Section 1 THE BASICS: What You need to know

DOPPLER PRINCIPLES AS THEY APPLY TO ACCURACY AND QUALITY OF THE EXAM

- Doppler shift
  - Johann Christian Doppler
    - Discovered that sound waves change frequency (frequency shift) when there is a change in position between the source of the sound waves and the receiver of the reflected sound waves (Figure 1.1 and Video 1.1)
  - What is a Doppler shift
    - We hear a Doppler shift when we hear a siren
      - As the pitch (frequency) increases we know the vehicle is coming toward us
      - As the pitch (frequency) decreases we know the vehicle is moving away from us
    - The Doppler shift in diagnostic ultrasound (Figure 1.2)
      - When Doppler sound is sent into the heart
        - Blood cells moving away from the transducer send back lower-frequency sound, creating a negative frequency shift (i.e., out with 5 MHz – back with 3.5 MHz)
          - The sound wave is trying to catch the cells – so it interacts with the cells less frequently
        - Blood cells moving toward the transducer send back higher-frequency sound, creating a positive frequency shift (i.e., out with 5 MHz – back with 7.0 MHz)
          - The sound wave is running into the cells – so it interacts with the cells more frequently

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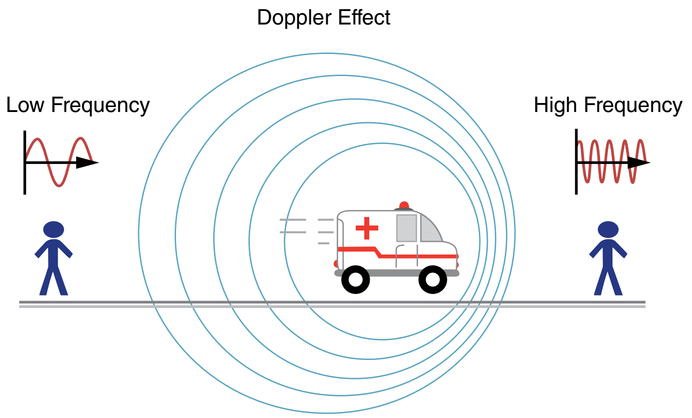
Doppler Echocardiography for the Small Animal Practitioner, First Edition. June A. Boon.

Companion website: www.wiley.com/go/boon/doppler



Video 1.1

Figure 1.1 As this ambulance drives toward the person on the right it encounters the wave front and wavelength frequency increases. As it moves away from the person on the left, it encounters the wave front less frequently so the wavelength frequency decreases.

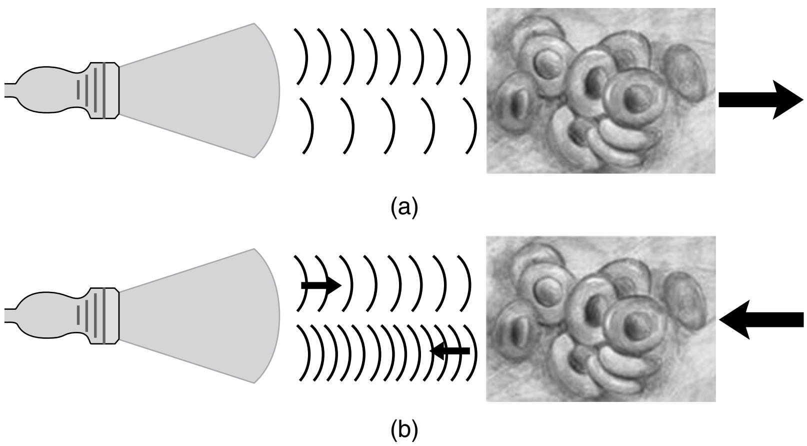


Figure 1.2 (a) As sound waves encounter blood cells moving away from the transducer the reflected sound is at a lower frequency, and the machine processes this negative frequency shift as blood cells moving away from the transducer. (b) As sound waves encounter blood cells moving toward the transducer the reflected sound is at a higher frequency, and the machine processes this positive frequency shift as blood cells moving toward the transducer.

- Types of Doppler
  - Pulsed wave (PW)
    - PW Doppler sends out pulses of sound to a specific location in the heart (Figures 1.3a and b)
    - Reflected sound from the red blood cells at that specific location needs to return to the transducer and be processed (frequency shift calculated) before the next pulse is transmitted

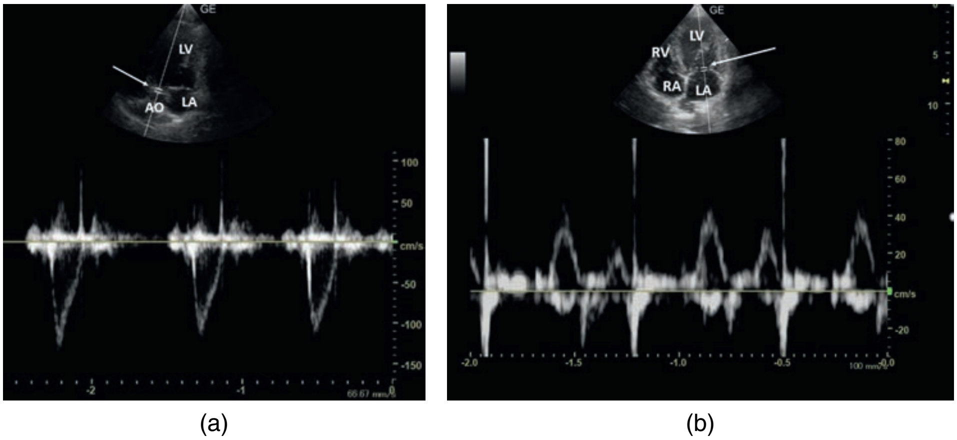


Figure 1.3 (a) A Doppler cursor placed in the aorta on an apical 5 chamber plane records blood flow moving away from the transducer, and the spectral waveform is displayed below the baseline which represents zero velocity. The pulsed wave (PW) gate here (small equal sign) is placed at the aortic valve, and the spectral flow profile is very specific for that location. (b) A Doppler cursor placed at the mitral leaflets on an apical 4 chamber plane records blood flow moving toward the transducer, and the spectral waveform will be displayed above the baseline which represents zero velocity. The PW gate here (small equal sign) is placed at the tips of the mitral valve leaflets, and the flow is very specific for that location.

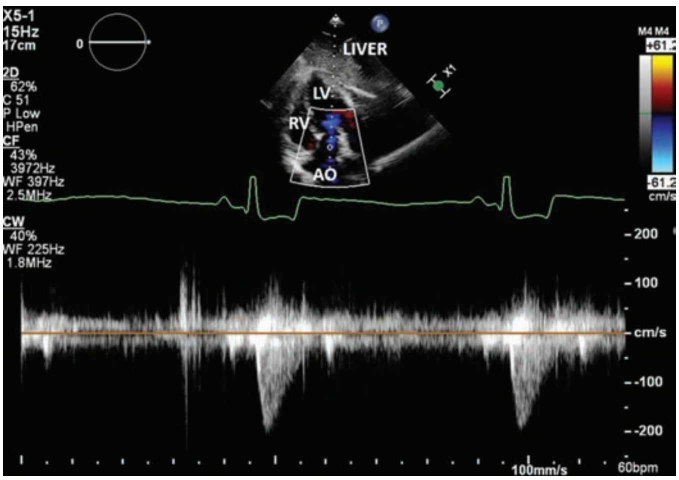
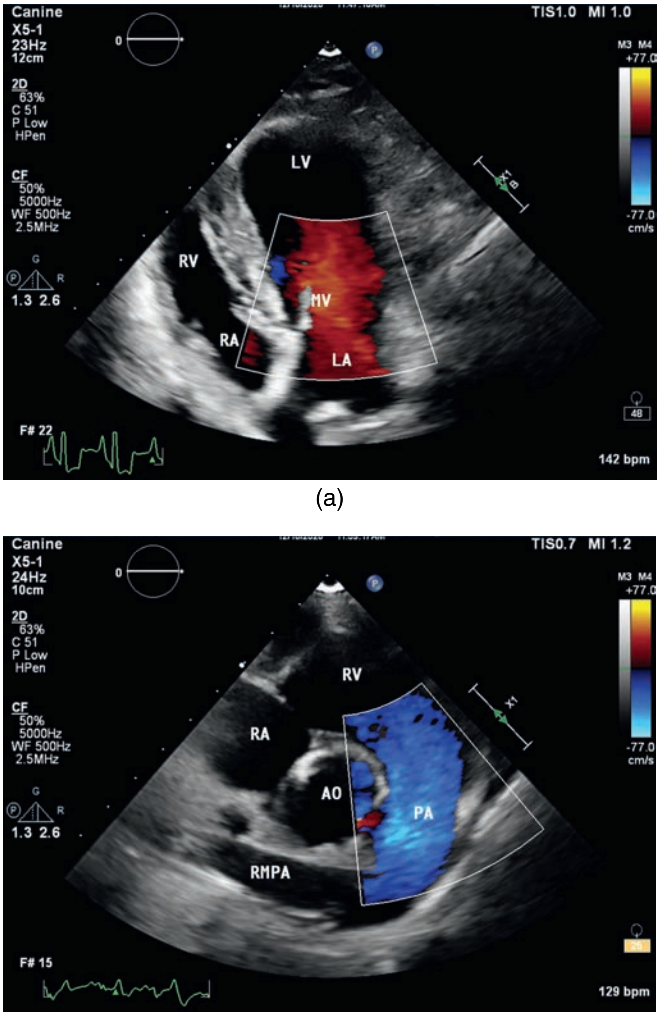


