Doppler Color Flow Imaging #4

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INTRODUCTION

Doppler color flow imaging is a method for noninvasively imaging blood flow through the heart by displaying flow data on the two-dimensional echocardiographic image. This capability has generated great excitement about the use of the technique for identifying valvular, congenital, and other forms of heart disease, as the color flow image imparts spatial information to the Doppler data. To inexperienced Doppler users, the color flow display makes the Doppler data more readily understandable because of the avoidance of complex spectral velocity displays.

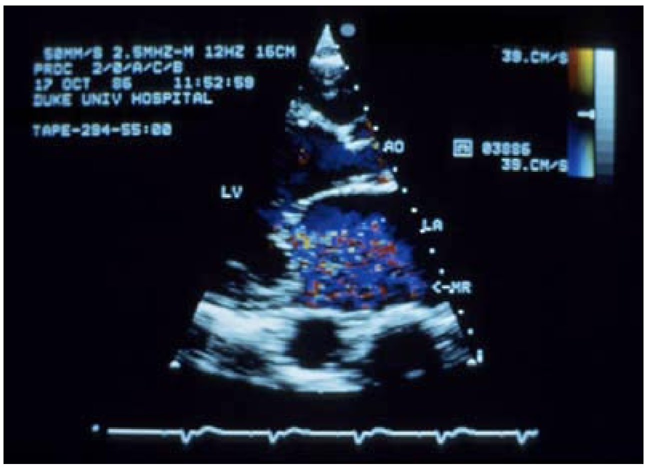

Figure 4. 1 Systolic parasternal long-axis color flow image of mitral regurgitation. The mitral regurgitation jet comprises a mosaic of varying colors. A variance map is used. Note the direction of flow indicated by the color bar on the right (Abbreviations, page 39).

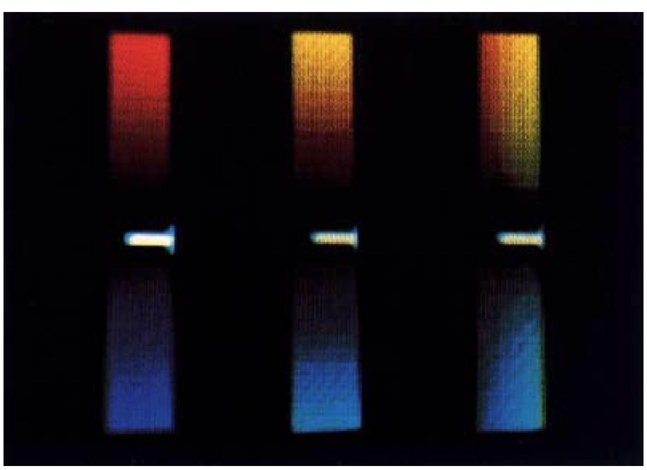

Figure 4. 2 Three color bars from a color flow system. When there is no flow, black is displayed (center) in the standard bar (left), flow toward the transducer at the top is in red, flow away in blue. Progressively faster velocities are displayed in brighter shades of red or blue. The center bar is in an enhanced map, and the right bar in a variance map (explained later in the text).

COLOR FLOW IMAGING IN CLINICAL PRACTICE

Doppler Color Flow Imaging

In **Figure 4.1** there is a mitral regurgitant jet into the left atrium in systole and the regurgitant blood flow is displayed on the two-dimensional echocardiographic image. In color flow imaging, the colors red and blue represent direction of a given jet; the various hues from dull to bright represent the differing velocities. When turbulence is present, a mosaic of many colors results. A two-dimensional display of flow is, therefore, produced with ready identification of size, direction, and velocity.

The Meaning of Color

The colors displayed on the flow map image contain useful information. By convention, Doppler color flow systems assign a given color to the direction of flow; red is flow toward, and blue is flow away from the transducer. Three typical color bars from a color flow imaging device are shown in **Figure 4.2** and give an initial frame of reference to the meaning of colors. Such color reference bars always appear on the screen of Doppler flow imaging devices. The center of the standard color bar on the left is black (white center reference mark) and represents zero flow.

In addition to simple direction, velocity information is also displayed. Progressively increasing velocities are encoded in varying hues of either red or blue. The more dull the hue, the slower the velocity. The brighter the hue, the faster the relative velocity.

In the color bar shown in the center of **Figure 4.2**, the colors have been "enhanced" so that the hues of red are increased from very dull red to bright yellow and the hues of blue are increased from very dull blue to a bright pale blue. The enhanced map helps a beginner to understand the relationship between velocity and color. The bar at the right demonstrates variance.

As will be seen later, color is also used to display turbulent flow and allows an operator to discriminate between normal and abnormal flow states.

The Angiographic Concept

One way of conceptualizing Doppler color flow methods is to recognize its similarity to angiography. It provides a noninvasive "angiogram" of blood flow, where the contrast medium is the moving red blood cells and the detector of this contrast is ultrasound. The complex Doppler ultrasound processing circuitry allows for the detection of movement of these red cells in various directions – forward and backward through the heart. Doppler color flow information, however, is obtained and displayed in a cross-sectional image, making the spatial details of flow and anatomy readily recognizable. In effect, Doppler color flow looks inside the cineangiographic silhouette.

Unlike angiography, Doppler color flow does not depend on dye dilution accumulated over several heartbeats. Rather it displays an abnormal flow jet for each cardiac cycle. This results in the ability to display the differing sizes of regurgitant jets depending on severity. The larger the volume of the regurgitant jet, the larger the size represented on the display.

CREATION OF THE COLOR IMAGE

The Importance of Time

Time is the key factor to keep in mind. A conventional two-dimensional ultrasound imaging system is already working as hard as it can. Pulses must be transmitted along a given line, reflected from the heart valves and walls, then received. The process is repeated, line by line, through the entire sector arc that comprises several hundred lines. This completes one frame of information, usually in one-thirtieth of a second. In order to have the image appear as though it is continuously moving, the entire image must be updated 30 times in a second (30 frames/second). This results in relatively long waiting periods for the transmit-receive sequence to be completed. It also means that considerable amounts of information need to be quickly processed and presented in the image.

A problem, therefore, results. If all this time is taken to simply create the image, where is there time to sample rapidly with the Doppler, left and right, in all portions of the image field? From earlier units in this series, we have already learned that high quality imaging and high quality pulsed Doppler cannot really be conducted simultaneously.

Anatomic and Flow Information Together

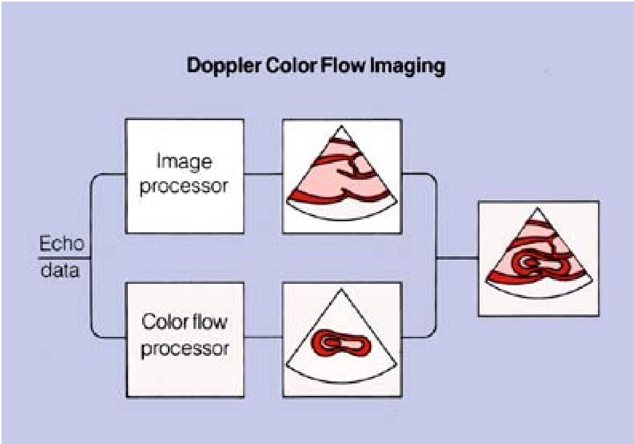

Figure 4. 3 In a color flow-imaging device, the returning echo data are processed through two channels that ultimately combine the image with the color flow data in the final display.

Expressed in its most simplistic terms, color flow systems add a separate processor that creates the color flow image based on the returning data and then integrates it with the two-dimensional anatomic image **(Fig. 4.3)**. Both the anatomic and the color flow data are then displayed in the final image.

The returning ultrasound data from any conventional scanner also contains frequency shift information that results from the encounter of the transmitted pulse with moving structures and blood. Until the advent of color flow imaging, this frequency shift data was simply ignored.

The key to color flow mapping is that the returning data may also be processed for the frequency shifts (or red blood cell velocities). Thus, color flow imaging systems take advantage of data that are available in every ultrasound image of the heart.

While this is a simplistic explanation, it is not true in most color flow systems. In reality, the lines of color flow data are alternated with lines of anatomic scan data. The anatomic data are acquired and received by conventional means and the color flow data are acquired, received, and processed separately.

Multigate Doppler

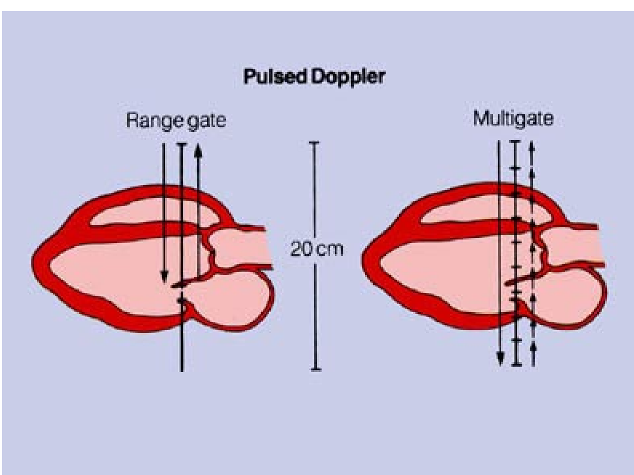

Figure 4. 4 Color flow Doppler systems use PW Doppler principles in a multigate, rather than range-gate format. For details, see text.

