Eco-Doppler

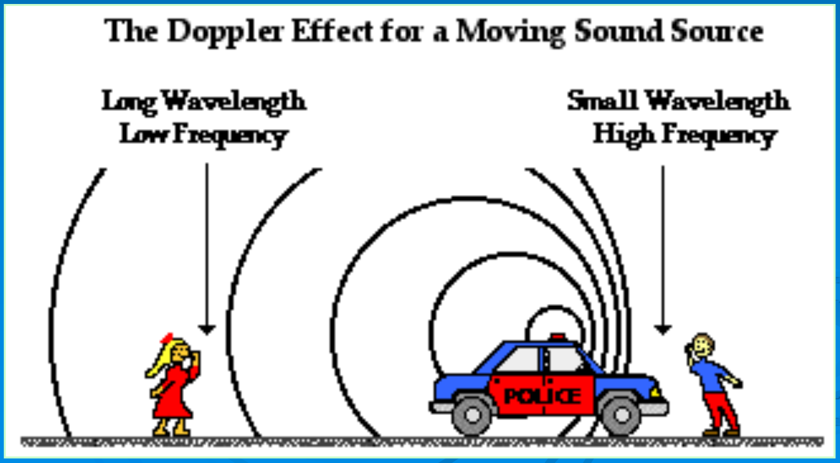
✓Ultrasound (US) is a relatively inexpensive, portable, safe, and real-time modality, all of which make it one of the most widely used imaging modalities in medicine

✓In addition, the Doppler effect is used to make quantitative measurements of absolute blood velocity and to map blood flow over a large field of view (FOV) in a semiquantitative manner

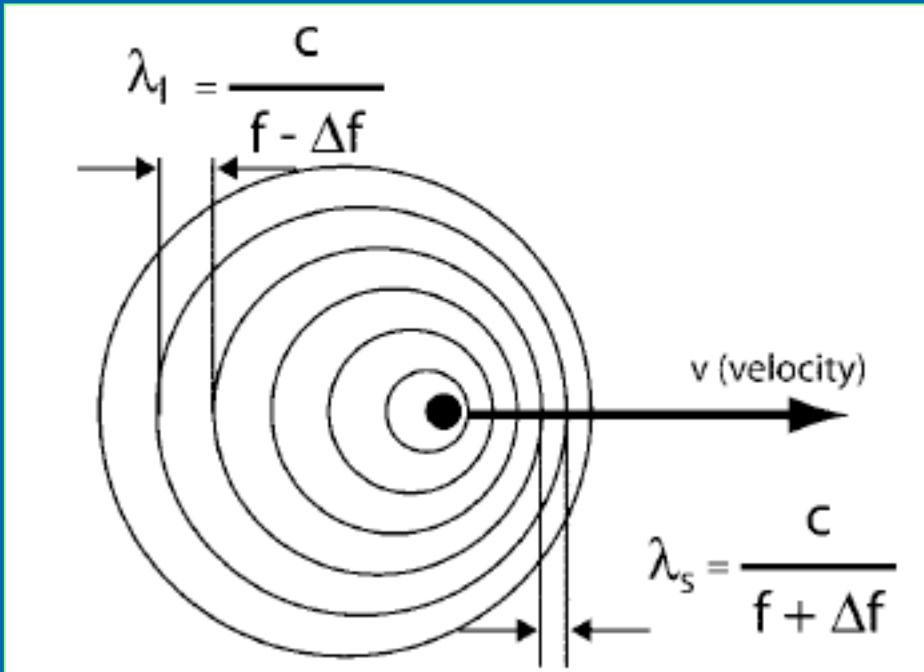
N.J. Hangiandreou RadioGraphics 2003; 23:1019–1033

Doppler effect

- The Doppler effect produced with US to determine whether flow is present
  - It has been used in medicine for ~ 50 years
- The underlying physics of the Doppler effect is simple
- Instrumentation and how the information is applied for diagnosis can be complex
  - involves a number of assumptions



Doppler effect



$$\lambda_1 = \frac{c+v}{f} = \frac{c}{f-\Delta f}$$

$$\lambda_s = \frac{c-v}{f} = \frac{c}{f+\Delta f}$$

These equations apply to the specific condition that the object is traveling either directly toward or directly away from the observer

c = speed of sound propagation
v = velocity of the moving object
f = frequency of the sound
λ_l λ_s wavelengths lengthened or shortened
Δf = Doppler effect– induced frequency shift

E.J.Boote RadioGraphics 2003; 23:1315-1327

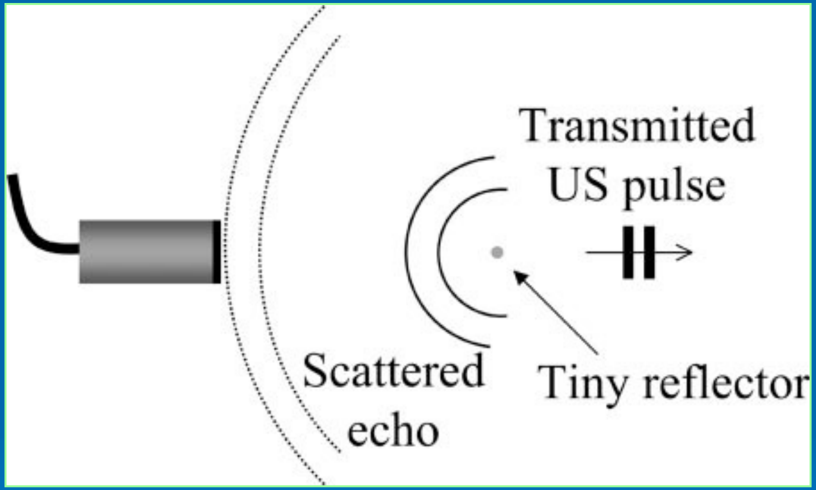
Doppler effect blood flow

US scattering back from moving objects

- Eg: red blood cells

I. Doppler effect with the sound arriving at the moving scattering object

II. Doppler effect as the sound is reflected from that object back toward the US transducer

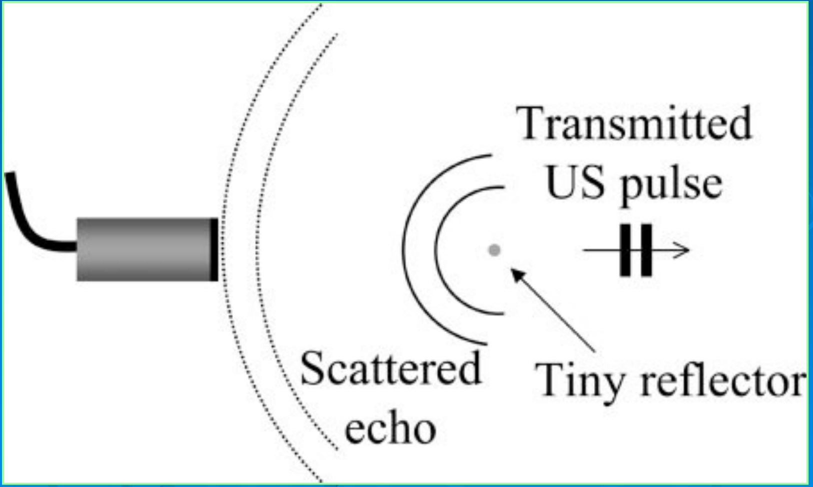


Doppler effect blood flow

- US scattering back from red blood cells
  - c= 1540 m/s
  - f_0 frequency of sound produced in a transducer,
    - propagating toward a red blood cell
  - v_{RBC} velocity of the red blood cell
  - f_{RBC} frequency of the sound as it is perceived by the red blood cell

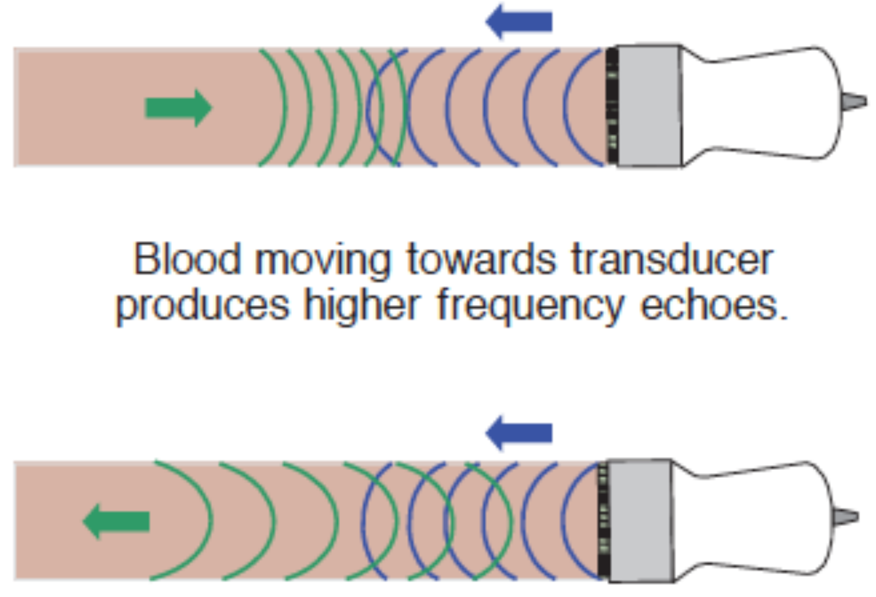
$$f_0 = \frac{c}{\lambda_0} \rightarrow \lambda_0 = \frac{c}{f_0}.$$

$$f_{RBC} = \frac{c + v_{RBC}}{\lambda_0} = f_0 + \frac{v_{RBC}}{\lambda_0}$$



Frequency returning back I

$$f' = f_{\mathrm{RBC}} + \frac{v_{\mathrm{RBC}}}{\lambda_{\mathrm{RBC}}} = f_0 + \frac{v_{\mathrm{RBC}}}{\lambda_0} + \frac{v_{\mathrm{RBC}}}{\lambda_{\mathrm{RBC}}}$$



Blood moving towards transducer produces higher frequency echoes.

Blood moving away from transducer produces lower frequency echoes.

- **The frequency of sound arriving back at the transducer (f') is shifted again in proportion to the v_{RBC}**
  - $\lambda_{RBC}=c/f_{RCB}$

Frequency returning back II

f' in terms of

- v_{RBC}
- f_0 the original frequency
- c the speed of sound

$$f' = f_0 + \frac{v_{RBC}}{\lambda_0} + \frac{v_{RBC}}{\lambda_{RBC}}$$

$$= f_0 + \frac{v_{RBC} f_0}{c} + \frac{v_{RBC} f_{RBC}}{c}$$

$$= f_0 + \left(\frac{v_{RBC}}{c}\right)(f_0 + f_{RBC})$$

$$= f_0 + \left(\frac{v_{RBC}}{c}\right)\left(f_0 + f_0 + \frac{v_{RBC}}{\lambda_0}\right)$$

$$= f_0 + \left(\frac{v_{RBC}}{c}\right)\left(2 \cdot f_0 + \frac{v_{RBC} f_0}{c}\right)$$

$$= f_0 + 2f_0\left(\frac{v_{RBC}}{c}\right) + f_0\left(\frac{v_{RBC}}{c}\right)^2.$$

Doppler shift frequency

$$f_D = f' - f_0$$
$$= f_0 + 2f_0\left(\frac{v_{RBC}}{c}\right) + f_0\left(\frac{v_{RBC}}{c}\right)^2 - f_0$$
$$= \frac{2f_0 v_{RBC}}{c} + f_0\left(\frac{v_{RBC}}{c}\right)^2.$$