Figure 1.4 The Doppler cursor is aligned with aortic flow leaving the left ventricle on this subcostal 5 chamber view. Using continuous wave (CW) Doppler, flow is recorded all along the Doppler cursor with no site specificity. Flow along this cursor varies dependent on location, and so the flow profile shows all of these velocities. The flow profile is filled in because of these various velocities, but the highest flow is what is seen at the peak of the flow profile.

- Continuous wave (CW)
  - CW Doppler sends sound out continuously along a line through the valves or vessels in the heart. There is no site specificity with CW Doppler
  - Reflected sound is processed continuously (frequency shifts are constantly calculated as red cells all along the line send reflected sound back to the transducer) (Figure 1.4)

- Color flow
  - Color flow Doppler is a form of PW Doppler
  - The color box has multiple Doppler lines with multiple gates along each line
  - Each gate sends flow information back to the transducer, which is assigned a color depending on which direction the blood is flowing
  - Flow toward the transducer is typically coded in red (Figure 1.5a and Video 1.5a)
  - Flow away from the transducer is typically coded in blue (Figure 1.5b and Video 1.5b)
  - Green variance maps are available to highlight a lot of variance in the flow being investigated
    - Variance is seen in turbulent flow
    - Not all green represents turbulence, however

- Advantages and disadvantages of each type of Doppler
  - PW
    - Advantages
      - Site specific – velocity only recorded at the gate (Figure 1.3)
    - Disadvantages
      - Cannot record high-velocity flow
  - CW
    - Advantages
      - Able to record high-velocity flow
    - Disadvantages
      - No site specificity – records velocities all along the Doppler line (Figure 1.4)
  - Color flow
    - Advantages
      - Potential abnormal flow is readily identified
    - Disadvantages
      - There is minimal quantitative information associated with color flow Doppler (Figure 1.6 and Video 1.6)
- The spectral display
  - Baseline
    - The baseline is moved up or down as necessary to display either upward or downward flow or both (Figures 1.7a–c)
    - When both upward and downward flows are being investigated and CW is used, the baseline is positioned and scale adjusted so that each flow profile is seen in its entirety
    - When there is upward and downward flow but PW is used, only one or the other can be recorded accurately since the gate is very site specific
    - The baseline is positioned to the top or bottom of the display and scale is adjusted to ideally display the full PW flow profile
  - Velocity scale
    - Velocity scales are seen both above and below the baseline
    - This scale is adjusted lower or higher by a velocity, PRF, or scale knob
    - As the baseline moves up or down the scale changes on each side of the baseline



(a)

(b)

Figure 1.5 The multiple lines of Doppler sound in a color flow sector are filled with PW gates. Each gate records a positive or negative frequency shift that is displayed as a specific color. (a) When reflected sound sends back a positive frequency shift from a PW gate, meaning blood cells are moving toward the transducer, the flow at that gate is color coded in red. Here blood flow is moving up through the mitral valve on this apical 4 chamber view, and the image shows red flow moving through the mitral valve into the left ventricle. (b) When reflected sound sends back a negative frequency shift from a PW gate, meaning blood cells are moving away from the transducer, the flow at that gate is color coded in blue. Here blood flow is moving down into the pulmonary artery on this right transverse view, and the image shows blue flow moving from the right ventricle into the pulmonary artery.

Video 1.5

- If the velocity scale is not adjusted while the baseline is moved, the total velocity remains the same; it is just redistributed above or below the baseline
- Velocity and baseline are adjusted to show a complete spectral flow profile and to eliminate aliasing if possible (Figures 1.7b and c)

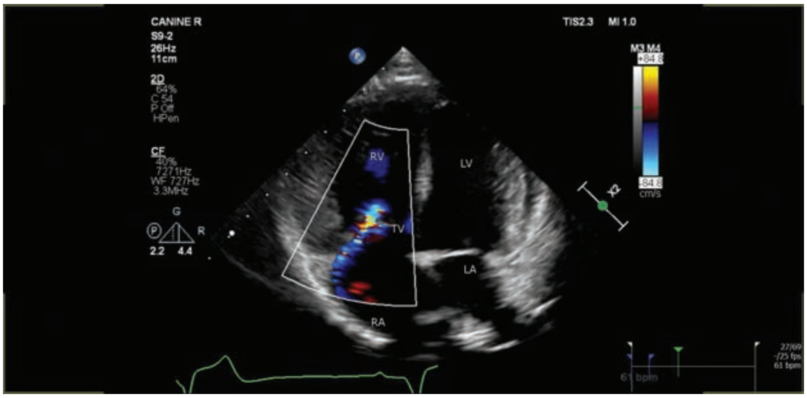
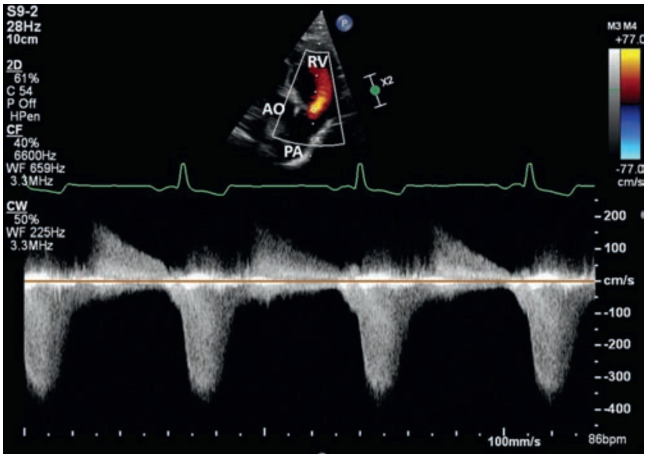


Figure 1.6 While color flow Doppler locates possible areas of abnormal flow rapidly, it provides minimal quantitative information. Tricuspid regurgitation (TR) in this foreshortened apical 4 chamber view is considered mild based upon the size of the color jet, but no hemodynamic information is provided.

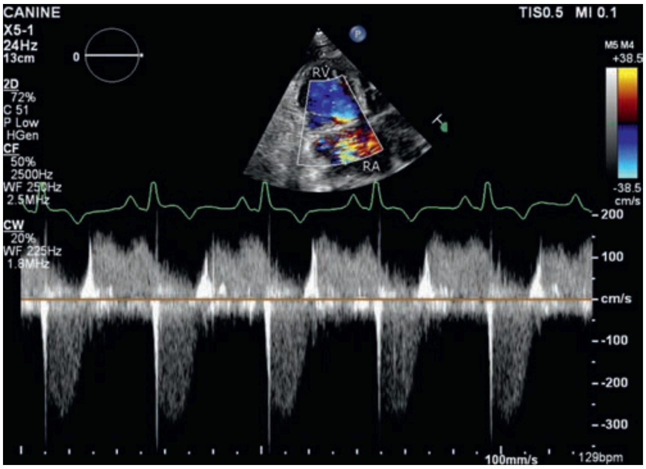
Video 1.6

- Information obtained from spectral display
  - Velocity (Figures 1.7b and c)
    - Velocity in meters/sec or cm/sec is displayed above and below the baseline
  - Direction (Figures 1.7a–c)
    - Blood cells moving toward the transducer are displayed above the baseline
    - Blood cells moving away from the transducer are displayed below the baseline
  - Timing (Figures 1.7a–c)
    - The horizontal axis of a spectral display represents time
    - Blood flow during diastole and systole are displayed at their respective times on the horizontal axis
    - An ECG may make identification of event timing more accurate
  - Intensity (Figure 1.7b)
    - The density of a spectral display is related to the number of blood cells involved in the flow
    - A small volume of blood cells would have less density than a large volume
    - This is accurate when the spectral displays are created with the same Doppler settings and alignment is parallel with both flows