Doppler color flow instruments are all currently based upon pulsed wave (PW) Doppler methods. Conventional PW techniques are range gated **(Fig. 4.4, left)**. The Doppler sample volume is determined in range by the time it takes for the ultrasound pulse to travel to the area of interest and then back. If the same method was employed in color flow, it would simply take too long to sample over the entire image and there would be serious compromises made in frame rate.

Instead, all color flow systems are "multigated". In the illustration in **Figure 4.4 (right)** a simple ten-gate system is illustrated and compared with the conventional PW approach. Here, a burst of ultrasound is sent into the tissue along a given line and then the system rapidly receives at ten incremental times. This results in the reception of

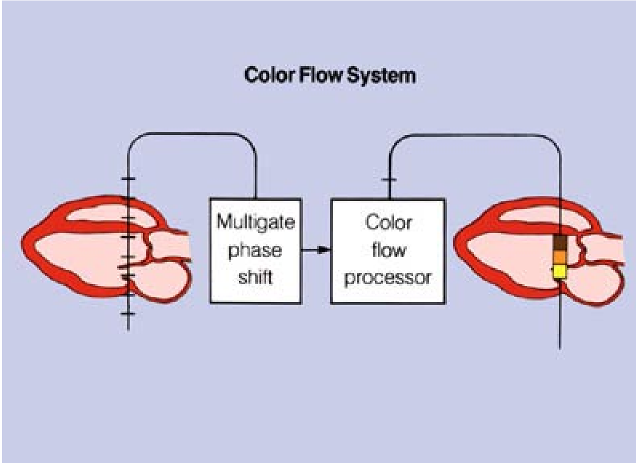

Figure 4. 5 Color flow imaging systems collect the phase shift information at each of the multiple gates and then process the information with color presented in the final display.

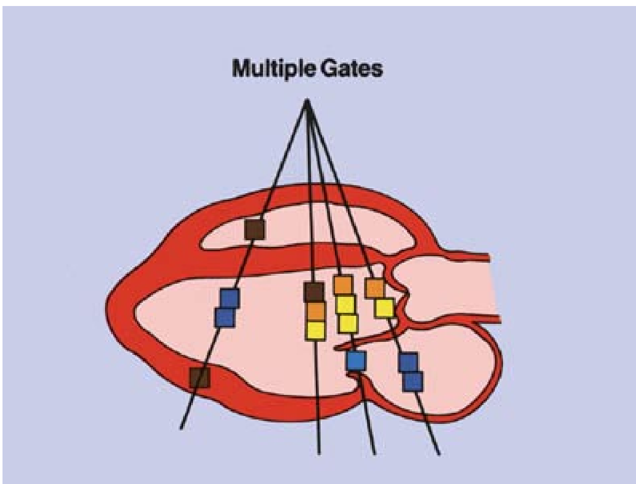

Figure 4. 6 Hundreds of gates are present along each line throughout the color flow image. In gates where there is target information, no color is displayed (open gate at lower left),

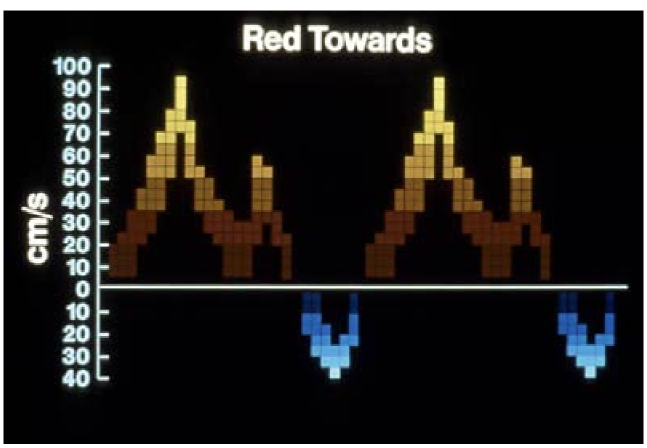

Figure 4. 7 If color was mapped on a conventional spectral recording, only one color could be placed in each bin. Progressively increasing velocities towards the transducer would be displayed in brighter hues of red while flow away would be displayed in blue.

Doppler data from the near flow areas first, while the pulse is still continuing into the tissue. Obviously, reception of the flow data in the far field occurs later.

This multigating takes advantage of Doppler information all along the line that is "ignored" in the conventional range-gated approach. In reality, each line has many gates that number in the hundreds. **Figure 4.5** demonstrates a simple ten-gate system where the amplitude and phase shifts are detected for each gate and presented to the color flow processor for final display of the color in each gate.

It is best to think of the color flow map image as comprising little gates throughout the field of view, each gate containing some composite of the Doppler information. A typical image can consist of as many as 256 lines depending upon sector size and depth of range. **Figure 4.6** demonstrates that multiple gates of color flow information are displayed throughout the entire image along each ultrasound line.

More About Color

All Doppler flow imaging systems encode the directions of flow into two primary colors: red and blue. Any number of color assignments could be made, but red and blue are chosen because they are primary colors of light (together with green).

If such encoding were done on a conventional spectral Doppler display, the result would look very much like **Figure 4.7**. There is also relative flow velocity information in the color hues; the brighter the color the higher the velocity detected. Thus, high velocities away from the transducer will appear as lighter shades of blue, and higher velocities toward the transducer will be represented by lighter shades of red, or even yellow. Low velocity flow will be represented by darker shades of these colors. Absence of flow is always represented by black.

Choosing a Velocity for Display

Even in laminar flow, many different velocities (and therefore colors) may be detected at any instant in time. In the two-dimensional color display, only one color can be displayed in each gate at any time. The problem is even worse when turbulent flows are detected where there may be a wide range of velocities at any instant. At each spatial location, or gate, only one color can be displayed for any selected map. What color should be chosen?

Detection of Mean Velocity

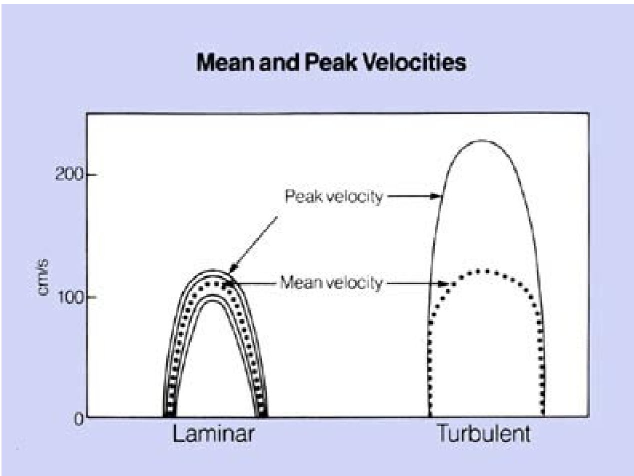

Figure 4. 8 Schematic representation of spectral recording showing the differences between peak and mean velocities. In the case of normal laminar flow, peak and mean velocities may be very close. For turbulent flow, there may be a significant difference between peak and mean velocity.

The color presented at each gate is determined by the mean velocity. Mean velocity is the average of all the different velocities detected at any moment in time. For normal laminar flow, mean and peak velocities are very close **(Fig. 4.8)**. In turbulent flow, when there are many different velocities, mean velocity may be only half of the peak velocity.

Thus, for a color flow map system to correctly assign a color into a given gate, it must be able to detect both the direction of flow and the mean velocity in the area sampled. Since everything happens very quickly, it is best to think of color flow map systems as estimating, rather than precisely calculating, the mean velocity at any gate.

About Pulses, Packets and Trains

The calculation of mean velocity presents an intriguing problem. If you were asked to determine the mean (average) height of a hundred people line up before you, you would want to measure each individual, then divide by the number of people measured and arrive at the true mean height. Such a procedure would take considerable time, equipment and personnel.

If such facilities were not available, you might want to measure just one person at random and hope that your number reflected the entire population. But if you were given another brief period to measure another person, you would arrive at a better estimate because you could take the height from the first sample and add it to the second sample, then divide by two. Given a third, fourth, and perhaps fifth sample period, you would progressively arrive at a better estimate of mean height in the population. This is an imperfect way to estimate mean height: under the limitation of time and equipment it is, however, the only way.

The problem is similar for the color flow Doppler device. Since there are very narrow time constraints for the system to do all of its estimations of mean velocity at any gate and then process the results for presentation, a method is needed to obtain the best estimates possible and then move on. Naturally, compromises must be made along the way.

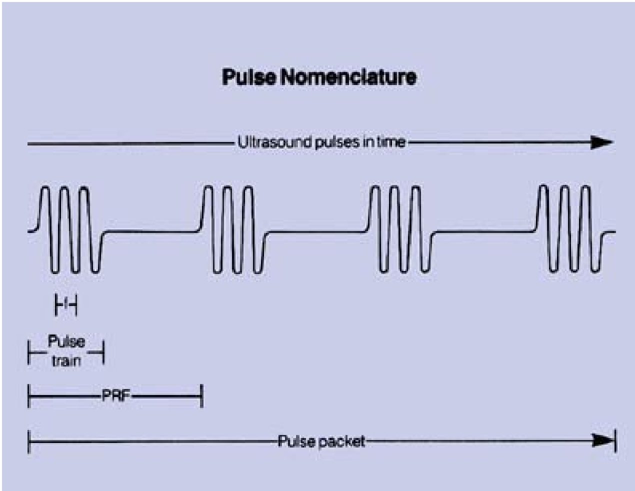

Figure 4. 9 Pulse nomenclature used in the development of color flow images. The number of pulse trains determines the size of the pulse packet. The larger the packet, the better the estimation of mean low velocity.

