# AAPM Tutorial

Stephen Balter, PhD

# Doppler US: The Basics[1]

*Christopher R. B. Merritt, MD*

Doppler ultrasonography (US) is an invaluable tool in the diagnosis of occlusive vascular disease and is assuming increasing importance in the diagnosis of abdominal, pelvic, and fetal disorders. The author presents for new users the basic physics principles of Doppler US in his discussions of the Doppler principle, instrumentation, signal processing and display, artifacts, and interpretation of data. An understanding of these principles will assist radiologists in using the full potential of Doppler US in the diagnostic workup.

## INTRODUCTION

The ability to detect and quantify blood flow by means of Doppler ultrasonography (US) has made this technique an indispensable adjunct to imaging. Although Doppler US has been used clinically for over 20 years, widespread interest in the use of Doppler techniques is a recent development. In the past, use of Doppler US was restricted to evaluation of a few well-defined indications in cardiac disease and assessment of carotid and peripheral arterial and venous disease.

The importance of flow information, however, extends well beyond the identification of stenosis, thrombosis, and occlusion of the major arteries and veins. Doppler US is playing a growing role in the diagnosis of abdominal, pelvic, and fetal disorders. Familiarity with the elementary principles of Doppler US is essential for proper use of duplex US and color Doppler imaging. This tutorial assumes an understanding of the basic principles of US and is intended to introduce the most basic principles of Doppler US for new users of this increasingly important ultrasound application.

**Abbreviations:** CW = continuous wave, FFT = fast Fourier transformation

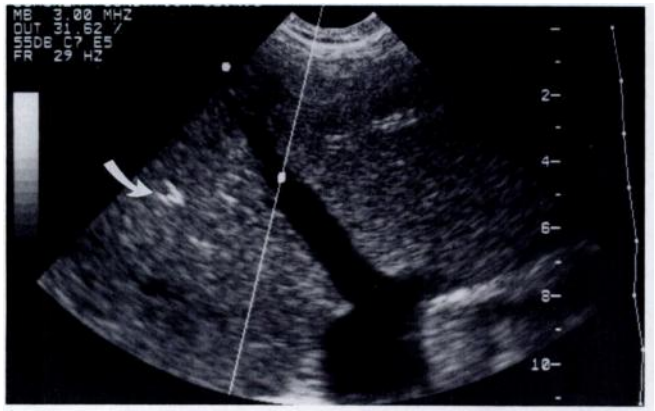
**Index terms:** Physics • Ultrasound (US), physics

**RadioGraphics 1991;** 11:109–119

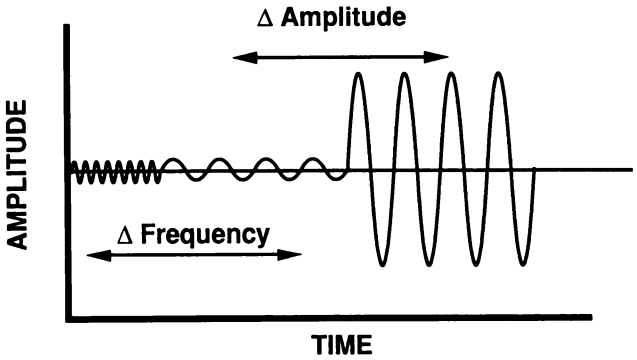
[1] From the Department of Radiology, Ochsner Clinic and the Alton Ochsner Medical Foundation, 1514 Jefferson Hwy, New Orleans, LA 70121. Received and accepted August 22, 1990. **Address reprint requests to** the author.

## THE ULTRASOUND SIGNAL

Conventional B-mode US uses pulse-echo transmission, detection, and display techniques. Brief pulses of ultrasound energy emitted by the transducer are reflected from acoustical interfaces within the body. Precise timing allows determination of the depth from which the echo originates. The gray-scale image derived from these reflected pulses uses only the amplitude information in the returning signal (Fig 1a). Rapidly moving targets, such as red cells within the blood stream, produce echoes of such low amplitude that they are not commonly displayed. Fortunately, the backscattered ultrasound beam contains more than the simple amplitude information needed to produce an image. The backscattered signal also varies from the transmitted signal in frequency and phase, and it is this additional information that permits the detection and measurement of target movement (Fig 1b).




a.




b.