- The color display
  - Direction (Figure 1.5)
    - Blood cells moving toward the transducer are coded in red
      - As velocity increases the color becomes brighter and moves into the yellows
    - Blood cells moving away from the transducer are coded in blue
      - As velocity increases the color becomes brighter and whiter
  - Velocity (Figure 1.5)
    - The scale on each side of the color bar shows the maximum velocity that is encoded in the specific color



(a)



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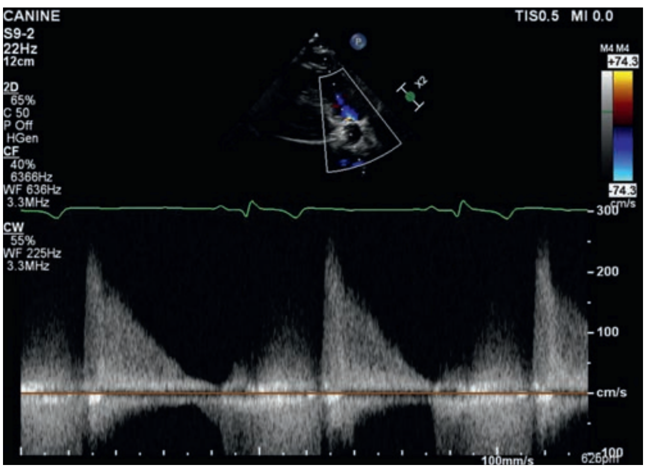
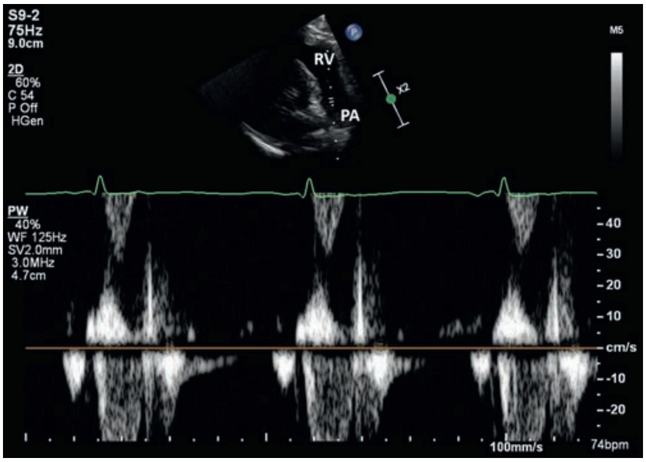


(c)

Figure 1.7 The spectral display baseline is moved up or down as needed to accommodate the direction and velocity of flow evaluated. Time is shown on the horizontal axis; the dots represent 1 second intervals. An ECG shows systole and diastole, but direction is intuitive based on the color display and location interrogated. (a) This CW display shows upward low-velocity flow (pulmonary insufficiency shown in red) and downward higher-velocity flow (PA systolic flow). The baseline and scale are adjusted accordingly. (b) This spectral display is focused on the high-velocity downward flow, so the baseline is moved to the top of the display and scale is adjusted to fill the spectrum. Downward flow density is less than upward flow intensity and represents fewer blood cells moving down than moving up. (c) This spectral signal is focused on upward flow, so the baseline is moved downward and the scale is adjusted to fill the spectrum.

- Nyquist limit and aliasing
  - PW (Figures 1.8a–f)
    - PW has a maximum velocity it can record
    - This maximum velocity is called the Nyquist limit
      - Flows that exceed this Nyquist limit will alias
      - An aliased flow signal will not show the complete flow profile
      - Maximum velocity cannot be determined
      - Moving the baseline up or down to maximize velocity either up or down can resolve mild aliasing but not significant aliasing
      - It is difficult to discern the direction of flow
      - Even though intuitively you may know the direction based upon location of the gate and using color flow Doppler
      - A streak from the top of the spectral display to the bottom representing flow is seen
    - CW Doppler is needed to show the peak velocity (Figure 1.8f)
      - There is no Nyquist limit with CW Doppler
  - Color flow (Figures 1.9a–c and Videos 1.9a and c)
    - Color flow has a maximum velocity it can record in pure color (red or blue)
    - This maximum velocity seen on the color bar is called the Nyquist limit
    - Flows that exceed this Nyquist limit will alias
    - An aliased flow signal has mixed colors of red and blue
      - Maximum velocity cannot be determined
      - Moving the baseline up or down to maximize color velocity either up or down may resolve the aliasing since maximum velocity in each direction is increased
      - It can be difficult to discern the direction of flow
      - Even though intuitively you may know the direction based upon location of the color sector
      - A mosaic color flow signal or a layered color flow signal is seen
  - Factors affecting Nyquist limit
    - Transducer frequency
      - Higher-frequency transducers result in lower PW Nyquist limits at any given depth (Figure 1.10a)
      - Lower-frequency transducers allow higher PW velocity to be recorded before aliasing occurs at any given depth (Figure 1.10b)
      - Higher-frequency transducers result in lower color flow Nyquist limits before aliasing occurs at any given depth (Figure 1.10c)
      - Lower-frequency transducers allow higher color flow velocity to be recorded before aliasing occurs at any given depth (Figure 1.10d)
    - Depth of interrogation
      - Increased gate depth at the same transducer frequency decreases the PW Nyquist limit (Figures 1.11a and b)
      - Therefore, higher velocity can be reached before aliasing occurs if PW gate depth is minimized



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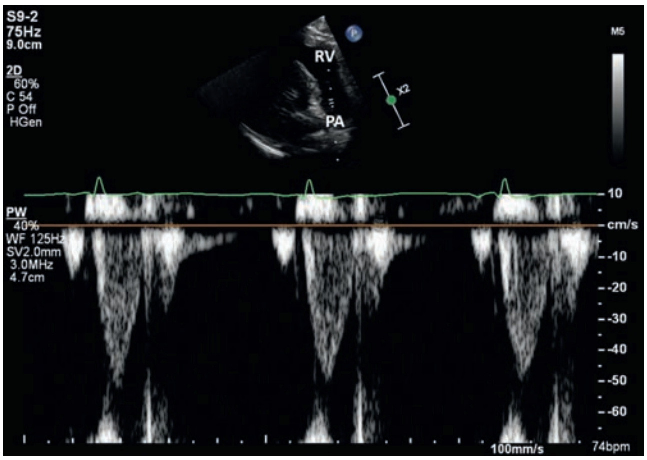

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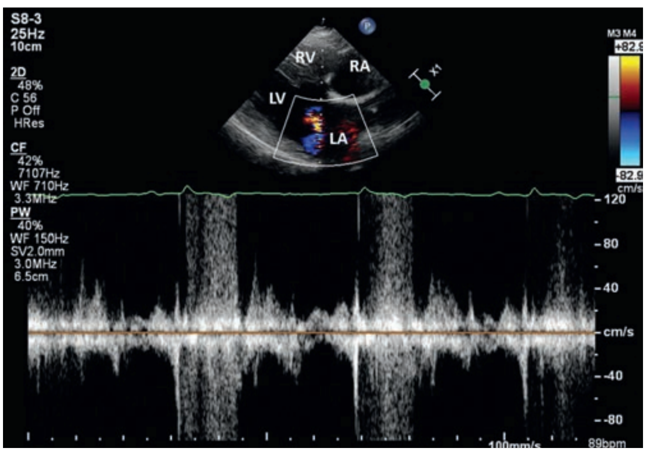
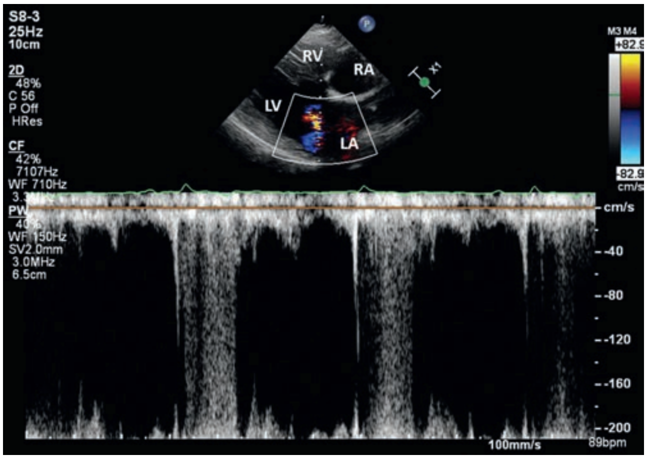