Color flow systems use an elaborate sequence of pulses to arrive at these estimates; all are shown in **Figure 4.9**. The ultrasound transducer transmits sound waves at a given frequency (f) and the frequency is fixed by the transducer being used (2.5, 3.5, or 5.0 MHz). Bursts of pulses are known as the "pulse train". The time between successive pulse trains determines the pulse repetition frequency (PRF). A number of pulse trains are also emitted at a given angle and this is called the "packet size". In color flow mapping, the principle of packet size is particularly important as it determines the length of time required for sampling to occur before the system moves on to the next beam line.

Conventional two-dimensional anatomic imaging uses only a single pulse train to acquire the necessary anatomic information. Conventional PW Doppler typically uses 128 pulse trains to obtain detailed velocity spectra from a single point in space. Since the sample volume is held in one place, there is plenty of time to perform the detailed spectral analysis. Because color flow mapping attempts to estimate velocity at multiple points in space, far fewer pulse trains can be employed. Time will not permit such detailed sampling with simultaneous construction of a two-dimensional flow image.

Color flow requires the most samples possible in the shortest period of time because so much Doppler information needs to be acquired. What results are small packet lengths, usually of at least three pulse trains per line (or a packet size 3), and up to sixteen pulse trains (or a packet size 16). Obviously, large packet sizes give the best estimates of flow but require the longest time.

Clinical Implications of Packet Size

The requirement for multiple pulse trains per line means that a greater period of time is required to sample along each beam direction than in conventional two-dimensional imaging. Therefore, some reduction in frame rate, line density, depth, or sector angle in comparison with routine two-dimensional imaging is necessary. When a machine is turned into the color flow mode, an operator will immediately notice compromises made in these factors.

Sector angle and depth range can be chosen. In some systems, packet size can also be selected. Once these factors are determined, frame rate and line density are automatically adjusted according to the specifications of the particular system (although in some systems line density can also be selected by the operator). In general, better quality flow data will be obtained with a higher packet size since this allows more sampling along each beam direction. Choosing a higher packet size, however, necessitates either a smaller line density or a lower frame rate and will affect the quality of the image in other ways that will be discussed later. In systems where the operator can control packet size, it is best to start with an individual manufacturer's recommended settings.

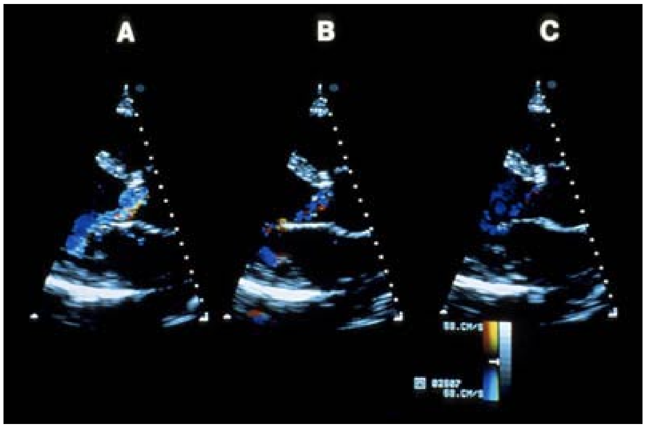

Figure 4. 10 Parasternal long-axis views of an aortic regurgitant jet showing the effect of packet size changes. Panel A was acquired with large packet size, panel B with medium packet size, and panel C with small packet size. Large packet sizes have the best estimates of mean flow but come at the expense of frame rate. Spatial filtering is used with variance maps.

The effects of higher and lower pulse packet sizes are seen in **Figure 4.10**. Better detection of aortic regurgitant flow is achieved using the larger pulse packet size **(panel A)** than when medium **(panel B)** or small **(panel C)** packet sizes are used.

Velocity and Color Assignments

The next step is to understand something of how these systems process the returning waveforms and assign a given color. The analysis of returning Doppler signals from each sector line is complex.

A pulse packet is sent and received along a given line. The frequency shift (or Doppler shift) between successive transmitted and returned packets is usually processed with a circuit called the "quadrature detector". This device employs common electronic circuits to allow determination of the frequency shift.

Simply explained, the quadrature detector supplies a measurement to be used later for the color flow processor in assigning the velocity, and thus the color, at any gate. The main function of the quadrature detector is to make this phase shift measurement for each pulse train, then convert it from analog to digital form (which simply means the data from a continuous sine wave form is assigned a given number to allow further high-speed processing). This digital measurement is then sent to the color flow processor for assignment of velocity and then color.

To obtain the best estimates of flow possible, the signals must first be cleaned as the frequency shifts are cluttered by system noise and signals that arise from heart valves and other cardiac structures. Returning data from one pulse train is held in the processor memory to be used for eliminating system noise from all the other pulse trains in the packet. Data from the second pulse train then returns and is compared with the first, leaving a single, clean signal. The third pulse train then returns and is cleaned in a similar fashion. To get a single phase shift, the two clean signals (second and third) are then compared. Thus, to get a single measurement of phase shift a minimum of three pulse trains are required. This filtering, or cleaning process, utilizes "clutter reject filters" or "comb filters".

Frequency shifts are determined from multiple sample volumes along the line, using the multigate approach previously described. Depending on the system employed, data from 250-500 points (or gates) along the beam line can be processed. Reflected ultrasound is simply analyzed at multiple times (corresponding to multiple gates) as a pulse train makes its way to, and back from, a given depth.

In the color flow processor, analysis of the filtered data from the quadrature detector is finally performed. This analysis cannot be accomplished by fast Fourier transform methods as is used in conventional PW Doppler, since only a few pulse trains are available in color flow imaging devices. Color flow systems must acquire data from thousands of gates throughout the entire field of view. They do not have the luxury of spending enough time in one place to deliver and receive such a high number of pulse trains. Thus, an alternative means of analysis, based on less data, is required to construct a two-dimensional flow map.

These data are analyzed in color flow mapping by utilizing one of two mathematical approaches. The methods are known as "autocorrelation" and "instantaneous frequency estimation". Some systems use a combination of the two methods, which we have termed a "hybrid". These methods are very difficult to understand and have minimal impact on the conduct of an examination. Simply stated, all make a frequency shift estimate for each gate along a given beam line.

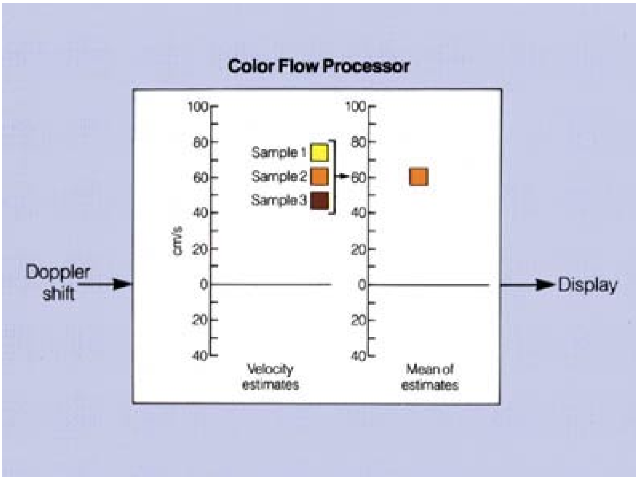

Figure 4. 11 A simple diagram showing the operation of a color flow processor where data from three pulse trains are used to estimate velocity, and one mean estimate is finally displayed in the gate.

The frequency shift information from each sample gate, obtained from successive pulse trains along the same beam line, is stored. The phase shift information is then assigned a velocity and color in the color flow processing section of the system for each packet (or series of pulse trains). This process if simply demonstrated in **Figure 4.11**, in a system using three phase shift estimates that result from a pulse packet size of 5. Mean velocity data, returning from a given pulse train, are simply called a sample. The mean of the frequency shift estimates obtained from the multiple pulse trains for each gate is then determined, and displayed as one color in each gate at any point in time.

The Price of Compromise

As noted above, the more pulse trains in a given line (higher packet size), the better will be the mean estimate of flow for each gate. Too small a packet size will likely result in unreliable flow data. As also explained previously, the minimal usable packet size is three. Too large a packet size will result in too much time being devoted to each line, and frame rate or line density or sector angle will be sacrificed. Most systems have a normal packet size of between six and eight.

The time taken for various flow map systems to create this two-dimensional image of flow is variable. To move quickly, and thus maintain rapid frame rates, color flow operation requires fewer samples to be collected and processed and the resultant displayed velocity estimates are made less reliable. Conventional, two-dimensional imaging has frame rates of 30 per second that preserve the smooth movement of the valves and walls. The time compromises in color flow imaging severely reduce the frame rate. The rate may, in fact, drop as low as four or six frames per second. This can create a situation that makes analysis of data quite difficult when flow is rapid, when rapidly moving anatomic targets are involved, or when heart rates are high as seen in neonates.

