   many gray shades

Spatial Resolution

seeing detail in an image



poor detail   good detail

Real Time Imaging & Temporal Resolution

Real-Time Imaging

The production of a motion picture.

A series of frames displayed in a rapid fashion so as to give the impression of constant motion.

> Machines displaying both real-time images and Doppler at one time are called **duplex**.

Temporal Resolution

- The ability to accurately locate moving structures at any particular instant in time.
- Resolution pertaining to time.
  "How high is the frame rate?' or
  "How fast can each frame be made?' or
  "How good is my movie?"

Determined By

- Temporal resolution depends only upon frame rate. More images per second improves temporal resolution.

Units

Frame rate has units of Hertz, or "per second"

Determined by 2 factors

1. **Imaging depth - shallower image depth**
   » higher frame rate
   » improved temporal resolution
2. **Number of pulses per frame - fewer pulses**
   » higher frame rate
   » improved temporal resolution

HINT narrow sector improves temporal resolution

HINT temporal resolution is unrelated to transducer frequency

chapter 5 Doppler

Doppler shift
or
Doppler frequency

a change or variation♥ in the frequency of sound as a result of motion between the sound source and the receiver (a moving interface in the body). Greater velocities create greater Doppler shifts.

difference between received and transmitted frequencies♥

- » **positive** change (or shift) when source and receiver are approaching each other. Reflected frequency is higher than transmitted.♥
- » **negative** change when the source and receiver are moving apart. Reflected frequency is less than transmitted frequency.

Note Doppler measures frequency shift, **not** amplitude.♥

Units Hertz, cycles per second ♥

Typical values **20 Hz-20 kHz** ♥, audible. Created when sound reflects off of red blood cells.

Note We still use 2 MHz to 10 MHz transducers to perform a Doppler ultrasound study, but the change in frequency (Doppler shift) ranges from 20–20,000 Hz.♥

Demodulation Thus, the low-frequency Doppler shift (10 kHz) “rides” or is “carried” on the much higher transducer frequency (5 MHz). **Demodulation** extracts the Doppler frequency from the transducer frequency and is performed by a **demodulator**. Bidirectional Doppler is analyzed with **phase quadrature** processing.

♥ **Hint:** Doppler shift = received frequency - transmitted frequency

If emitted frequency is FE and reflected frequency is FR, then Doppler frequency (FD) = FR - FE

Doppler EQUATION - *know this!*

$$\text{Doppler shift} = \frac{2 \times \text{reflector speed} \times \text{incident frequency} \times \cos(\text{angle})}{\text{propagation speed}}$$

Doppler shift is **directly related** to the
blood cell speed
frequency of the transducer
cosine of the angle between flow and the sound beam

Doppler shift is **inversely related** to the
speed of sound in the medium

Hint What does the *2* in the Doppler equation represent?♥

In clinical Doppler, there is a double Doppler shift. The first occurs when the sound strikes the cell. The second shift results from the moving blood cell reflecting the wave back to the transducer.

Hint In order to accurately determine velocity, the angle between the directions of flow and sound beam must be known.♥

Speed vs Velocity

Doppler measures velocity, not speed.♥

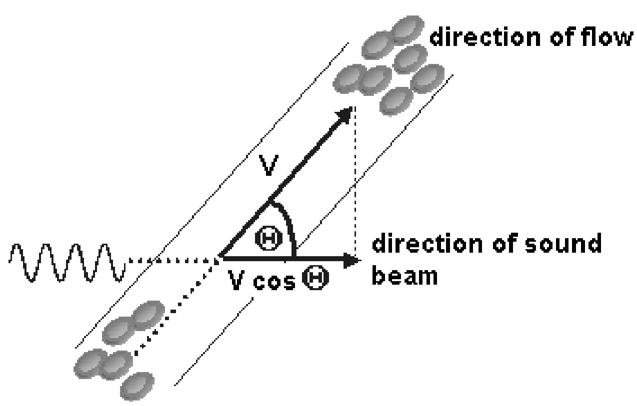
Speed **magnitude** only.

Velocity **magnitude** and **direction.**♥

Doppler frequency depends on direction. The magnitude of shift depends upon the cosine of the angle between the sound beam and the direction of motion. ♥

Equation $\text{velocity (measured)} = \text{true velocity} \times \cos(\text{angle})$

Angle	Cosine
0 degrees	1
20 degrees	.94
30 degrees	.87
60 degrees	0.5
90 degrees	0



At 0° or 180° between the direction of motion and the sound beam, the measured velocity is equal to the true velocity. At 90°, the measured velocity is zero because the cosine of 90° is zero. At angles between 0° and 90°, only a portion of the true velocity is measured.

