In addition to presenting detailed, high-resolution anatomical information, ultrasound energy can also be used to obtain and display information about some aspects of human physiology. More specifically, most ultrasound imaging systems also have Doppler display formats that provide important information about blood flow states, or hemodynamics. Contemporary sonographic imaging systems integrate two-dimensional anatomical and Doppler spectral or color displays on a single screen, a display that is referred to as duplex imaging. To properly and accurately interpret a duplex image, it is critical to master the physical principles that create Doppler data and to understand the fundamentals of human vascular hemodynamics. To accomplish this important educational task, a review of the physical concepts pertinent to Doppler sonography is in order. These are the same physical principles governing the acquisition of sonographic images presented from a slightly different perspective.

**Interaction with Soft Tissue**

**REFLECTION:** “to cast back.” That portion of the incident beam which, after encountering a tissue of different acoustic impedance, returns to the transducer, is used in the production of diagnostic information.

- The strongest reflections arise from the greatest changes in mechanical or elastic properties of adjacent tissue. Mathematically related to the difference in acoustic impedance.

- Approximately 1% of incident beam can be reflected from smooth connective tissues such as those found in the renal capsule, surrounding major muscle bundles, and in the walls of small blood vessels.

- At normal incidence \((\cos \theta = 90^\circ)\) the amount of reflection is proportional to the difference in acoustic impedance between two tissues.

**SPECULAR REFLECTION** occurs when the wavelength is smaller than the boundary between the tissue planes. The smoother the interface, the more the magnitude of reflection depends upon the incident angle. Maximum reflection occurs at \(90^\circ\). For most anatomic structures, the wavelength is considerably smaller than the interface; therefore the best reflection occurs when the transducer is at \(90^\circ\) to the interface.

**SCATTERING** is the diffusion or redirection of the sound beam in many directions after encountering particles in suspension or a rough surface. It typically occurs...
when the wavelength is larger than the boundary or structures that the beam encounters. The weak echoes resulting from scattering are used in image acquisition to provide information about the homo- or heterogeneity of parenchymal structures. On Doppler displays, scatterers are the source of most of the color and spectral information presented.

The primary scatterers in the human body are red blood cells, which have a dimension of about 8 - 10\(\mu\)m. Each red cell will absorb a certain amount of ultrasound energy; the remainder will re-radiate in all directions. This type of scattering is referred to as Rayleigh scattering, and there are several factors that influence its intensity. All factors are directly proportional to scattered intensity.

### Factors Influencing Scattered Intensity:

1. **Dimension** of the scatterer. As size increases, (i.e., approaches the size of the incident wavelength) scattered intensity increases.
2. **Number** of scatterers present. As number increases, scattered intensity increases. Studies have shown that scattering from blood is proportional to hematocrit in certain situations. (Hematocrit is a clinical laboratory measurement of the volume of red cells in human blood). Scattering from myriad small moving reflectors creates wave fronts (Huygen's principal) that very intensity.
3. **Inhomogeneity** of scatterer. As the difference in acoustic impedance between scatterer and surrounding material increases, scattered intensity increases. This phenomenon is similar to the amplitude of reflection being dependent upon degree of acoustic impedance mismatch. (See Reflection. P.27)
4. **Frequency** of incident beam. As frequency increases, scattered intensity increases to the fourth power. Clinical application of this phenomenon dictates that the sonographer select the highest-frequency probe available when doing Doppler studies. Of course, the trade-off between high-frequency and attenuation remains a consideration.

### Doppler Physics

The **Doppler effect** is a change in frequency (\(\Delta F\)) caused by the interaction of sound with a moving structure. The classic example of the Doppler effect is the perceived change in the sound of a train whistle or a fire-engine siren as it passes the ear of the listener. In these examples, as the sound source approaches the listener, the frequency (pitch) apparently increases; as the source moves past the listener, the frequency (pitch) decreases. The same phenomenon occurs when an ultrasound beam encounters moving Rayleigh scatterers in the human body: there is a frequency shift that can be detected by the transducer which is then analyzed and displayed in various formats by the imaging system. Doppler information, regardless of how it is formatted or displayed, represents the movement of blood cells in all sonographic medical imaging applications.
**DOPPLER SHIFT**: The Doppler frequency ($F_d$) is the difference between incident frequency ($F_o$) and reflected frequency ($F_r$). This relationship is represented mathematically by the formula:

$$F_d = F_r - F_i$$

**EXAMPLE**: If the central incident frequency is 5 MHz, and the receiver detects a 4.5 MHz returning frequency, the Doppler shift is .5 MHz.