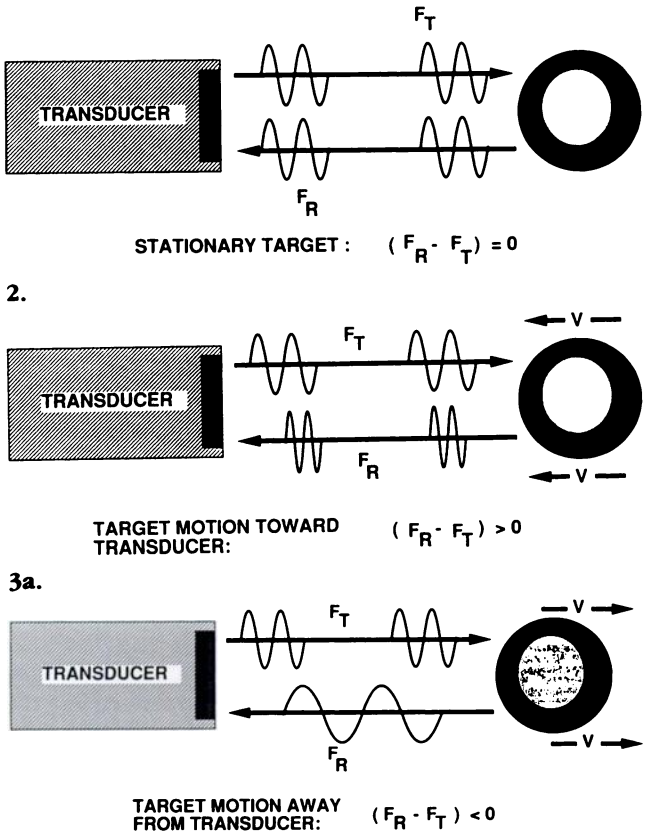
**Figure 1.** **(a)** Sonogram of the liver. To produce this gray-scale image, differences in amplitude of backscattered ultrasound are displayed. These differences are related to strength of the interface reflecting the incident sound and are not related to movement of the target. High-amplitude echoes are seen as bright areas, and in this image represent connective tissue surrounding portal vein branches (arrow). **(b)** Backscattered ultrasound contains frequency as well as amplitude data. The backscattered signal varies in frequency as well as amplitude if the target is moving relative to the transducer. These frequency changes are related to velocity of the moving target by the Doppler equation and are evaluated in the Doppler mode of ultrasound signal processing.

## THE DOPPLER PRINCIPLE

The Doppler principle can be understood by considering the interaction of ultrasound with a reflecting interface (Figs 2, 3). The difference between the frequency of the reflected ultrasound and the transmitted frequency is directly proportional to the velocity of the reflecting interface relative to the receiver and is a result of the Doppler effect. The relationship of the returning ultrasound frequency to the velocity of the reflector is described by the Doppler equation

$$\Delta F = (F_R - F_T) = (2F_T \cdot v)/c,$$

where $\Delta F$ = Doppler frequency shift, $F_R$ = frequency of sound reflected from the moving target, $F_T$ = frequency of sound emitted from the transducer, $v$ = velocity of the target toward the transducer, and $c$ = velocity of sound in the medium. The




**Figures 2, 3.** Diagrams illustrate the interaction of ultrasound with a reflecting interface or target when it is stationary **(2)** and moving toward **(3a)** and away **(3b)** from the transducer. If the target is stationary **(2)**, the reflected ultrasound has the same frequency or wavelength as the transmitted sound, and there is no difference in the transmitted ($F_T$) and reflected ($F_R$) frequencies. If the target is moving with respect to the transmitted ultrasound beam, there is a change in the frequency of the sound scattered by the moving object. If the target moves toward the transducer **(3a)**, the difference in reflected and transmitted frequencies is greater than 0; if the target is moving away from the transducer **(3b)**, this difference is less than 0. The Doppler equation relates this change in frequency to the velocity of the moving object.