Continuous Wave Doppler

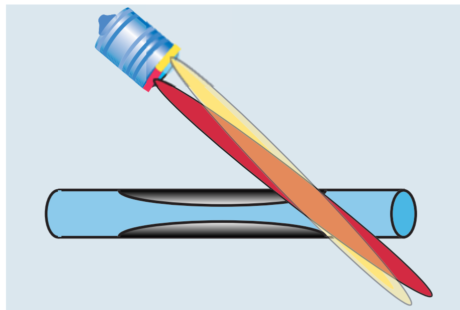
Number of crystals — **Two crystals** (minimum) in the transducer: ♥

- » one crystal is continuously transmitting
- » the other is continuously receiving

Advantage — **High velocities are accurately measured**♥

Disadvantage — Echoes arise from entire length of overlap between the transmit and receive beams, called **range ambiguity**.

Note — The term ‘range’ means ‘depth.’



Pulsed Wave Doppler

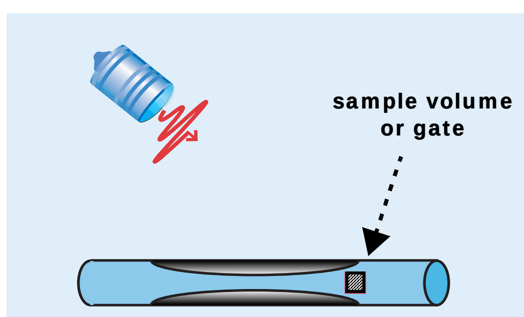
Number of crystals — **One crystal** (minimum)**,** alternates between sending and receiving. ♥

Advantage — Echoes arise only from the area of interrogation, the **sample volume** or **gate**. **We adjust the receive gate.** ♥

This is called a **range resolution** or **range specificity** or **freedom from range ambiguity** artifact.

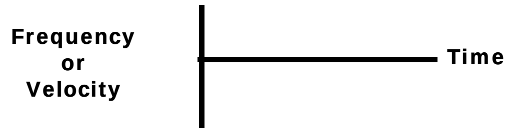
Disadvantage — Aliasing, errors in measuring high velocities.

Note — Imaging and pulsed Doppler can be performed with a single crystal transducer. Simultaneous imaging & Doppler is known as **duplex** ultrasound.♥



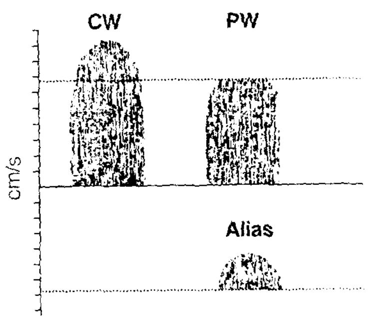
Axes The horizontal axis (or X-axis, side-to-side) of a Doppler spectrum is **time**.

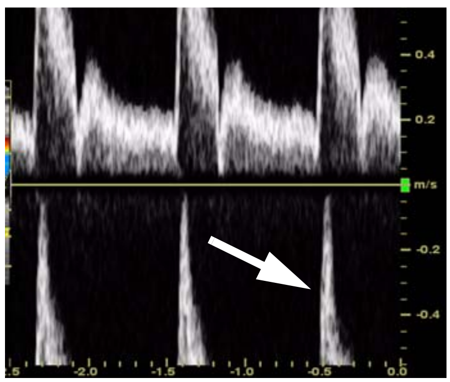
The vertical axis (or Y-axis, up and-down) of a Doppler spectrum is **Doppler shift or velocity**. ♥

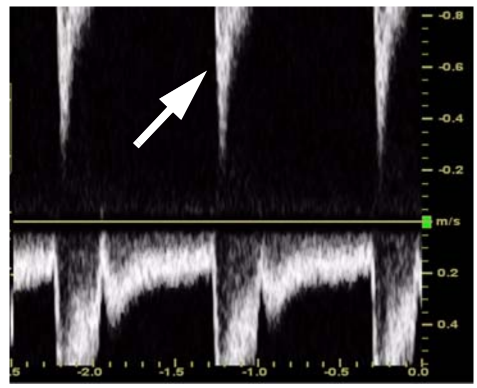


Aliasing

High velocities appear negative. **With pulsed Doppler**, high velocity measurements are inaccurate if the pulsed-Doppler sampling rate (the PRF) is too low in comparison to measured Doppler shift.







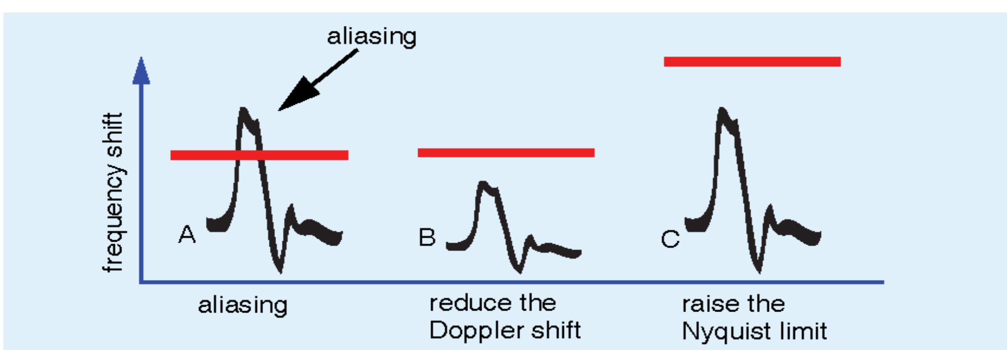
Nyquist frequency The Doppler frequency at which aliasing occurs, equal to ½ the PRF.