While the basic Doppler concept of *frequency change* is expressed by the Doppler shift formula above, there are several other factors that affect the actual characteristics of the Doppler shift obtained when using ultrasound technology to obtain diagnostic information from the human body. These factors include the frequency of the ultrasound beam used (incident frequency); speed of sound in soft tissue (1540 m/s); the velocity of the moving reflectors; and the angle of incidence of the sound beam. The relationship between these factors can be expressed mathematically as:

$$F_d = \frac{2 F_i V \cos \theta}{C}$$

Where:
- $F_i$ = incident frequency (beam emitted from transducer)
- $V$ = velocity of reflectors (RBCs)
- $C$ = speed of sound in soft tissue (1540 m/sec)
- $\theta$ = angle of insonation

1. **INCIDENT FREQUENCY ($F_o$)**. *Directly related*. As frequency increases, Doppler shift increases.
   In clinical practice, the highest-frequency transducer is preferred when performing Doppler studies. The same tradeoff between frequency and penetration exists in vascular applications as in imaging applications: higher frequencies provide more information, but are attenuated more rapidly, making them less useful for deeper structures. In carotid arterial and peripheral arterial and venous duplex studies, 5 MHz to 10 MHz linear array transducers are best suited to both image the vessels and assess hemodynamics present.
2. **VELOCITY OF REFLECTOR (V).** *Directly related.* Doppler shift increases as velocity increases. Changes in the velocity of blood flow, particularly in arteries, provide critical information about the presence, absence, and degree of disease states. Because velocity of the reflectors (red blood cells) will directly affect the Doppler shift, this information can be displayed and measured accurately with spectral waveform analysis. Other quantitative measurements of blood flow patterns, such as indices and ratios, can also be obtained because of the ability of spectral Doppler to calculate velocity.

3. **ANGLE OF INSONATION (COS θ).** *Inversely related.* As incident angle increases (approaches 90°) Doppler shift decreases. For a sound beam incident at an angle other than 0°, the detected Doppler frequency shift is reduced by \( \cos \theta \). (See Appendix A. Sines and Cosines p. 189)

Doppler angle is a significant technical consideration in performing many types of arterial duplex examinations. There are several different approaches to adjusting and correcting for Doppler angle in clinical practice; no one is absolutely correct or better than the other. What is important is that, regardless of the approach used, the Doppler angle be set appropriately for the protocol being used because of its importance in determining accurate blood flow velocity.

4. **DIRECTION OF MOVEMENT.** If a reflector is moving toward the source (transducer), the reflected frequency will *increase* or be greater than the incident frequency: a positive Doppler shift. If a reflector is moving away from the source (transducer), the reflected frequency will *decrease* or be less than the incident frequency: a negative Doppler shift.

Since this positive or negative shift is determined by the direction of flow, it ultimately determines how a particular Doppler format will display movement. **Display of flow direction is always relative to the transducer.** In *spectral displays*, flow toward the transducer is displayed as information *above the baseline*. In *color Doppler displays*, flow toward the transducer is displayed as the hue on the *top part of the color bar*.

*See Appendix D – Color Plates (p.205)*
EXAMPLES OF DOPPLER FORMULA CALCULATIONS:

1. Calculate the Doppler shift experienced by a 5.0MHz sound wave interrogating a blood flow jet moving at 120cm/sec. The angle of insonation is 30 degrees.

\[ F_d = \frac{2 F_o V}{C} \cos \theta \]

\[ F_d = \frac{2(5 \times 10^6 \times 1.2 \times 10^2)}{1.54 \times 10^5} \cos 30 \]

\[ F_d = 2(6.0 \times 10^8) \cos 30 \]

\[ F_d = \frac{1.2 \times 10^9}{1.54 \times 10^5} \cos 30 \]

\[ F_d = 0.8 \times 10^4 = 8,000 \cos 30 \]

\[ F_d = 8,000 \times \cos 30 (0.5) \]

\[ F_d = 4,000 \text{ Hz} \]

2. Calculate the Doppler shift experienced by a 7.0MHz sound wave interrogating a blood flow jet moving at 70cm/sec. The angle of insonation is 90 degrees.

\[ F_d = \frac{2 F_o V}{C} \cos \theta \]

\[ F_d = \frac{2(7 \times 10^6 \times 7 \times 10^1)}{1.54 \times 10^5} \cos 90 \]

\[ F_d = \frac{2(4.9 \times 10^8)}{1.54 \times 10^5} \cos 90 \]

\[ F_d = \frac{9.8 \times 10^8}{1.54 \times 10^5} \]

\[ F_d = 6.36 \times 10^3 = 6,360 \]

\[ F_d = 6,360 \cos 90 \]

\[ F_d = 0.0 \]
Chapter 10. The Doppler Effect