**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 |

Doppler frequency shift $\Delta F$, as described above, applies only if the target is moving directly toward or away from the transducer as is shown in Figure 4a. In the clinical setting, the direction of the ultrasound beam is seldom directly toward or away from the direction of flow, and the ultrasound beam usually approaches the moving target at an angle designated as $\theta$, the Doppler angle (Fig 4b). In this case, the frequency shift $\Delta F$ is reduced in proportion to the cosine of this angle and

$$\Delta F = (F_R - F_T) = [(2F_T \cdot v)/c]\cos\theta,$$

where $\theta$ is the angle between the axis of flow and the incident ultrasound beam. If the Doppler angle can be measured, flow velocity can be estimated. Accurate estimation of target velocity requires precise measurement of both the Doppler frequency shift and the angle of insonation to the direction of target movement. As the Doppler angle $\theta$ approaches 90°, the cosine of $\theta$ approaches 0. At an angle of 90°, there is no relative movement of the target toward or away from the transducer, and no Doppler frequency shift is detected (Fig 5a). Since the cosine of the Doppler angle changes rapidly for angles more than 60°, accurate angle correction requires that Doppler measurements be made at angles of less than 60°. Above 60°, relatively small changes in the Doppler angle are associated with large changes in cos $\theta$; therefore, a small error in estimation of the Doppler angle may result in a large error in the estimation of velocity (Fig 5b). For this reason, the use of a Doppler angle of less than 60° is recommended to obtain accurate estimates of velocity. In most clinical applications, it is highly desirable that the measurements of Doppler frequencies be corrected for the Doppler angle to provide velocity measurement. This allows data from systems using different Doppler frequencies to be compared and eliminates error in interpretation of frequency data obtained at differing Doppler angles.

The interrelationships of transducer frequency $F_T$ and the Doppler angle $\theta$ to the Doppler frequency shift and target velocity, which are described by the Doppler equation, are of great importance in proper clinical use of Doppler equipment. Table 1 illustrates these relationships for velocities, scanning angles, and Doppler frequencies commonly used in clinical practice.

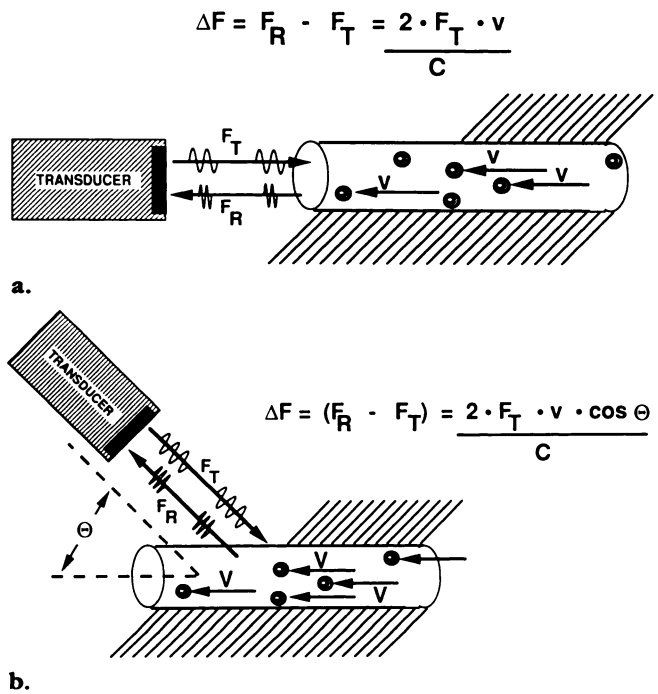



**Figure 4.** Diagrams illustrate the Doppler equation. The Doppler equation describes the relationship of the Doppler frequency shift to target velocity. In its simplest form, it is assumed that the direction of the ultrasound beam is parallel to the direction of movement of the target **(a)**. This situation is unusual in clinical practice; thus, the equation must take into account the angle of the Doppler beam to the direction of flow **(b)**.