EQUATION♥ **Nyquist limit (kHz) = PRF / 2**

When Aliasing Occurs Aliasing appears (panel A, on the left) when the Doppler shift exceeds the Nyquist limit.

Aliasing can be eliminated when the Doppler spectrum shrinks (panel B, in the middle).

Aliasing can be eliminated when the Nyquist limit is raised (panel C, on the right)

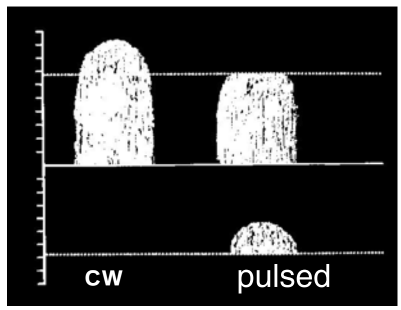


Eliminating Aliasing

Five ways to eliminate the unwanted effects of aliasing:
1. use continuous wave Doppler (no aliasing with CW).
2. select a transducer with a lower frequency (this reduces the Doppler shift for a given velocity, or shrinks the spectrum).
3 select **new view** with a shallower sample volume (this increases the PRF & Nyquist limit.).
4. increase the scale, **same view** (this increases the PRF & Nyquist limit.)
5. baseline shift (this is for appearance only.)

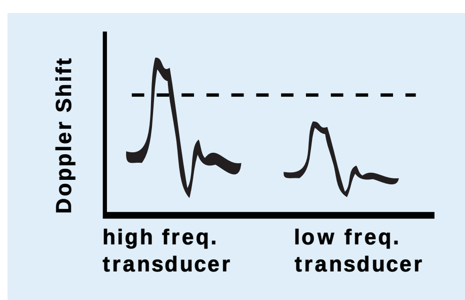
Continuous Wave Doppler

Aliasing cannot occur with continuous wave Doppler.



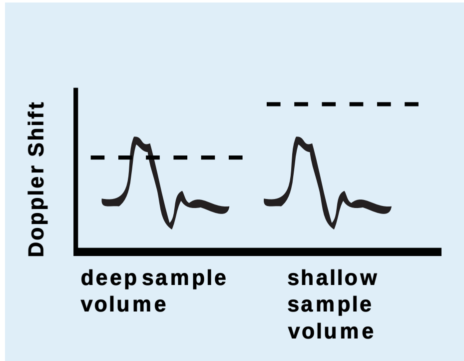
Lower Frequency Transducers

♥ **Lower frequency transducers reduce the Doppler shift and shrink the spectrum - when looking at the frequency.** With lower frequency transducers, the Doppler shift for a given velocity is lower than with higher frequency transducers. Less aliasing occurs. Therefore, lower frequency transducers are desirable for pulsed Doppler.



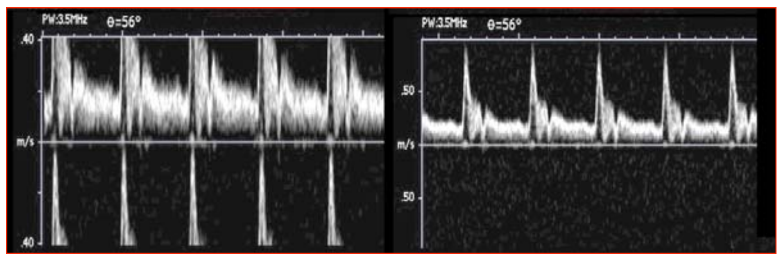
Shallow Sample Volume
different view

With shallow sample volumes, PRF and therefore Nyquist frequency is higher (aliasing less likely)



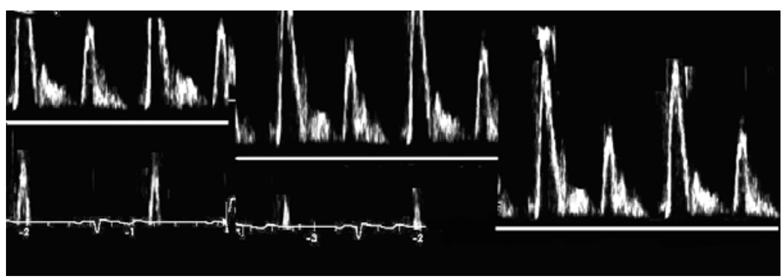
Increase the scale
same view

With greater scale, PRF and therefore Nyquist frequency are higher (aliasing less likely). This can only be accomplished when the system is initially "underdriven."