By sacrificing completeness of velocity information at each point, it is possible to determine only mean velocity, but at many points. As the ultrasound line sweeps through the sector arc, mean velocity is determined throughout the field of view. All of this velocity information is then converted to color and finally combined with the anatomic image. This leads to the display of a cineangiogram-like picture of intracardiac blood flow.

Line Averaging

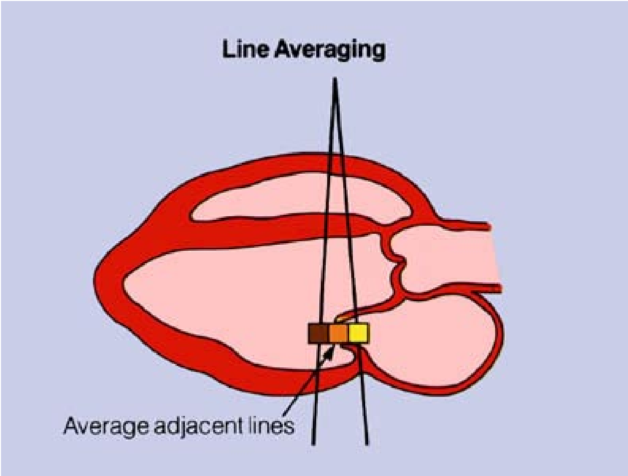

Figure 4. 12 At the far ranges gates are separated due to divergence of the radial scan lines. Data from adjacent gates are averaged to smooth the image.

As the ultrasound lines diverge into the far field of the image, they become increasingly separated. At some point in space they are so far apart that the resultant image would appear broken. To overcome this problem, data from a gate on the line are averaged with data on the adjacent line **(Fig. 4.12)**. This process is repeated for each frame of color data throughout the field of view. The resultant averaging smoothes the appearance of colors in the final display and is called "interline interpolation". This type of processing is also applied to the two-dimensional anatomic data as well.

Aliasing in Color Flow

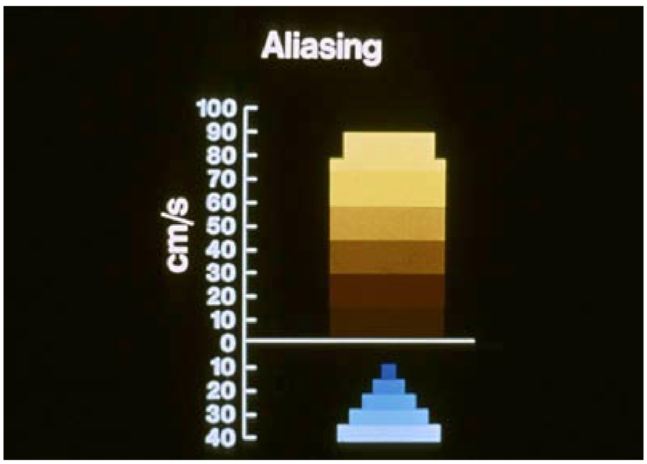

Figure 4. 13 If the color flow data were displayed in a spectral format, aliased flow towards the transducer would be cut off at the top and the aliased flow into the opposite channel would be reversed in color.

As with conventional PW Doppler, aliasing occurs when using color flow methods. The reasons for this are identical to those described in Unit 1. Like conventional PW Doppler, both depth and transducer ultrasonic frequency will determine the actual velocities at which aliasing occurs. Less aliasing would be encountered when using lower frequency transducers than with those of higher frequency.

The implications for this in clinical scanning are significant. The highest resolution ultrasound scanning is carried out with higher frequency transducer systems, yet these frequencies have the greatest problem with aliasing. In small children, with rapid flow rates, aliasing may present tremendous interpretive difficulties differentiating between normal (but aliased) flow and abnormal (but aliased) flow.

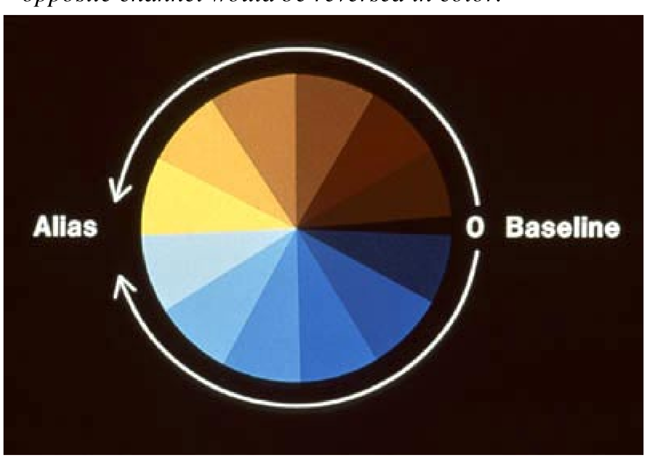

Figure 4. 14 Using a color wheel, baseline, or zero, flow is displayed in black. High mean velocity data are aliased between brighter hues of red and blue and may be easily recognized in the final display.

The color correlates of aliasing are shown in **Figure 4.13** with colors depicted on a spectral-type recording. In the "red-toward" mapping schema this would be displayed as a reversal of flow to the opposite direction and therefore as blue.

It is best to think of aliasing as a color wheel with zero flow at the right and represented as black. Such a color wheel with zero flow is shown in **Figure 4.14 (right)**. In the enhanced rendition of colors, the hues of red and blue are accentuated into very bright colors. This is used to aid the beginner in understanding how aliasing appears in the color display. In either direction, as the mean velocities rise, increasingly brighter colors are encountered until the aliasing point is reached at which there is a reversal of color into the opposite directional channel. Note that at the aliasing point the brightest hues of red and blue are adjacent. This fact aids the eye in the recognition of aliasing in the final display. Some aliasing may be present in the Doppler color flow images of normal flows, but it is usually minimal.

The aliasing point for color flow systems is also dependent upon the maximum range of the field of view selected. As explained in Unit 1, conventional PW Doppler systems will have variable aliasing points depending on the location of the sample volume in the field. For color flow imaging, the same principle applies but its effect in the final image is a little different than with conventional systems. In color systems, the maximum pulse repetition frequency is set by the maximum overall depth selected. This influences each gate in the entire image field and is independent of whether the gate is near or far from the transducer. More aliasing will be seen throughout the image when scanning at deep range settings than at shallow range settings.

Using standard 2.5MHz transducers, aliasing is frequently associated with the higher velocities and turbulent flow that are found in disease states.

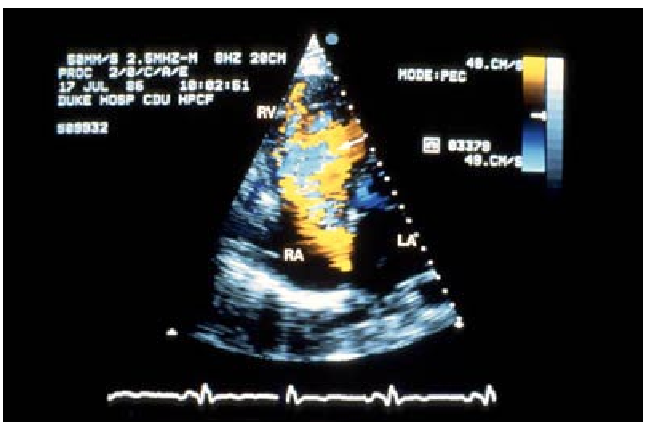

Figure 4. 15 Modified apical four-chamber view of flow through an atrial septal defect and into the tricuspid orifice in diastole. The bright yellow flow aliases into bright blue within the central core of the flow jet (arrow). This is an enhanced map.

On the color display, as the signal is aliased from one color to the next, it appears as a mosaic of the very bright hues at the aliasing point. In **Figure 4.15** there is a large mosaic encountered in a jet from an atrial septal defect as it moves through the right atrium and tricuspid valve into the right ventricle in diastole. The red flow towards the transducer aliases into bright shades of blue. Note that the brightest of the red and blue are adjacent to one another, indicating the aliasing point. The dullest of the colors are also adjacent to one another, indicating the zero flow point.

While aliasing is a major problem for conventional PW Doppler echocardiography, it is less so for color flow. Because the aliasing is displayed in two dimensions as a mosaic, it frequently allows the operator to readily recognize areas of turbulence associated with disease states. Aliasing is therefore, frequently used to advantage in the color flow map since it may dramatically highlight the presence of abnormal high velocities.

Variance

In some of these difficult states, detection and display of variance is helpful in differentiating the complex flows. In laminar flow, mean velocity is very close to peak velocity. As seen in *Unit 1*, the velocity spectrum is narrow. In turbulent flow, the velocity spectrum is broadened with many different velocities being presented at any one time.