(c)

Figure 1.8 (a) The downward flow is not fully displayed and wraps to the top of the spectral display. (b) Moving the baseline up allows the entire display to be seen without aliasing. (c) The baseline is in the middle of this spectral display. The Nyquist limit in each direction is 120 cm/s. Adjusting the scale (velocity or PRF) knob does not increase this velocity. The Nyquist limit has been reached. There is no discernable direction of flow, and peak velocity cannot be determined. (*Continued*)



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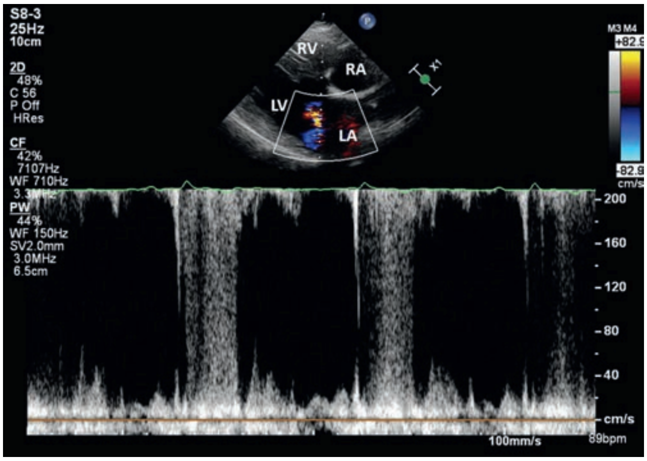

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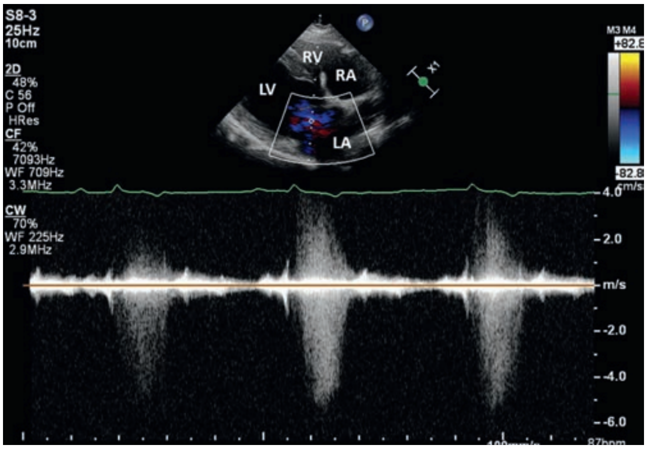
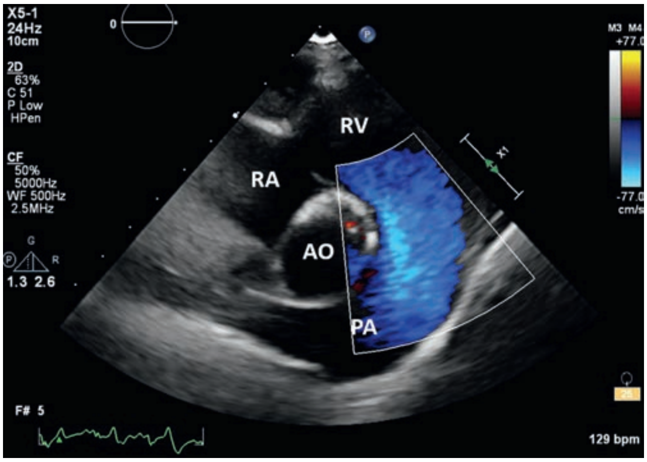


(f)

Figure 1.8 (*Continued*) (d) Moving the baseline up to maximize velocity in the downward direction to over 200 cm/s does not resolve the problem. This is aliased flow, exceeding the Nyquist limit with no discernable direction of flow or peak velocity. (e) Moving the baseline down does not remedy the situation. There is still no discernable direction or peak velocity. (f) Changing to CW Doppler allows higher velocity to be recorded. Peak velocity in a downward direction can now be determined.



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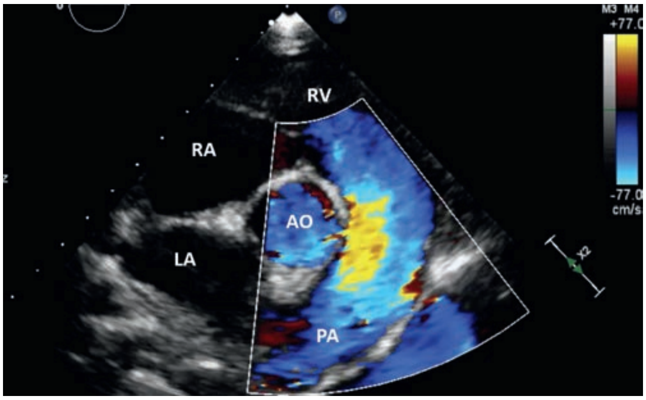

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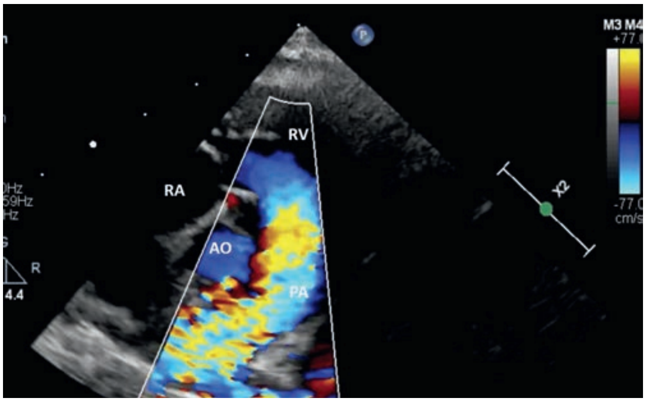


(c)

Figure 1.9 (a) Pulmonary artery systolic flow in this image does not exceed the Nyquist limit of 77 cm/s, so color is seen as pure blues with no aliasing. (b) The colors are layered in this pulmonary artery systolic flow image. Normal pulmonary artery systolic flow may be nearly 2m/s, and this flow exceeds the 77 cm/s, which results in an aliased signal, wrapping and layering the colors. (c) The color bar shows a Nyquist limit of 77 cm/s. Flow exceeding this velocity will start mixing colors. Here the pulmonary artery shows a mosaic of color representing the high-velocity turbulent flow associated with pulmonary stenosis.