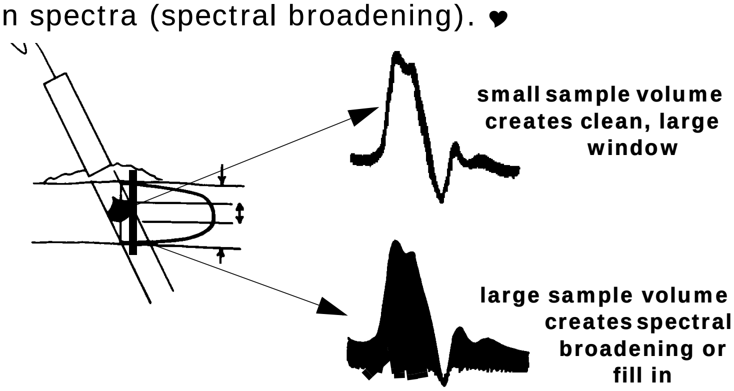
Zero baseline shift

Numbers 1 through 4 actually eliminate aliasing. Number 5, baseline shift simply alters the display.



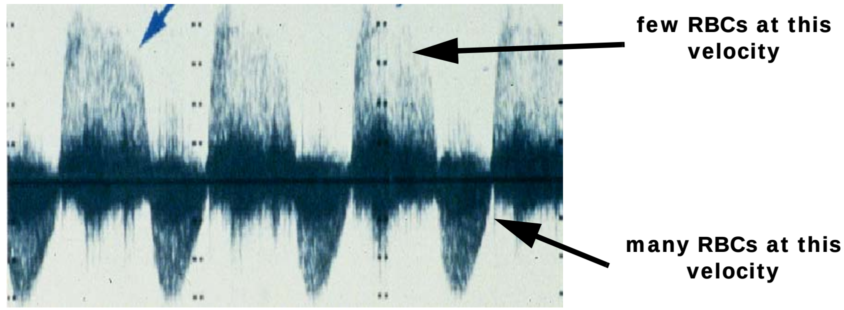
Relationship Between Sample Volume Size and Doppler Spectrum

Smaller sample volumes (gates) create Doppler spectra with cleaner spectral window. ♥
Larger sample volumes (gates) create Doppler spectra with filled-in spectra (spectral broadening). ♥



Gray Shades of a Spectrum

♥Gray shades on a Doppler spectrum are related to:
1) amplitude of the reflected signal or
2) number of red blood cells creating the reflection



Pulsed vs CW Doppler

Pulsed Doppler	Continuous Wave Doppler
minimum of one crystal	minimum of two crystals
range resolution	range ambiguity
limit on maximum velocity (aliasing)	unlimited maximum velocity
uses damped, low Q, wide bandwidth transducer	uses undamped, hi Q, low bandwidth transducer (allows for higher sensitivity to small Doppler shifts)

Imaging vs Doppler

Imaging	Doppler
normal incidence (90°)	0° or 180° incidence (oblique)
higher frequencies - better resolution	lower frequencies - less aliasing
pulsed wave only	pulsed or continuous wave
at least one crystal	one (pulsed) or two (CW) crystals

Color Flow Doppler

Instead of measuring velocities at one location (with pulsed Doppler) or along a single cursor line (with CW Doppler), color flow is a form of 2-D, multigated Doppler. The Doppler shifts are coded into colors and superimposed on a 2-D image.

» black-and-white identifies anatomic structures

» color identifies blood flow velocities and function

Color Doppler is based on **pulsed** ultrasound & is subject to:

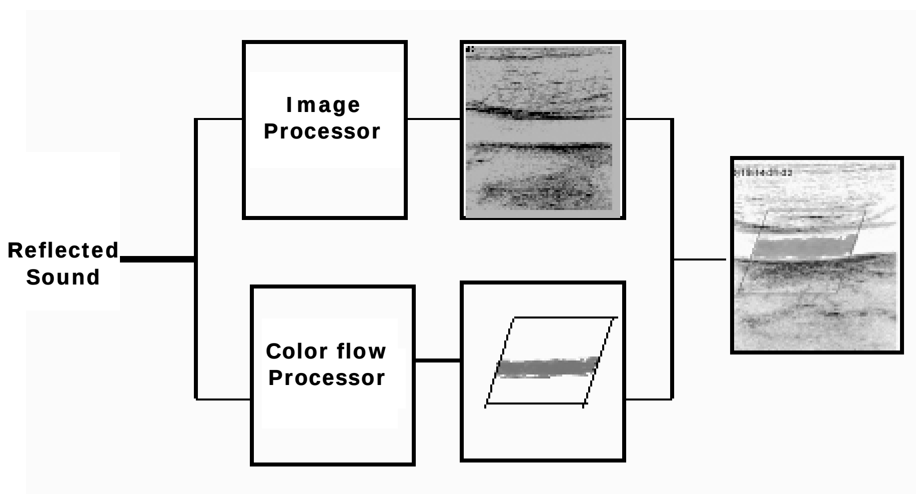
» range resolution or specificity♥

» aliasing ♥

Color Doppler provides information regarding direction of flow. It is semi-quantitative, so knowledge of angle is not especially important.