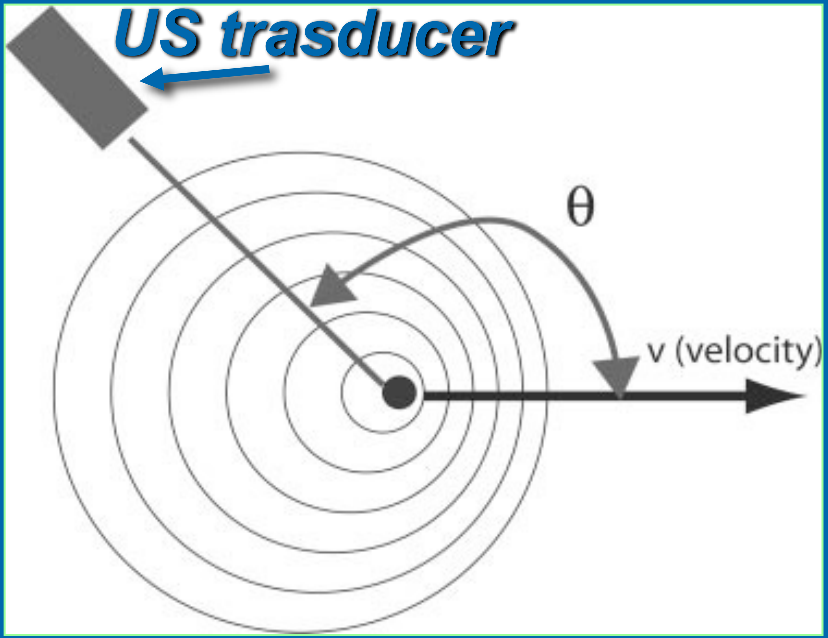
Since $v_{RBC} << c$

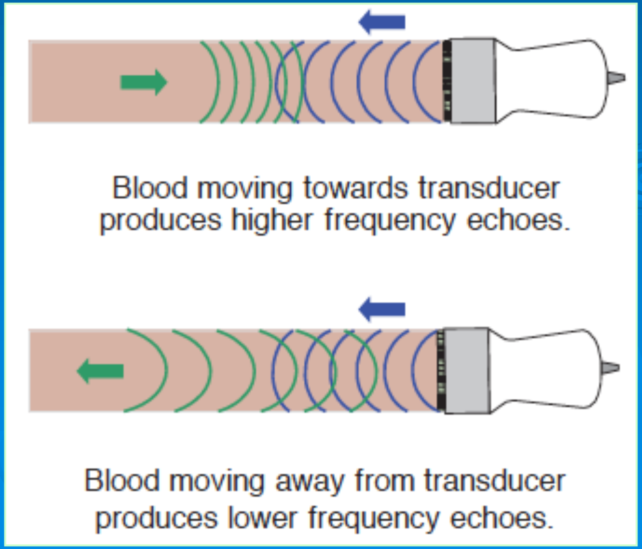
$$f_D \cong \frac{2f_0 v_{RBC}}{c}$$

$v_{RBC} \sim 0.1\%$ c

General geometry

- The relative velocity between the RBC and the transducer is dependent on the angle of the line down which the US is traveling and the direction of the RBC motion
  - If the RBC were traveling directly toward the transducer the relative velocity would be at a maximum
    - or the negative maximum

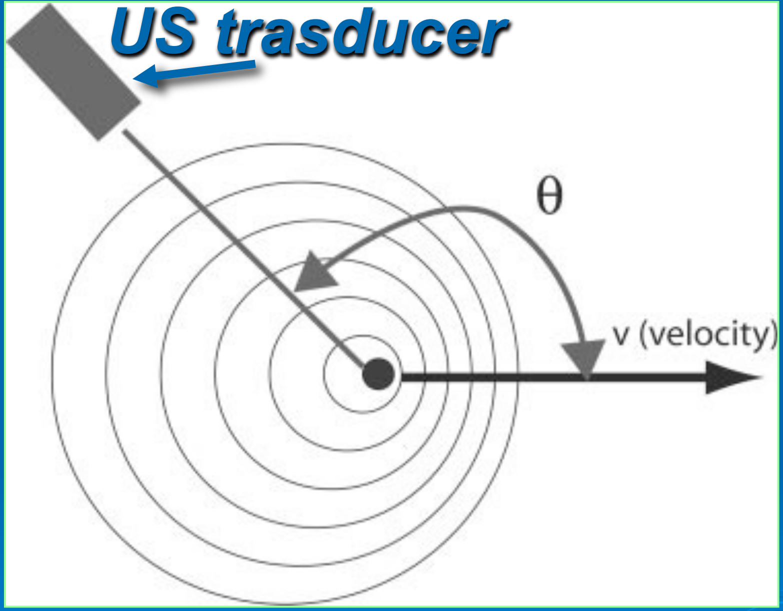




General geometry

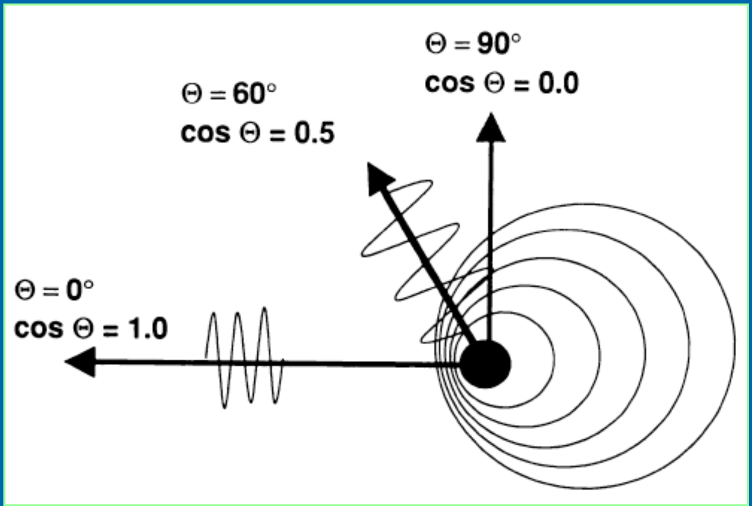
$$f_D = \Delta f = \frac{2 \cdot f_0 \cdot v_r}{c} = \frac{2 \cdot f_0 \cdot v_{RBC} \cdot \cos\theta}{c}$$

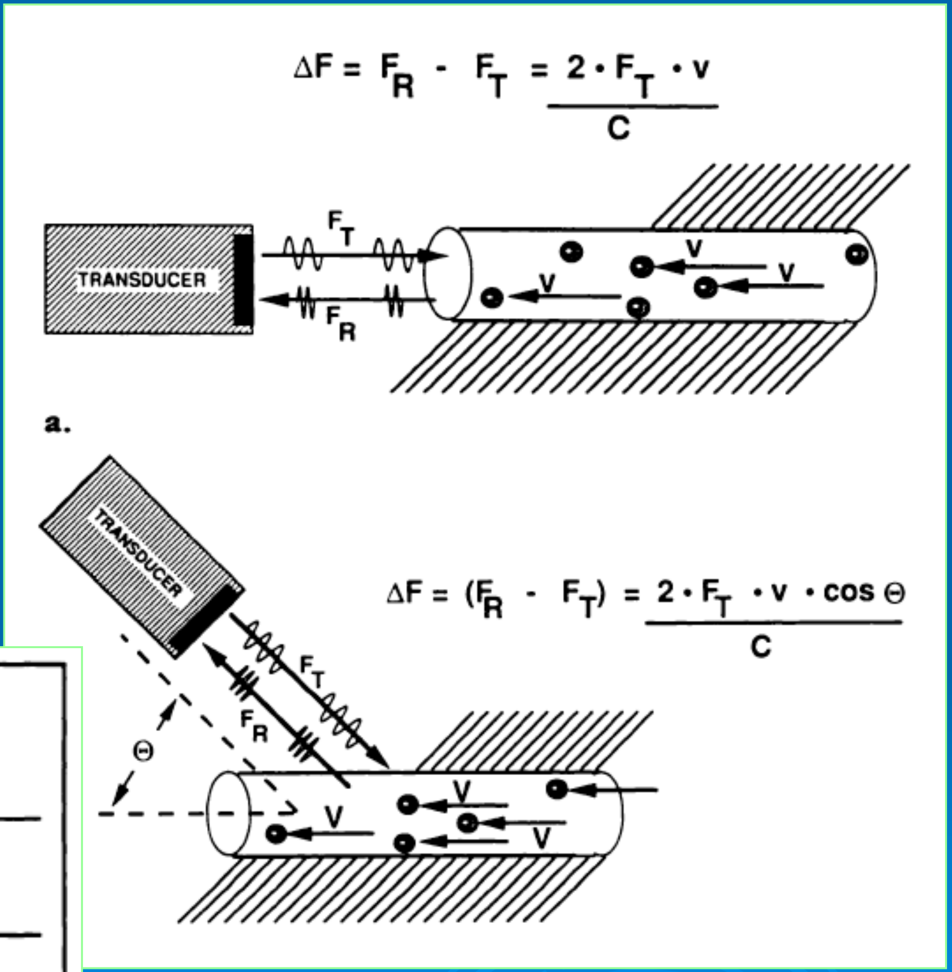
$$v_{RBC} = \frac{f_D}{f_0} \cdot \frac{c}{2 \cdot \cos\theta} = \left(\frac{f' - f_0}{f_0}\right) \cdot \frac{c}{2 \cdot \cos\theta}$$



- v_{RBC} is estimated by Δf, f_0 and $\cos\theta$
- v_r relative velocity between the RBC and the transducer

General geometry





The frequency shift is in the audible range: 15 Hz to 20 kHz

Table 1
Doppler Frequency Shifts (kHz) for a Target Moving 1.00 m/sec

	Scanning Angles			
F_T (kHz)	0°	45°	60°	80°
2.0	2.6	1.8	1.3	0.5
2.5	3.2	2.3	1.6	0.6
3.0	3.9	2.8	1.9	0.7
5.0	6.5	4.6	3.2	1.1
7.5	9.7	6.8	4.9	1.6

C.R.B. Merritt

RadioGraphics 1991; 11:109-119

Doppler US

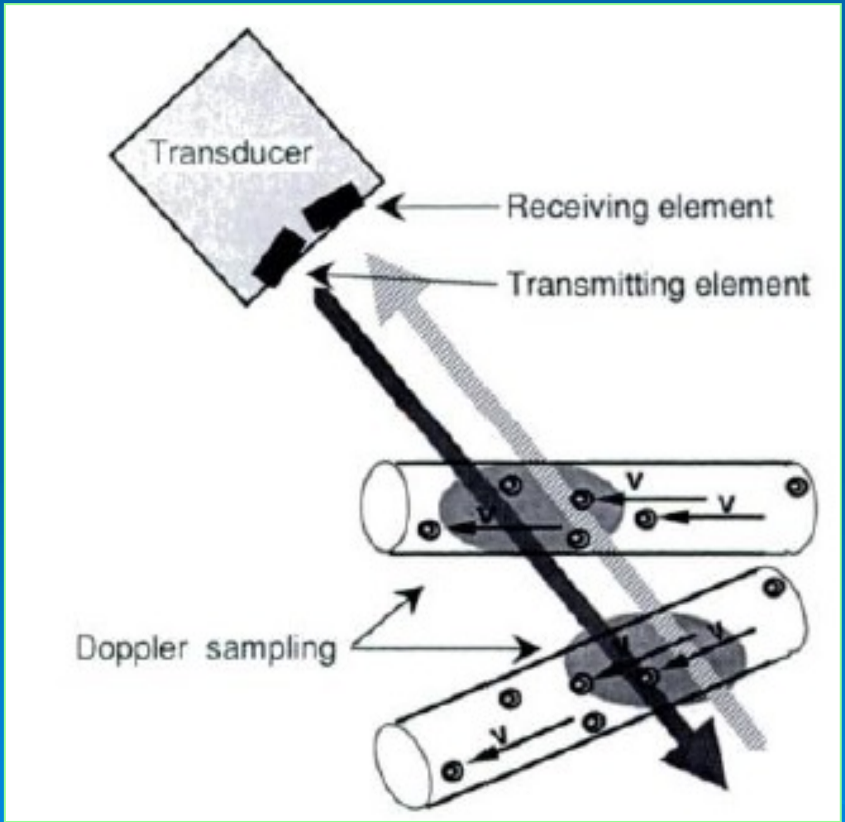
Limitations in clinical practice:

- the geometry of the blood vessel and the ultrasound beam
- varying blood flow velocities across the vessel lumen
- the variation of blood flow velocity with the cardiac cycle

Compromises are used to achieve an efficient measurement of blood velocity that can be resolved in both time and space

https://www.youtube.com/watch?v=9nzkF0hmy04

Basic Doppler US Technology
Continuous-wave Doppler US



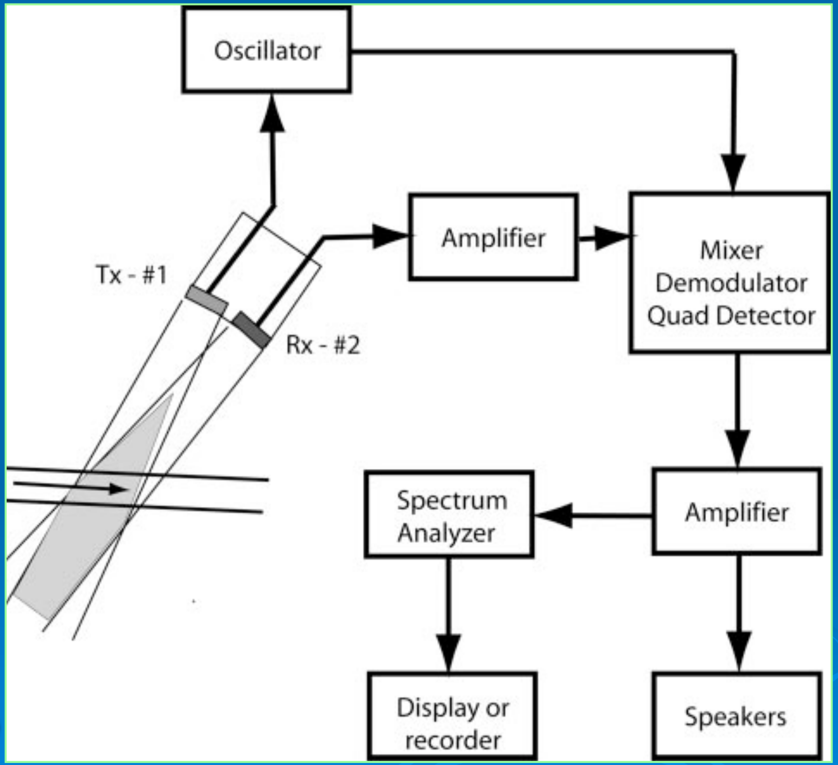
Continuous wave:

- sound is emitted from a transmitting transducer 100% of the time
- echoes back must be detected by a second receiving transducer

The continuous wave Doppler system is the simplest and least expensive device for measuring blood velocity

Basic Doppler US Technology Continuous-wave Doppler US

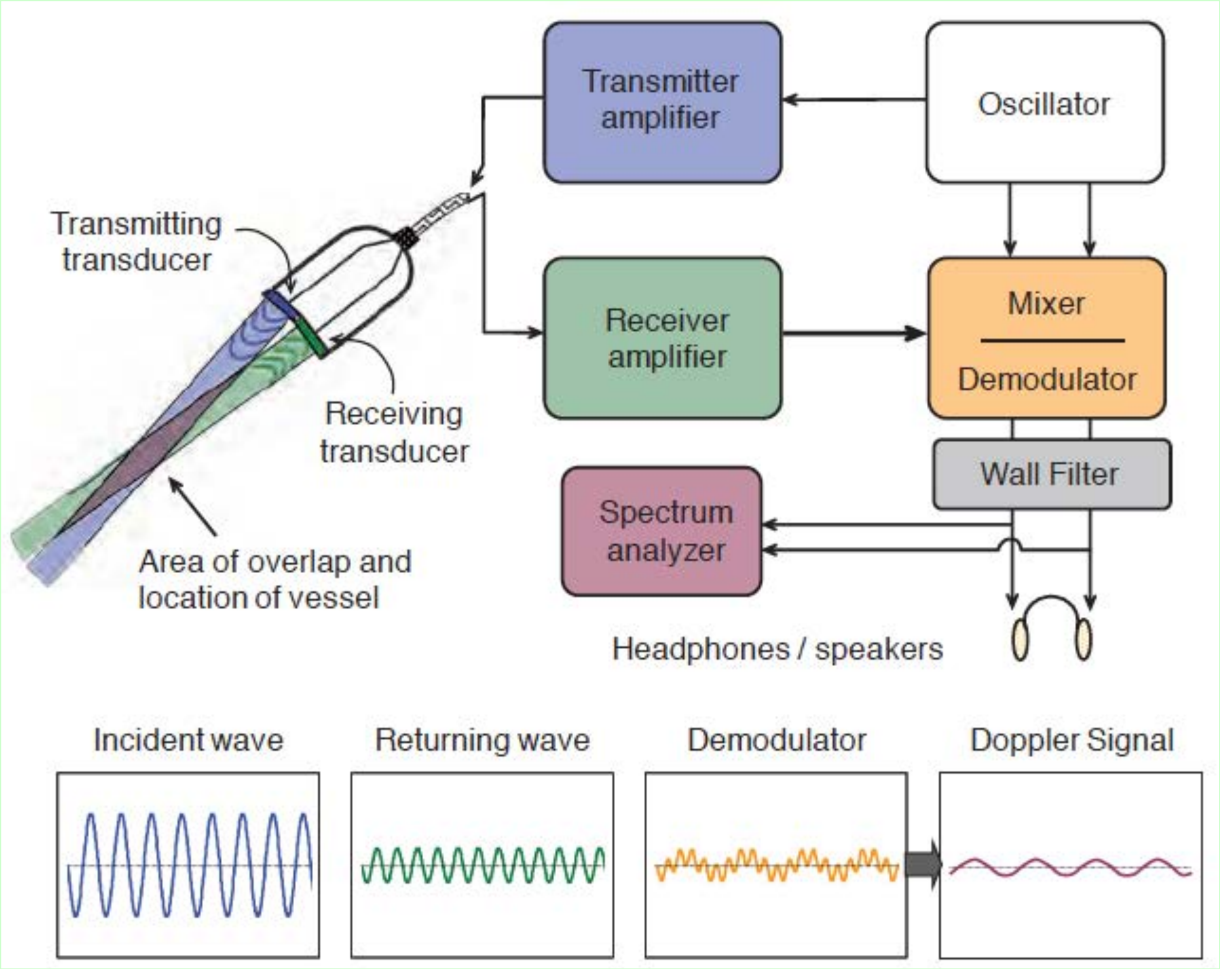
- **Transducer #1:** continuous sound source
- **Transducer #2:** backscattered sound detector
- **Analysis circuit:** the outgoing signal frequency is compared with the returning signal to determine the shift in frequency



Basic Doppler US Technology Continuous-wave Doppler US

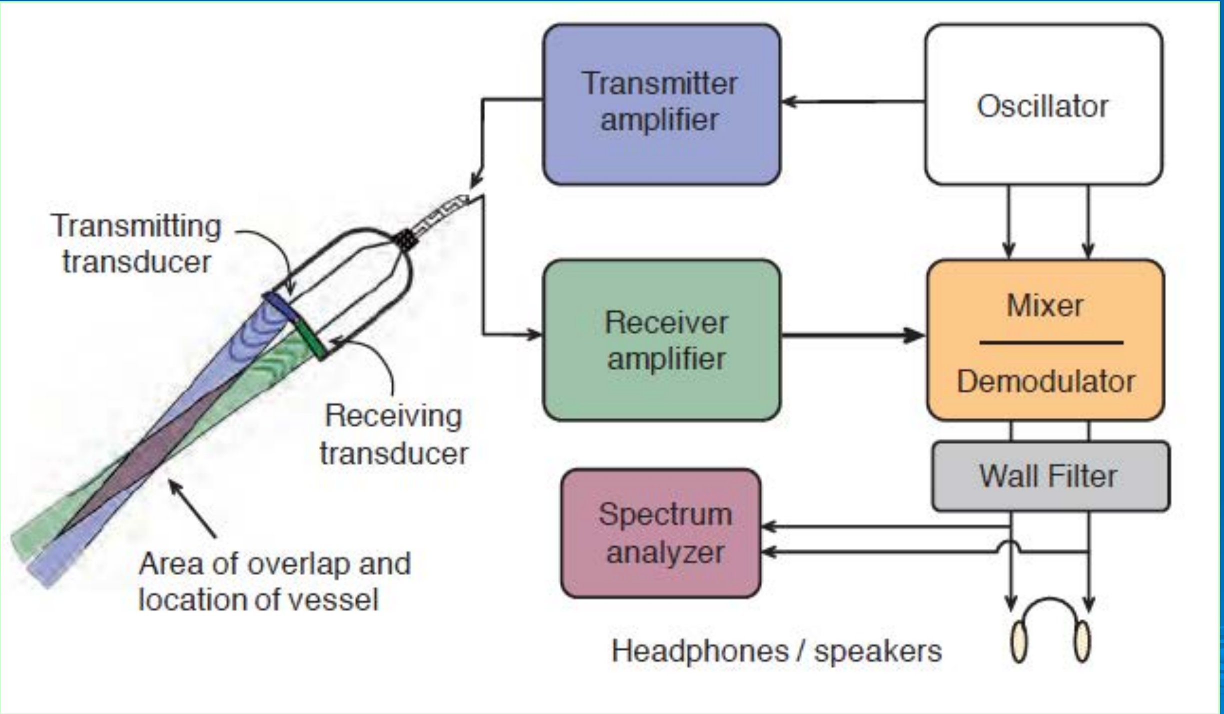
Signals comparison by mixing the transmitted with the incoming signal then filtering out the high-frequency result

- mixing-demodulation



Continuous-wave Doppler US

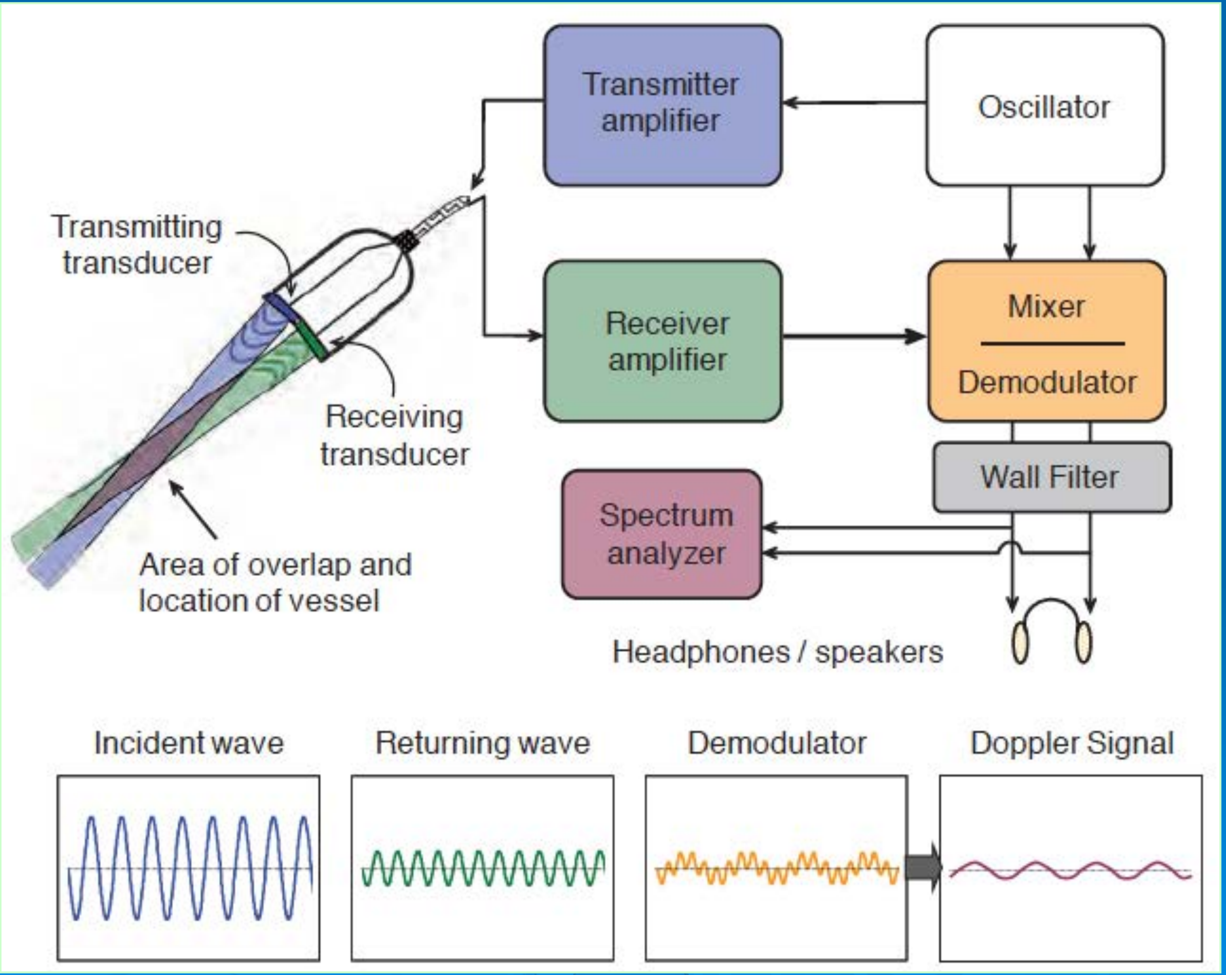
- Continuous wave Doppler suffers from depth selectivity
- Overlying vessels will result in superimposition