Video 1.9

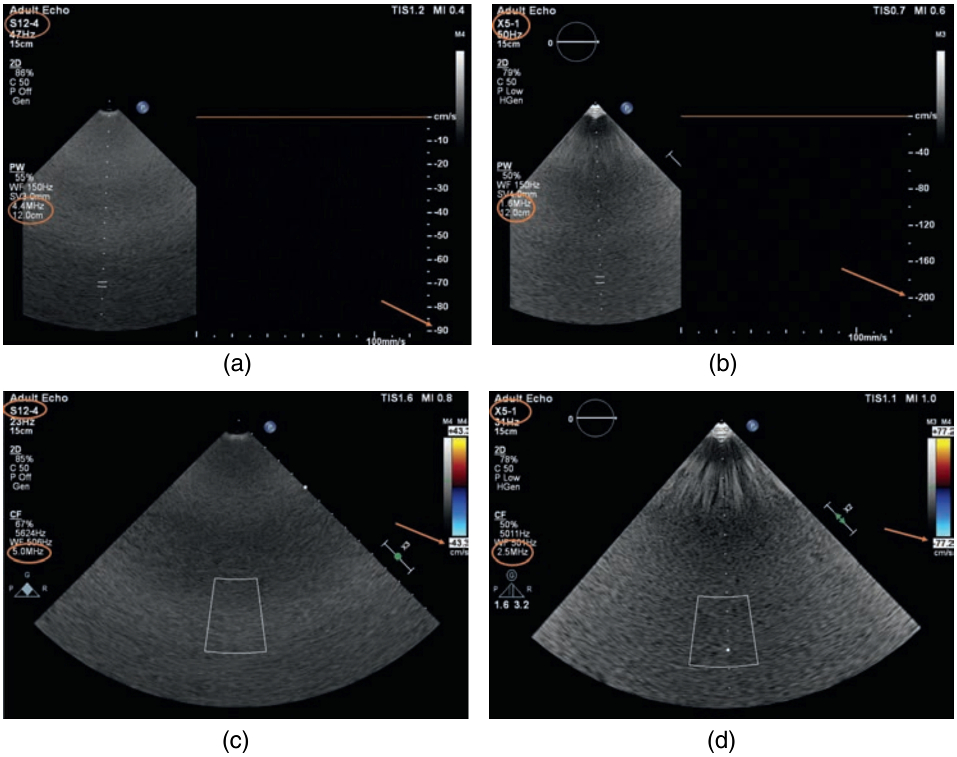


Figure 1.10 (a) This high-frequency transducer has a PW frequency of 4.4 MHz (orange circle) and an aliasing velocity (Nyquist limit) of 90 cm/s (arrow). (b) Lower transducer frequencies allow higher aliasing velocity (Nyquist limits). This PW frequency is 1.6 MHz (orange circle), which allows the maximum velocity to reach just over 200 cm/s (arrow) before aliasing occurs. (c) Using color flow Doppler, the transmitting frequency of 5 MHz (orange circle) in this image allows the Nyquist limit to reach 43.3 cm/s (arrow) before color starts aliasing. (d) A lower transmitting frequency of 2.5 MHz (orange circle) in this color flow Doppler image allows the aliasing velocity to increase to 77.2 cm/s (arrow) before the color signal aliases.

        - Increased depth of the color flow box at the same transducer frequency decreases the Nyquist limit (Figures 1.11c and d)
        - Therefore, higher velocity can be reached before aliasing occurs if color box depth is minimized
- Accuracy of spectral flow information
    - Angle of incidence (Figures 1.12a–c)
        - A Doppler beam aligned perfectly parallel with the flow of interest provides an accurate flow velocity
        - An angle away from parallel to flow of any degree in any direction will underestimate flow velocity
    - Measuring the peak velocity – no fuzz
        - Measure peak velocity at the dense envelope (modal velocity) – not the fuzz below or above (Figures 1.13a and b)

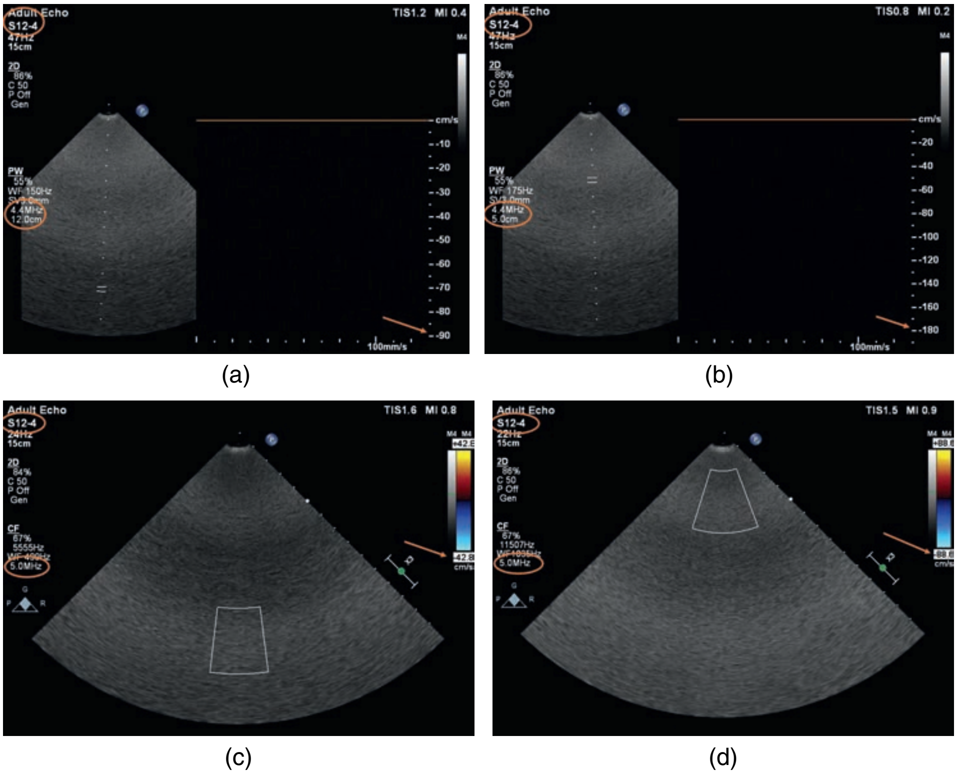
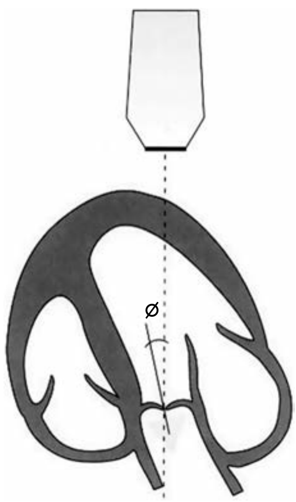
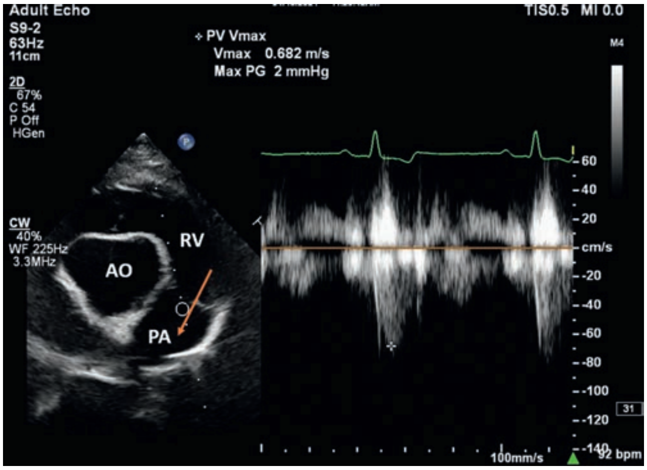


Figure 1.11 Increasing depth of a PW gate decreases the Nyquist limit, resulting in lower aliasing velocities, and decreased depth allows for higher aliasing velocities. (a) At a Doppler frequency of 4.4 MHz and gate depth of 12 cm (circle) the aliasing velocity is 90 cm/s (arrow). (b) At a Doppler frequency of 4.4 MHz and gate depth of 5 cm (circle) the aliasing velocity is 180 cm/s (arrow). (c) At a Doppler frequency of 5 MHz (circle) and a deep color box the aliasing velocity is 42.8 cm/s (arrow). (d) At a Doppler frequency of 5 MHz (circle) and a shallow color box the aliasing velocity is 88.6 cm/s (arrow).



(a)

Figure 1.12 Any deviation from parallel to flow will underestimate the true velocity. (a) Here the actual direction of flow into the aorta is the solid line and the Doppler cursor (dashed line) is not parallel to the flow. Flow velocity will be underestimated. (*Continued*)