Color flow systems can, however, present only one color at any one gate. In an attempt to present turbulence in the color image, methods have been developed to detect this spectral broadening (“variance detection”). Variance expresses the degree to which velocities within a

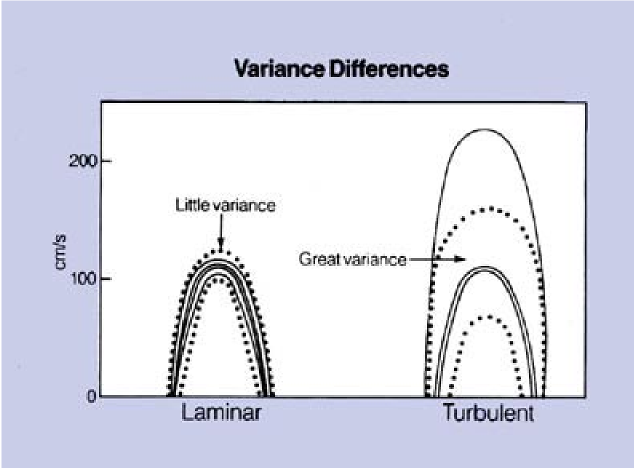

Figure 4. 16 In laminar flow there is little variation (variance) of velocities on either side of the mean velocity. In turbulent flow, when many different velocities are present, there is great variance.

given sample volume differ from the mean velocity within that sample **(Fig. 4.16)**. The more the velocities differ within a sample volume, the greater will be the variance. In this example of laminar flow, there is very little variance (difference) in velocity about the calculated mean. Since turbulent flow is characterized by flow at multiple different speeds in many different directions, the variance in a region of turbulent flow is high. Variance estimation circuits within the color flow imaging system detect variance around the mean and, when present beyond a given point, incorporate it into the display.

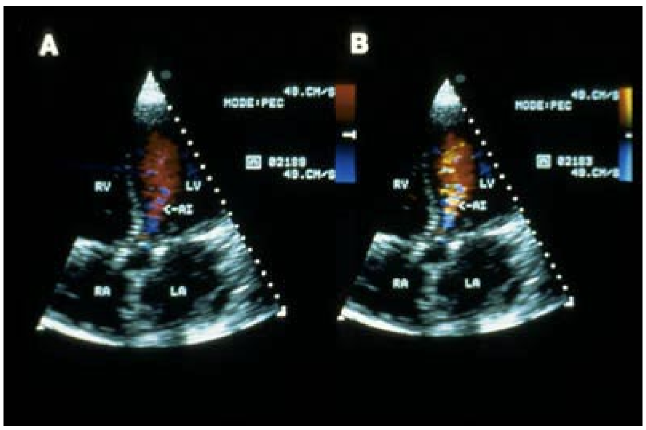

Figure 4. 17 Apical four-chamber diastolic view of aortic insufficiency demonstrating two different maps. The image is identical except for the map changes. Panel A shows a conventional red/blue map. Panel B shows a velocity/variance map where the regurgitant jet is readily identified.

A better understanding of how variance is displayed can be achieved by studying the colors of the aortic regurgitation jet seen from the apical window in **Figure 4.17**. The accompanying color bars to the right of each image help to identify which maps are being used. In **Figure 4.17 (panel A)**, a standard color velocity display of direction (red or blue) and relative velocity (varying brightness of each color) makes identification of the aortic regurgitation difficult. In most systems, shades of green are added when greater variance in blood velocity is present (when turbulence is greater). This results in the incorporation of green into the display as show in **Figure 4.17 (panel B)**. Here, the variance is seen overlaid on the identical image in the left panel and renders the aortic regurgitation jet recognizable.

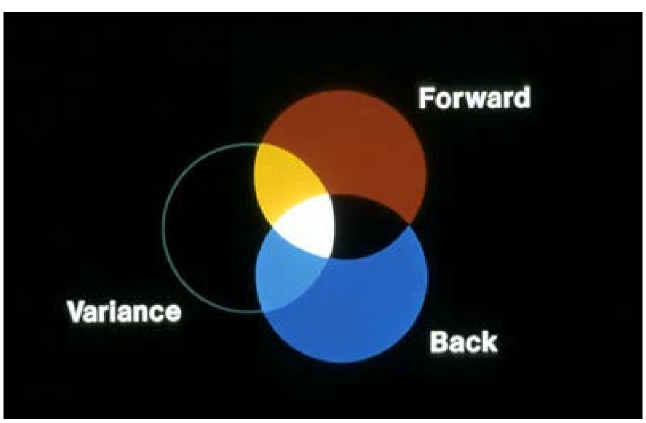

Figure 4. 18 When variance is detected, hues of green may be added to the red and blue flows, resulting in shades of yellow, white, and blue-green (cyan).

The method chosen for the display of variance is demonstrated by the intersecting circles of color in **Figure 4.18** (also see **Fig. 3.21**). Green is the third primary color of light. Since red and blue are already in the display, green is simply added on top of each of these colors. Forward flow with turbulence would result in yellow. Backward flow with turbulence results in cyan (blue-green). Pure green is rarely present in the display. If multi-directional turbulence could be encountered at the same time, the result of all three colors would be white. If multidirectional flow without turbulence could be encountered, combinations of red and blue (without green) would result in magneta.

These intersecting color wheels have been presented to enhance your understanding of the rules that govern the final color display. In reality, the red and blue circles do not intersect, as color flow systems can assign only one color to a gate. Since the color is finally assigned to a mean velocity estimate, it is either in the red or blue direction. There is no true white or magenta in the final display. It is important to recognize that a variance display in green can only be used with the standard red-blue map as baseline. Adding green to red and blue results in the various colors of yellow and cyan. Since these colors are already used in the enhanced map, the addition of green would have no visible effect. Thus, yellow in an enhanced map only reflects velocity information. Yellow in a variance map reflects turbulence. When turbulence is present, the range of mean velocities is broadened, and variance is detected. The result in the display is a "mosaic" of reds, blues, yellows, and cyan in the turbulent area.

Mechanical and Phased Array Scanners

For some time, it was thought that mechanical scanning systems could not be used to perform color flow analysis due to marked frequency artifacts introduced by the moving scan heads. While this may be true, some systems currently under development minimize this problem and may produce acceptable color flow images from mechanical scanning systems. Currently, since phased array systems have no such problem, they are the most common type of color flow system in use.

USE OF THE COLOR FLOW CONTROLS

From system to system, the color flow controls may be simple and readily recognized, or excessively complex, intimidating, and sometimes buried in many pages of software. Essential controls are very few.

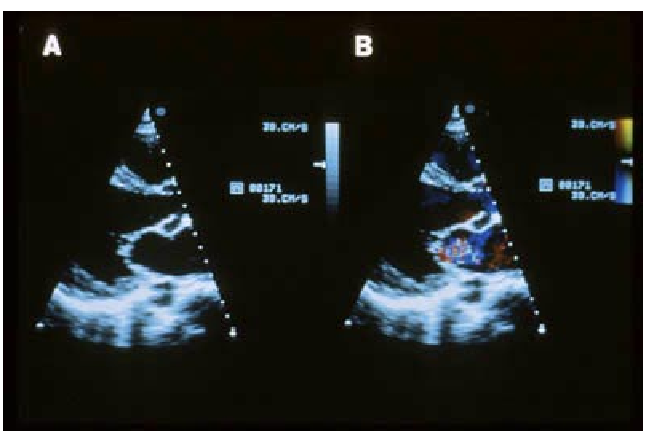

Figure 4. 19 Parasternal long-axis view of two-dimensional echocardiogram (panel A). The color is switched on (panel B) revealing the mitral regurgitant jet. A variance map is used.

The Doppler Color Flow Examination

The color flow examination is most easily accomplished during the two-dimensional examination when there is suspicion that any abnormal flow state exists, such as valvular regurgitation or communication between the cardiac chambers. The color flow may be readily switched on and off using the *color on* control while the operator proceeds with the two-dimensional examination as the various routine, or other pertinent views, are obtained. In **Figure 4.19** the same parasternal long axis image is shown without **(panel A)** and then with the color flow superimposed **(panel B)**. Conducting a separate color flow examination after the normal two-dimensional examination is unnecessarily time-consuming.

Gain

The next most important control is the *color gain*. Optimal adjustment of the gain setting is essential, as too much gain will result in excessive noise in the image and detract from image quality and interpretability. In most systems, excess gain is readily recognized by the appearance of background noise and distortion in the continuity of flow. Like conventional Doppler, this obscures the flow data. Too low a gain setting will diminish the sensitivity of the system in detecting small flow disturbances. It will further make large flow disturbances appear artificially smaller as the spatial representation of the limits of an abnormal flow jet are entirely dependent upon gain. **Figure 4.20 (panel A)** demonstrates a mitral regurgitant jet with too little gain; the area appears small. Slight increase in the gain reveals the full extend of the regurgitant jet **(Fig 4.20 panel B)** that fills virtually all of the left atrium. In our experience, it is quite difficult to make small jets abnormally large by the use of excess gain. It is however, easy to make large jets appear very small by the lack of proper gain settings.