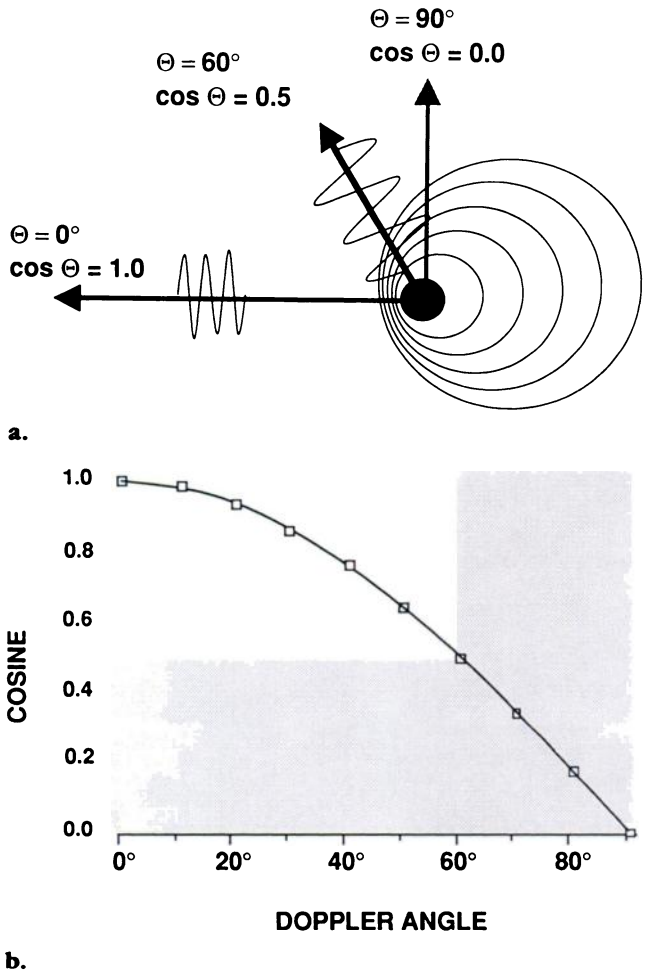


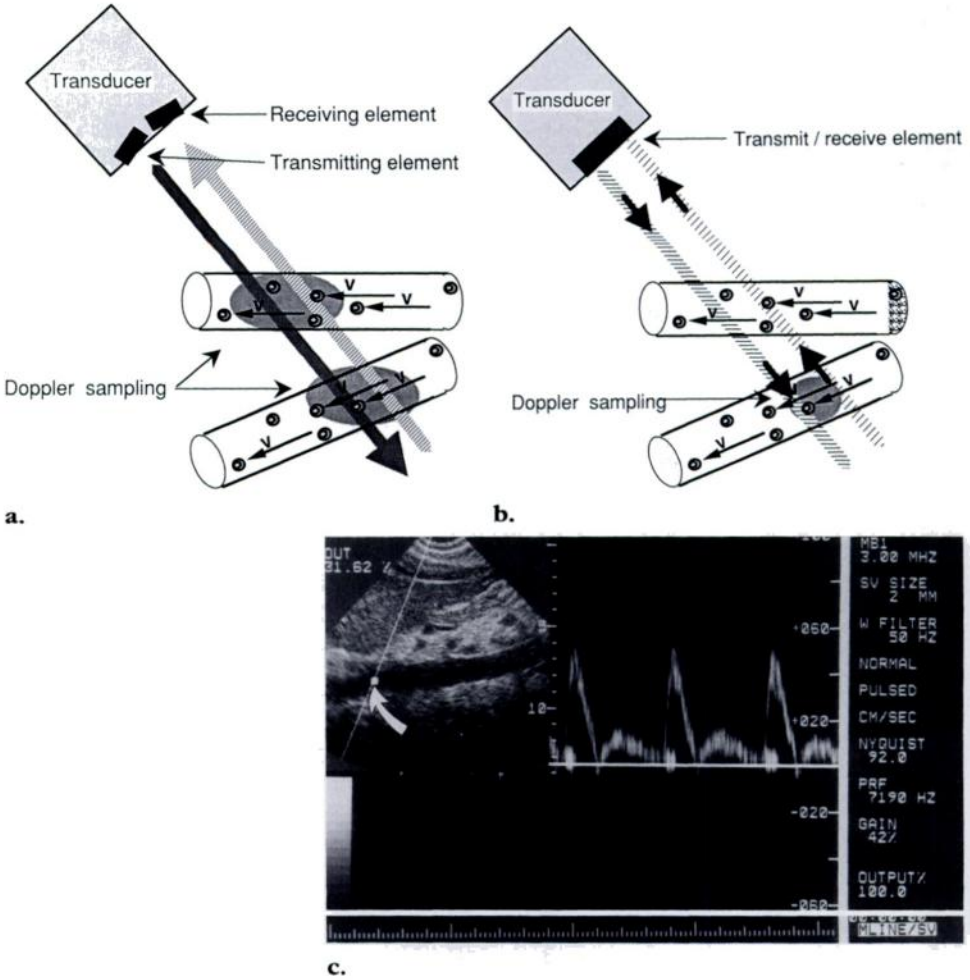

**Figure 5.** **(a)** Diagram illustrates the effect of the Doppler angle on the Doppler frequency shift detected. At an angle of 60°, the detected frequency shift is only 50% of the shift detected at an angle of 0°. At 90°, there is no relative movement of the target toward or away from the transducer, and no frequency shift is detected. The detected Doppler frequency shift is reduced in proportion to the cosine of the Doppler angle. Because the cosine of the angle changes rapidly at angles above 60° **(b)**, the use of Doppler angles of less than 60° is recommended in making velocity estimates, and Doppler angles included in the gray area shown should not be used.

## DOPPLER US INSTRUMENTATION

The simplest form of Doppler US involves use of continuous wave (CW) rather than pulsed ultrasound. CW Doppler devices usually employ two transducers, which transmit and receive ultrasound continuously. These two beams overlap in a sensitive volume at some distance from the transducer (Fig 6a). Although direction of flow can be determined with CW Doppler devices, they do not allow discrimination of motion coming from various depths, and the source of the signal being detected is very difficult to ascertain with certainty. Relatively inexpensive and portable, CW Doppler instruments are used primarily at the bedside to confirm the presence of flow in superficial vessels.