Continuous-wave Doppler US

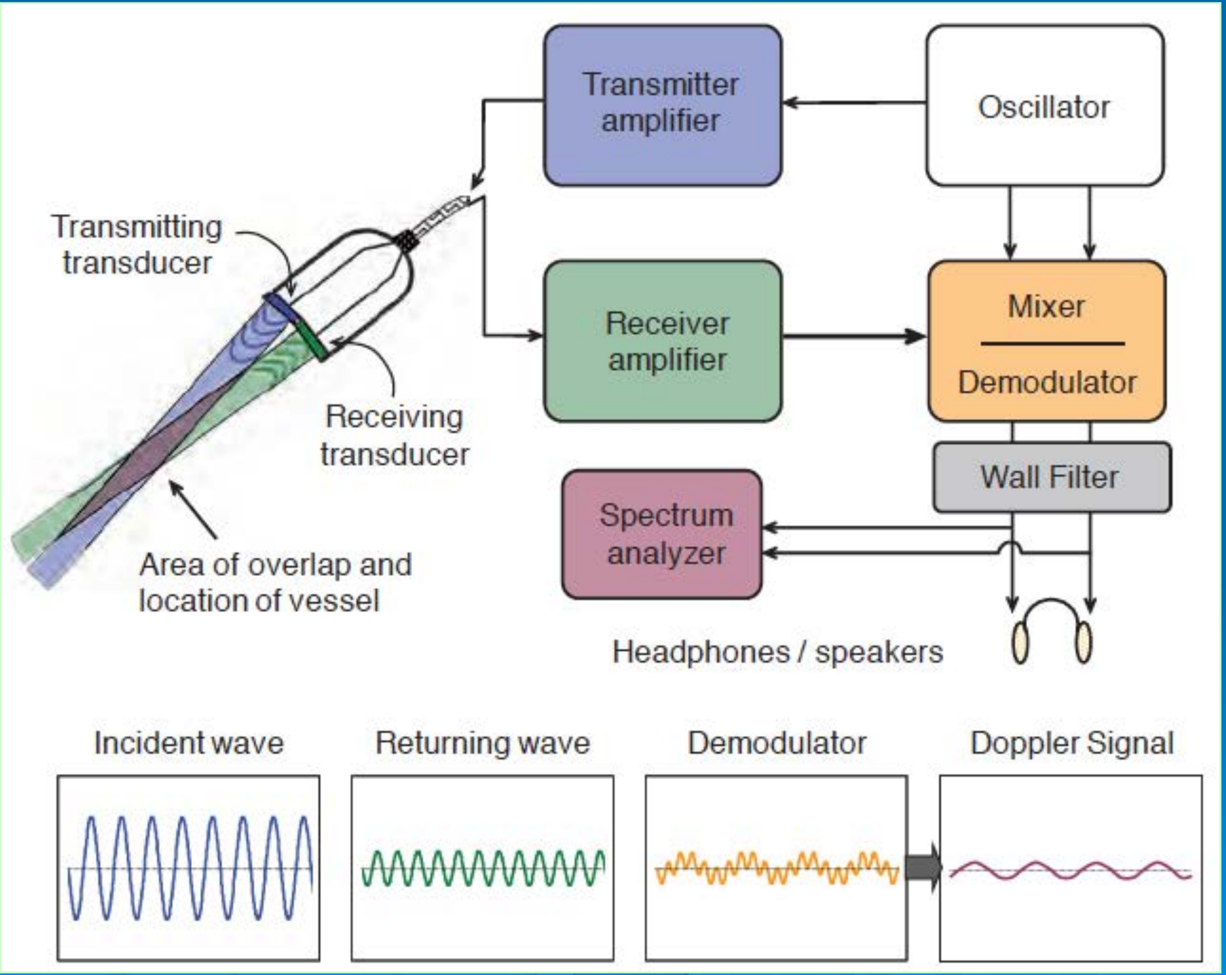
Advantages:

- high accuracy of the Doppler shift measurement because a narrow frequency bandwidth is used
  - no aliasing when high velocities are measured



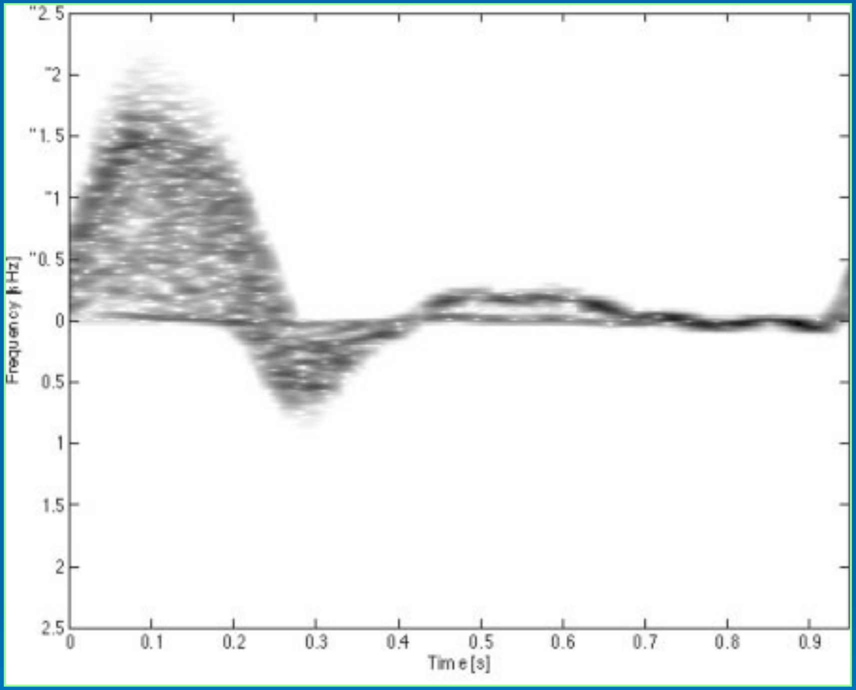
Continuous-wave Doppler US Quadrature detection

- The demodulation technique measures the magnitude but does not reveal the direction of the Doppler shift
  - flow toward or away from the transducers
- Quadrature detection technique is phase sensitive and indicates the direction of flow



Frequency Content

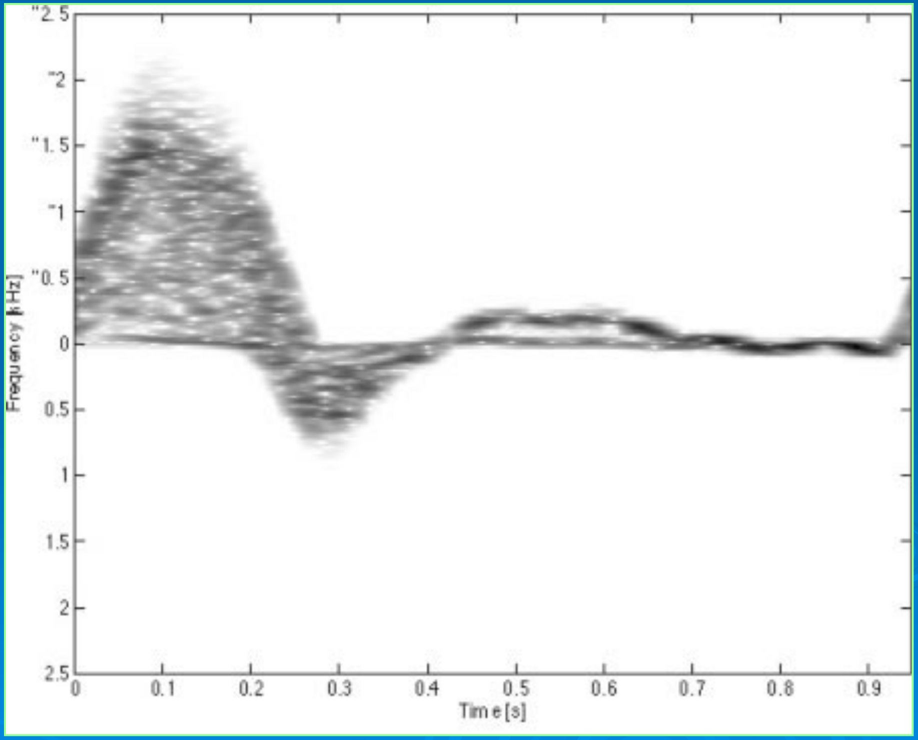
- The Doppler shifted frequencies returned from a vessel are not of a single frequency
- A range of frequencies corresponding to a range of blood flow velocities is present in the backscattered signal
  - spectral broadening
  - frequencies range vary over time and the duration of the cardiac cycle



Frequency Content

Doppler frequency spectrum

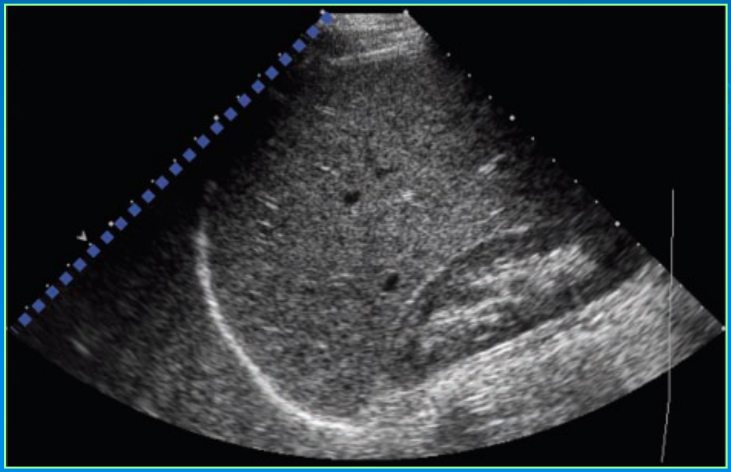
- Time along the x axis and Doppler shift frequencies along the y axis
  - expressed in units of velocity
- The relative intensities of Doppler shift frequencies are depicted by using varying gray scales



Pulsed wave Doppler US

- In continuous-wave Doppler US no image formation
- Pulsed Doppler US combines the velocity determination of continuous wave Doppler systems and the range discrimination of pulse-echo imaging
  - Bright mode

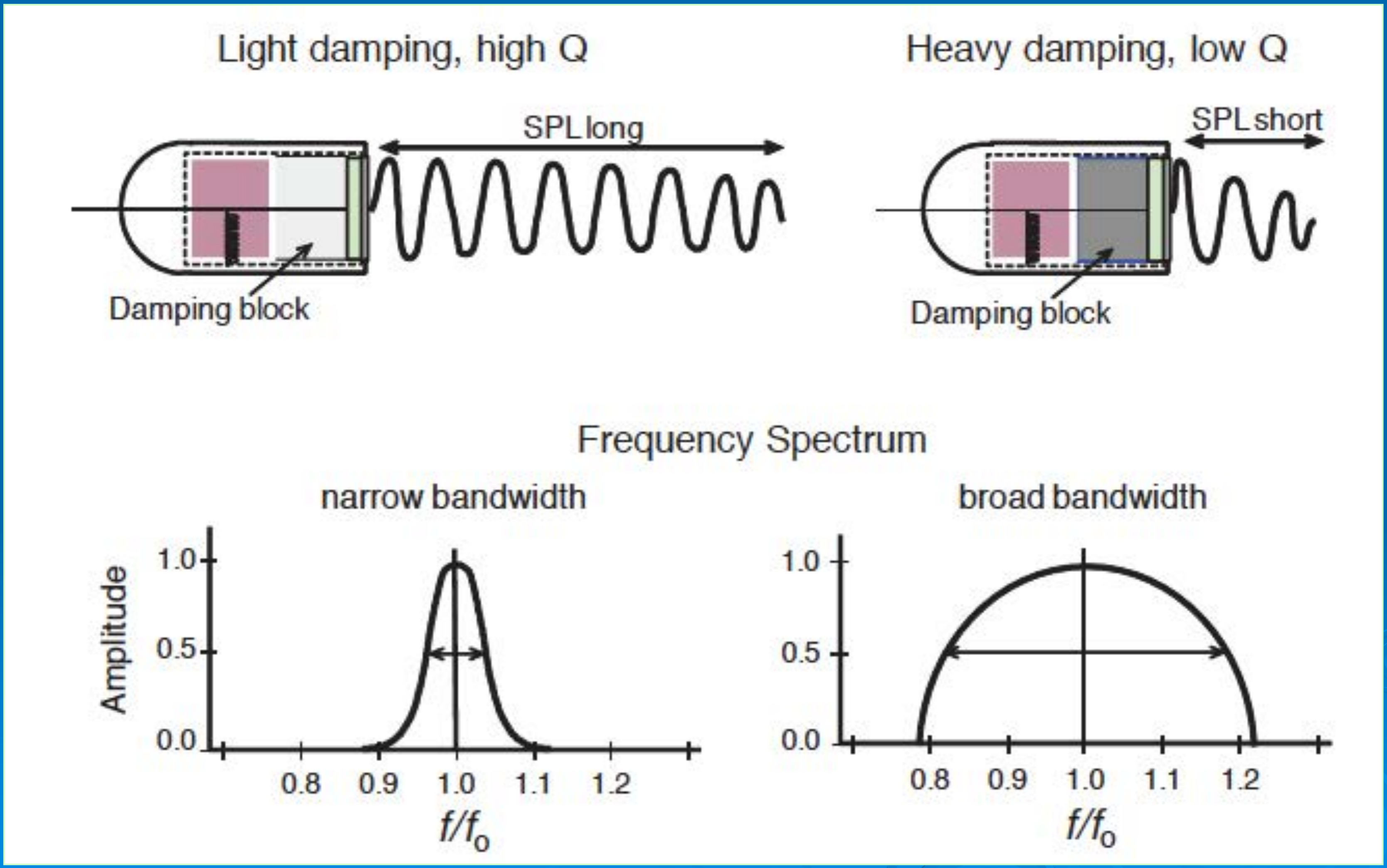
$$t_{\text{echo}} = \frac{2 \cdot d_{\text{object}}}{c} \Rightarrow d_{\text{object}} = \frac{t_{\text{echo}} \cdot c}{2}$$



Pulsed wave Doppler US

- A transducer tuned for pulsed Doppler operation is used in a pulse-echo format
  - similar to imaging
- The SPL is longer to provide a higher Q factor and improve the measurement accuracy of the frequency shift
  - SPL spatial pulse lengh
  - a minimum of 5 cycles per pulse up to 25 cycles per pulse
    - at the expense of axial resolution