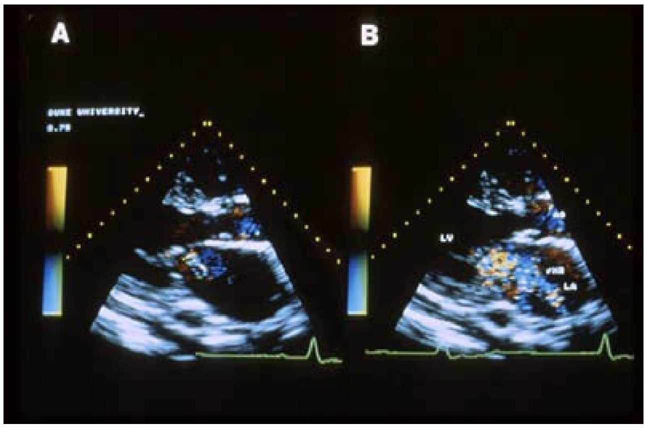

Figure 4. 20 Parasternal long-axis images of mitral insufficiency demonstrating the effect of color gain on the area of a regurgitant jet.

Other Controls

Most color systems will not map flow where there is anatomic target data on the display. It is very important, therefore, not to have excessive *image gain* on the two-dimensional display before switching to color flow, because excessive gain on the anatomic image may obscure flow on the color display.

Sector size and location may also be selected. Large sectors, however, reduce frame rates as previously discussed. Of the several choices available, the two most commonly used are the color image, within a wedge of the full sector arc and color within the entirety as a small sector arc. Increasing *depth* range will also decrease PRF, resulting in increased aliasing at lower velocities. Decreasing depth range will consequently decrease aliasing.

Some systems have various *color processing settings* that allow a choice of the way in which color is used to display flow information. Color processing controls may be generically grouped into four categories that provide choices of direction and turbulence/enhance displays: wall filters, spatial filters, color reject, and packet size. All have an effect on the final display.

Wall filter processing controls may be changed in some systems. Baseline filter controls variably eliminate low velocity flow information that results from the movement of the heart walls and valves. Without the use of these controls, considerable artifact results in the image from the moving anatomic structures. This is referred to as “ghosting” and appears in the display as dull hues of red or blue depending on the direction of movement of the given structure. Most newer systems have preset wall filter controls that considerably reduce the ghosting artifact.

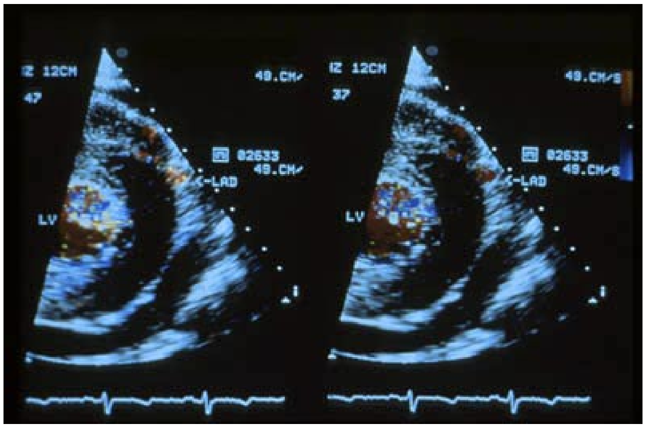

Figure 4. 21 Parasternal short-axis view showing the left anterior descending coronary artery. The flow within the vessel is obscured by the surround tissue artifact in the panel A. The panel B shows good separation between flow and vessel wall.

Some of these controls may be used to discriminate between flow and target data more precisely. **Figure 4.21 (panel A)** demonstrates one setting where flow in the left anterior descending coronary artery is obscured by the surrounding tissue artifact. In **panel B** an alternative setting is used that renders flow in this coronary artery separate from the vessel wall.

Spatial filtering is complex; most systems have some spatial filter built in and preset. Spatial filtering results in a smoother color image but comes at the cost of eliminating bright and dull hues from the display. *Packet size* may also be changed in some systems, and this effect has been previously shown.

Other Combinations

Most color flow systems also have a color flow M-mode presentation. This allows for the freezing of the two-dimensional image and the presentation of line-selectable M-mode with the color superimposed. M-mode is sometimes very helpful for displaying information where critical timing of flow events is desired. Other combinations of controls such as the use of combined color flow and conventional pulsed or continuous wave Doppler will be discussed later.

COLOR FLOW IMAGING OF VALVULAR REGURGITATION

Perhaps the most useful application of color flow imaging is in the detection of valvular regurgitation. Many of the patients examined in echocardiography laboratories dealing primarily with adult populations undergo Doppler examination for the presence and relative severity of valvular insufficiency. Color flow techniques avoid time-consuming PW Doppler examination mapping techniques and thus reduce patient examinations and interpretation times.

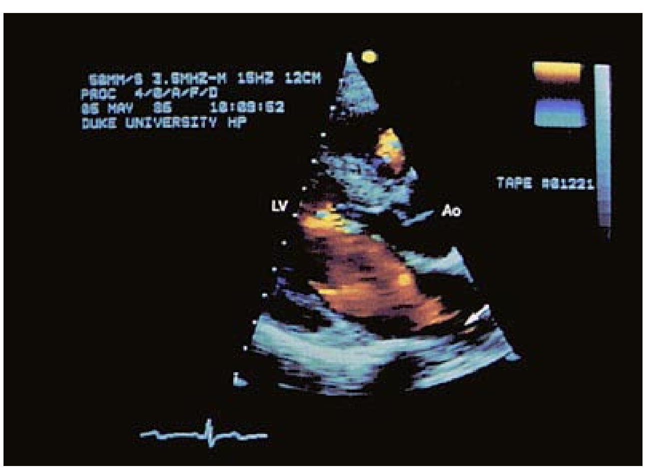

Figure 4. 22 Left parasternal long-axis view of blood emerging from a pulmonary vein (arrow) and filling the mitral valve orifice. An enhanced map was used.

Normal flows through the heart are easily detected, but to a beginner may simply appear as confusing flashes of color. Normal flows rarely alias and serve as a background for recognition of the aliasing that occurs with abnormal flows, such as valvular regurgitation.

Mitral Regurgitation

Normal diastolic flow through the mitral valve is very low velocity and rarely exceeds 1.5 m/s. Aliasing is, therefore, seldom seen during diastole when using a 2.5 MHz transducer. **Figure 4.22** demonstrates normal diastolic flow emerging from a

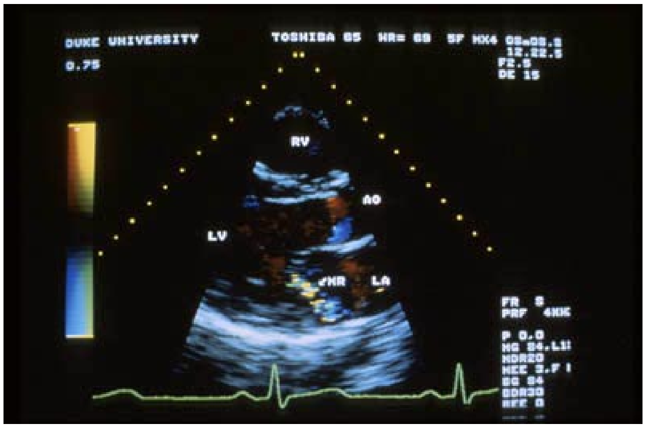

Figure 4. 23 Parasternal long-axis view of mitral regurgitation directed toward the posterior left atrial wall. A turbulence map was used.

superior pulmonary vein and then entering the left ventricle through the open mitral valve leaflets.

During systole, the left atrium is usually free from color. In **Figure 4.23** mild mitral regurgitation is seen to be directed along the posterior mitral leaflet toward the posterior left atrial wall. Aliasing is present due to the increased velocity and turbulence through the closed valve orifice, and appears as a bright mosaic of colors.

Mitral regurgitation can usually be detected using any view, even the parasternal long axis when the jet is perpendicular to the ultrasound beam. This is possible because most abnormal flows within the heart are turbulent. Many eddy currents exist in literally hundreds of directions simultaneously. Thus, while the main vector of the regurgitant jet may be generally perpendicular to the interrogating beam, some of the eddies within the main jet are oriented parallel to the beam. In most cases, these signals are sufficiently strong to be detected by the color flow imaging device. Thus, some spatial representation of flow will be seen by color flow methods.

Figure 4. 24 Left parasternal long-axis view showing a more severe degree of mitral regurgitation than seen in the previous figure. A variance map was used.

Quantifying the severity of valvular regurgitation is based approximately on the size and configuration of the regurgitant jet. Very small jets, localized just to the proximal side of the regurgitant valve, usually signify trivial valvular insufficiency. Large jets that fill the receiving chamber usually indicate significant valvular insufficiency **(Fig. 4.1)**.

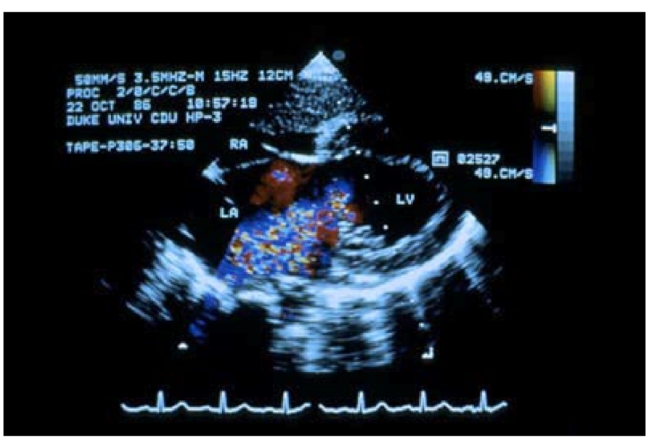

Figure 4. 25 Subcostal view of severe mitral regurgitation. A variance map was used; spatial filters are off.