Average or Mean velocity

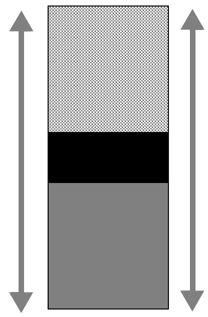
Color Doppler reports **average velocities** (also called **mean velocities**.)♥



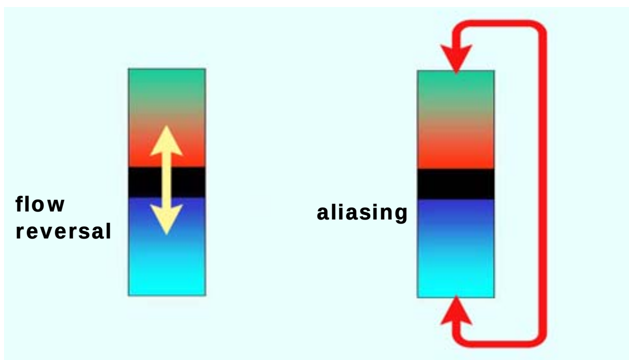
Color Maps

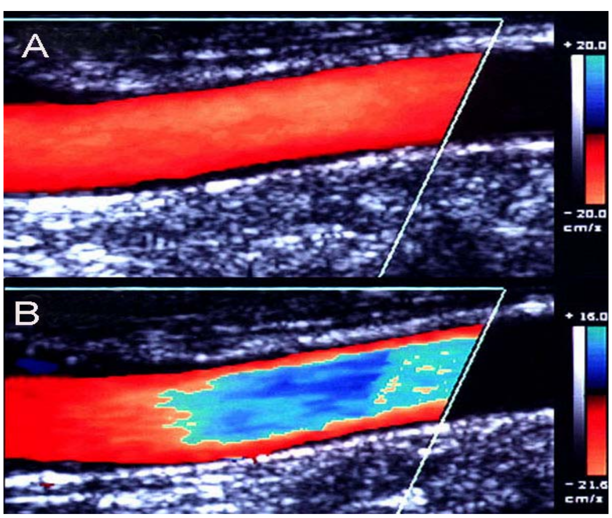
Doppler shifts yield information regarding velocity

Color Doppler uses a "dictionary" or look-up table to convert measured velocities into colors.



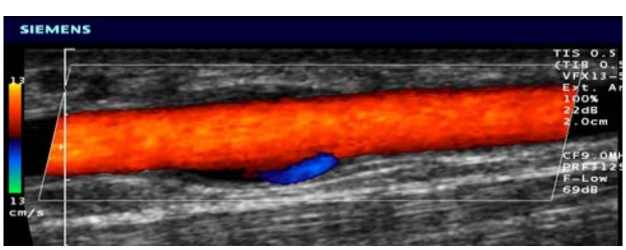
Aliasing - Color Doppler





Vessel A illustrates flow in the 'away color' or red. This indicates flow from the right to the left on the image.

Vessel B illustrates aliasing in the center of the lumen. The colors in the center of the lumen wrap around the extremes of the color map, from red to light blue to dark blue. This transition pattern indicates aliasing.



Aliasing or Flow Reversal? In this image, the color transition within the vessel is from red to black to blue. These colors pass through the center of the map - indicating flow reversal.

Aliasing would have appeared as red to yellow to green to blue.

Doppler Packets

Multiple ultrasound pulses are needed to accurately determine red blood cell velocities by Doppler. A single measurement is not enough.

Packet

These multiple pulses are called a **packet**, or **ensemble length**.

SMALL PACKET	LARGE PACKET
less accurate Doppler	more accurate Doppler
less sensitive to low velocity flow	more sensitive to low velocity flow
higher frame rate, improved temporal resolution	lower frame rate, reduced temporal resolution

The packet size must balance between accurate velocity measurements and temporal resolution. ♥

This is why color Doppler measures "**mean**" velocity! ♥

Hint

Spectral Doppler (pulsed & CW) measures peak velocity.

Color flow measures mean velocity.

Spectral Analysis

An echo returning after striking mass of moving blood cells is a complex signal with many varied Doppler shifted frequencies.

Spectral analysis is performed to extract or identify the individual frequencies making up the complex signal. It is used to interpret individual velocities in the signal.

Current methods

For pulsed or CW Doppler - Fast Fourier Transform (FFT)

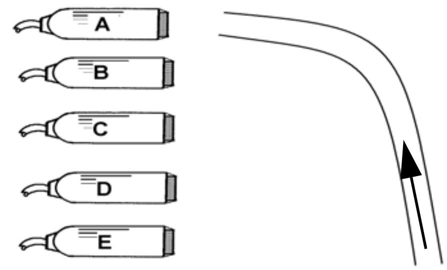
For color flow Doppler - autocorrelation or correlation function. ♥

- Both FFT and autocorrelation are **digital techniques** that are performed by computers.

