

Blood Flow Hemodynamics, Cardiac Mechanics, and Doppler Echocardiography

THE CARDIAC CYCLE

Figure 4.1

The cardiac cycle showing superimposed hemodynamic and echocardiographic parameters. A4C: apical 4-chamber view; A5C: apical 5-chamber view; AC: aortic valve closure; AO: aortic valve opening; E- and A-waves: spectral Doppler depiction of early and late diastolic filling of the left ventricle; MC: mitral valve closure; MO: mitral valve opening; LA: left atrium; LV: left ventricle; left atrial "a" and "e" waves reflecting atrial pressures; EDV: end diastolic LV volume; ESV: end-systolic LV volume.

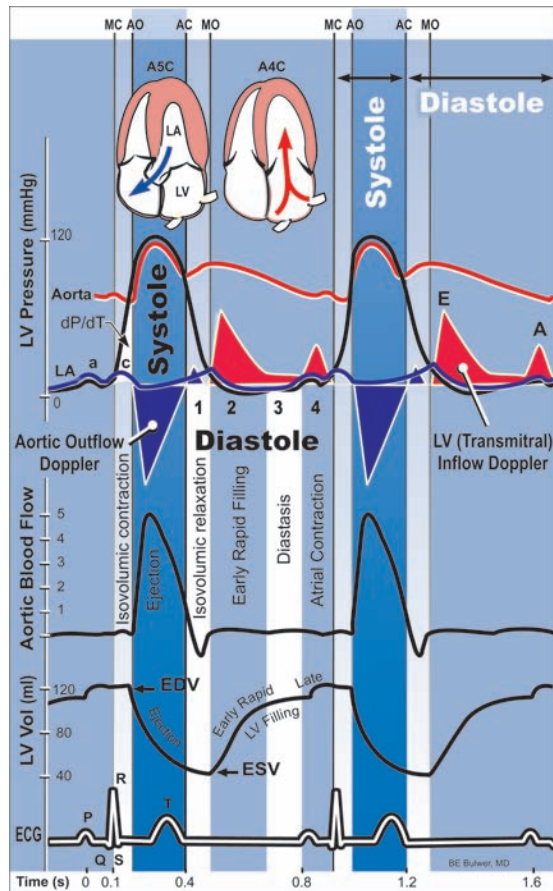
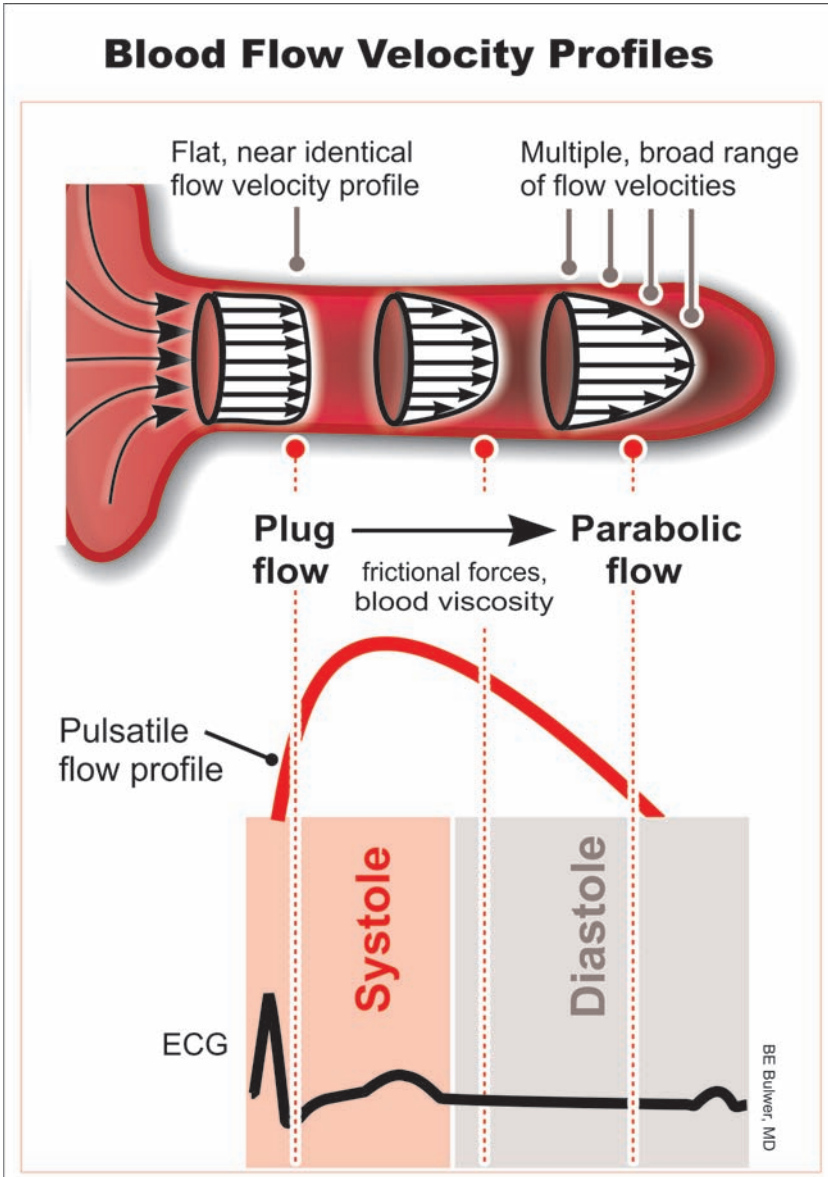


Figure 4.2

Flow velocity profiles in normal pulsatile blood flow. Normal blood flow through the heart and blood vessels, at any instant in time, is not uniform. There is a range or spectrum of velocities at each instant during the cardiac cycle. This spectrum, at each instant during the cardiac cycle, can be differentiated and displayed using Doppler echocardiography (see Figures 4.3–4.22).



BLOOD FLOW VELOCITY PROFILES

Doppler echocardiography can assess blood flow velocity, direction and flow patterns/profiles (e.g., plug), and laminar, parabolic, and turbulent flow (Figures 4.3–4.19). Crucial to understanding Doppler echocardiography is the need to understand certain basic characteristics of blood flow. Blood vessel size, shape, wall characteristics, flow rate, phase of the cardiac cycle, and blood viscosity all influence blood flow velocity profiles. Even within the cross-sectional area of a blood vessel, there exists a differential pattern of flow.

The range or spectrum of blood flow velocities widens or broadens at sites of blood vessel narrowing and near stenotic or regurgitant heart valves (Figures 4.7, 4.14, 4.15). Even within the normal heart and blood vessels, various blood flow velocity profiles are seen as vessels curve around valve orifices (Figures 4.7, 4.9, 4.14, 4.15, 4.17–4.19). Normal blood flow through the heart, however, is mostly *laminar* or streamlined, but exhibits *turbulence* or disorganized flow in the presence of diseased heart valves.

Laminar flow within cardiac chambers and great arteries generally exhibits an initial flat or *plug flow* profile during the initial systolic cardiac upstroke (Figures 4.2, 4.17, 4.19). With plug flow, almost all of the blood cells (within the sample volume) are flowing at the same velocity. On the time-velocity spectral Doppler display, this appears as a narrow band or range of velocities.

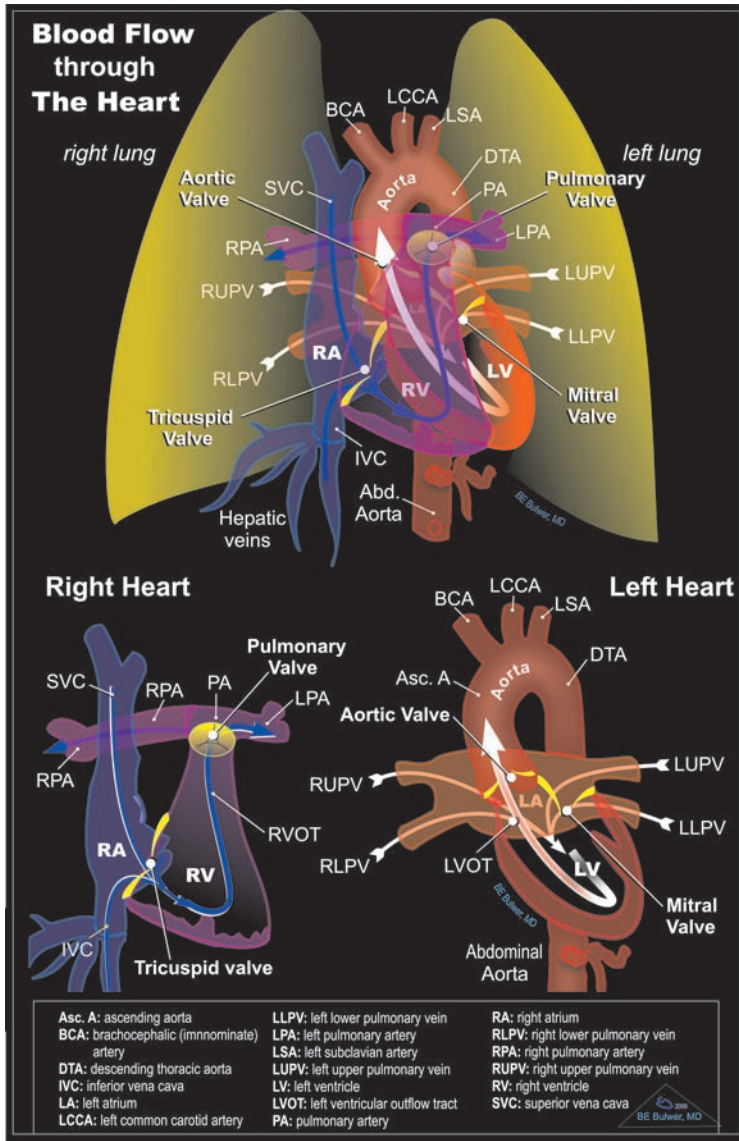
As blood flow proceeds, the velocity flow profile becomes more *parabolic*, especially within long straight vessels like the descending thoracic and abdominal aortae. With laminar flow, concentric streamlines (laminae) glide smoothly along the blood vessel. Laminar flow with a parabolic flow profile exhibits the highest (maximum) velocities at the axial center of the vessel (Figures 4.2, 4.17). Velocities are lowest, approaching zero, adjacent to the vessel wall.

Turbulent flow is disorganized blood flow and exhibits the widest range of flow velocities, including high-velocity and multidirectional flow (Figures 4.7, 4.14, 4.15). Turbulent flow is typically seen with obstructive and regurgitant valvular lesions, prosthetic heart valves, shunts, and arteriovenous fistulae (Figures 4.7, 4.14, 4.15).