Because of these limitations, range-gated pulsed Doppler systems are used in most diagnostic applications (Fig 6b). In a pulsed Doppler system, the sensitive volume from which flow data are sampled can be controlled in terms of shape and position. When pulsed Doppler capability is combined with a two-dimensional real-time B-mode imager in the form of a duplex scanner, the position of the sample can be precisely controlled and monitored (Fig 6c). Control is accomplished by precise timing, and only those echoes returning from a specific depth are accepted for processing. Since velocity of sound in tissue is relatively constant, the

**Figure 6.** **(a)** Diagram depicts CW Doppler transducer with separate transmit and receive crystals. Signals arising from different depths (shaded areas) cannot be differentiated. **(b)** Diagram shows a pulsed Doppler transducer. In this system, data from selected depths are sampled by processing only signals that return to the transducer after precisely timed intervals. **(c)** Image of the proximal abdominal aorta obtained with a duplex system, which allows the operator to view on the display the location from which the Doppler data are sampled. Sample volume (arrow) is positioned in the lumen of the aorta, and the Doppler frequency spectrum from this site is displayed.

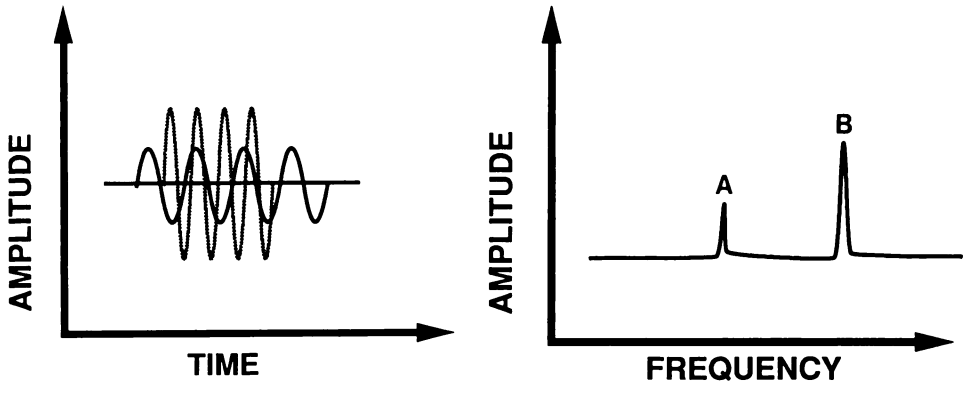


processing of signals received a specified time after the pulse is transmitted can be related to the depth from which those signals arise. A user-controlled range gate aids in the selection of the sites from which the Doppler data are to be analyzed.