Damping and Q factor

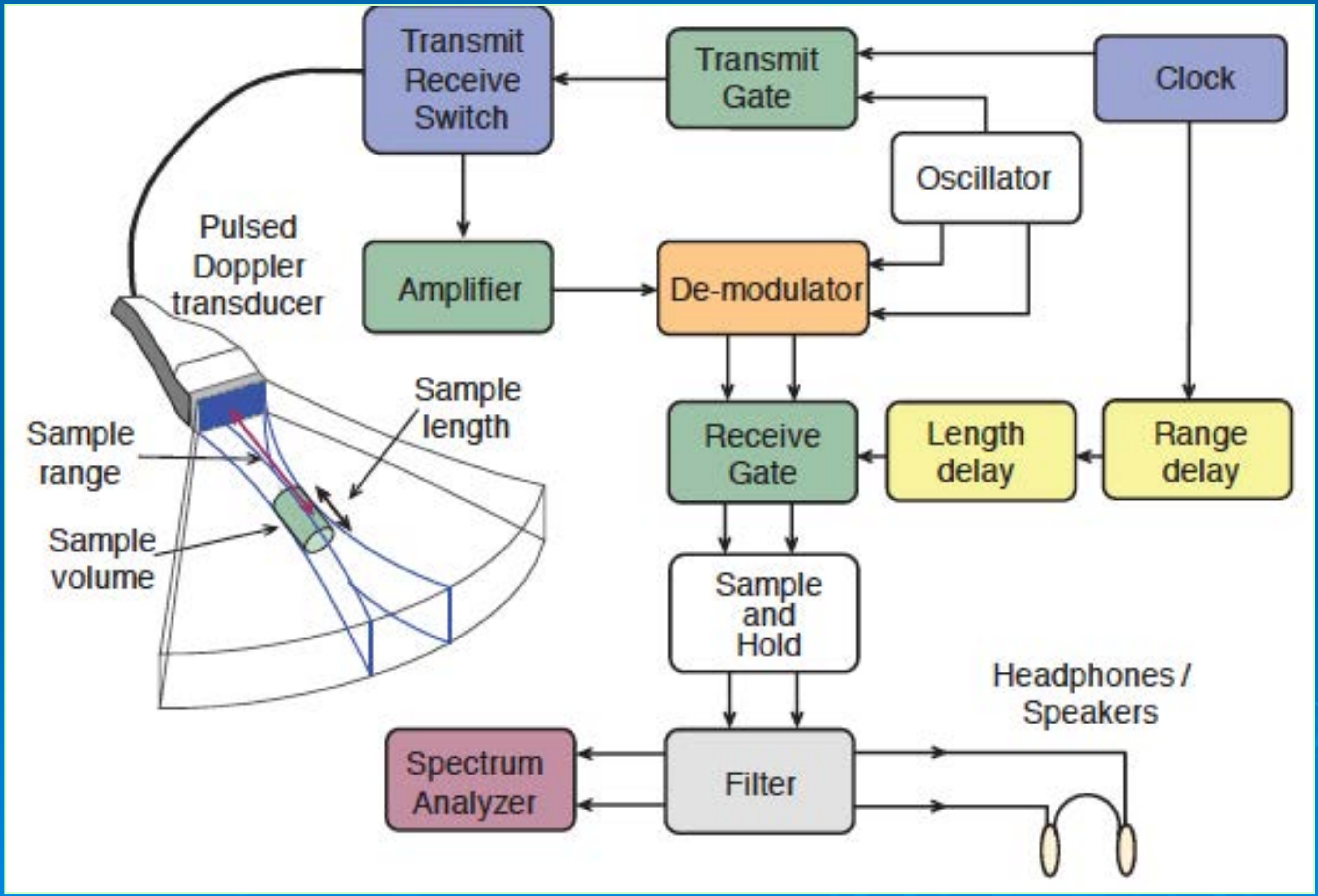


low Q does not imply poor quality in the signal

Pulsed wave Doppler US

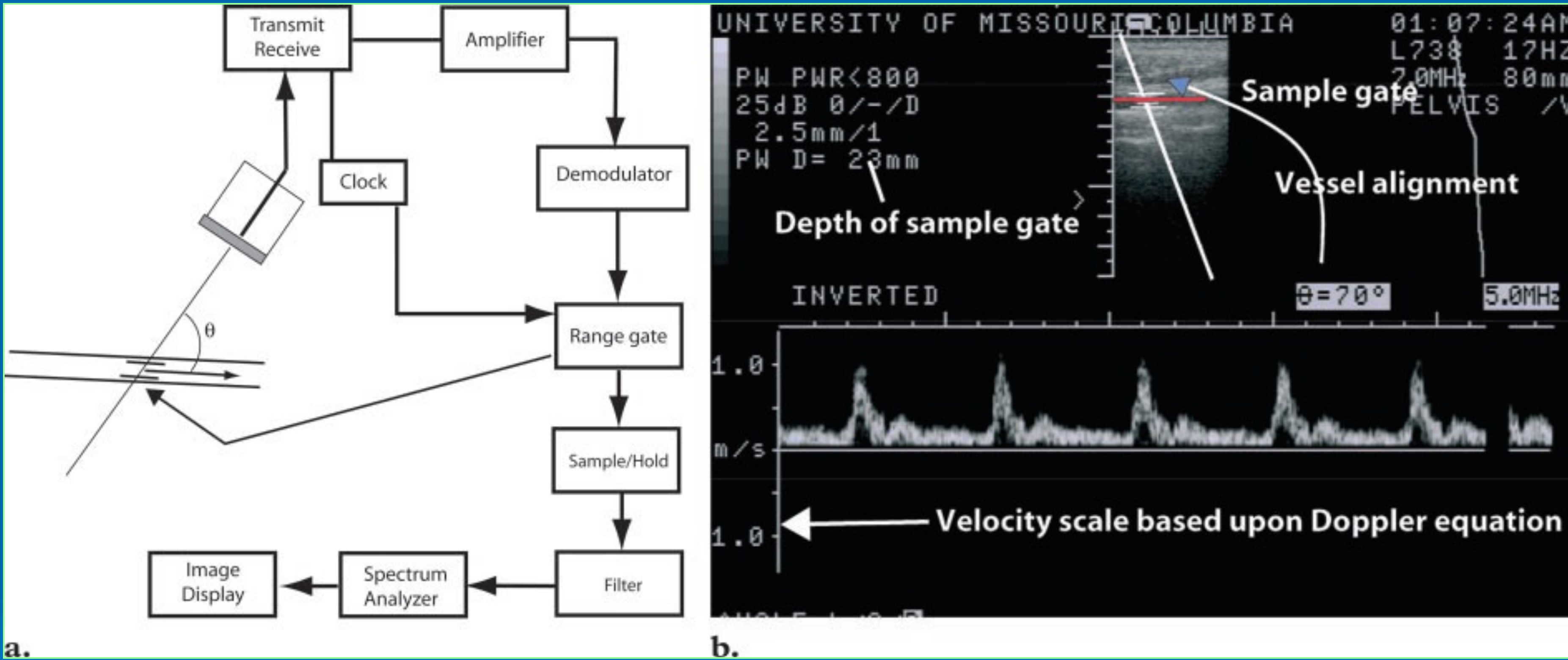
Depth selection is achieved with a time gate to reject all echo signals except those falling within the gate window

- **Determined by the operator**



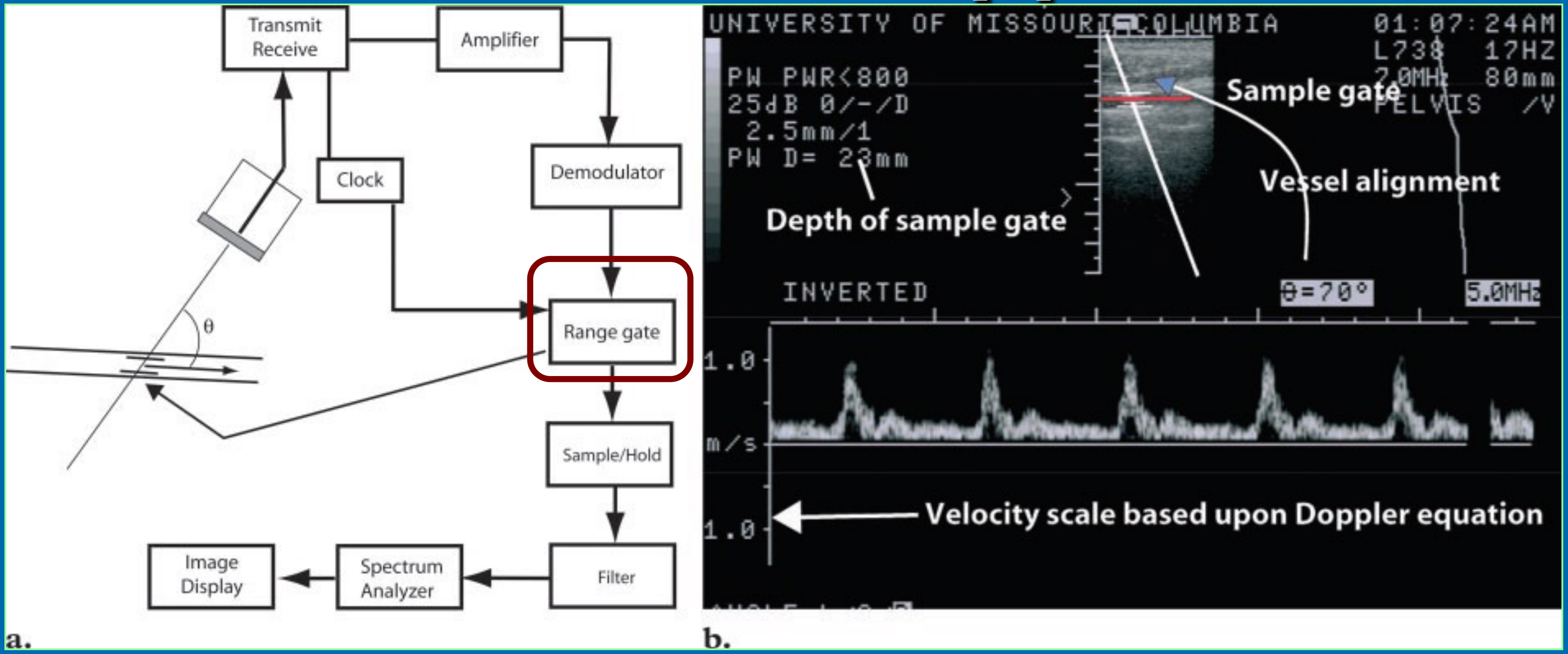
https://www.youtube.com/watch?v=tQn8jKtwk6o

Pulsed wave Doppler US



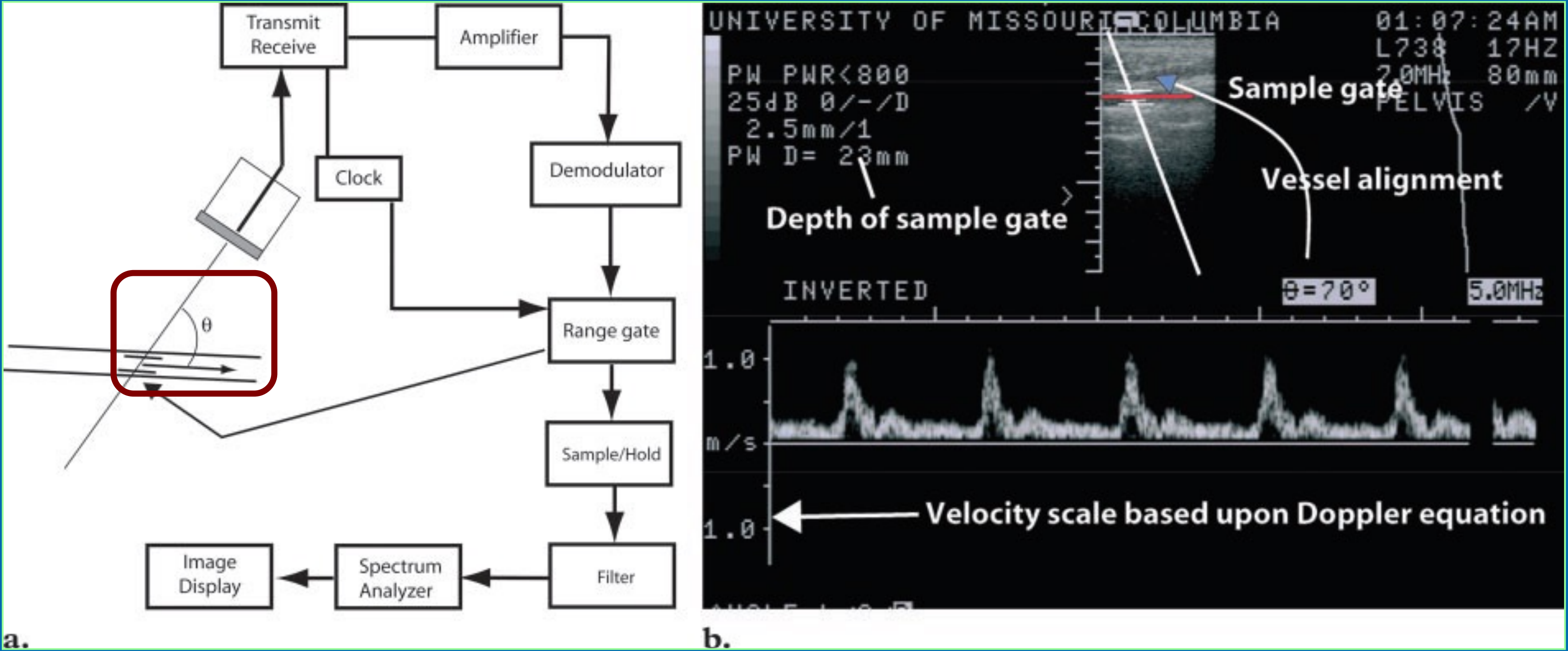
a. **A single transducer is used in pulse-echo mode**
b. **Image display from pulsed-wave Doppler US**
   - **Red line indicates the axial line used to interrogate a volume contained within the range gate**
   - **The angle correction is also indicated**