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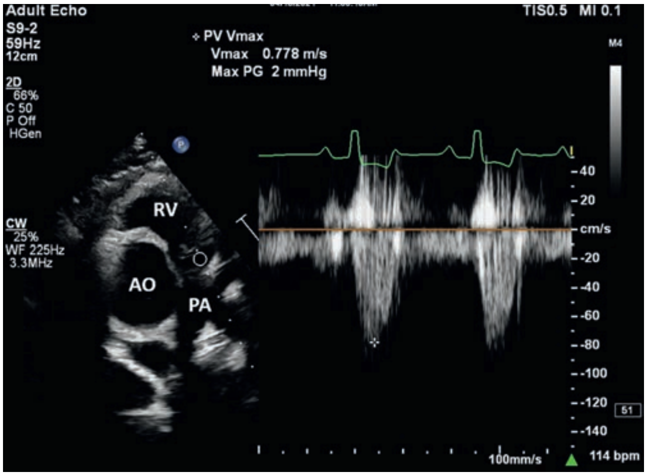
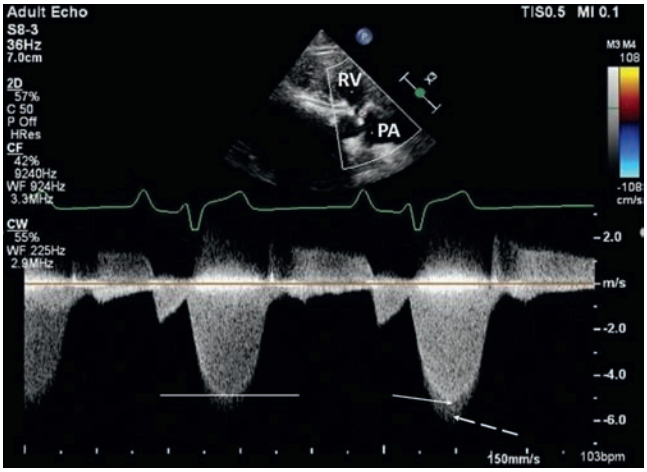


(c)

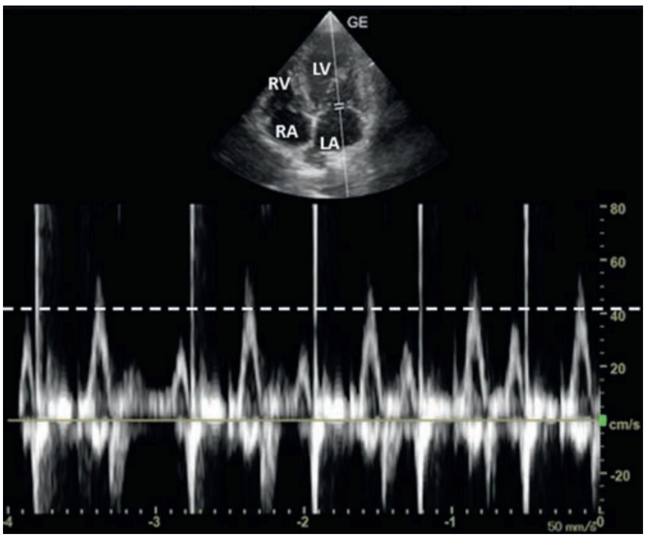
Figure 1.12 (*Continued*) (b) The direction of flow on this right parasternal transverse view of the pulmonary artery is represented by the orange line. The dotted line representing the Doppler cursor is not parallel to flow. The recorded flow velocity is .68 m/s. (c) On this left cranial transverse view of the pulmonary artery in the same dog, the dotted Doppler cursor is lined up more parallel to flow resulting in a higher flow velocity of .78 m/s.

OPTIMIZING DOPPLER DISPLAYS

- Color flow
  - Factors affecting color image quality
    - Color gain (Figures 1.14a–c and Video 1.14)
      - Often gain appears to be adequate when color is activated, but always check the color gain
      - Increasing gain until speckling occurs over the color and 2D image, then turn down again until speckling just disappears



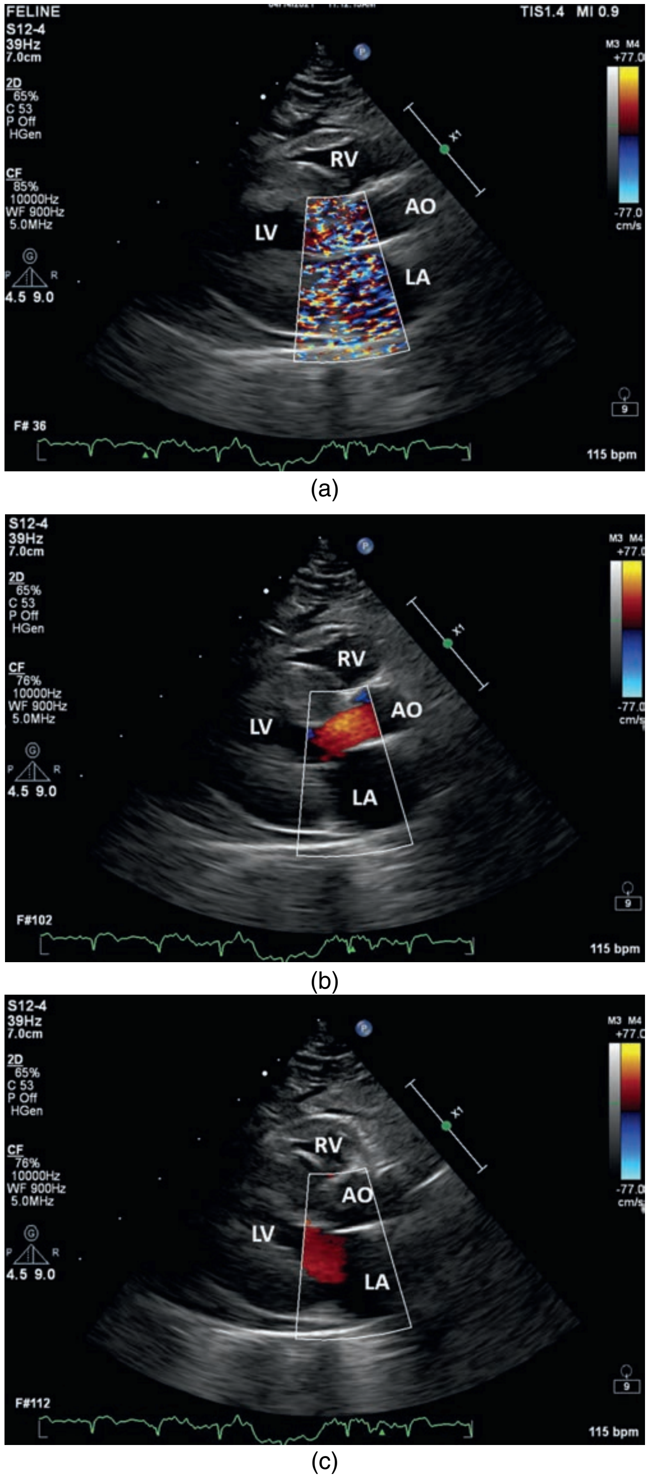
(a)



(b)

Figure 1.13 Peak flow should be measured at the modal velocity. This is the bright border of the spectral flow profile. (a) The modal velocity is measured (solid line and arrow) and the gray fuzzy density below it (dashed line) is ignored. (b) The spikes and fuzzy areas above the mitral spectral flow profiles are ignored when measuring peak velocity. Peak velocity measurements of the trans mitral valve E wave are at the dotted line.

- 2D gain (Figures 1.15a and b and Videos 1.15a and b)
  - Turn 2D gain down until chambers and vessels are mostly black
  - Too high of a 2D gain setting prevents good color filling of the area being evaluated
- Image orientation (Figures 1.16a and b and Videos 1.16a and b)
  - Although color flow Doppler is not as angle dependent as spectral Doppler, aligning the 2D image a bit more parallel with the direction of flow helps with color quality
  - Angled and apical views provide the best color filling if the appropriate transducer is used



Video 1.14

Figure 1.14 (a) Adjust color gain until speckling occurs over the color and 2D image. (b) Turn the gain down slowly until the speckling disappears. Here good red flow is seen entering the aorta. (c) And correct color gain setting over the mitral valve shows red flow filling the left ventricular inflow pathway without speckles.