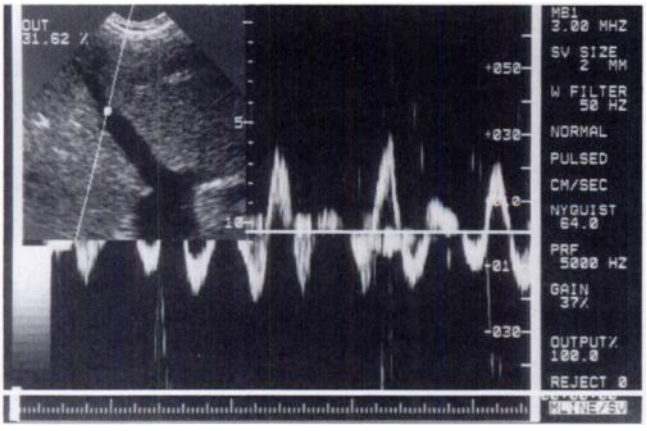
## DOPPLER SIGNAL PROCESSING AND DISPLAY

Several options exist for processing of Doppler frequency shifts to provide useful information about direction and velocity of the moving target (usually red blood cells). Typical Doppler frequency shifts are in the audible range and may be analyzed by ear; with training, many flow characteristics may be identified. This approach is, however, subjective and not suitable for quantitative analysis. More commonly, the Doppler shift data are displayed in graphic form as a time-varying plot of the frequency spectrum of the returning signal. A fast Fourier transformation (FFT) is used to perform the frequency analysis (Fig 7). This transformation is important because it permits the Doppler frequency shift information measured by the instrument to be displayed in a fashion that accurately reflects the range of velocities present in the sample being measured. Most Doppler instruments pro-

**Figure 7.** **(a)** Diagram depicts the two frequency components present in the signal, one of high amplitude and high frequency (gray line), the other of low amplitude and low frequency (black line). **(b)** Diagram depicts variations in Doppler frequency shift, which have been transformed from the time domain to the frequency domain by a FFT performed in real time. *A* = low-frequency, low-amplitude signal; *B* = high-frequency, high-amplitude signal. **(c)** Duplex image shows the Doppler frequency spectrum of flow in the middle hepatic vein. Changes in flow velocity and direction are indicated by vertical deflections of the waveform above and below the baseline. Width of the waveform is determined by the range of frequencies present at any instant in time. A brightness (gray) scale is used to indicate the relative amplitude of each frequency component.



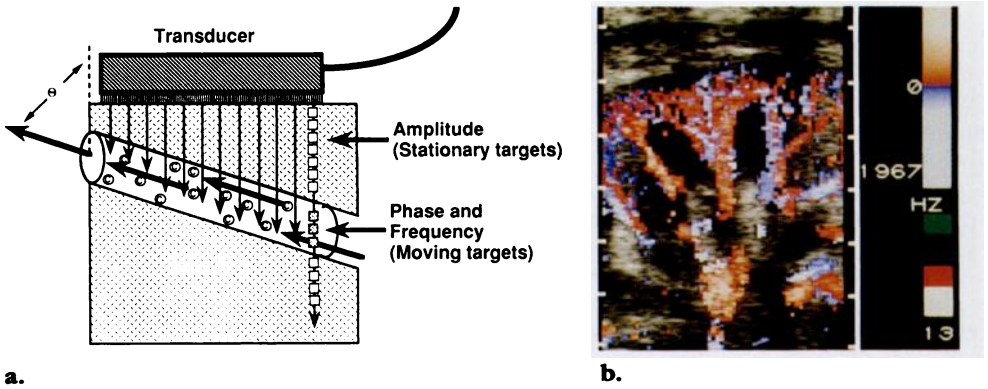

a. b.




c.

vide a graphic display of Doppler frequencies obtained by means of the FFT at each instant in time against a time base so that temporal variations in the frequency spectrum can be studied. The resulting Doppler frequency spectrum displays (*a*) the variation with time of the Doppler frequencies present in the volume sampled; (*b*) the envelope of the spectrum, which represents the maximum frequencies present at a given point in time; and (*c*) the width of the spectrum at any point, which indicates the range of frequencies present. In many instruments, the amplitude of each frequency component is displayed in gray scale.

In color Doppler imaging systems, velocity information determined from Doppler measurements is displayed as a feature of the image itself (Fig 8). In addition to the detection of Doppler frequency shift data from each pixel in the image, these systems may also provide range-gated pulsed Doppler with spectral analysis for display of Doppler data.