Pulsed wave Doppler US



- The range gate is a means by which the returning echoes from a particular range in time are separated out for analysis by the Doppler instrumentation
  - adjusted by the operator

Pulsed wave Doppler US



Doppler angles between 30˚ and 60˚ are easiest to image while providing the minimal error in velocity estimation

Table 1
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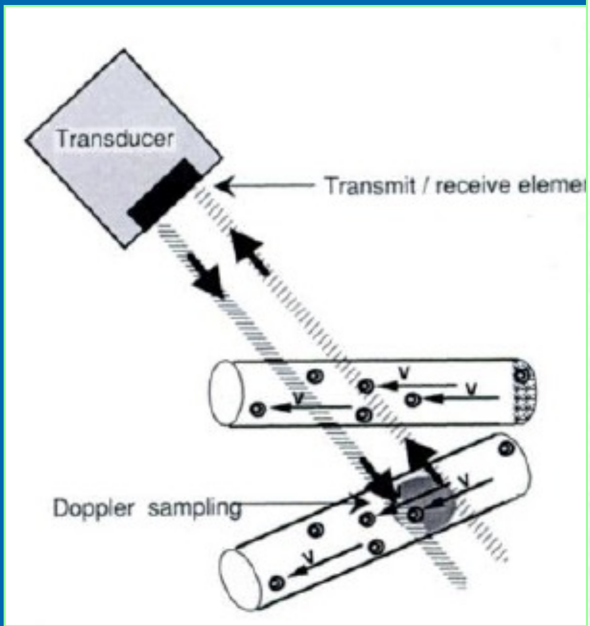
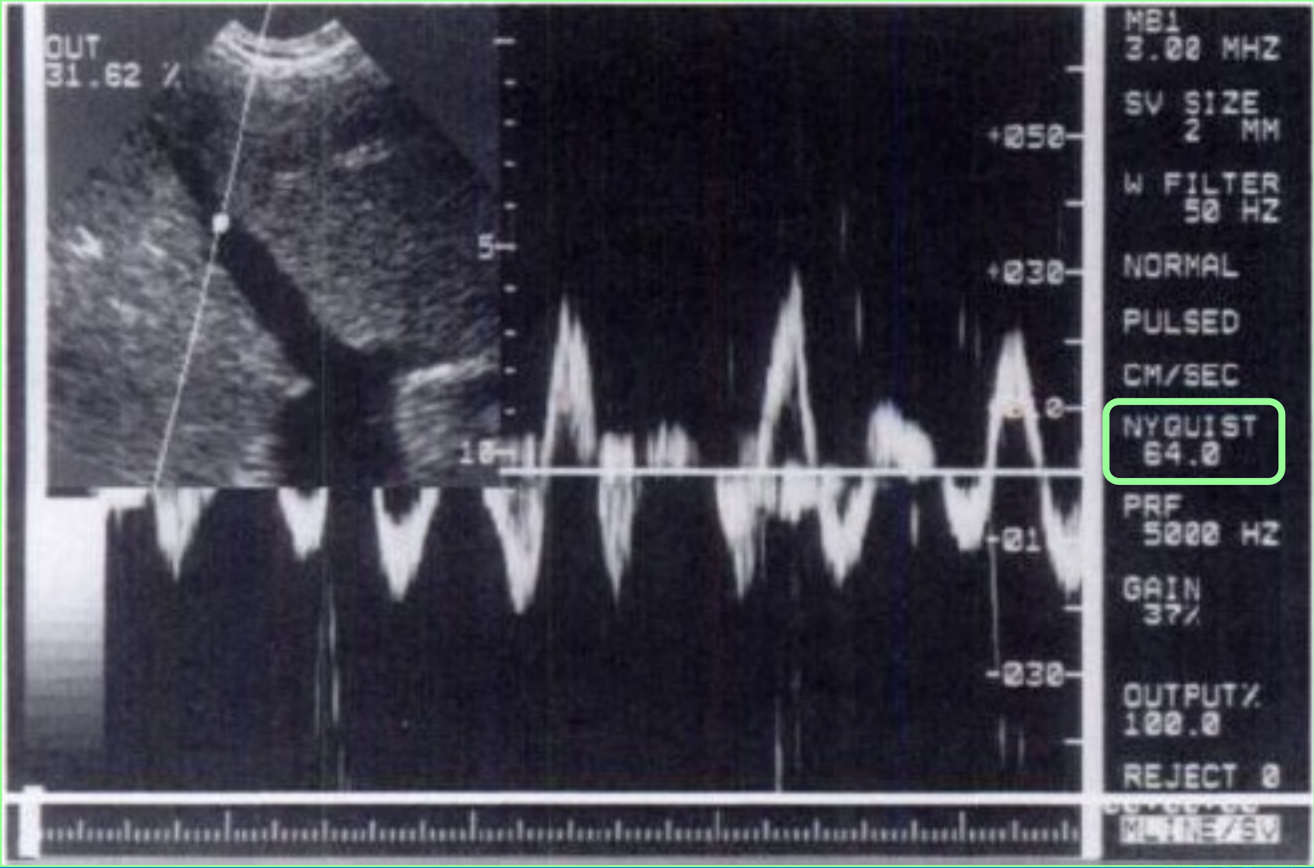
2.5	3.2	2.3	1.6	0.6
3.0	3.9	2.8	1.9	0.7
5.0	6.5	4.6	3.2	1.1
7.5	9.7	6.8	4.9	1.6

Aliasing

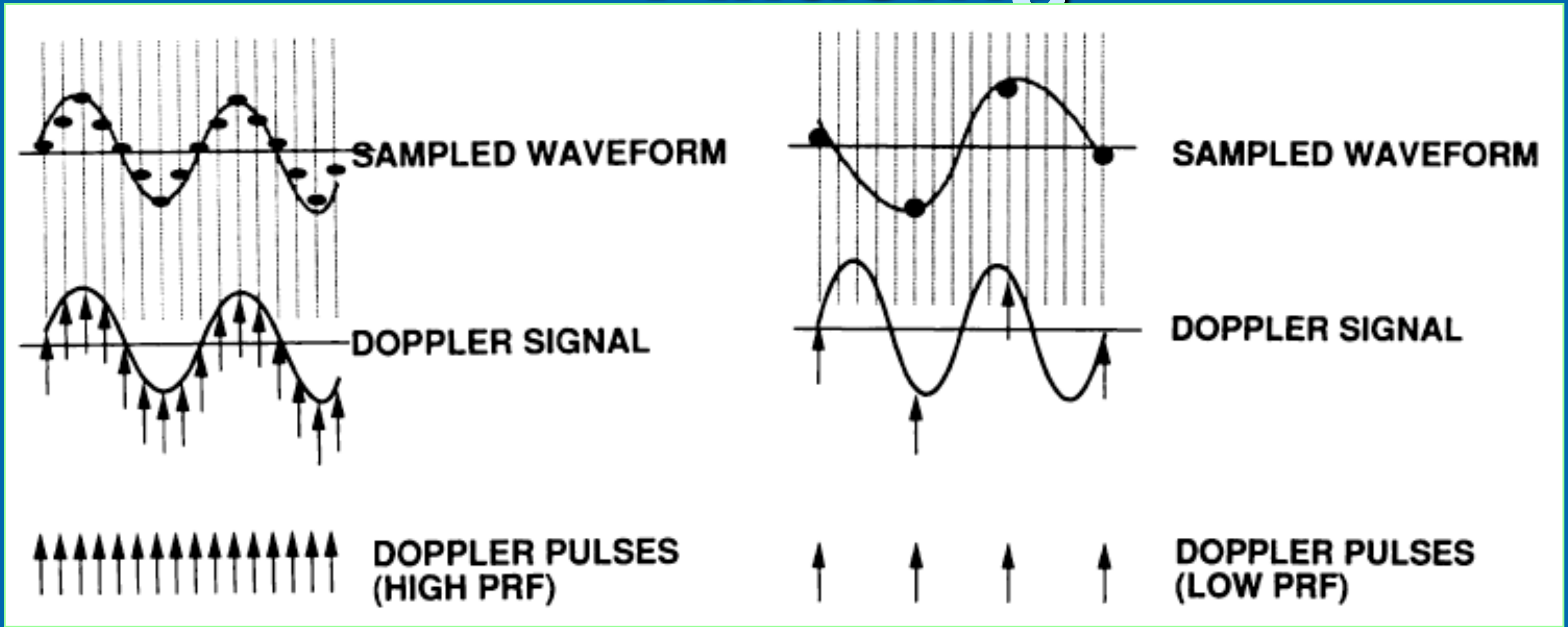




Aliasing occurs in pulsed-wave Doppler US when the rate at which interrogating pulses are sent to obtain the phase shift information is less than two times Doppler shifted frequencies

- **Nyquist criteria**

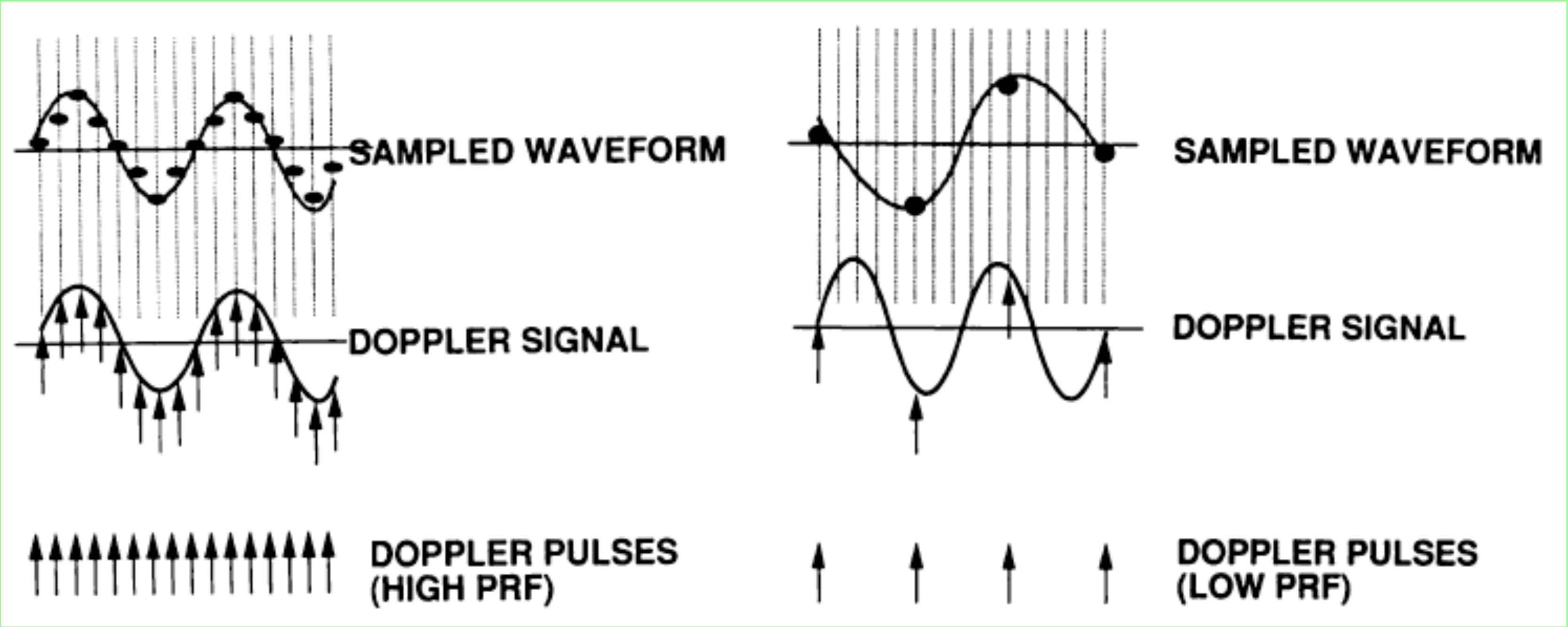
Aliasing



- **Nyquist criteria dictate that there must be at least 2 samples per period of the maximum frequency**
- **Anything less will result in an artifactually lower frequency being reconstructed**
- **The sampling rate is dictated by the depth of the range gate in the body !**