NORMAL BLOOD FLOW THROUGH THE HEART

Figure 4.3

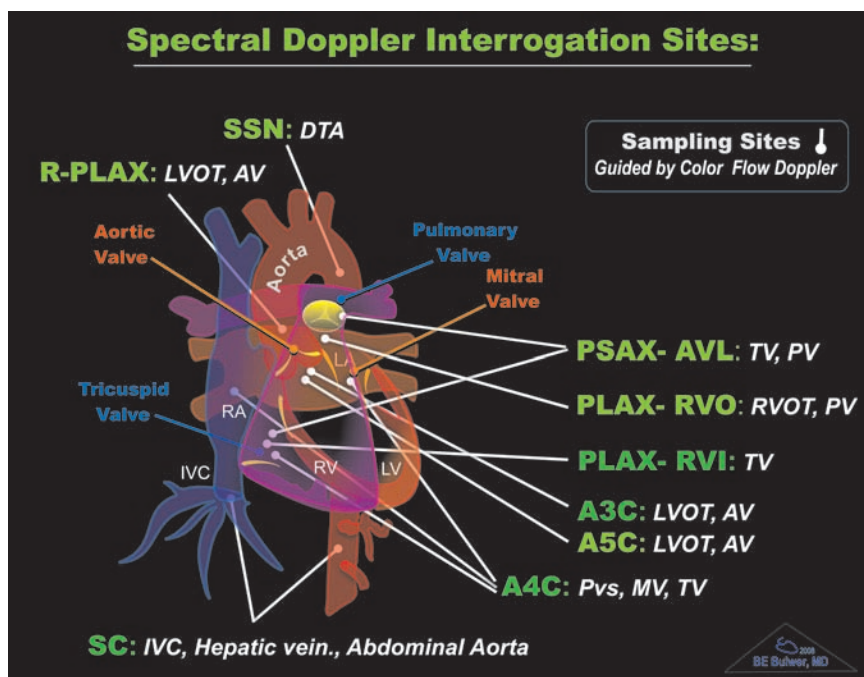
Normal blood flow patterns through the heart (anteroposterio projections). Right-sided deoxygenated flows returning to the heart en route to the lungs are shown in blue. Oxygenated flows returning to the heart from the lungs are shown in red. Isolated right and left heart flow patterns are shown below.



DOPPLER INTERROGATION SITES

Figure 4.4

Doppler echocardiography, both color flow Doppler and spectral Doppler, provides accurate noninvasive assessment of normal and abnormal intracardiac blood flow, and flow across the heart valves. AV: aortic valve; DTA: descenders thoracic aorta; IVC: inferior vena cava; LVOT: left ventricular outflow tract; LA: left atrium; LV: left ventricle; MV: mitral valve; PV: pulmonary valve; RVOT: right ventricular outflow tract; TV: tricuspid valve.



Assessment of blood flow velocities and flow patterns, made possible by Doppler echocardiography, are a routine part of the normal echocardiography examination. Two basic types of Doppler displays are used to assess blood flow velocities: the spectral Doppler time-velocity graph and color flow Doppler map (Figures 1.1, 4.6, 4.7, 4.12, 4.13, 4.16, 4.21).

The spectral Doppler time-velocity graph displays the spectrum of blood flow velocities found within the sample volume. The sample volume is the specified region interrogated during the Doppler exam. It ranges from a few millimeters in length (with pulsed-wave [PW] Doppler), to several centimeters in length (as with continuous-wave [CW] Doppler). CW Doppler is used to assess high-flow velocities, but lacks depth specificity, i.e., CW Doppler can measure the highest velocities, but it cannot accurately pinpoint the exact location where

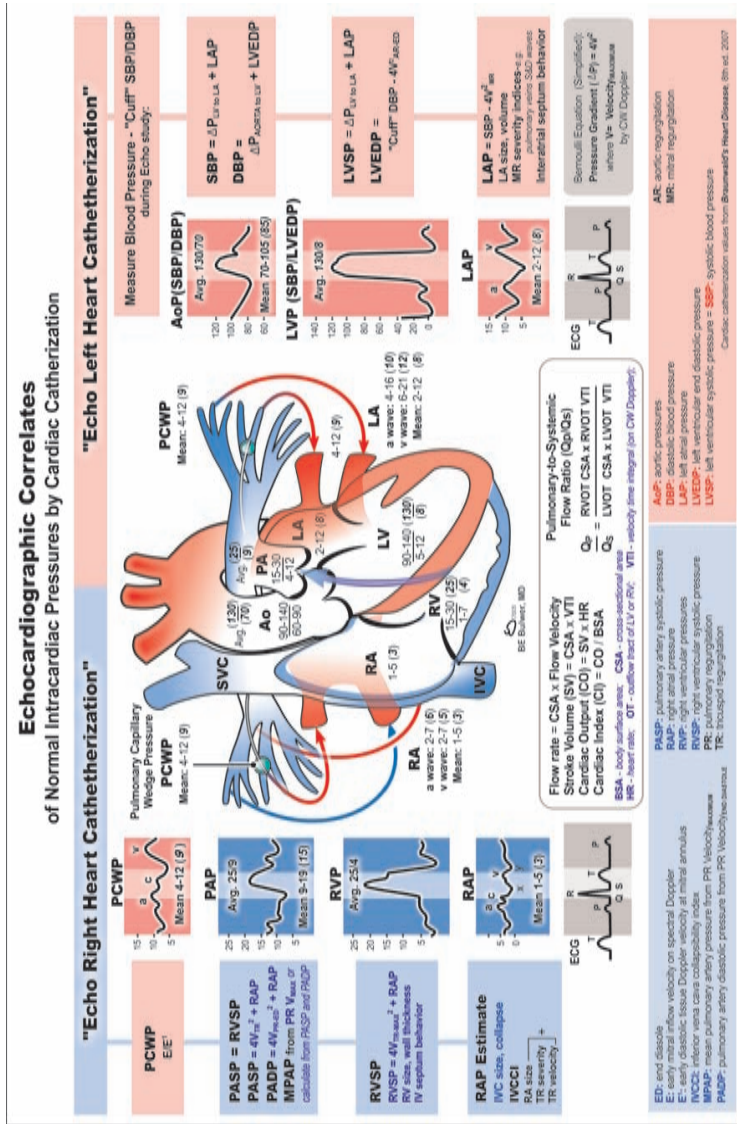
such high blood velocities occur. PW Doppler echocardiography, in contrast, measures flow at specific sites, but it is handicapped by a measurement artifact called *aliasing* that imposes a limit (*Nyquist limit*) on the maximum measurable velocity. Aliased velocities erroneously appear on the opposite side of the baseline (Figure 4.22).

Color flow Doppler imaging is a PW Doppler-based technique that displays blood flow velocities as real-time color flow patterns mapped within the cardiac chambers (Figures 4.9–4.13). Conceptually, this can be considered as a type of “color angiogram.” By convention, color flow Doppler velocities are displayed using the “BART” (Blue Away Red Toward) scale (Figures 4.9–4.11). Flow toward the transducer is color-coded red; flow away from the transducer is color-coded blue. Color flow Doppler is beset by the same flow velocity measurement limitations called *color aliasing*. This occurs even at normal intracardiac flow rates. In this case, however, aliasing appears as a color inversion, where flow blue switches to yellow-red, and vice versa (Figure 4.22). Turbulent flow appears as a mosaic of colors.

NORMAL INTRACARDIAC PRESSURES

Figure 4.5

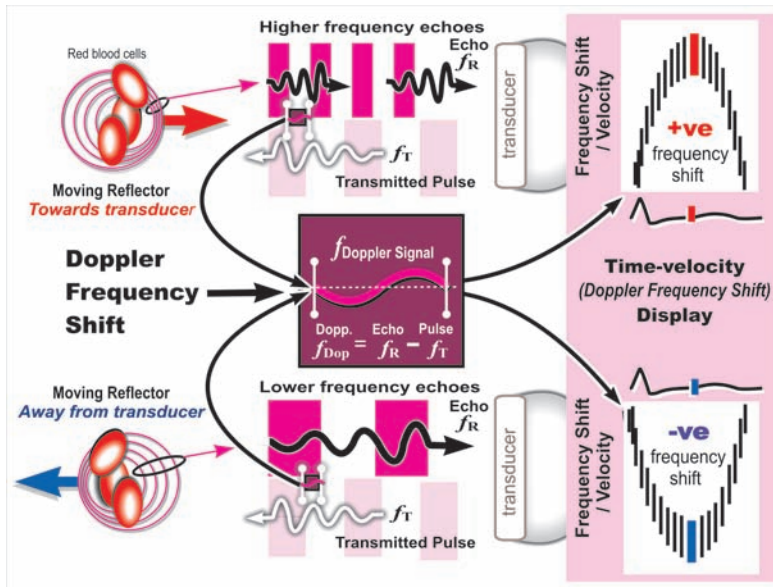
Doppler echocardiography is an accurate noninvasive alternative to cardiac catheterization for estimating blood flow hemodynamics, intracardiac pressures, and valvular function. The relationship between blood flow velocities and intracardiac pressures is quantitatively defined by the Bernoulli equation (see Figure 4.14).



DOPPLER FREQUENCY SHIFT

Figure 4.6

The Doppler frequency shift is a change or *shift* in the *frequency* of the returning echoes compared to the frequency of transmitted ultrasound waves. **Top panel.** When blood flows toward the transducer, the received echoes return at higher frequencies compared to the transmitted ultrasound—a positive frequency shift. **Bottom panel.** When blood flows away from the transducer, the converse is seen. **Central panel.** Doppler echocardiography uses this observed and measurable change in frequency—the Doppler frequency shift—to derive information on blood flow velocity and direction (see Figure 4.7). The Doppler frequency shift is itself a wave, with its own frequency characteristics.



The shift in frequency of the received echoes compared to that of the transmitted pulse—the Doppler frequency shift—is the basis for calculating blood flow velocities.

- **Negative frequency shift:** Echoes reflected from blood flowing away from the transducer have lower frequencies, compared to the transmitted ultrasound (Figures 4.6, 4.7).
- **Positive frequency shift:** Echoes reflected from blood flowing toward the transducer have higher frequencies, compared to the transmitted ultrasound (Figures 4.6, 4.7).
- **No frequency shift:** Echoes reflected from blood flowing perpendicular to the transducer exhibit no change in frequency, compared to the transmitted ultrasound (Figure 4.7).

$$\text{Doppler Frequency Shift (F}_{\text{Doppler}}) = F_{\text{Echo}} - F_{\text{Transducer Pulse}}$$

Figure 4.7

Simplified schema of the Doppler examination of flow velocities within the thoracic aorta as viewed from the suprasternal notch window. **Left column.** Note (blue) flow in the descending thoracic aorta away from the transducer, the associated negative Doppler frequency shift, and corresponding time-velocity spectral display below the baseline. **Center.** Doppler examination of (red) flow in the ascending aorta shows just the opposite pattern—a positive Doppler frequency shift with velocities displayed above the baseline. **Right column.** During turbulent flow, as in aortic stenosis, higher velocities and a wider range of velocities is evident. Note the broadening of the spectral Doppler time-velocity display—a reflection of a wider range of velocities—appears as a “filled-in” window. Compare with Figure 4.9.