Autocorrelation is used with color Doppler because of the enormous amount of Doppler information that requires processing. Autocorrelation is slightly less accurate, but substantially faster, than FFT.

know this !

Example:



Questions

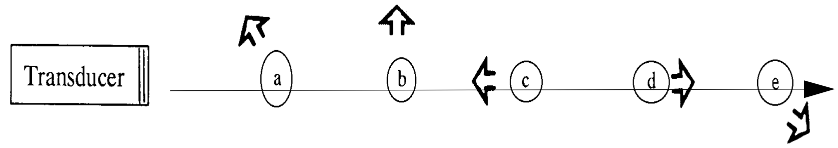
Blood is flowing at a constant velocity in a vessel in the direction of the arrow.

1. Which transducer measures the greatest Doppler shift?
2. Will the Doppler shift be positive or negative?
3. Which transducer measures a reflection with the greatest amplitude?

Answers

1. Transducer A measures the greatest Doppler shift because the angle between the direction of flow and the direction of the sound beam is 0^{o} or parallel.
2. The Doppler shift will be positive since the blood is flowing toward the transducer.
3. Transducer A will receive a reflection with the greatest amplitude since the blood cells are **located closest** to the transducer and therefore undergo less attenuation.

know this too!



The sound beam from the transducer is going to the right. All of the blood cells (RBC) are traveling at 2 m/s in a direction identified by the small arrows.

Questions

1. Are the red blood cells traveling at the same speed?
2. Are the red blood cells traveling at the same velocity?
3. Which RBC produces the maximum negative Doppler shift?
4. Which RBC produces the maximum positive Doppler shift?
5. Which RBC produces a reflection with no Doppler shift?
6. Which two RBCs produce negative Doppler shifts?
7. Which RBC creates a reflection with the highest amplitude?
8. Which RBC creates a reflection with the lowest amplitude?

Answers

1.yes **2.**no **3.**d **4.**c **5.**b **6.**d&e
7. a (it is closest to the transducer)
8. e (it is furthest from the transducer)

Review—Doppler

1. The Doppler effect is presented as a ____ when the source and the receiver are ____.
2. A sound beam is traveling from east to west. Blood is traveling from north to south. Which statement is true?
   a. no Doppler shift will be created
   b. a maximum Doppler shift is created
   c. a minimum Doppler shift is created
   d. the Doppler shift is in the MHz range
3. Starting from the same point, the sound source is moving towards the west at 12 miles/hour and the receiver is moving towards the west at 10 miles/hour. The Doppler shift is ____ (+ or -).
4. Starting from the same point, the receiver is moving towards the west at 12 miles/hour and the source is moving towards the west at 10 miles/hour. The Doppler shift is ____ (+ or -).
5. Doppler shift produces information about ____.
6. At what angle between the sound beam and the direction of motion will the Doppler shift be a maximum?
7. At what angle between the sound beam and the direction of motion will the Doppler shift be a minimum?
8. What is the difference between speed and velocity?
9. What are the current methods of processing spectral and color Doppler signals?
10. What method of processes bidirectional Doppler signals?
11. What is the typical range of Doppler shift found in diagnostic imaging examinations?
12. The phenomenon where high velocities appear negative is called ____.
13. The frequency at which aliasing occurs is called ____.
14. The area of interrogation in a pulsed Doppler exam is called ____.
15. (True or False) The higher the emitted frequency, the more likely a pulsed wave signal is to alias.
16. (True or False) The shallower the sample volume is, the more likely a signal is to alias.
17. (True or False) Only pulsed wave Doppler exams have a sample volume.
18. An 8MHz transducer with a pulse repetition frequency of 5,000 Hz is imaging to a depth of 7cm. What is the Nyquist frequency?
   a. 4MHz
   b. 3.5Hz
   c. 2.2kHz
   d. 2.5dB
19. What feature does pulsed wave Doppler have that continuous wave Doppler does not?

Answers

1. Frequency Shift, In Motion Relative To Each Other.
2. A. This scenario describes normal incidence. There is no Doppler shift with normal incidence.
3. The Doppler shift is Negative because the source and receiver are moving farther apart. Remember, they started at the same point.
4. The Doppler shift is Negative because the source and receiver are moving farther apart. Remember, they started at the same point.
5. Doppler shift produces information about Velocity.
6. 0° Degrees or 180° (The sound beam and the direction of motion should be parallel).
7. 90°. No Doppler frequency exists because the cosine of 90° is zero.
8. Speed has only a magnitude. Velocity has magnitude and direction.
9. The Fast Fourier Transform (FFT) method of spectral analysis for pulsed and CW. Autocorrelation for color flow Doppler.
10. Phase quadrature processing
11. between 20Hz and 20kHz. In the audible range.
12. Aliasing
13. Nyquist limit
14. Sample volume
15. True
16. False
17. True
18. c. The actual Nyquist limit is one-half of the PRF, in this example 2.5kHz or 2,500Hz. In this example, the “perfect” answer does not appear in the choices. In cases such as this, select the answer that is closest to the actual answer
19. Pulsed wave Doppler has a **receive gate that is adjusted** by the sonographer.♥

One Fact Is All We Need

The typical equations in Ultrasound Physics can be simply explained by knowing only one fact. Here it is:

Speed of Sound in soft tissue = 1.54 km/s. This is true for all sound waves.