PRF: pulse repetition frequency

Aliasing



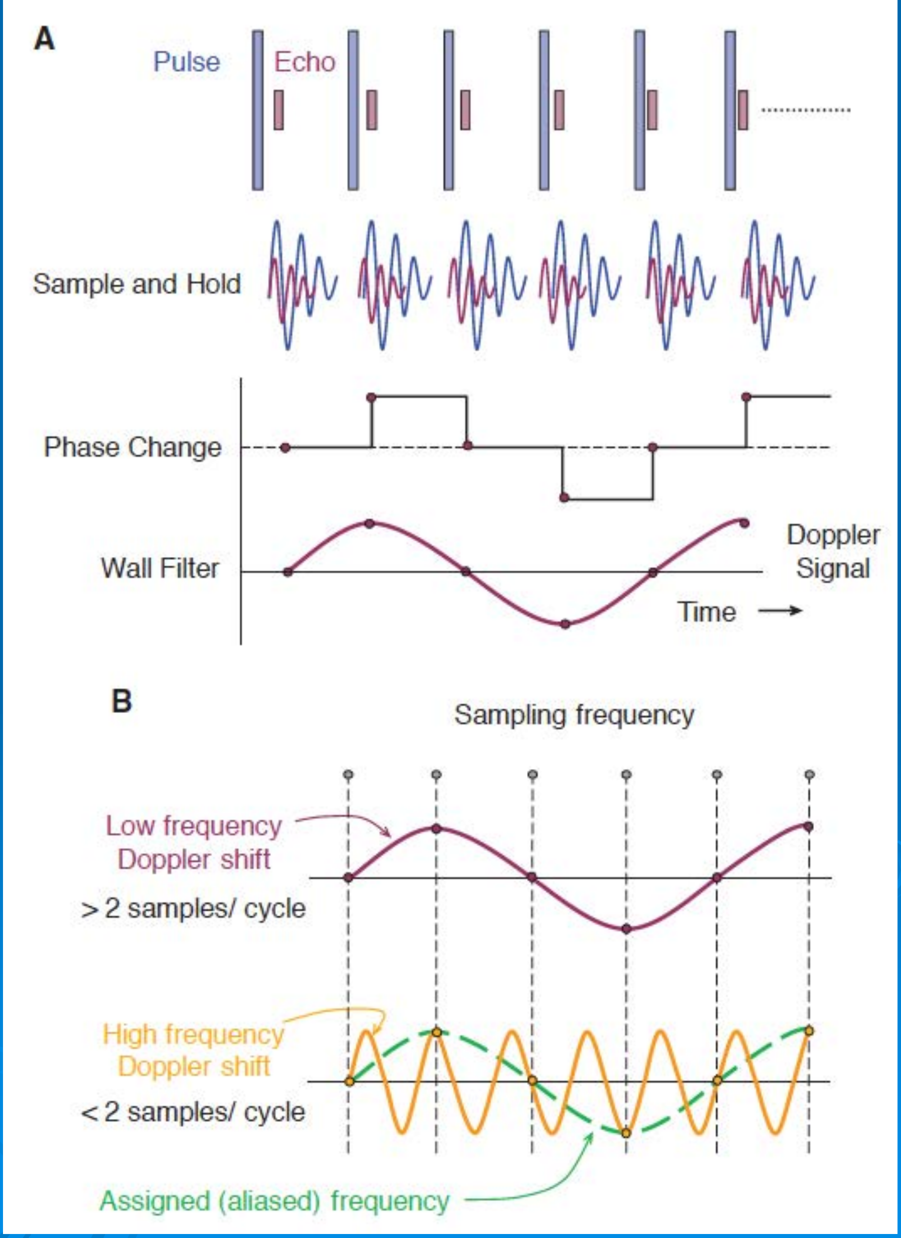
$$\Delta f_{max} = \frac{PRF}{2} = \frac{2 f_0 V_{max} \cos(\theta)}{c}$$

$$V_{max} = \frac{c \times PRF}{4 \times f_0 \times \cos(\theta)}$$

PRF: pulse repetition frequency

Aliasing

- PRF can reach only a maximum that is allowed by the round trip time between the transducer and the range gate depth
  - identical to the pulse-echo range equation



The Essential Physics of Medical Imaging
Bushberg et al, 2012
Lippincott Williams & Wilkins

Aliasing

Any one of the following changes will allow v_{max} to increase:

- Reducing the depth of the range gate will allow an increase in the PRF
- Reducing the frequency of the transmitted pulse, f_0, will reduce the Doppler shift frequency
- Increasing the angle between the beam axis and the vessel axis will reduce the Doppler shift frequency

Table 2
Doppler Frequency Shifts (kHz) for Targets of Differing Velocities*

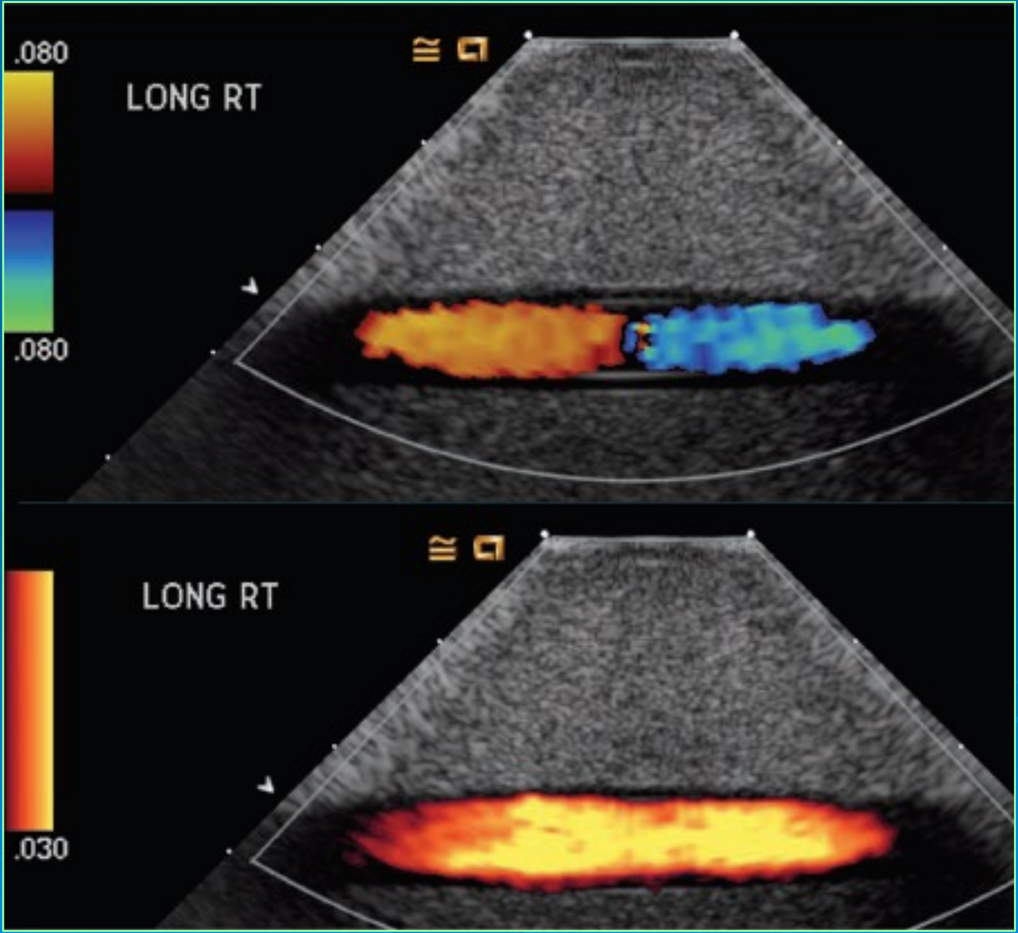
	Velocity (m/sec)			
F_T (kHz)	0.01	0.10	1.00	5.00
2.0	0.018	0.18	1.8	9.18
3.0	0.028	0.28	2.8	13.78
5.0	0.046	0.46	4.6	22.96
7.5	0.069	0.69	6.9	34.50

* Calculated for a 45° scanning angle.

Color Doppler & Power Doppler

Color flow (top) and power Doppler (bottom) images of the same phantom under the same conditions

- The directions of flow toward and away from the transducer are seen in the color flow image
- The power Doppler image displays only the intensity of the Doppler shift



Power Doppler

A comparison of color Doppler and power Doppler

Enhanced sensitivity of the power Doppler acquisition

- particularly in areas perpendicular to the beam direction
  - where the signal is lost in the color Doppler image

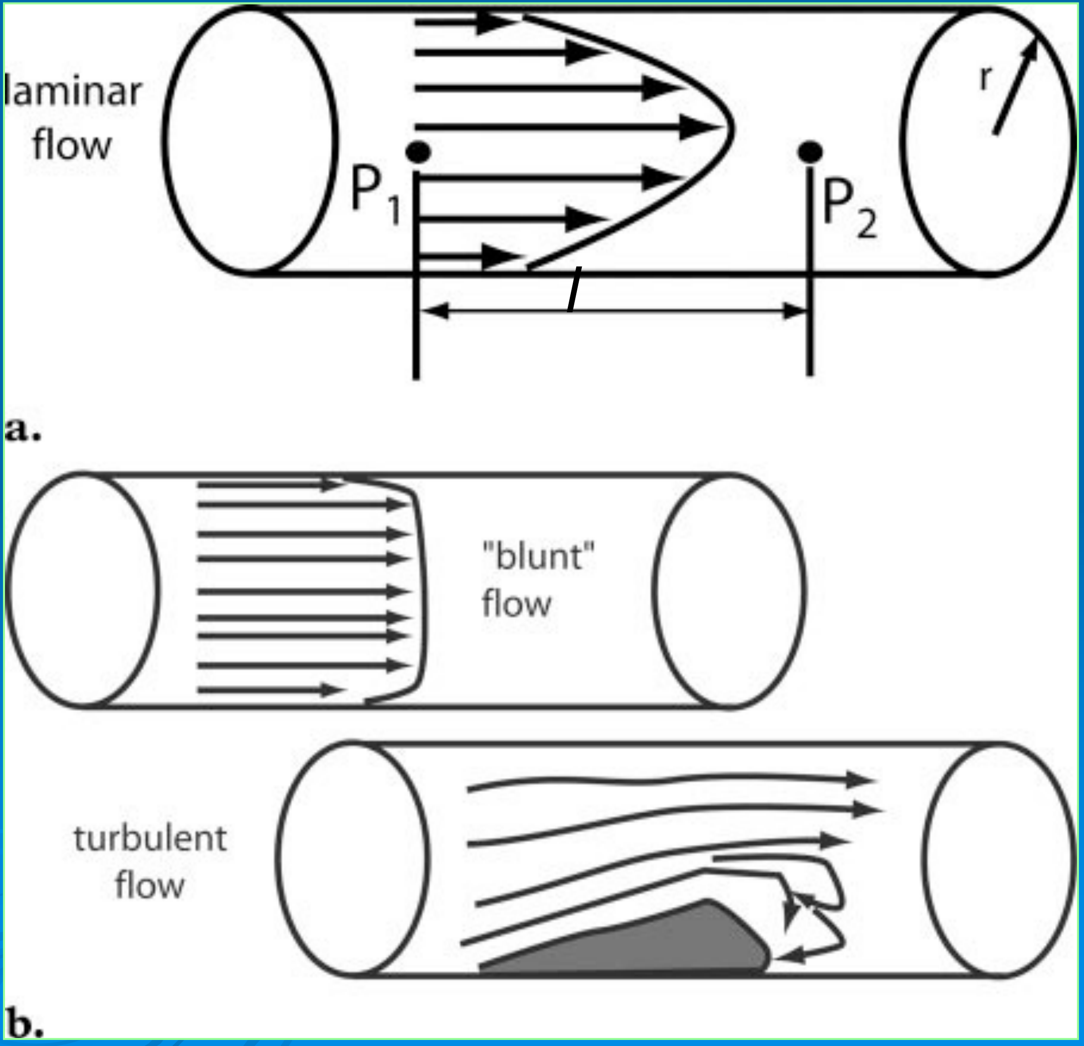
Types of Blood Flow and Physics of Flow Resistance