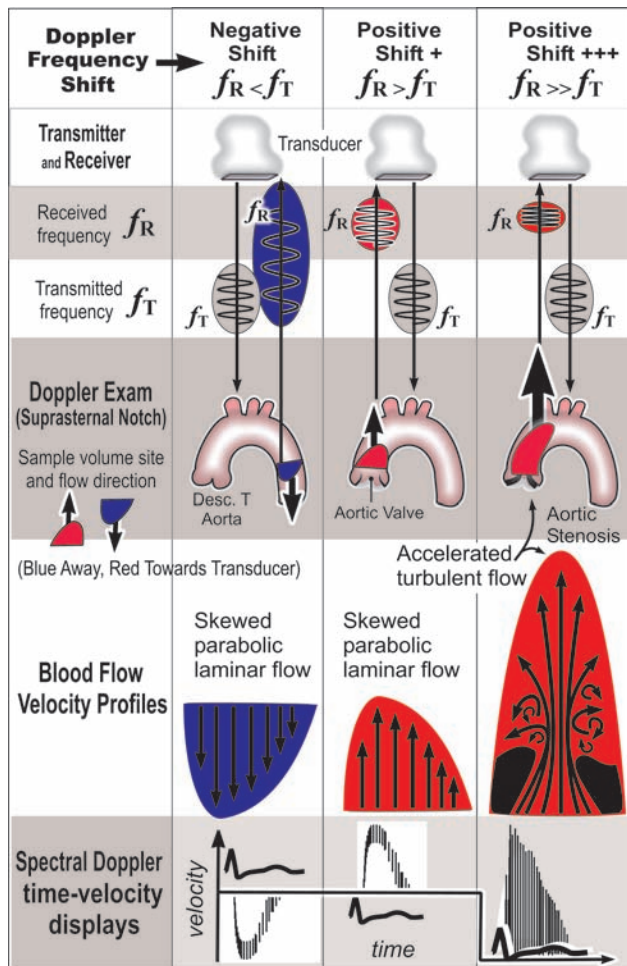


Figure 4.8

The Doppler angle and the Doppler equation. Doppler assessment of blood flow velocities is most accurate when the transducer ultrasound beam is at a Doppler angle of 0° or 180° , i.e., when aligned parallel to blood flow direction. The larger the Doppler angle or the less parallel the alignment, the greater will be the underestimate of true blood flow velocity.

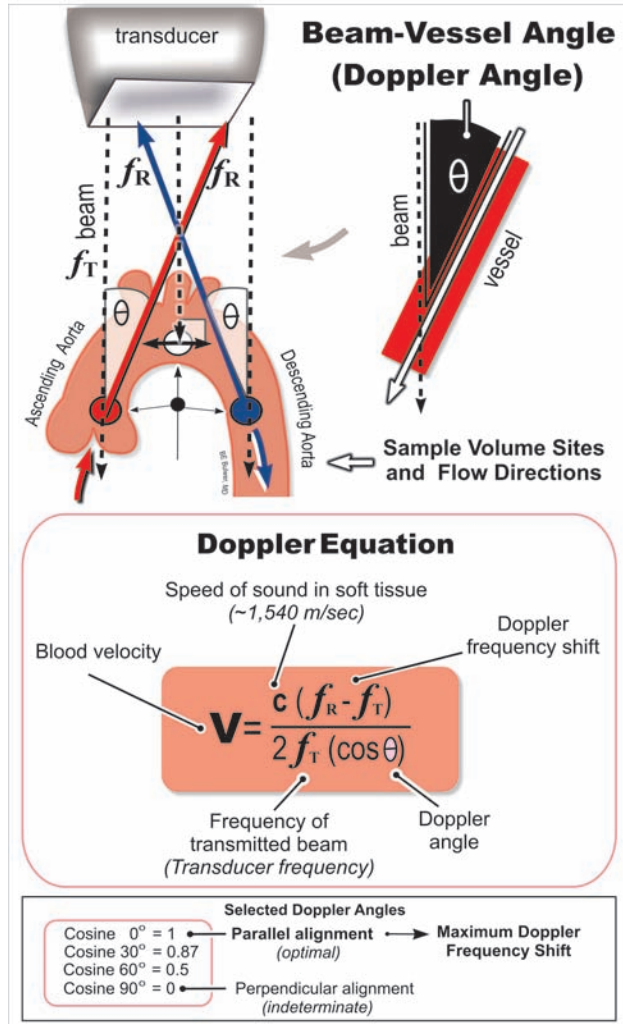
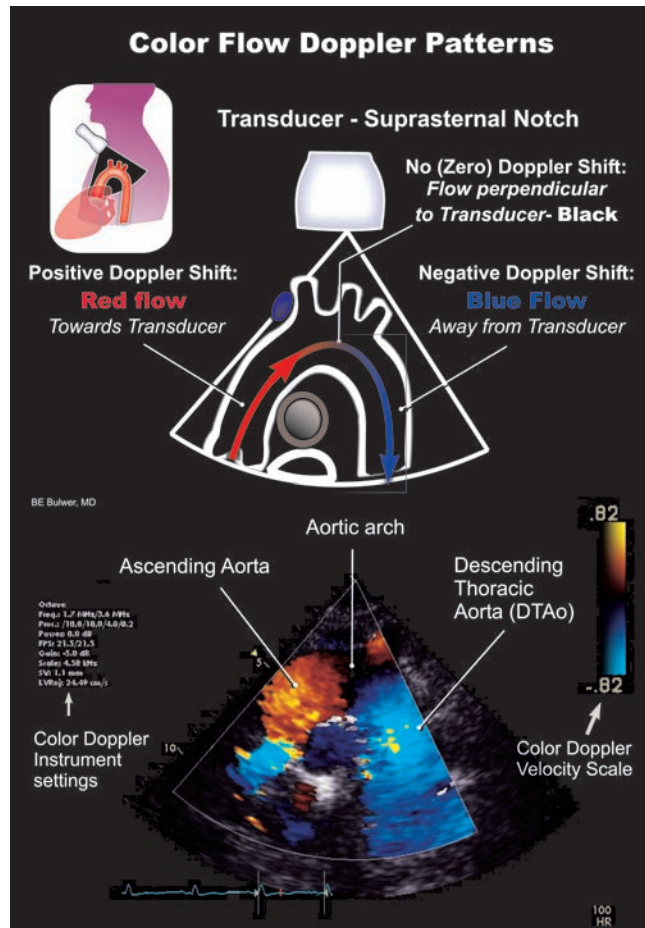


Figure 4.9

Color flow Doppler patterns viewed from the suprasternal notch. Note the flow velocity patterns based on the conventional “BART” (Blue Away Red Toward) scale. Compare this with Figures 4.7, 4.10–4.12. Although the above image shows a wide-angle color scan sector (that covers the entire aortic arch), a narrow color scan sector (that focuses on a narrower region) is recommended. To optimize the color flow Doppler recording: (i) narrow the scan sector, (ii) image at shallower depths (i.e., more superficial structures), (iii) optimize color gain settings, and (iv) set color velocity scale at maximum allowed Nyquist limit for any given depth (generally 60–80 m/s).



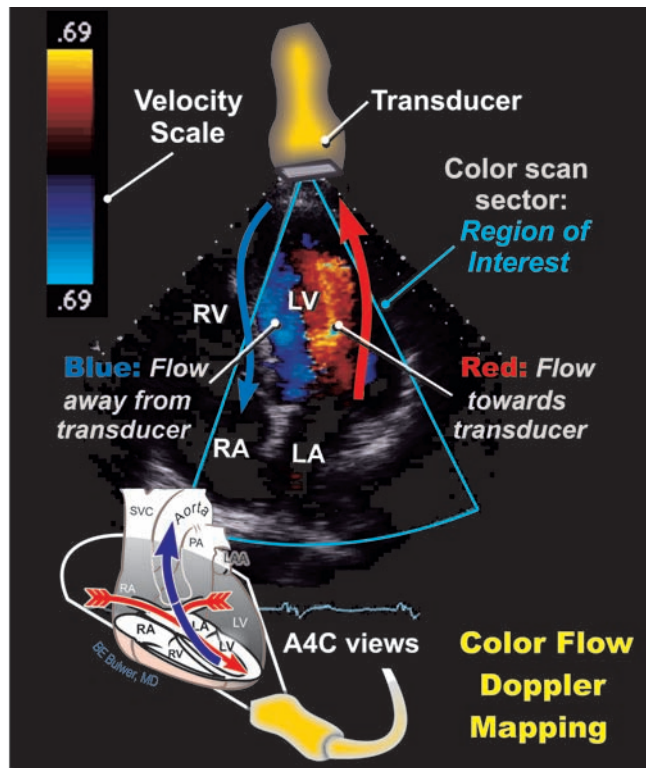
CLINICAL UTILITY OF COLOR FLOW DOPPLER ECHOCARDIOGRAPHY

Color flow Doppler imaging provides information on blood flow direction, velocity, and flow patterns, e.g., laminar versus turbulent flow, by displaying blood flow as color-coded velocities superimposed in real time on the 2D or M-mode image (Figures 4.9, 4.10).

This “angiographic” display is a more intuitive depiction of blood flow velocities, and it is extremely useful for the preliminary assessment of blood flow characteristics during the examination. For this reason, color flow Doppler imaging is the initial Doppler modality to use when interrogating flows within cardiac chambers and across valves, and it serves as an important guide for subsequent placement of the sample volume during PW and CW Doppler examination (Figure 4.16).

Figure 4.10

Color flow Doppler convention “BART” scale: **B**lue **A**way, **R**ed **T**oward. Apical four-chamber (A4C) view showing the color flow Doppler map superimposed on a B-mode 2D image. Flow direction during early systole reveals (blue) flow along the left ventricular outflow tract moving away from the transducer. The red color flow indicates flow toward the apex of the left ventricle, i.e., toward the transducer.



COLOR FLOW DOPPLER VELOCITY AND VARIANCE SCALES

Figure 4.11

Color Doppler scales are velocity reference maps. The standard red-blue velocity "BART" scale (left), the variance scale (center), and the color wheel (right) depicting the concept of color aliasing (wrap around) are shown. Variance maps employ an additional color, usually green, to emphasize the wider spectrum of multidirectional velocities present during turbulent flow.