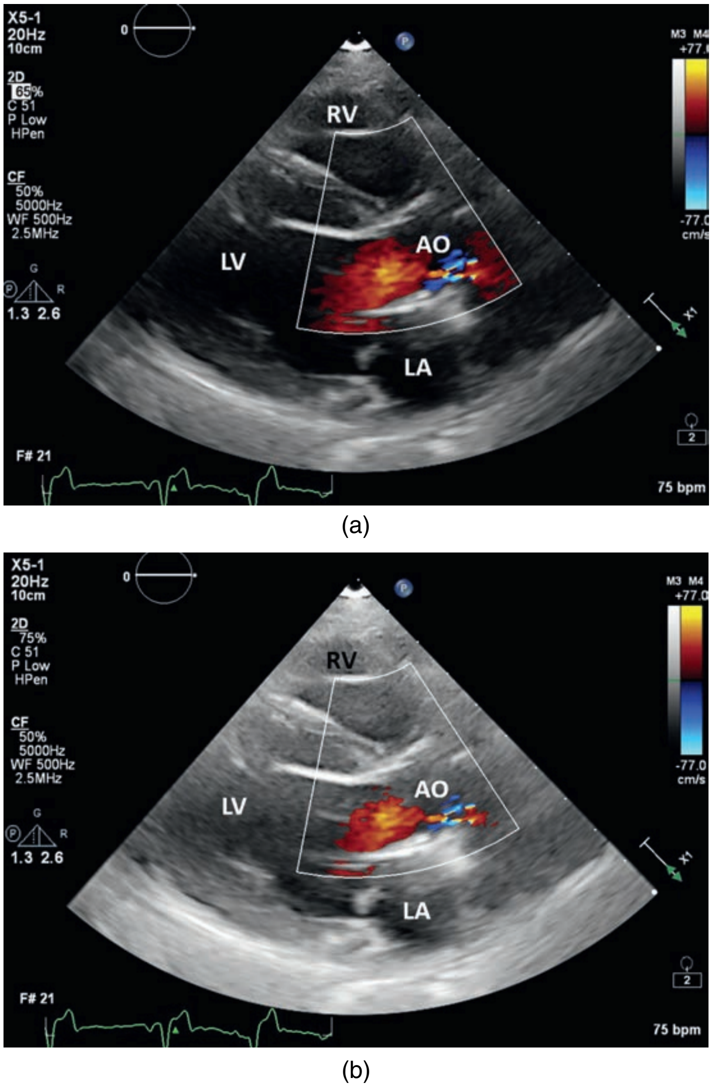
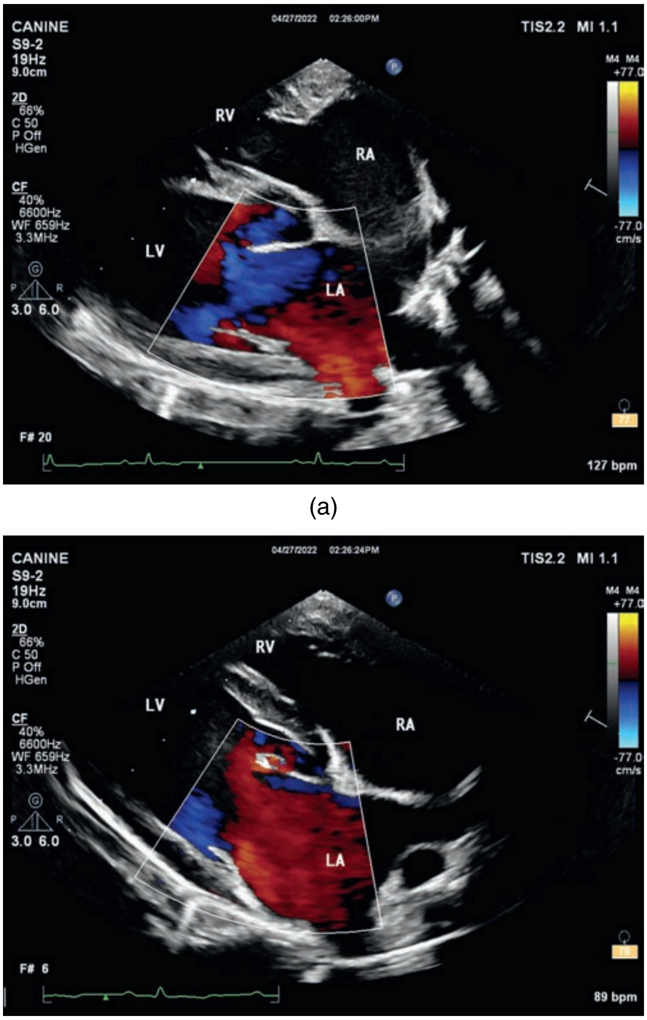


Figure 1.15 Two-dimensional gain that is set too high can prevent color Doppler from filling the areas of interest. (a) Good color gain and appropriate 2D gain setting, where the fluid-filled chambers and vessels are black, allow the left ventricular outflow tract to fill well with red color. (b) High 2D gain where chambers and vessels are filled with noise prevents color from filling the left ventricular outflow tract to the same degree as in Figure 1.15a.

Video 1.15

- Nyquist limit (Figures 1.17a and b and Videos 1.17a and b)
  - Decreasing Nyquist limits will create aliasing at lower velocity
    - This can overestimate the significance of a regurgitant jet
  - Increasing Nyquist limits will cause aliasing to develop at higher-flow velocities
    - This can limit the visibility of low-velocity flow like pulmonary veins
  - An optimal Nyquist limit for most purposes in about 70–90 cm/s



(a)

(b)

Video 1.16

Figure 1.16 Although color flow Doppler is forgiving of angles, images that line up the direction of flow more parallel to the Doppler beams allow for better color flow processing, and flow is more filled in and diagnostic. (a) This horizontal 2D image shows color with poor diagnostic value because the color is blotchy, without good representation of flow into the LV chamber. (b) This angled view shows more diagnostic color with distinct red flow moving into the LV chamber.

- Frame rates
  - Frame averaging
    - As more frames are averaged the color from different frames will overlap
    - This creates a well-filled-in color image, but the result of too much frame averaging is a slow-motion blurred image
    - One or maybe two averaged frames are recommended for cardiac studies
- Color sector size (Figures 1.18a and b and Videos 1.18a and b)
  - Increasing color sector box width adds Doppler beams and PW gates
    - This adds processing time and color often lags when the box is too wide
  - This especially matters with fast heart rates
    - Keep color sectors small

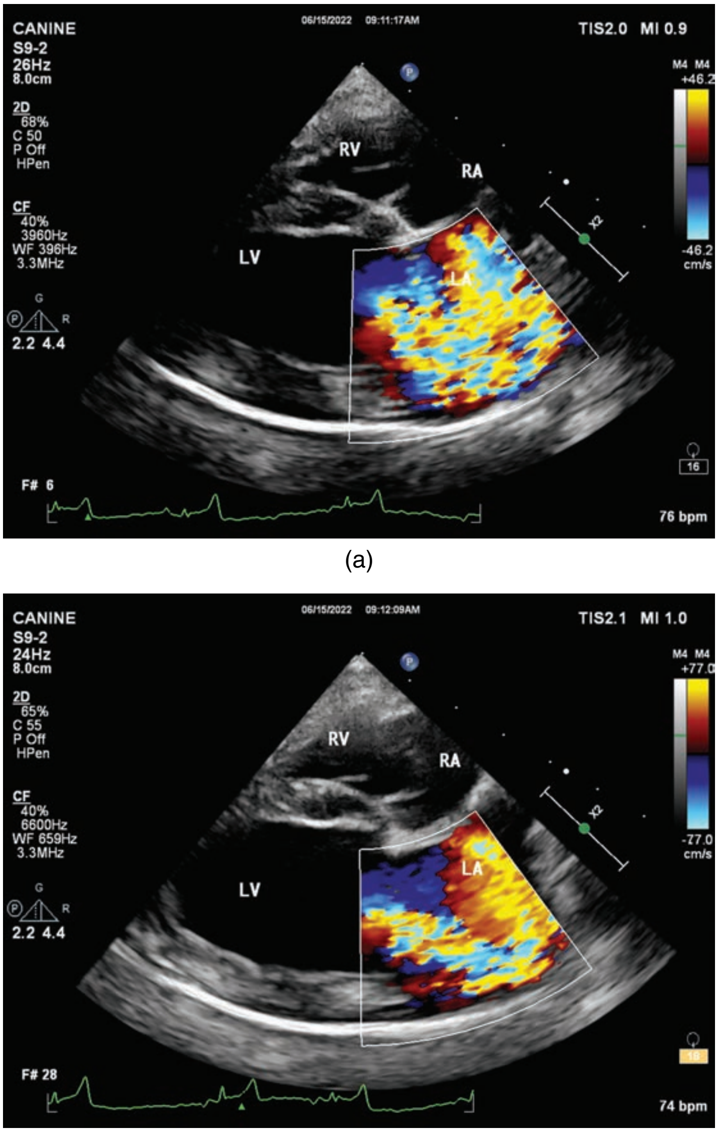
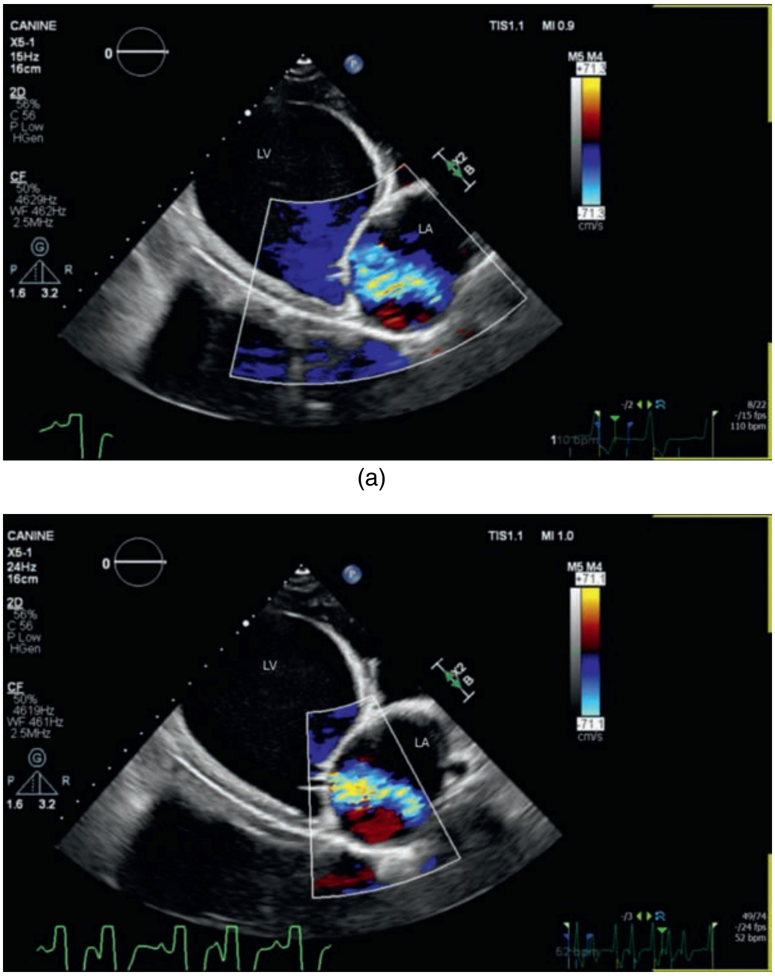