Moderate mitral regurgitation is shown in **Figure 4.24**. Again, the hallmark is the systolic appearance of a posteriorly directed jet comprising aliased colors and turbulence. Regurgitant jets may go in any direction and have virtually any appearance. **Figure 4.25** demonstrates mitral regurgitation seen from the subcostal view in a 5-year-old boy where the jet is more diffuse and occupies almost all of an enlarged left atrium. In this case, severe mitral regurgitation is present.

It is imperative to remember that many factors influence the size, configuration, and appearance of regurgitant lesions. Among them are the volume of the jet, pressure difference between the regurgitant and receiving chamber, size of the regurgitant orifice, configuration of the regurgitant orifice and the size of the receiving chamber. Other factors such

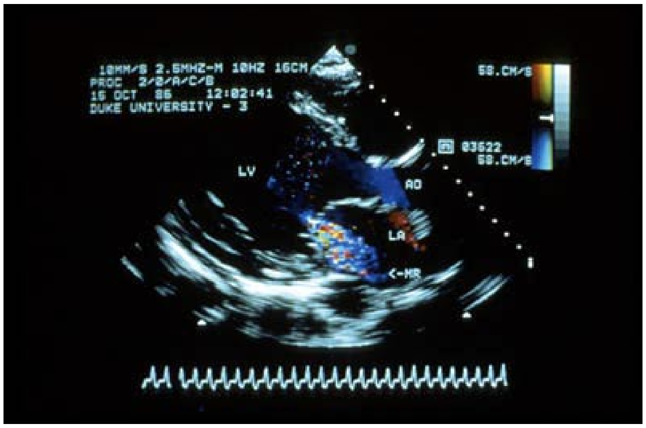

Figure 4. 26 Parasternal long-axis views of a mitral regurgitant jet in a patient with a diffuse cardiomyopathy. A variance map was used.

as the timing of regurgitation, loading conditions, heart rate, and rhythm may also be of importance. As mentioned above, the orientation of the jet to the beam is also a factor. Considerable work remains in verifying the significance of these and other influences.

Mitral regurgitation may be found by color flow imaging in any clinical state associated with this lesion, and may result from prolapse, rheumatic, infectious or other etiologies. Continued use of color flow imaging has revealed the frequent association of mitral regurgitation **(Fig. 4.26)** in patients with diffuse cardiomyopathies of virtually any origin. In our laboratory, we have encountered mitral regurgitation in 100% of patients with this disorder when the left ventricle measures 6 cm or greater in diastole. In each case, the mitral regurgitation was quantified at 2+ or greater (out of a scale of 4). Of further interest is the fact that there is a surprisingly high prevalence of regurgitation of the other heart valves. In patients with dilated cardiomyopathy, there is 2+ or greater regurgitation of the tricuspid valve in 91%, the aortic valve in 23%, and the pulmonic valve in 58%. In these patients, forward flow is usually of very low velocity and results in dull hues of color.

Due to the considerable savings of time, we now use only the color flow approach in routine cases for detection of all valvular insufficiencies. This is not done, however, without attending to all the factors that may affect the reliability of our estimation of severity.

Operator skill is important. The use of too little gain will make regurgitant lesions appear unduly small, and can be a prime source of underestimation. Proper transducer angulation into the regurgitant lesion is also important. For small and eccentrically direct jets, extra time is required to be sure of proper identification. Hastily conducted studies limited only to traditional views may not reveal these types of abnormalities.

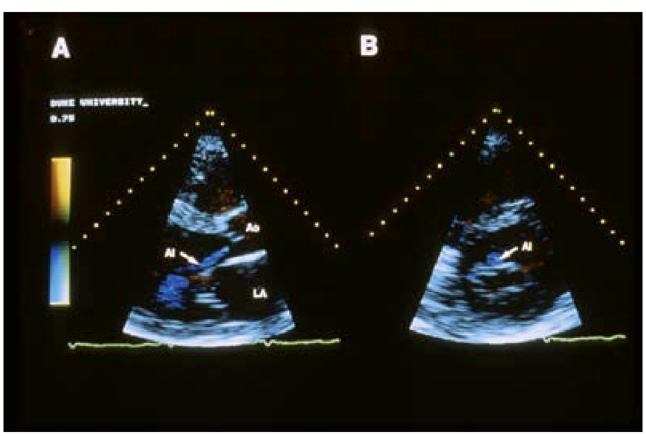

Figure 4. 27 Panel A shows a left parasternal long-axis view of a patient with a very narrow jet of aortic insufficiency. Panel B shows the limits of the jet in short axis.

Aortic Insufficiency

Almost all of the previous comments also apply to the detection and approximate quantification of aortic insufficiency. Aortic regurgitant jets may be small and narrow. When they are, location and mapping by convention PW techniques may be very time-consuming. Color flow approaches can readily identify these abnormalities, as seen in **Figure 4.27**. This narrow jet occupied only a very small portion of the area of the outflow tract when viewed in short axis **(Fig. 4.27, panel B)**.

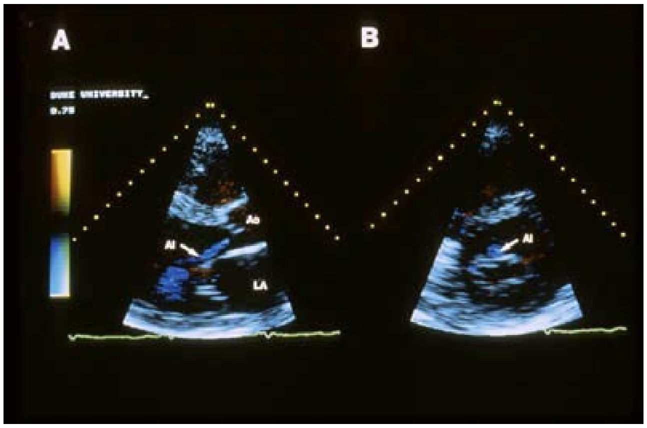

Figure 4. 28 Left parasternal long-axis view of aortic insufficiency filling the entirety of the left ventricular outflow tract in diastole. A variance map was used.

More typically, a strong turbulent signal is detected and aliasing occurs. **Figure 4.28** demonstrates the resultant mosaic across the entire left ventricular outflow tract in diastole resulting from aortic insufficiency.

The various directions of flow produced by aortic insufficiency also reveal useful information other than presence or severity alone. In **Figure 4.29** an aortic regurgitant jet is directed toward the anterior mitral valve leaflet, then reflected off to the left in a patient with a low-pitched diastolic rumbling murmur suggestive of mitral stenosis. No aortic insufficiency murmur was audible. No mitral stenosis was present by conventional echocardiography or by Doppler. Even though the degree of aortic insufficiency was small, the direction of the jet readily explained the origin of the murmur, as it was likely that the regurgitant jet set the mitral valve into rapid vibrations. This is the classical description of the origin of the Austin-Flint mitral rumble.

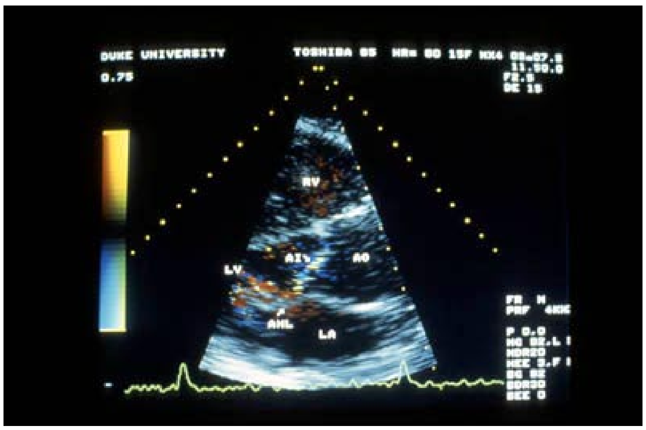

Figure 4. 29 Parasternal long-axis view of a narrow aortic regurgitant jet directed at the anterior mitral valve leaflet. This jet seems to bounce off the leaflet toward the left.

Use of the color M-mode is frequently helpful for timing of cardiac events. In **Figure 4.30** there is a parasternal long-axis view from a 30-year-old patient who had had mild fevers and two positive blood cultures several months prior to admission with a large and markedly turbulent aortic insufficiency jet direct toward the apex of the left ventricle along the posterior aspect of the interventricular septum. With the M-mode beam directed through the mitral valve, premature closure of the mitral valve apparatus was noted to occur well before the QRS complex, probably as a result of the significant hemodynamic load of the aortic insufficiency **(Fig. 4.31)**. The left ventricular diastolic pressure was high enough to close the mitral valve before the onset of systole. Of note is the fact that most of the mitral regurgitation was seen before mechanical systole began; following the QRS complex, little mitral regurgitation was noted.