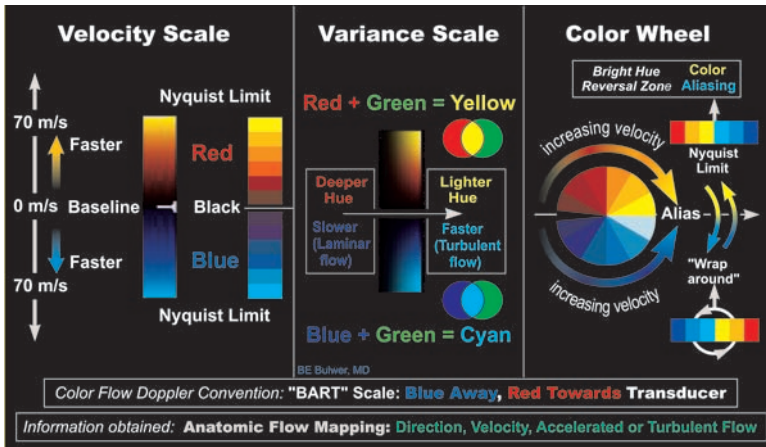
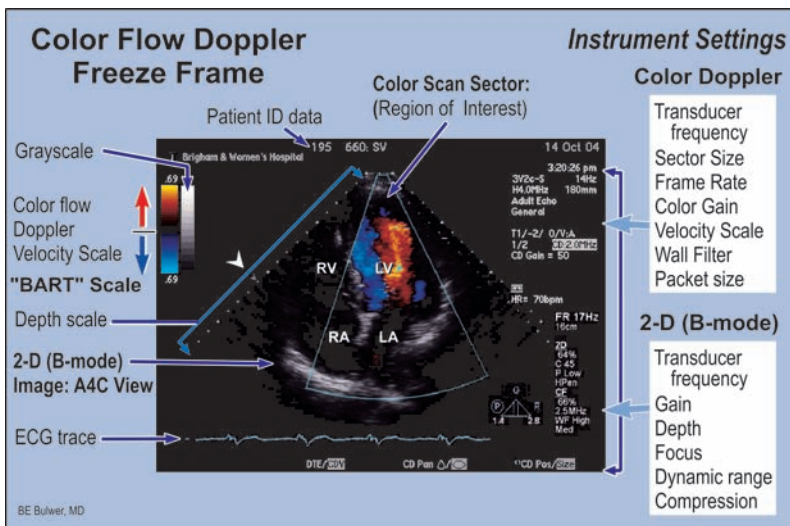


Figure 4.12

Color flow Doppler freeze frame showing components, variables, and instrument settings.



INSTRUMENT SETTINGS INFLUENCING COLOR FLOW DOPPLER IMAGING AND DISPLAY

Main factors (Figures 4.12, 4.13, 4.22):

- **Transmit power:** acoustic power output
- **Color gain setting:** amplifies the strength of the color velocities; avoid too much or too little gain
- **Transducer frequency:** trade-off between image resolution and tissue penetration; influences color jet size (for example, in mitral regurgitation)
- **Color velocity scale, Pulse-repetition frequency (PRF):** higher PRFs reduce aliasing but reduce sensitivity to low-flow velocities; lower PRFs increase the sensitivity to detect lower-flow velocities, but increase aliasing
- **Baseline shift:** determines range of color velocities displayed in a particular direction on the color velocity scale. This adjustment is also necessary for the assessment of the severity of valvular regurgitation and stenosis using the proximal isovelocity surface area (PISA) method (see Chapter 6, Figures 6.25, 6.26).
- **Color scan sector size:** improved frame rate and hence color display quality with narrow color scan sector
- **Packet (burst, ensemble) size and line density:** set at medium—a trade-off between measurement accuracy, image resolution, and frame rate
- **Focus:** color flow imaging is optimal at the focal zone

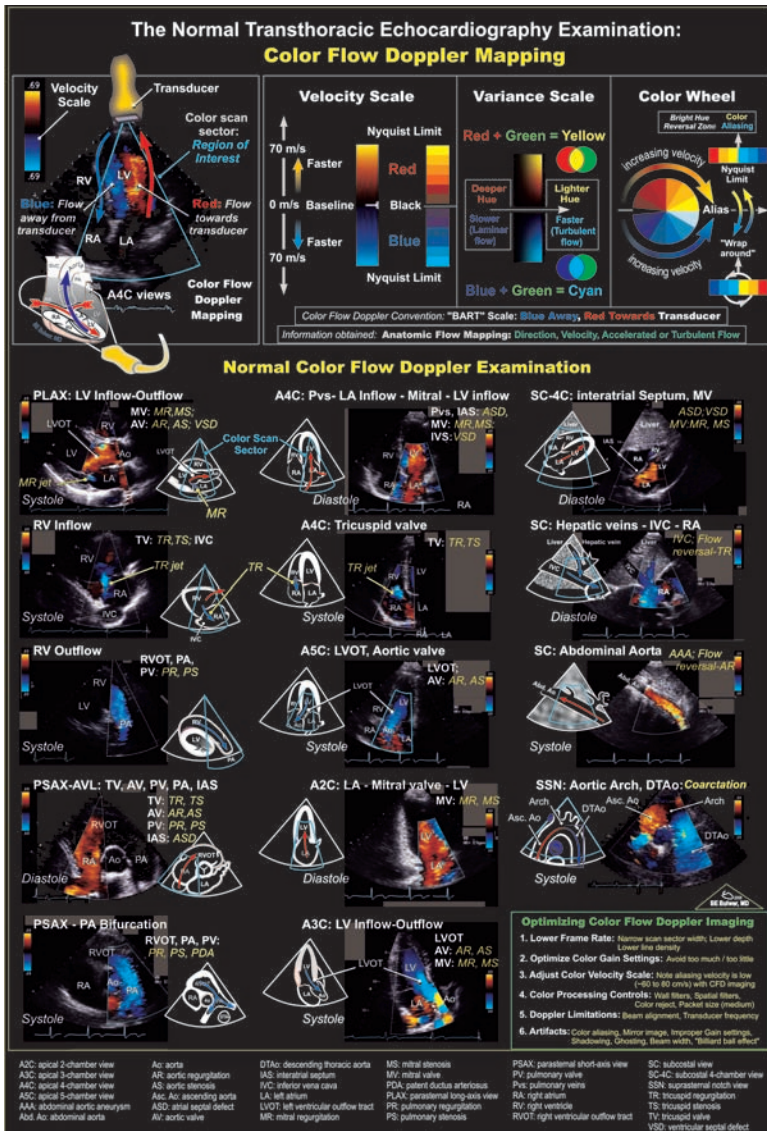
Other factors:

- **Persistence (smoothing, temporal filtering):** a higher setting delivers a smoother image, but lowers image resolution
- **Wall filter (threshold/high-pass filter):** this setting reduces artifacts due to vessel wall motion

COLOR FLOW DOPPLER EXAMINATION SUMMARY

Figure 4.13

Summary chart of the color flow Doppler examination. The color flow Doppler exam is an integral part of the standard transthoracic examination (see Table 5.4, Figures 4.21 and 5.4). As outlined in the standard transthoracic examination protocol, color flow Doppler is used to interrogate specific heart valves and chambers after optimizing the 2D image. Color flow Doppler-guided pulsed wave (PW) and continuous-wave (CW) Doppler examination typically follow.



OPTIMIZING COLOR FLOW DOPPLER CONTROLS

Modern echocardiography instruments have important controls for optimizing the color flow Doppler examination (Figures 3.4, 4.12). Each laboratory should implement internal standards that conform to the recommended instrument settings guidelines.

In general, the following practical steps to optimize color flow Doppler imaging should be employed as the transthoracic examination proceeds.

- **Optimize the 2D (or M-mode) image for optimal Doppler beam alignment:** Color Doppler, like all other Doppler techniques, is angle dependent. Parallel alignment is required for optimal color velocity assessment. The region of interest should therefore be optimally aligned (Figures 4.10, 4.12, 4.13).
- **Activate color flow Doppler imaging mode:** On/off knob or switch. During the transthoracic examination, the normal sequence is to (i) optimize the 2D image, (ii) apply color Doppler imaging, and (iii) use the color flow display as a guide to spectral (PW, CW) Doppler sample volume placement (Figure 4.16).
- **Use the narrowest color scan sector (smallest color window):** In general, the active color window or scan sector should be made as small as is necessary to increase frame rate, reduce aliasing, minimize artifact error, and improve overall color resolution/sensitivity (Figures 4.10, 4.12).
- **Adjust color gain control:** The color gain setting is a major determinant of the appearance of the color Doppler flow. Too little color gain can cause the jet to appear smaller or disappear altogether. Excessive gain can cause the jet to appear much larger, thereby overestimating, for example, the valvular regurgitation severity. To optimize this setting, increase the color gain until color pixels start “bleeding” into the B-mode (grayscale) tissue. Stop increasing at this point, then slightly reduce color gain to eliminate such “bleeding.”
- **Color velocity scale/pulse-repetition frequency (PRF):** Lowering the velocity scale, i.e., lowering the PRF, enables the detection of lower velocities and hence a larger color jet, but the tradeoff is increased color aliasing. Increasing the velocity scale, i.e., at a higher PRF, reduces color aliasing, but results in a smaller jet. Aliasing on color flow Doppler manifests as “color inversion” or “wrap around” (Figures 4.11, 4.22).

PRESSURE-VELOCITY RELATIONSHIP: THE BERNOULLI EQUATION

Figure 4.14

The velocity of flow across a fixed orifice, e.g., a stenotic heart valve, depends on the pressure gradient or difference (ΔP , "driving pressure") across that orifice. The Bernoulli principle and equation describes this relationship. It serves as the basis of converting blood flow velocities measured by Doppler into intracardiac pressures and pressure gradients. When the proximal velocity (V_1) is significantly smaller (and ~ 1 m/s) than the distal velocity (V_2), the former can be ignored and the simplified form ($P = 4V^2$) is used. P = intracardiac pressure gradient and V = blood flow velocity. ρ = mass density of blood.