Figure 1.17 Lower Nyquist limits entrain lower flow velocities into the aliased signals. (a) A Nyquist limit of 46.2 cm/s creates a larger regurgitant jet area than a Nyquist limit of (b) 77.0 cm/s, where flow is not aliased until velocities reach 77.0 cm/s. Low Nyquist limits in regurgitant flows can overestimate the significance of the regurgitation.

Video 1.17

- Spectral Doppler
  - Factors affecting image quality
    - Depth of gate (Figure 1.11)
      - Increasing gate depth decreases the Nyquist limit
      - Aliasing will occur at lower velocities than if a shallower gate position is used
      - Decreasing gate depth is not always possible and is dependent upon the valve or vessel being evaluated



Video 1.18

Figure 1.18 Larger color sector boxes slow down frame rate, resulting in slow motion or late color mapping. (a) A smaller color box size allows frame rates to be high and color processing to map color accurately. The mitral regurgitation jet in this image is clearly defined. (b) This large color sector makes processing time longer, and color is less clearly defined. The mitral regurgitation in this image of the same dog as in Figure 1.18a is poorly defined because of this low frame rate. These differences are more visible in the associated videos.

- Interrogation angle (Figure 1.12a)
  - Aligning the Doppler beam parallel to flow results in the most accurate assessment of velocity
- Gate size
  - Gate size is typically set at 2–3 mm
  - Increasing gate size can help record very small flows
- Baseline (Figure 1.7)
  - Move the baseline up or down as necessary to see the entire spectral envelope

- Scale (Figure 1.7)
  - Adjust scale as necessary to optimize the display
  - If aliasing occurs when scale is at its maximum, switch to CW if possible
- Frequency (Figure 1.10)
  - Higher transducer frequencies decrease the maximum velocity of the spectral display
  - Lower transducer frequencies increase the possible velocity before aliasing occurs

LAMINAR AND TURBULENT FLOW

- Normal laminar flow (Figure 1.19, Figure 1.3)
  - Normal blood flow travels in a linear path at similar velocities
  - As a result, normal blood flow has hollow PW envelopes (Figure 1.20)
- Turbulent flow
  - When flow becomes turbulent it is no longer laminar and multiple velocities are recorded (Figure 1.21)
    - This results in a filled-in PW flow profile (Figure 1.22)
    - This is referred to as spectral broadening
  - CW Doppler envelopes are always filled in since flow velocities are recorded all along the Doppler line (Figure 1.4)

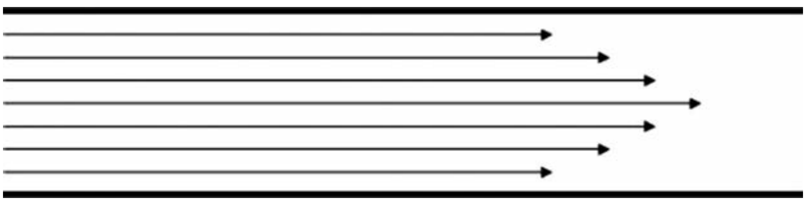


Figure 1.19 Normal blood flow through the heart is laminar. Blood travels in a linear path at similar velocities.

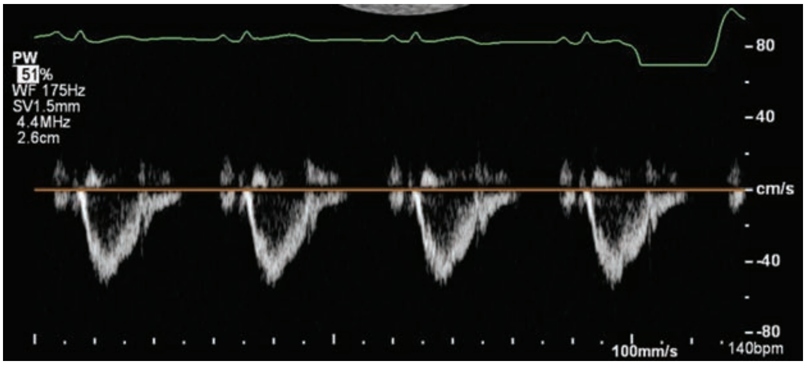


Figure 1.20 Normal laminar blood flow has hollow PW envelopes since there is no great spread in velocity.

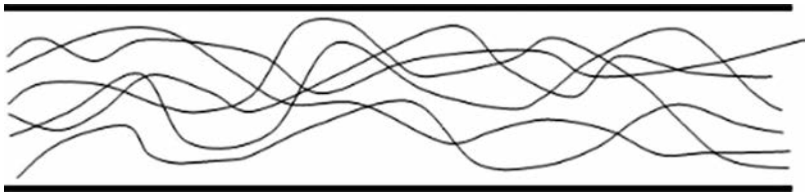


Figure 1.21 When flow becomes turbulent it is no longer laminar, and multiple velocities and directions are present.

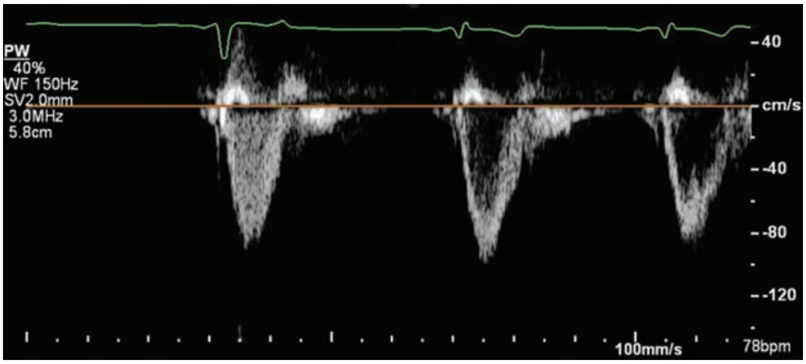


Figure 1.22 Non-laminar flow causes filled-in PW flow profiles. This is called spectral broadening. However spectral broadening can occur secondary to technical error. Flow here shows spectral broadening in the first flow profile and laminar flow in the latter profiles at the same gate location. The laminar flow is correct. Flow does not change from turbulent to laminar in the same location.

- Causes of spectral broadening
  - High gain settings
  - Poor angle of incidence relative to flow
  - Turbulence
  - Always seen in CW