**a.** **b.**

**Figure 8.** **(a)** Diagram illustrates the relationship of velocity information to color in color Doppler imaging. Amplitude data from stationary targets provide the basis for the B-mode image. Signal phase provides information about the presence and direction of motion, and changes in frequency relate to the velocity of the target. Backscattered signals from red blood cells are displayed in color as a function of their motion toward or away from the transducer, and the degree of the saturation of the color is used to indicate the relative velocity of the moving red cells. **(b)** Color Doppler image of the kidney shows flow toward the transducer in the renal arteries in red and flow away from the transducer in the renal veins in blue. The less saturated colors indicate higher mean velocities. (Reprinted, with permission, from Merritt CRB. Noninvasive diagnostic techniques in vascular disease. In: Bernstein EF, ed. Real-time Doppler color flow imaging: other applications. St Louis: Mosby, 1990; 42–56.)

## PULSE REPETITION FREQUENCY AND ALIASING

Like other forms of US, Doppler US is subject to important limitations and artifacts. With Doppler US, the transducer frequency and the rate at which the ultrasound pulses are generated are particularly important. As with US imaging, increased Doppler frequency results in increased sensitivity and resolution, but at the price of penetration. With pulsed Doppler systems, the pulse repetition frequency determines the maximum depth from which unambiguous data can be obtained. If the pulse repetition frequency is less than twice the maximum frequency shift produced by movement of the target, an artifact called aliasing results. Aliasing occurs because, in order to assure that samples originate only from a selected depth, it is necessary to wait for the echo from the area of interest before the next pulse is transmitted. This limits the rate at which pulses can be generated, a lower pulse repetition frequency being required for regions of interest at greater depth. If the pulse repetition frequency is less than twice the frequency shift being detected, an artifactual display of lower frequency shifts than are actually present occurs (Fig 9). Doppler samples from stenotic vessels having extremely high flow velocities may exhibit aliasing. Because of the need for lower pulse repetition frequencies to reach deep vessels, signals from deep abdominal arteries are also prone to aliasing. In practice, aliasing is usually readily recognized and can be reduced by increasing the pulse repetition frequency, by increasing the Doppler angle (thereby decreasing the frequency shift), or by using a lower frequency Doppler transducer (Table 2).

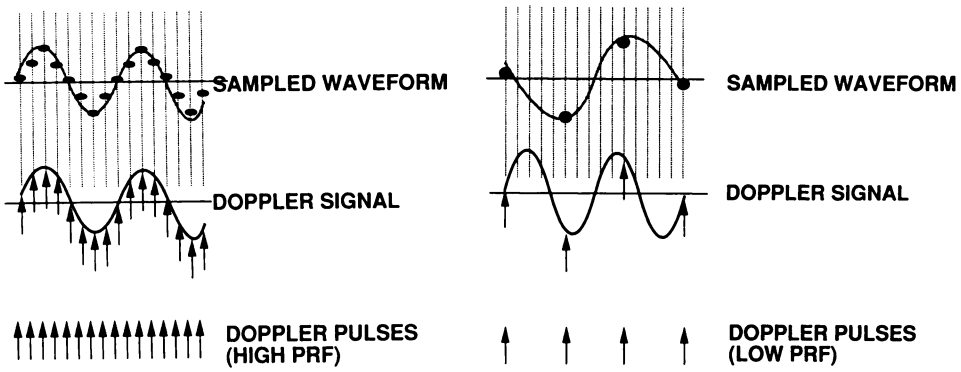



**Figure 9.** Diagrams illustrate effects of different pulse repetition frequencies (*PRF*). If the pulse repetition frequency is sufficiently high, the sampled waveform resembles the original waveform **(a)**. If the sampling frequency is too low as a result of a low pulse repetition frequency, the sampled waveform will have a lower frequency than the original **(b)**.

**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.

## INTERPRETATION OF DOPPLER INFORMATION

For the beginner, the interpretation of the graphic display of Doppler data may be difficult or confusing. Components of Doppler data that must be evaluated, both in spectral display and in color flow imaging, include the Doppler frequency shift and amplitude, the Doppler angle, the spatial distribution of frequencies across the vessel, and the temporal variation of the signal. Because the Doppler signal itself has no anatomic significance, the examiner must interpret the Doppler signal and then determine its relevance in the context of the image.