Poiseuille' s law

$$P_2 - P_1 = \frac{8 l \eta Q}{\pi r^4}$$

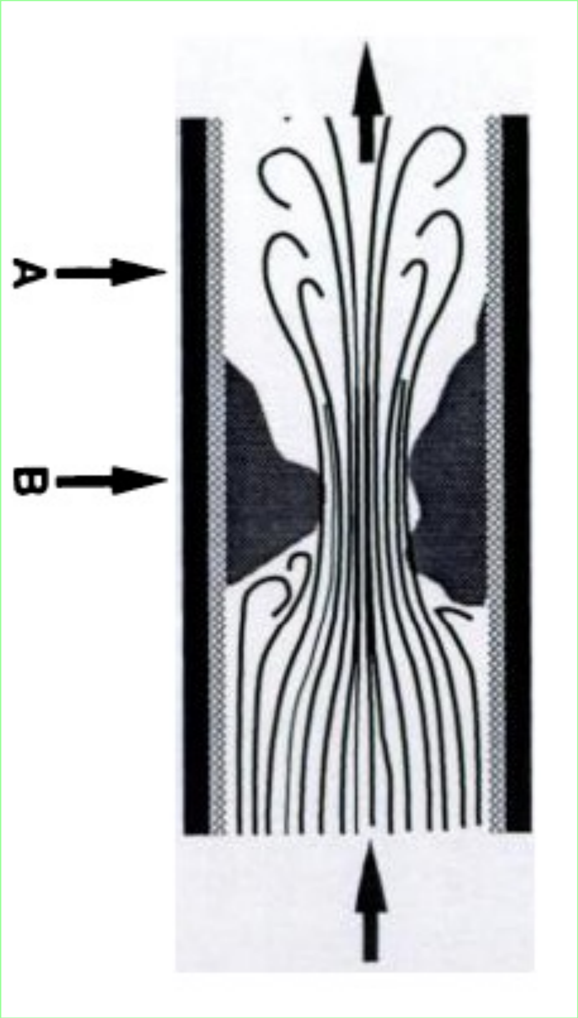
- P_2-P_1 pressure difference
- l length
- r radius
- η viscosity
- Q flow rate

General model: the flow rate through a cylindrical vessel is determined by pressure difference



Types of Blood Flow and Physics of Flow Resistance

- Blood is a complex fluid, exhibiting properties that are referred to as non-Newtonian
- The viscosity of blood increases as the flow rate slows down
- The vessel structure itself is very complex
- Blood vessels are curved, can branch and change diameter, and are viscoelastic
  - (eg, behave like plastics)



Flow Parameters: Derivations and Meaning

- Doppler US demonstrates changes in flow
- US-based quantitative values provide diagnostic thresholds for disease conditions
- Absolute quantification of the flow velocity is difficult because of the angle dependence of the Doppler equation
  - In some cases, it is problematic to make an adequate estimate of the Doppler angle

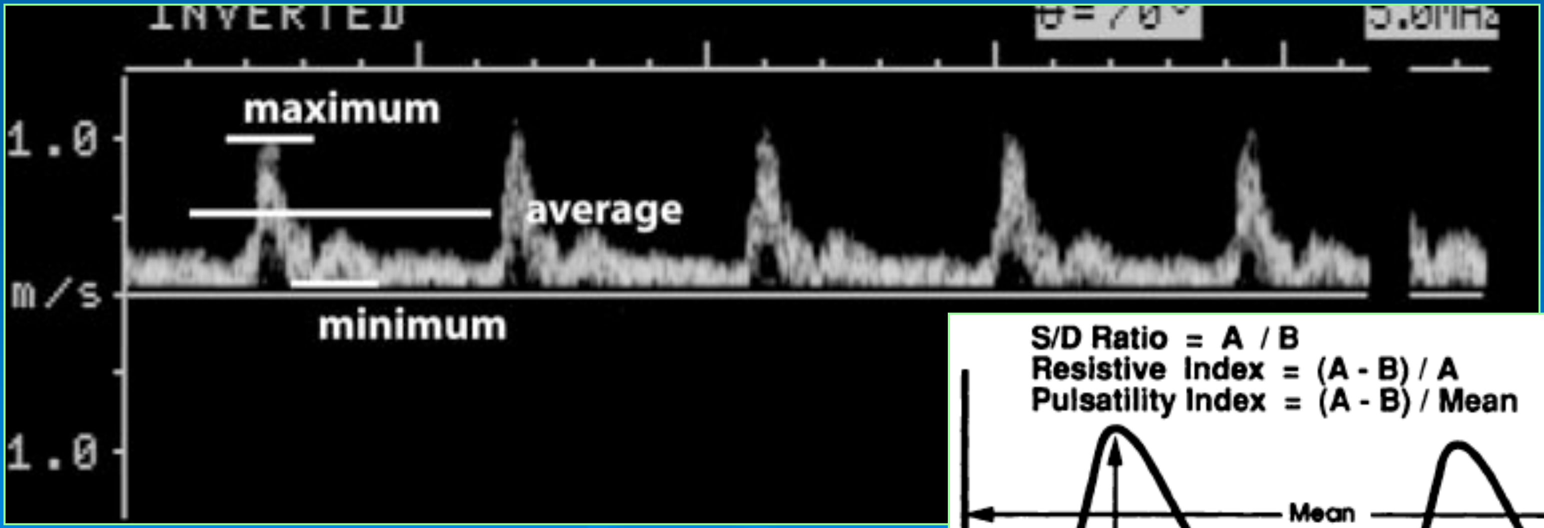
Flow parameters

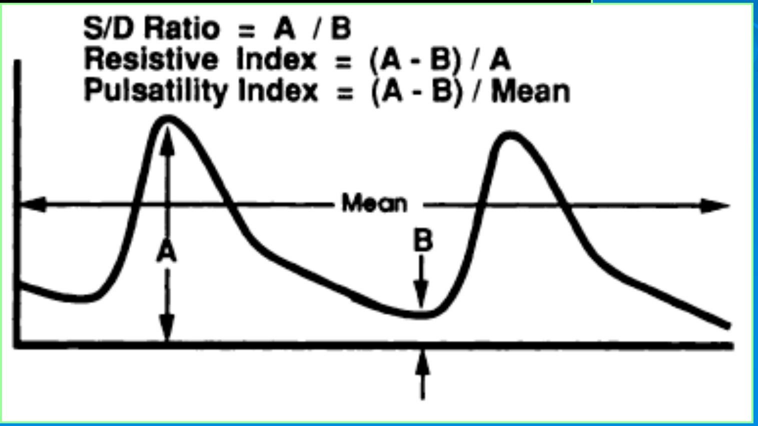
- PI pulsatility index
- RI resistivity index

$$v_{RBC} = \frac{f_D}{f_0} \cdot \frac{c}{2 \cdot \cos \theta}$$

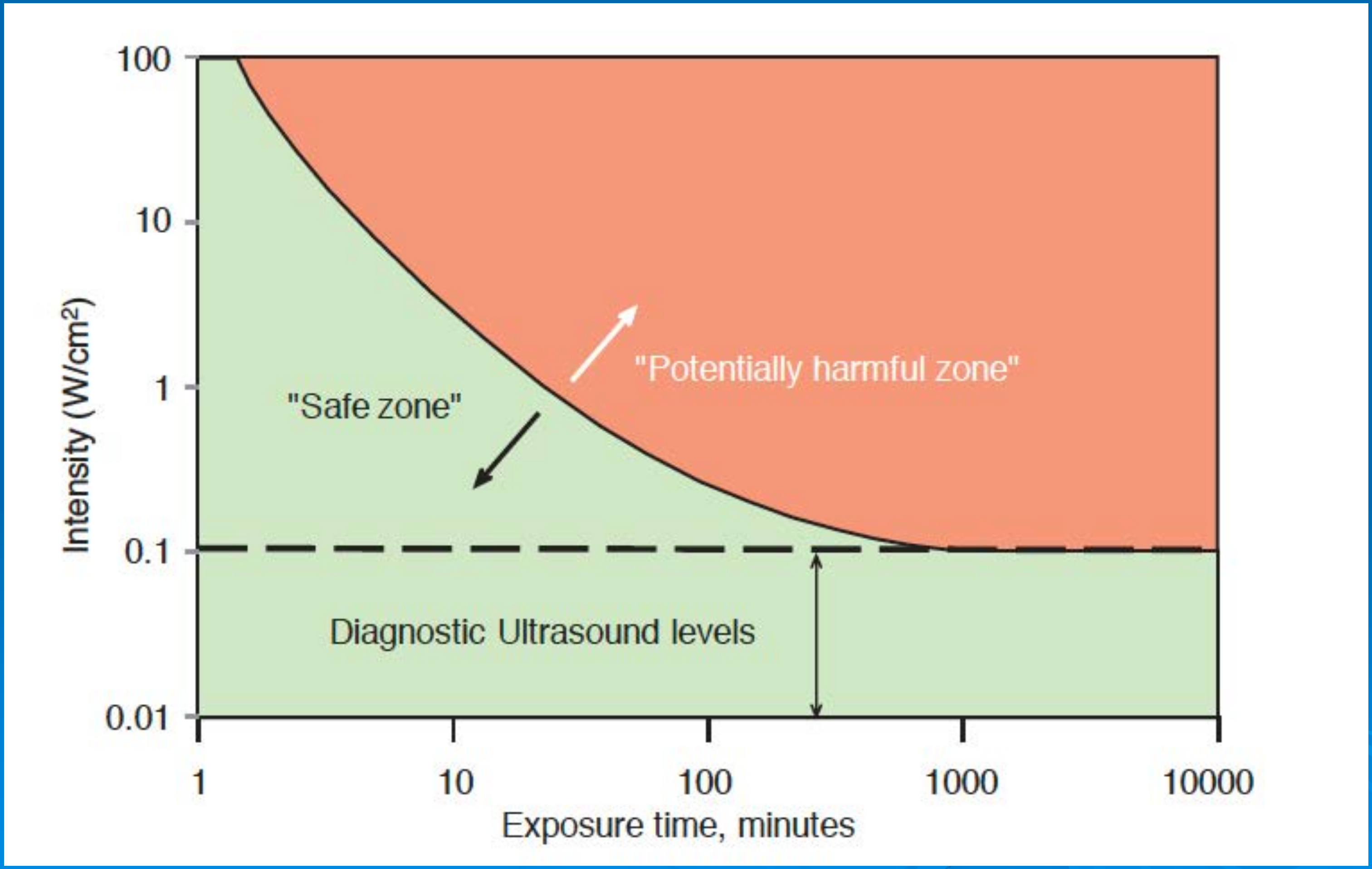
$$PI = \frac{v_{max} - v_{min}}{v_{mean}} = \frac{S - D}{mean}$$

$$RI = \frac{v_{max} - v_{min}}{v_{max}} = \frac{S - D}{S}$$





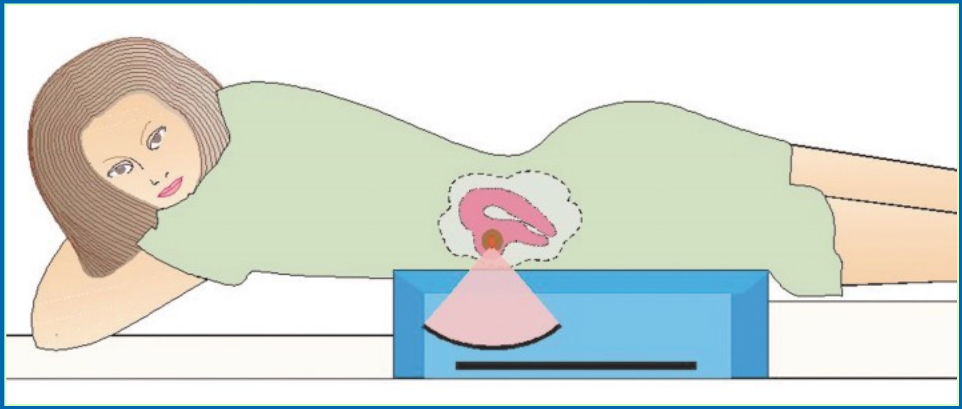
US potential bioeffects



High Intensity Focused Ultrasound (HIFU) Therapy

The ability to focus and accurately target a lesion with HIFU allows precise ablation of lesions of any shape without damage to surrounding structures

- by using real-time US or magnetic resonance imaging guidance



- Schematic representation of patient lying focused ultrasound system ready to be placed into MRI unit.
- Ultrasound transducer found in sealed water bath within MR table

J. Hindley et al
MRI Guidance of Focused Ultrasound Therapy of Uterine Fibroids
AJR 2004;183:1713–1719

References

US

- Doppler US: The Basics
  - CRB Merritt, RadloGraphlcs 1991; 11:109-119
- Fundamental Physics of Ultrasound and Its Propagation m Tissue
  - Marvin C. Ziskin, RadloGraphics 1993; 13:705-709
- B-mode US: Basic Concepts and New Technology
  - N.J. Hangiandreou, RadioGraphics 2003; 23:1019–1033
- Doppler US Techniques: Concepts of Blood Flow Detection and Flow Dynamics
  - Evan J. Boote, RadioGraphics 2003; 23:1315–1327