Other ways to say this are: 1.54 km/s = 1,540 m/s = 154,000 cm/s = 1.54 mm/µs

Aside: Sound travels approximately 1 mile per second in soft tissue. This is a good thing since it allows us to perform real time imaging!

1. What is the wavelength of sound of a specific frequency when the sound is traveling in soft tissue?

We know that the speed of sound in soft tissue may be reported as 1.54 mm/µs.

This means that sound travels 1.54 mm in one-millionth of a second. When the frequency of a sound wave is 1 MHz or one million per second, the period (time of one cycle) is 1 millionth of a second. During that time, sound travels 1/54 mm.

When a cycle takes 1 µs and sound travels 1.54 mm/µs, the wavelength will be 1.54 mm.

$$\frac{1.54\ mm/\mu s}{1\ MHz} = 1.54\ mm$$

What if the frequency is 2 MHz? In soft tissue, sound always travels 1.54 mm/ µs. With 2 MHz sound, 2 cycles occur in 1 µs. $Each\ cycle\ takes$ 0.5 µs. . When a cycle takes 0.5 µs, then the wavelength will be

$$wavelength = 1.54\frac{mm}{\mu s}\ x\ 0.5\ \mu s = 0.77\ mm$$

Another way to present this is

$$\frac{\mathbf{1.54\ mm/\mu s}}{\mathbf{2\ MHz}} = 0.77\ mm$$

What if the frequency is 3 MHz? Sound still travels 1.54 mm/us. With 3 MHz sound, we have 3 cycles in 1 us. When a cycle takes 0.333 us, the wavelength will be

$$wavelength = 1.54\frac{mm}{\mu s}\ x\ 0.333\ \mu s = 0.51\ mm$$

Another way to say this is:

$$\frac{1.54\ mm/\mu s}{3\ MHz} = 0.51\ mm$$

These three examples defines the relationship. Here is the rule:

RULE: In soft tissue,

$$\mathbf{wavelength\ (mm)} = \frac{\mathbf{1.54\ mm/\mu s}}{\mathbf{Frequency\ (MHz)}}$$

Or simply

$$\mathbf{wavelength\ (mm)} = \frac{\mathbf{1.54}}{\mathbf{Frequency}}$$

Example: What is the wavelength of 10 Mhz sound in soft tissue:

$$wavelength = \frac{1.54}{10} = 0.154\ mm$$

In soft tissue, 10 MHz sound has a wavelength of 0.154 mm

Question #2: How long does it take for a sound pulse to travel to and from a reflector that is 1 cm deep? This time is also known as **time-of-flight** or **go-return time**.

Since the sound pulse must travel round-trip, the total distance travelled is 2 cm (to the reflector at a depth of 1 cm and back to the transducer). So, how much time does it take for sound to travel a total of 2 cm?

$$Time = \frac{distance}{speed}$$

Let's make sure the units are correct:

$$Time\ (\mu s) = \frac{distance\ (mm)}{speed\ (\frac{mm}{\mu s})}$$

Let's convert 2 cm into 20 mm.

$$Time\ (\mu s) = \frac{20\ mm}{1.54\ mm/\mu s} = 13\ \mu s$$

This important rule in Ultrasound Physics,

The 13 µs Rule tells us that the time for sound to travel 1 cm round trip is 13 µs.

Example: What is the time-of-flight for a sound pulse to travel to and from a reflector that is 5 cm deep? Using the 13 us rule,

$$Round\ trip\ time(\mu s) = 13\frac{\mu s}{cm} x\ 5\ cm = 65\ \mu s$$

Example: What is the time-of-flight when a reflector is 10 cm deep?

$$Round\ trip\ time(\mu s) = 13\frac{\mu s}{cm} x\ 10\ cm = 130\ \mu s$$

RULE:

$$\boldsymbol{Round\ trip\ time(\mu s) = 13\frac{\mu s}{cm} x\ reflector\ depth\ (cm)}$$

or simply

$$\boldsymbol{Round\ trip\ time(\mu s) = 13\ x\ reflector\ depth\ (cm)}$$

2nd Application of the 13 us Rule: The go-return time a pulse to bottom of an image is called the Pulse Repetition Period (PRP). Only after the PRP has elapsed can an ultrasound system transmit another pulse.

The **13 µs Rule** is used to determine the Pulse Repetition Period (PRP).