The clinical applications of Doppler US include the identification of vessels, the determination of the direction of blood flow, the evaluation of narrowing or occlusion, and the characterization of flow to organs and tumors. Analysis of the

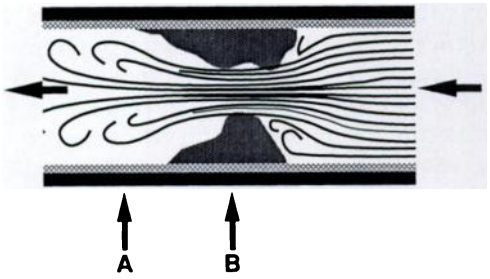
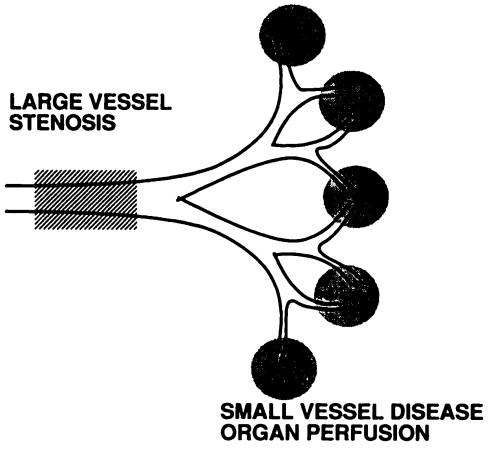
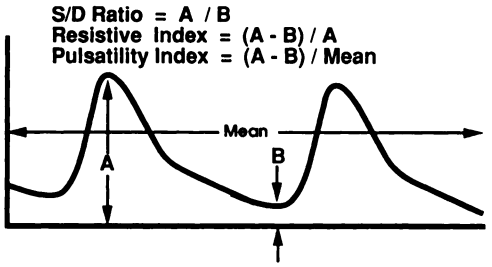



**Figure 10.** Diagram of a stenosed vessel. Measurements of peak systolic and diastolic velocity at the site of greatest narrowing (*B*) permit estimates of reduction of cross-sectional area of vessels. A broad Doppler spectrum indicates turbulent flow (*A*) and may provide clues to stenosis and other vascular abnormalities.




a.




b.

**Figure 11.** Doppler US is capable of providing information about flow in both large and small vessels (**a**). Small vessel changes may be identified using flow indexes reflecting the impedance or resistance of small vessels distal to the site of measurement (**b**). Commonly used Doppler indexes include the systolic/diastolic (*S/D*) ratio, the resistive index, and the pulsatility index. *A* = peak systolic frequency or velocity, *B* = end diastolic frequency or velocity.

Doppler frequency shift as it varies with time (ie, in the cardiac cycle) can also be used to infer both proximal stenosis and changes in distal vascular impedance. Most radiologists who have used pulsed Doppler US have emphasized the detection of stenosis, thrombosis, and flow disturbances in major peripheral arteries and veins. In these applications, measurements of peak systolic and end diastolic frequency or velocity, analysis of the Doppler spectrum, and calculation of certain frequency or velocity ratios have been the basis of analysis (Fig 10).

More recently, the use of Doppler US in the inference of abnormalities in the peripheral vascular bed of an organ or tissue has gained attention. Changes in the spectral waveform, which are measured in terms of indexes that compare flow during systole and diastole, provide insight into the resistance of the vascular bed supplied by the vessel and indicate changes caused by a variety of pathologic conditions (Fig 11). Changes in these indexes, compared with normal values, may be important in the early identification of rejection of transplanted organs, parenchymal dysfunction, and fetal compromise due to intrauterine growth retardation. Also, characteristic Doppler signals have been described that may eventually aid in differentiation of benign from malignant masses.

## CONCLUSION

Doppler US has now become an indispensable part of the US evaluation of most parts of the body. A solid understanding of Doppler principles is essential to use the full potential that flow information adds to the US examination.

## SUGGESTED READINGS


Burns PN. The physical principles of Doppler and spectral analysis. JCU 1987; 15:567–590.

Merritt CRB. Doppler color flow imaging. JCU 1987; 15:591–597.

Nelson TR, Pretorius DH. The Doppler signal: where does it come from and what does it mean? AJR 1988; 151:439–447.

Taylor KJ, Holland S. Doppler US. I. Basic principles, instrumentation, and pitfalls. Radiology 1990; 174:297–307.