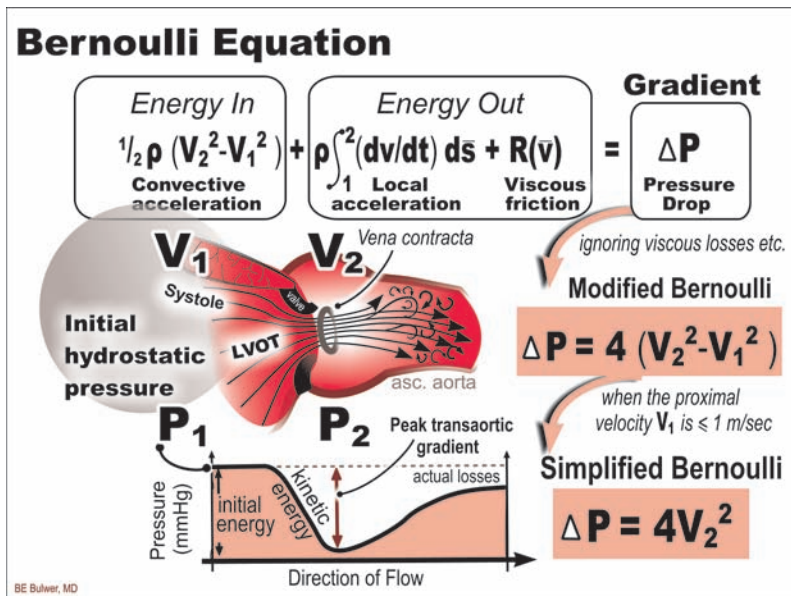


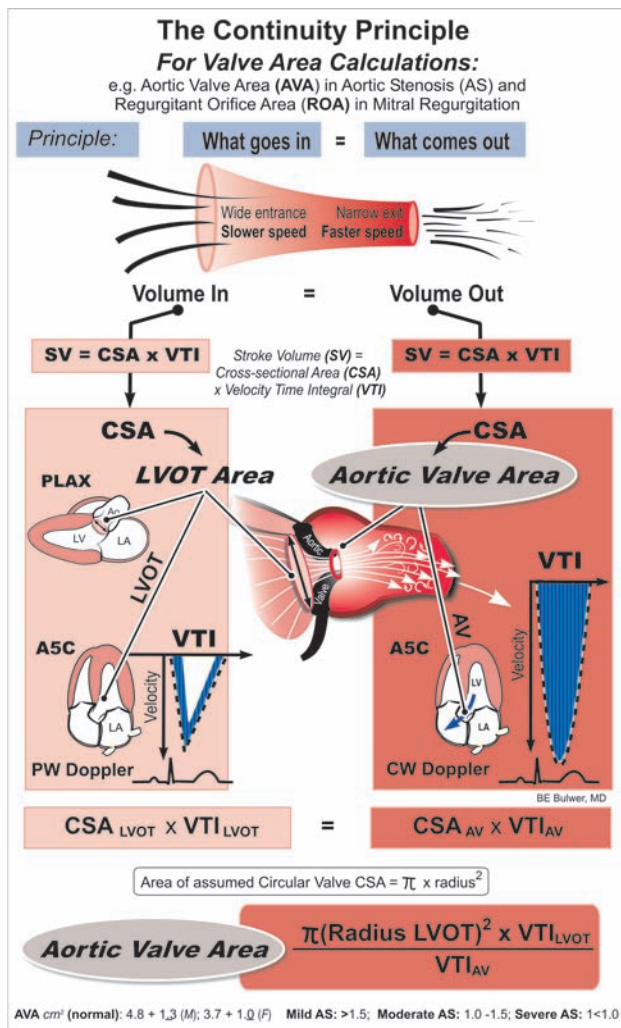
Table 4.1 NORMAL INTRACARDIAC BLOOD VELOCITIES (M/SEC) AND DOPPLER MEASUREMENT SITES

Valve/vessel	Mean	Range	Echo windows/views
Mitral valve	0.90	0.6–1.3	A4C, A2C, A3C
LVOT	0.90	0.7–1.1	A5C, R-PLAX
Aorta	1.35	1.0–1.7	A5C, SSN
Tricuspid valve	0.50	0.3–0.7	RV inflow, PSAX-AVL, A4C
Pulmonary artery	0.75	0.6–0.9	RV outflow, PSAX-AVL

Source: Adapted from: Hatle L, Angelsen B. *Doppler Ultrasound in Cardiology: Physical Principles and Clinical Applications*, 2nd ed. Philadelphia: Lea & Febiger, 1985.

Figure 4.15

The continuity principle applied to the calculation of valve area in aortic valvular stenosis. The calculation of proximal isovelocity surface area (PISA) in valvular heart disease, particularly in mitral regurgitation, is another widely used application of the continuity equation. *A5C*: apical 5-chamber view; *LVOT*: left ventricular outflow tract.



GRAPHICAL DISPLAY OF DOPPLER FREQUENCY SPECTRA

To generate the spectral Doppler display (Figures 4.6, 4.16–4.21), the received raw echo signals must be processed to extract the Doppler frequency shifts, from which are derived blood flow velocities.

Like a prism that separates white light into its spectral colors, and the cochlea that separates audible sounds into its spectrum of frequencies, so must the raw Doppler data be transformed into a spectrum of Doppler frequency shifts (that correspond to blood flow velocities (Figure 4.2)). This is achieved using a computational analysis called the fast Fourier transformation. Within each vertical spectral band, there is a range of Doppler frequency shifts—maximum and minimum—that corresponds to the range of velocities present within the sample volume at each measured instant in time (Figure 4.18). This range or spectral band is narrow, or broad, depending on the range of flow velocities found within the sampled blood volume. How narrow, or how broad this band is, is a reflection of the blood flow profile—whether plug, or parabolic, or turbulent (Figures 4.7, 4.15, 4.17–4.20).

A plot of Doppler frequency spectra displayed in real time during the cardiac cycle generates the time-velocity spectral Doppler display, variously called the Doppler velocity profile, envelope, or flow signal (Figures 4.16–4.22). Therefore, time-velocity spectral Doppler display reveals a number of important characteristics about the interrogated blood flow:

1. **The range or spectral band of Doppler frequency shifts:** These correspond to the range of blood flow velocities within the sample volume at each instant during the cardiac cycle. The spectral distribution of Doppler shifts at a given instant in time is a measure of flow characteristics, e.g., plug versus parabolic or turbulent flow patterns. With PW Doppler, plug flow (during the early systolic upstroke) exhibits a narrow range or spectrum of Doppler frequency shifts, which manifests as a narrow spectral band with a resultant spectral “window” (Figures 4.6, 4.16–4.22). In later systole, and during diastole, this spectral band broadens due to laminar parabolic flow, i.e., blood with a broader range of velocities. Turbulent flow exhibit the widest range of velocities—regardless of the phase of the cardiac cycle—and appear as broad spectral bands (spectral broadening) with a “filled-in” spectral window on PW Doppler. The Doppler window is characteristically absent or filled-in on the CW Doppler display. This reflects the wide range of velocities normally found within the large CW Doppler sample volume (Figures 4.20–4.22).
2. **Positive, negative, or no Doppler frequency shift:** This indicates the presence and the direction of blood flow (Figures 4.6–4.22). Positive shifts are displayed above the baseline, and they are indicative of flow toward the

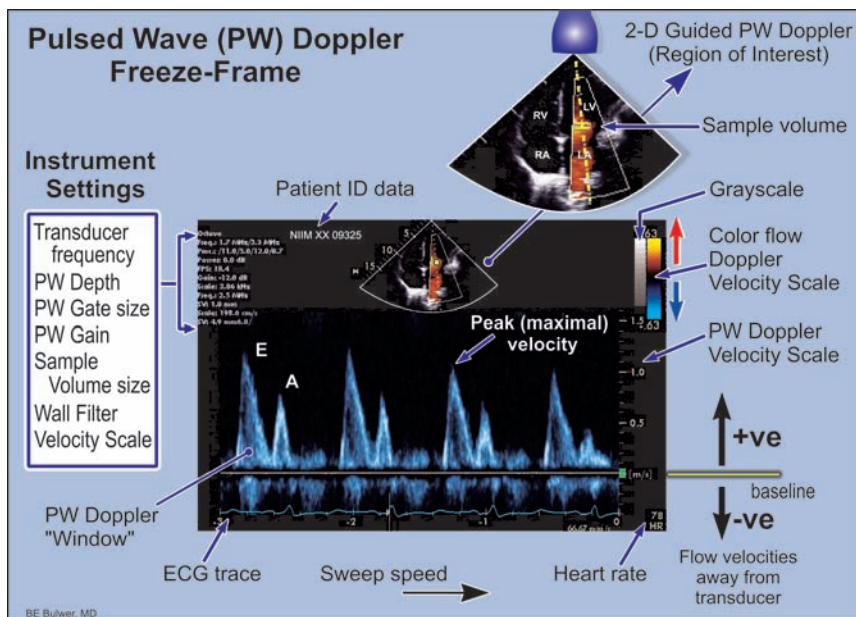
transducer. Negative shifts are displayed below the baseline, indicating flow away from the transducer (Figures 4.6–4.10). No measured Doppler shifts, or zero flow, results when the Doppler angle is 90° , or when flow is absent, or the sample volume is beyond the range of the transducer.

3. **The amplitude of the Doppler frequency shifts:** This is apparent from the intensity or brightness of the Doppler display, and corresponds to the percentage of blood cells exhibiting a specific frequency within the individual (vertical) Doppler spectral band (Figures 4.17–4.20).

The Doppler frequency shifts are also within the audible range (0–20 kHz), and such audio signals can guide Doppler sample volume placement, especially when using the dedicated nonimaging (pencil or Pedoff) Doppler probe.

Figure 4.16

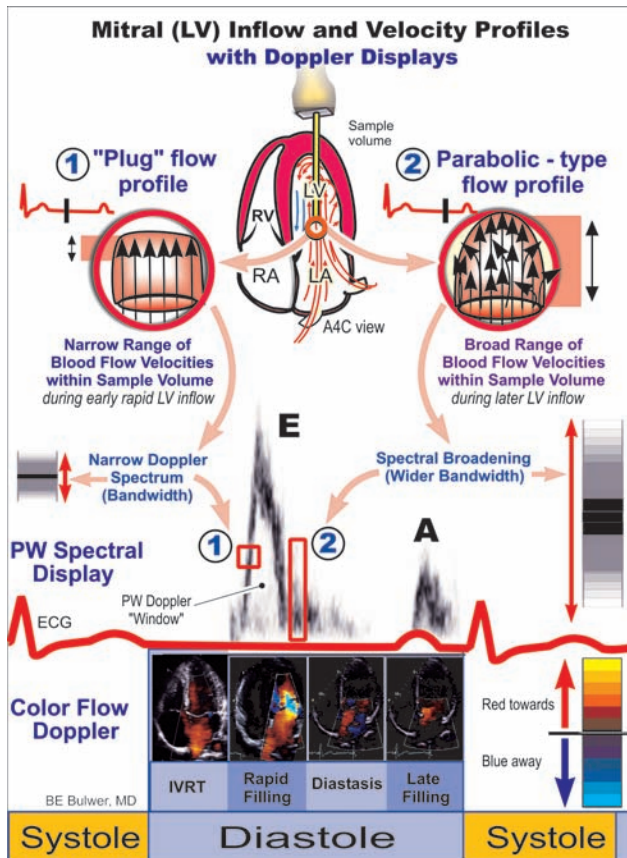
The PW Doppler spectral display showing normal mitral inflow (left ventricular filling) patterns obtained from the apical 4-chamber (A4C) view. With PW Doppler imaging, optimal information is derived when close attention is paid to proper technique, including optimal transducer alignment (Doppler angle), as well as the appropriate instrument settings (see Table 4.2).