Example: What is the PRP when the maximum imaging depth is 5 cm? (In other words, how long does it take a sound pulse to travel to and from the bottom image that is 5 cm deep?

$$PRP\ (\mu s) = 13\frac{\mu s}{cm} x\ 5\ cm = 65\ \mu s$$

Example: What is the PRP when the maximum imaging depth is 10 cm? (In other words, how long does it take a sound pulse to travel to and from the bottom image that is 10 cm deep?

$$PRP\ (\mu s) = 13\frac{\mu s}{cm} x\ 10\ cm = 130\ \mu s$$

RULE:

$$\boldsymbol{Pulse\ Repetition\ Period(\mu s) = 13\frac{\mu s}{cm} x\ image\ depth\ (cm)}$$

or simply

$$\boldsymbol{Pulse\ Repetition\ Period(\mu s) = 13\ x\ reflector\ depth\ (cm)}$$

Question #2: How many pulses can a system create each second?

If we consider that sound travels to and from the transducer to a reflecting object, then sound can travel round trip to a depth of 77,000 cm and back in one second. 77,000 cm to the reflector and 77,000 back to the skin, a total of 154,000 cm

Of course, this is a silly statement, however the concept is important. Let's proceed.

First, a definition PRF (pulse repetition frequency) = the number of sound pulses created each second.

What is the PRF when we image to a depth of 77,000 cm? (I know, it's silly)

$$PRF\ (Hz)\ = \frac{77{,}000\,\frac{cm}{s}}{imaging\ depth\ (cm)}$$

$$PRF\ (Hz)\ = \frac{77{,}000\,\frac{cm}{s}}{77{,}000\ (cm)} = 1\ Hz$$

What is the PRF when we image to a depth of 7 cm?

$$PRF\ (Hz)\ = \frac{77{,}000\,\frac{cm}{s}}{imaging\ depth\ (cm)}$$

$$PRF\ (Hz)\ = \frac{77{,}000\,\frac{cm}{s}}{7\ cm} = 11{,}000\ Hz$$

An ultrasound system imaging to a depth of 7 cm produces 11,000 pulses per second.

What is the PRF when we image to a depth of 10 cm?

$$PRF\ (Hz)\ = \frac{77{,}000\,\frac{cm}{s}}{imaging\ depth\ (cm)}$$

$$PRF\ (Hz)\ = \frac{77{,}000\,\frac{cm}{s}}{10\ cm} = 7{,}700\ Hz$$

An ultrasound system imaging to a depth of 10 cm produces 7,700 pulses per second.

RULE:

$$\boldsymbol{PRF\ (Hz)\ = \frac{77,000\,\frac{cm}{s}}{imaging\ depth\ (cm)}}$$

or simply:

$$\boldsymbol{PRF\ (Hz)\ = \frac{77,000}{imaging\ depth\ (cm)}}$$

This is very important in Pulsed Doppler!

EXTRA CREDIT:

PRP and PRF are reciprocals. In other words, when multiplied together, the result is 1 (a unitless number)

Let's try that:

$$PRF \quad X \quad PRP \quad = 1$$

$$\frac{77{,}000\frac{cm}{s}}{imaging\ depth\ (cm)}\ X\ \left(13\,\frac{\mu s}{cm}\,x\ imaging\ depth\ (cm)\right) = 1$$

The imaging depth terms cancel each other since one is in the numerator while the other is in the denominator

$$\frac{77{,}000\frac{cm}{s}}{\cancel{imaging\ depth\ (cm)}}\ X\ \left(13\,\frac{\mu s}{cm}\,x\ \cancel{imaging\ depth\ (cm)}\right) = 1$$

This leaves: $$77{,}000\,\frac{cm}{s}\quad X\quad 13\,\frac{\mu s}{cm} = 1$$

The units of cm cancel each other out since one is in the numerator while the other is in the denominator

$$\frac{77{,}000}{s}\ X\ \ 13\ \mu s = 1$$

Now, lets convert 13 µs to seconds. 13 µs = 0.000013 seconds

$$\frac{77{,}000}{s}\ X\ \ 0.000013\ s\ \ = 1$$

The units of S cancel each other out since one is in the numerator while the other is in the denominator. Thus, all of the units have been cancelled. Perform the multiplication:

$$77{,}000\ \ X\ \ 0.000013\ \ =\ \ 1$$

$$1 = 1$$

All of this is true!

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The Bare Minimum. If you're concerned only about the equations, know these:

$$\mathbf{wavelength\ (mm)} = \frac{\mathbf{1.54}}{\mathbf{Frequency\ (MHz)}}$$

$$\boldsymbol{Round\ trip\ time}(\mu \boldsymbol{s}) = \mathbf{13}\ \boldsymbol{x}\ \boldsymbol{reflector\ depth}\ (\boldsymbol{cm})$$

$$\boldsymbol{Pulse\ Repetition\ Period}(\mu \boldsymbol{s}) = \mathbf{13}\ \boldsymbol{x}\ \boldsymbol{reflector\ depth}\ (\boldsymbol{cm})$$

$$\boldsymbol{PRF}\ (\boldsymbol{Hz}) = \frac{\mathbf{77,000}}{\boldsymbol{imaging\ depth}\ (\boldsymbol{cm})}$$