PULSED DOPPLER VELOCITY PROFILE: LEFT VENTRICULAR (TRANSMITRAL) INFLOW

Figure 4.17

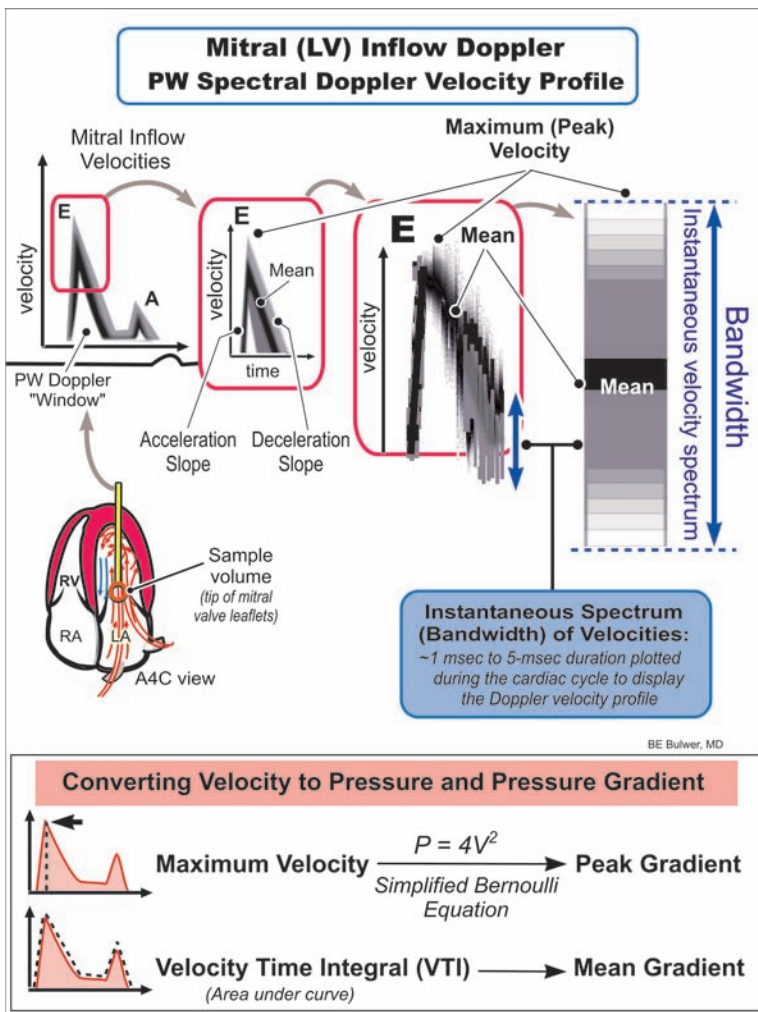
Normal transmitral left ventricular inflow: velocity profile and Doppler patterns. During early diastole (1), early rapid inflow exhibits "plug" laminar flow pattern where blood cells are moving en masse at almost the same velocity—hence a narrow spectrum is seen on the pulsed wave (PW) Doppler spectral display. As diastole proceeds (2), a more parabolic laminar flow profile ensues where a much broader range of flow velocities—hence a broader spectrum—is seen. Note the corresponding color flow Doppler patterns (with color-coded mean flow velocities).



PW DOPPLER AND VELOCITY PROFILE: MEAN AND MAXIMUM VELOCITIES

Figure 4.18

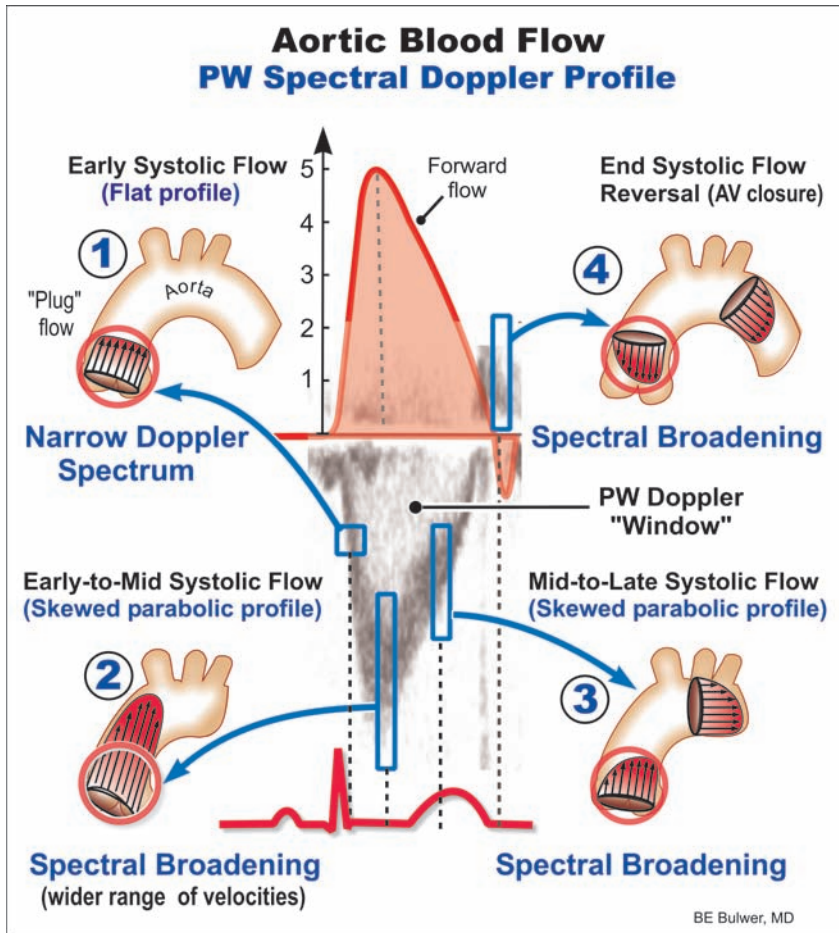
Pulsed-wave (PW) Doppler spectral display of the transmitral LV inflow (compare with Figure 4.17). *Above, from left to right:* Closer scrutiny of the spectral Doppler display reveals vertical bands (spectra) representing the Doppler frequency shifts/blood flow velocities at each measured instant in time (milliseconds). Each vertical spectral band shows the range of velocities—maximum and minimum—present in each measurement. This spectral band is narrow, or broad, depending on the range of flow velocities found within the sampled blood volume. How narrow, or how broad this band is, is a reflection on the blood flow profile—whether plug, or parabolic, or turbulent. E and A waves represent early and late diastolic filling, respectively. *Below:* Doppler-derived blood flow velocities can be converted into pressure gradients using the Bernoulli equation (see Figure 4.14).



PULSED DOPPLER VELOCITY PROFILE: LEFT VENTRICULAR OUTFLOW

Figure 4.19

Simplified schema of flow velocity profiles and corresponding pulsed-wave Doppler display in the ascending aorta as measured from the apical 5-chamber (A5C) view. **1.** During early ejection, plug flow predominates—and hence a narrow spectrum or range of flow velocities is seen on the spectral display. **2 and 3.** As systole ensues, drag forces contribute to a more parabolic type flow profile with a wider spectrum of velocities. **4.** During late systole, some amount of backflow occurs within the ascending aorta. This manifests as “positive” (above the baseline) flow and results in aortic valve closure.



CONTINUOUS-WAVE (CW) DOPPLER: PEAK AND MEAN VELOCITIES AND GRADIENTS

Figure 4.20

Continuous-wave (CW) spectral Doppler display of the aortic outflow using the apical 5-chamber view. Note the wide spectrum of frequencies/velocities that broaden the Doppler frequency spectrum. Compared to the PW Doppler display (Figure 4.19, the CW spectral displays show spectral broadening with a “filled-in” Doppler window). This is a reflection of the large CW Doppler sample volume, wherein lies a broad range of blood flow velocities.

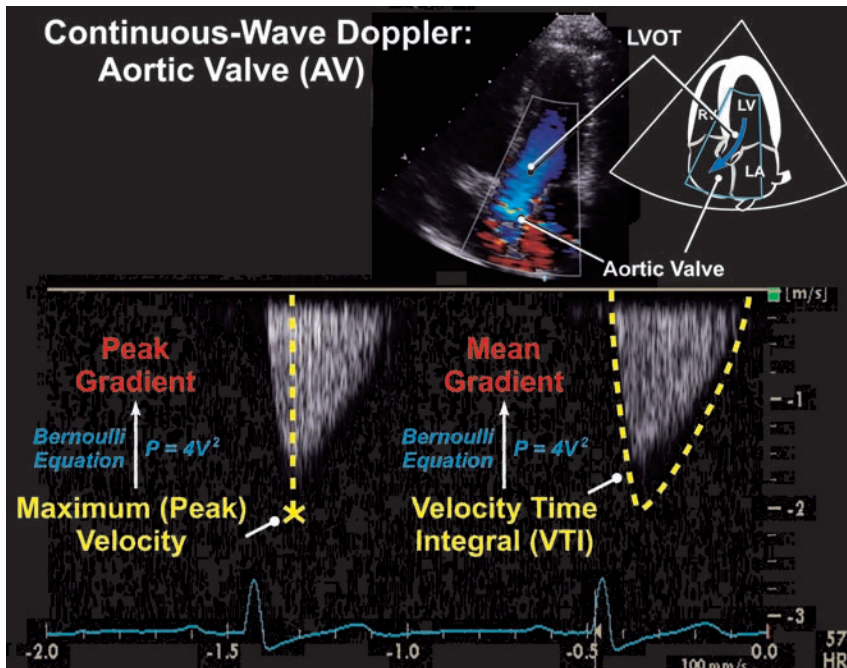


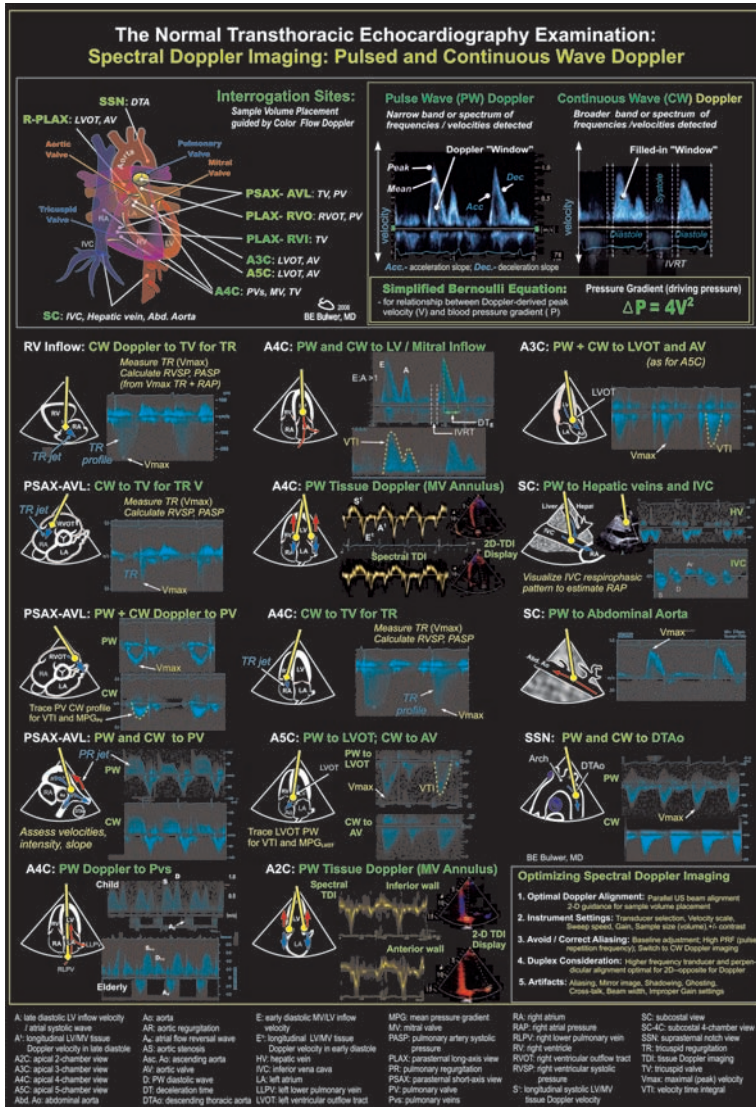
Table 4.2 OPTIMIZING THE SPECTRAL DOPPLER EXAMINATION

1. Optimize beam-vessel alignment: minimize Doppler angle (see Fig. 4.8).
2. Color flow Doppler-guided placement of Doppler sample (see Fig. 4.16).
3. Adjusting baseline and velocity scales settings (see Fig. 4.16).
4. Doppler gain settings: minimize noise and artifact.
5. Wall filter settings: minimize low frequencies (from vessel wall and valves) to optimize appearance of spectral Doppler display.
6. Sample volume size/Gate length: normally a sample volume of 2 to 5 mm is best for PW. Larger sample volumes diminish range specificity and broaden the Doppler spectrum.
7. Doppler harmonic imaging.
8. Doppler contrast imaging.

SPECTRAL DOPPLER EXAMINATION SUMMARY

Figure 4.21

Summary chart of the spectral Doppler examination. The spectral Doppler exam is an integral part of the standard transthoracic examination (see Table 5.4, Figures 4.21 and 5.4). As outlined in the standard transthoracic examination protocol, spectral Doppler is used to interrogate specific heart valves and chambers after optimizing the 2D image. The pulsed-wave (PW) and continuous-wave (CW) Doppler examination typically follow the color flow Doppler examination, which serves as a useful guide to optimal positioning of the spectral Doppler sample volume. This is especially useful when assessing abnormal flow patterns.



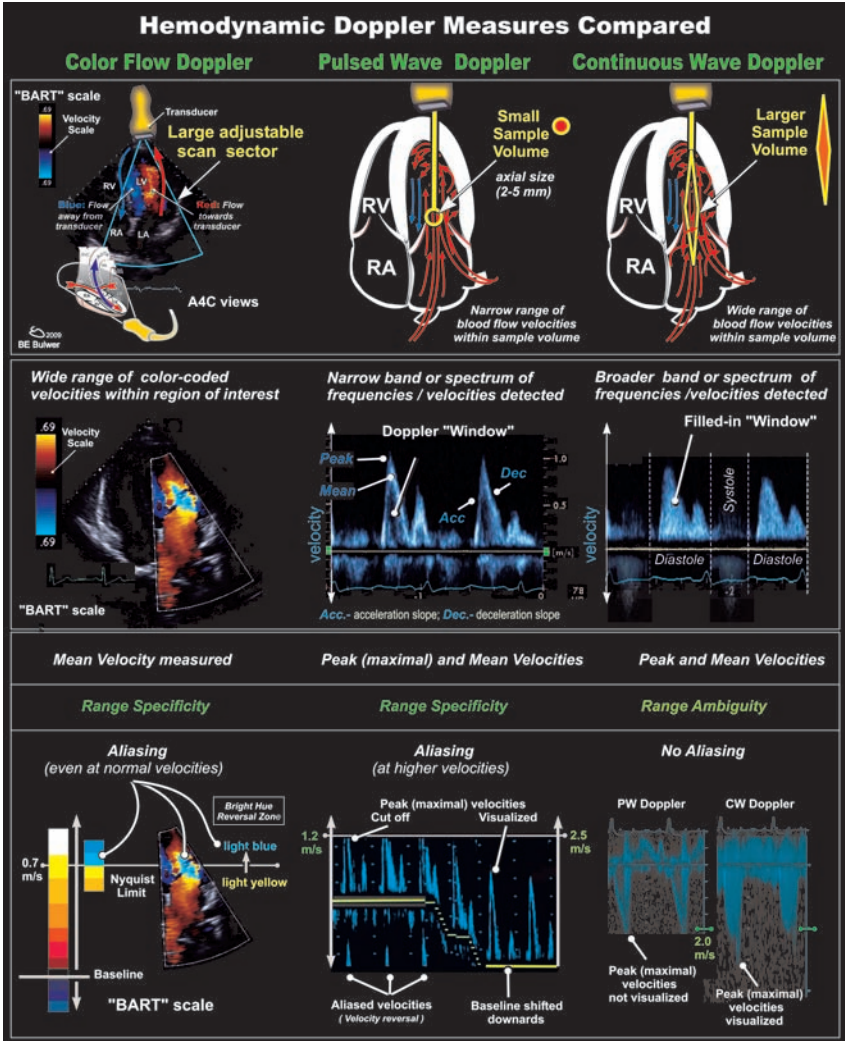
COMPARISON: CW, PW, AND COLOR FLOW DOPPLER**Table 4.3** COMPARISON OF THE MAJOR DOPPLER MODALITIES USED IN ECHOCARDIOGRAPHY

	Continuous-wave (CW) Doppler	Pulsed-wave (PW) Doppler	Color flow Doppler
Sample volume	Large (measured in cm)	Small (2-5 mm)	Large (adjustable color scan sector size)
Velocities measured	A spectrum: maximum-to-minimum (hence the term “spectral” Doppler)	A spectrum: maximum-to-minimum (hence the term “spectral” Doppler)	Mean velocity (each color pixel or voxel codes for mean velocity and flow direction on “BART” scale)
Display format	Time-velocity spectral graph	Time-velocity spectral graph	Color-coded velocity pixels (2D) and voxels (3D) superimposed on B-mode image
Spectrum of blood flow velocities detected and displayed	Wide; Spectral broadening (no “window” seen on time-velocity graphical display)	Narrow; Spectral window (but spectral broadening seen with turbulent flows)	Wide; Wide spectrum of velocities displayed as color mosaic—green color added to conventional “BART” scale
Detection of high blood flow velocities	No aliasing; accurate assessment	Aliasing; inaccurate assessment with high flow velocities	Color aliasing (even with normal intracardiac flows)
Aliasing artifact and display see Fig. 4.22	No aliasing; no Nyquist velocity limit; peak velocities on the correct side of baseline	Aliasing; Nyquist limit; aliased velocities appear on opposite side of baseline	Aliasing; color aliasing appears as color inversion on BART scale (e.g., light blue-light yellow and vice versa)
Depth resolution/ range ambiguity	Range ambiguity	Range resolution (single gate)	Range resolution (multiple gates)

2D: two-dimensional echocardiography; 3D: three-dimensional echocardiography; BART: “Blue Away Red Toward”

Figure 4.22

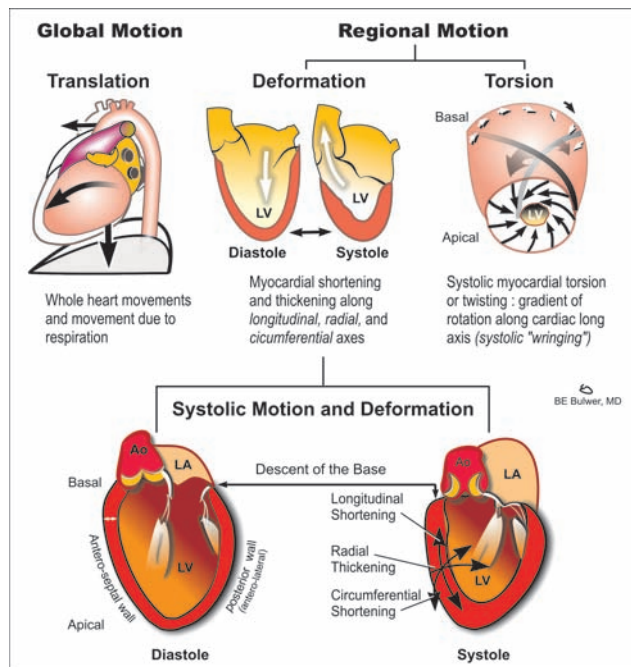
Comparison of hemodynamic Doppler measures. See Table 4.3.



CARDIAC MECHANICS: NORMAL CARDIAC MOTION

Figure 4.23

Cardiac mechanics. Cardiac motion is complex, and it involves global translational movement as it occurs during inspiration and expiration, as well as whole heart movements during the cardiac cycle. Regionally, the heart's movements are highly orchestrated.



The heart does not simply “squeeze.” A more accurate description is that the heart—more specifically the left ventricle—simultaneously *shortens, thickens, and twists* (torsion or wringing action) during systole, with reversal of these movements during diastole. The atria act in concert, exhibiting partially reciprocal movements (see Chapter 7, [Figure 7.15](#), Left atrial dynamics).

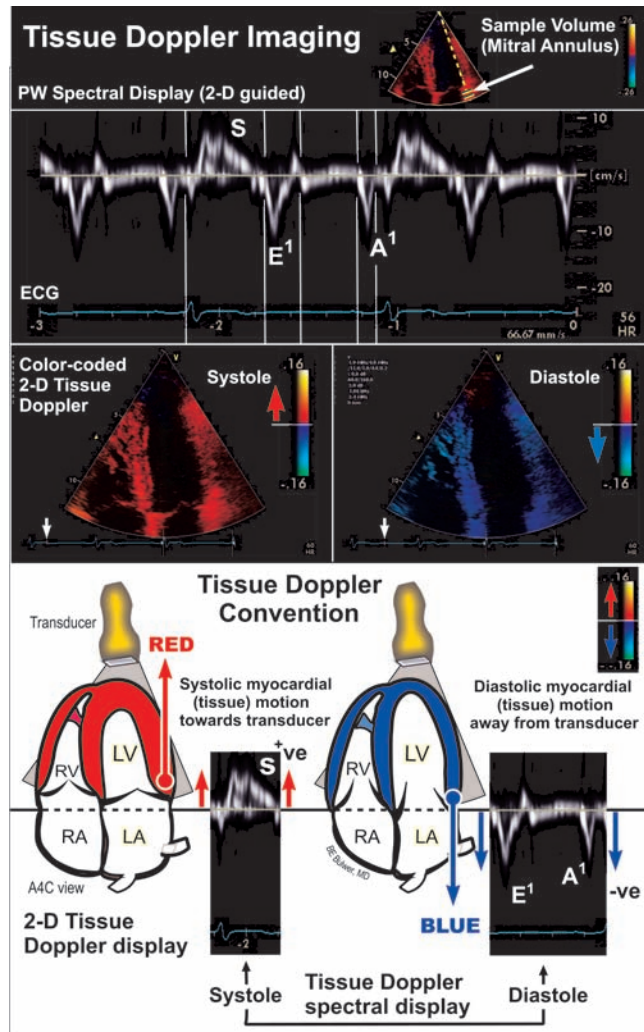
The complex behavior of the left ventricle (LV) reflects its helical cardiac muscle fiber architecture and the elaborate innervation systems. Ventricular shortening and thickening are obvious during echocardiography. LV torsion is readily appreciated during open-heart surgery, but it is evident primarily on short-axis views of the apical LV segments.

Note: The LV endocardium and inner LV walls thicken or “squeeze” far more than the LV’s outer wall. This is readily apparent on echocardiography. For this reason *failure to clearly visualize the endocardium during echocardiography can lead to falsely underestimating cardiac systolic function parameters, e.g., the left ventricular ejection fraction (LVEF).* See Chapter 6, [Figures 6.19–6.22](#).

TISSUE DOPPLER IMAGING (TDI)

Figure 4.24

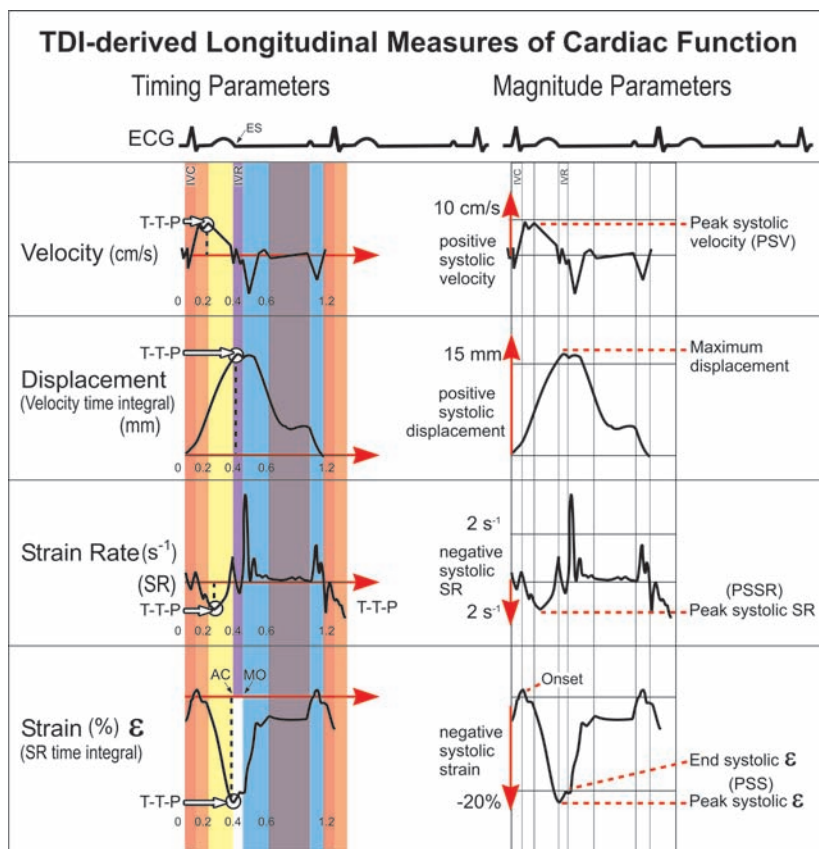
Tissue Doppler imaging (TDI). Longitudinal shortening and lengthening of the left ventricle (LV) can be assessed using a PW TDI technique that selectively examines the low-frequency, high-amplitude echoes arising from the myocardium instead of the high-frequency, low-amplitude echoes reflected from blood cells. *Top panel:* The TDI data can be displayed as TDI-spectral profile that shows positive systolic (S) velocities (red motion) toward the transducer plus two negative (blue motion) diastolic (E_1 and A_1) velocities that reflect biphasic LV myocardial lengthening. *Mid and bottom panel:* Alternatively, the TDI velocities can be simultaneously displayed as red tissue motion toward the transducer during systole, with blue tissue motion velocities away from the transducer during diastole.



TDI-DERIVED MEASURES: VELOCITY, DISPLACEMENT, STRAIN, AND STRAIN RATE

Figure 4.25

Tissue Doppler-based parameters: 1) tissue velocity, 2) displacement (velocity $\times$ time), 3) strain (myocardial deformation), and 4) strain rate (SR) (rate of myocardial deformation). Tissue velocities merely reflect motion, but do not distinguish normal tissue motion from that of nonviable myocardial (because of tethering). Strain and strain rate measures can distinguish true contractile tissue motion from motion simply due to tethering. These measures have promising applications in patients with coronary artery disease. ϵ : strain; AC: aortic valve closure; ES: end systole; IVC: isovolumetric contraction; IVR: isovolumetric relaxation; MO: mitral valve opening; S: peak systolic velocity.



ULTRASOUND ARTIFACTS

Understanding artifacts, their mechanisms, and occurrence are important in echocardiography because: (i) they are common, (ii) their recognition is crucial for proper interpretation, and (iii) they can cause unnecessary alarm, unwarranted investigations, and inappropriate intervention.

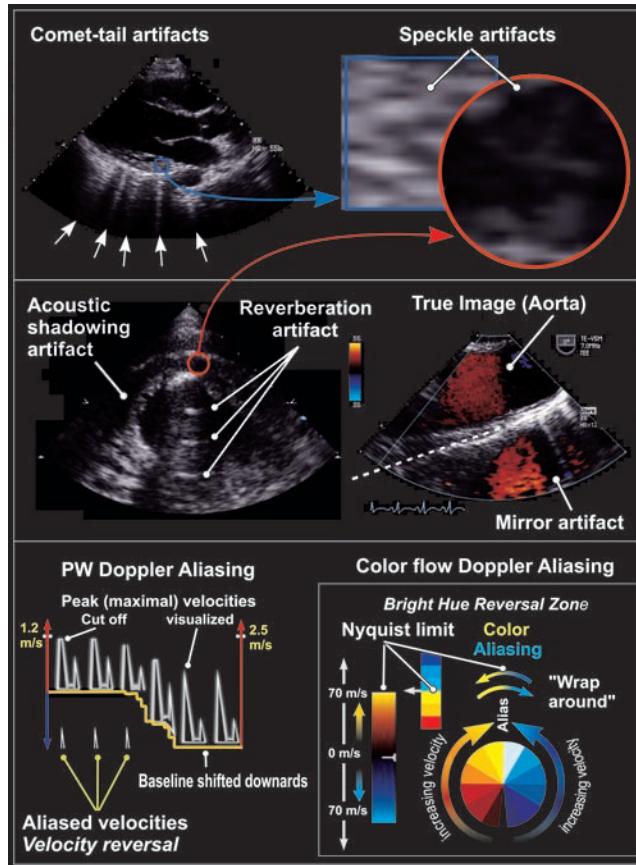
Cardiac ultrasound artifacts may result from:

1. **Faulty equipment:** Instrument malfunction, e.g., faulty transducer, or interference, e.g., from electrocautery.
2. **Improper instrument settings:** Poor transducer selection, e.g., using a 3.5 MHz transducer with an obese patient; suboptimal imaging technique; gain settings too low or too high; inadequate dynamic range, imaging depth, scan sector width too large with color Doppler imaging.
3. **Improper or suboptimal imaging technique and/or patient characteristics:** Sonographer inexperience, “technically limited” studies in patients with obstructive lung diseases, truncal obesity, and post-chest surgery; limitations of technique, e.g., aliasing with pulsed-wave and color flow Doppler.
4. **Acoustic or sonographic artifacts:** These result from interaction of ultrasound with tissues, e.g., attenuation, acoustic speckling, reverberation, mirror-image, and side lobe artifacts [Figure 4.26](#) and [Table 4.4](#).

ULTRASOUND ARTIFACTS

Figure 4.26

Examples of common artifacts seen in echocardiography. Familiarity with ultrasound artifacts is crucial to optimal image acquisition and interpretation. Ultrasound artifacts are common, and are often misinterpreted. Some, like comet tail artifacts, are a minor nuisance. Others, like speckle artifacts, are useful in speckle tracking echocardiography—a recent advance based on the ubiquitous myocardial “signature” patterns that can be tracked throughout the cardiac cycle. Pulsed-wave (PW) Doppler can interrogate specific areas of flow (range specificity) but exhibits aliasing artifacts seen in valvular heart disease. Color flow Doppler imaging, a PW Doppler-based technique, is also plagued by color aliasing that occurs even with normal flows (see Figure 4.22).



COMMON ULTRASOUND ARTIFACTS

Table 4.4 COMMON ACOUSTIC ARTIFACTS SEEN IN ECHOCARDIOGRAPHY

Acoustic artifacts	Mechanism	Examples, Comments
Attenuation artifact (acoustic shadowing) See Fig. 3.9	Progressive loss of ultrasound beam intensity and image quality with imaging distance (depth) due to reflection and scattering of the transmitted ultrasound beam. Attenuation is most marked distal to strong reflectors and manifests as image dropout or reduced image quality (acoustic shadowing). Less attenuation is seen with low-frequency transducers (1 MHz) compared to high-frequency transducers (5 MHz).	Distal to bony ribs, calcified structures, e.g., valve leaflets and annulus, prosthetic heart valves and intracardiac hardware. Air strongly reflects ultrasound. Use coupling gel on skin (to overcome the acoustic impedance difference) to aid beam transmission.
Acoustic speckling See Figs. 3.9, 3.10, and 4.26	Grainy pattern or “speckle” is normal in echocardiographic images, especially the ventricular myocardium. They result from interference patterns created by reflected ultrasound waves (echoes). They are useful in tracking cardiac motion and deformation in speckle tracking echocardiography.	Ventricular myocardium Speckles are not actual structures: constructive and destructive interference of reflected ultrasound waves (echoes) lead to this granular appearance typical of echocardiography images.
Reverberation artifact, comet tail or “ring-down” artifact See Fig. 4.26	These result from back-and-forth “ping pong” reflections (reverberations) between two highly reflective surfaces. They appear as strong linear reflections distal to the causative structure. “Comet-tail” artifacts are a type of reverberation artifact appearing distal to strong reflectors.	Ribs, pericardium, intracardiac hardware, e.g., prosthetic valves, LVAD—(left ventricular assist device) inflow. Comet-tail artifacts are almost the rule, and they are seen radiating distal to the pericardium-pleural interface.
Mirror image artifact See Fig. 4.26	An apparent duplication of a structure or Doppler signal because of strong reflector.	Aorta on transesophageal echocardiography.
Side lobe	Erroneous mapping of structures arising outside of the imaging plane (due to ultrasound beam side lobes) into the final image. Side lobe artifacts appear at the same depth as the true structures, giving rise to them.	Duplication of aortic wall within aortic lumen—may be misinterpreted as an aortic dissection flap.

(continues)

Table 4.4 COMMON ACOUSTIC ARTIFACTS SEEN IN ECHOCARDIOGRAPHY (*continued*)

Acoustic artifacts	Mechanism	Examples, Comments
Aliasing artifact See Figs. 4.22 and 4.26	A limitation of pulsed-wave Doppler-based techniques that erroneously displays Doppler blood velocities. Aliased PW Doppler-measured blood velocities occur when measuring high blood velocities. They appear as decapitated spectral Doppler velocities on the opposite side of the baseline. Color flow Doppler aliased velocities appear as unexpected shade of light blue, when they should instead appear as light red, or vice versa. See Fig. 4.22 .	PW Doppler measurement of aortic stenosis and mitral regurgitation. See Figs. 6.25 and 6.29 . Adjust baseline and use continuous-wave (CW) Doppler. Color flow Doppler mapping of high blood flow velocities; mosaic colors indicating the turbulent flows seen. Note: color flow aliasing is also commonly seen with normal intracardiac flow velocities.