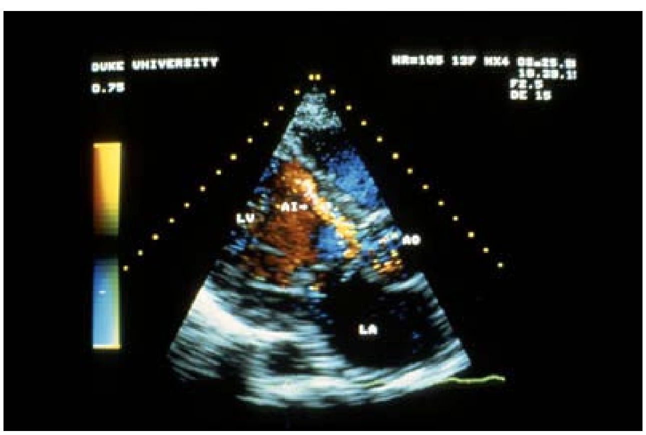

Figure 4. 30 Parasternal long-axis view of severe aortic insufficiency following the posterior portion of the interventricular septum. A variance map was used. This is the same patient as shown in the next figure.

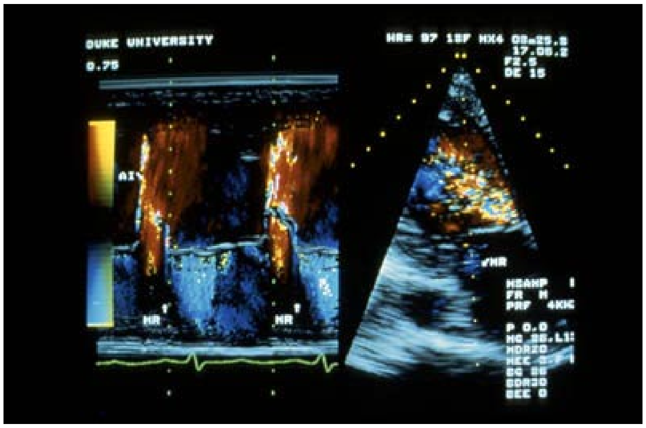

Figure 4. 31 The severe aortic regurgitation is seen on the right. The simultaneous M-mode color recording (left) shows premature closure of the mitral valve apparatus and the onset of mitral regurgitation in mid-to-late diastole. A variance map was used.

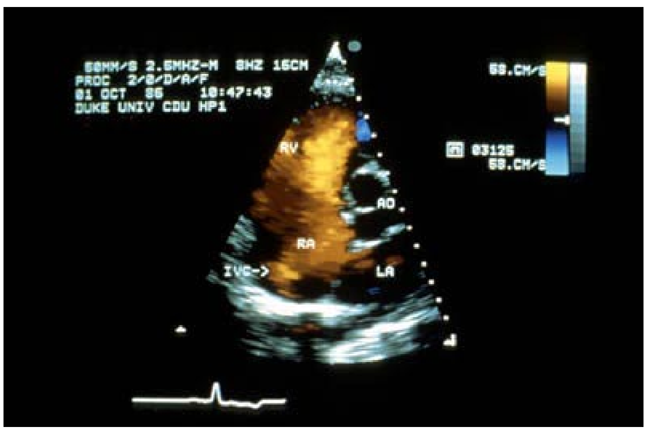

Figure 4. 32 Left parasternal short-axis view of the aortic root and right atrium. Low velocity flow can be seen to emerge from the inferior vena cava and move through the right atrium and tricuspid valve into the right ventricle. An enhanced map was used.

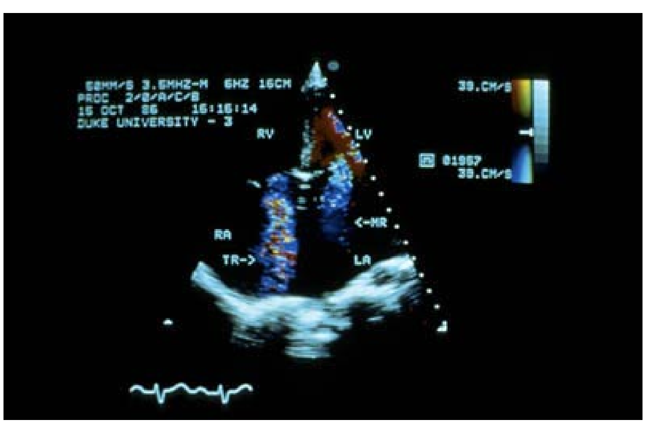

Figure 4. 33 Apical four-chamber view of both tricuspid and mitral regurgitations. The tricuspid regurgitant jet is directed toward the interatrial septum. A variance map was used; spatial filters are off.

Tricuspid Regurgitation

In **Figure 4.32** is shown the typical low-velocity appearance of blood flow emerging from the inferior vena cava and moving into the right ventricle through the open tricuspid valve. Note that flow in the right ventricle curling toward the outflow tract at the upper right exhibits a color change corresponding to the direction.

Regurgitation of the tricuspid valve, like all the other cardiac valves, is best detected during the two-dimensional echocardiographic examination. The most common views where such insufficiency is found are the apical four-chamber, short-axis parasternal at the level of the aortic root, subcostal, and right ventricular inlet views.

As with the other valves, tricuspid regurgitant jets may be found in any size, spatial configuration, and direction. **Figure 4.33** demonstrates a long and narrow jet of tricuspid regurgitation that nearly reaches the posterior wall of the right atrium, directed toward the interatrial septum. Tricuspid regurgitation is frequently found, even in normal patients. In these cases, the area of the regurgitation is usually small.

The effects of tricuspid insufficiency may also be seen in the inferior vena cava as shown in **Figure 4.34**. Here a burst of red is visible in systole as the flow is typically reversed in direction backwards into the hepatic veins.

Pulmonic Insufficiency

As blood emerges from the right ventricular outflow tract into the proximal pulmonary artery in systole, velocities are increased and aliasing frequently occurs. Very early systolic flow into the main pulmonary artery is shown in **Figure 4.35 (panel A)**. **Panel B** demonstrates the marked aliasing that occurs an instant later in systole, which is typical of normal right ventricular outlflow. Note also that the flow can typically be detected to the bifurcation of the main pulmonary artery and

Figure 4. 34 Long-axis view of the inferior vena cava during systole where tricuspid regurgitant flow is shown in red. Note the regurgitant flow into the hepatic vein. A variance map was used; spatial filters are on.

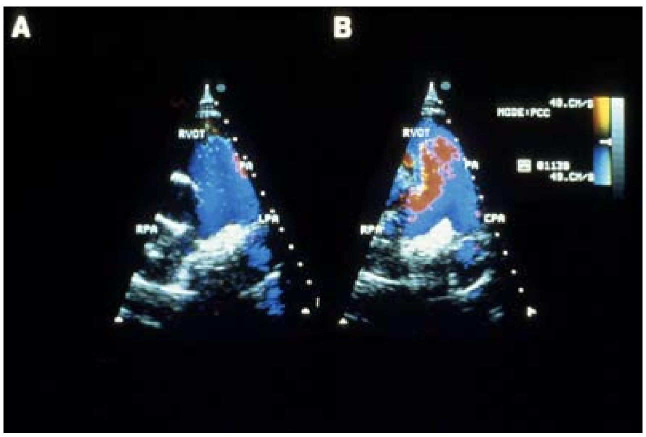

Figure 4. 35 Parasternal short-axis views of the aortic root showing the pulmonary outflow tract. Panel A shows flow in very early systole as it fills the proximal pulmonary artery to the bifurcation. Panel B shows flow an instant later when marked aliasing normally occurs. Variance maps were used.

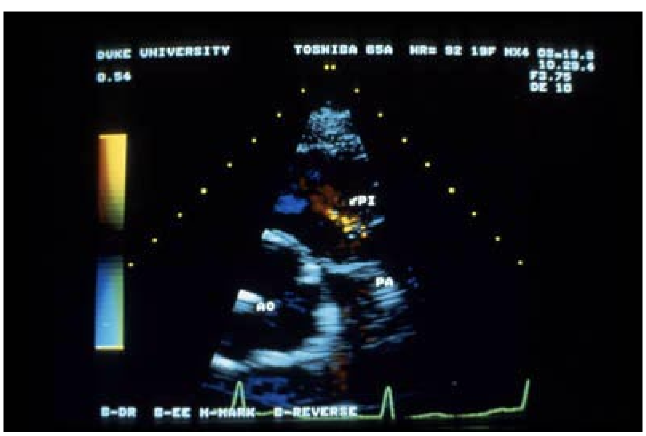

Figure 4. 36 A flame-like appearance of pulmonic insufficiency is seen in the left parasternal short-axis view. A turbulence map was used.

occasionally into the right and left pulmonary arteries.

Color flow detection of pulmonary insufficiency is typically manifest in the left parasternal short-axis view where the flame-like regurgitant jet is seen in diastole **(Fig. 4.36)**. An operator may need to angle the beam to open the right ventricular outflow tract more fully to detect and appropriately record small degrees of this disorder.

COLOR FLOW IMAGING OF VALVULAR STENOSIS

Doppler color flow imaging methods allow for identification of the presence of certain valvular stenotic jets. There are, however, no specific characteristics in the color display of stenotic flows that assist in quantifying the severity of valvular obstruction at the present time. Spatial location of the direction of a jet is possible and this may be used to direct a conventional CW Doppler beam at an optimum angle to flow for precise measurement of peak velocity data.

Mitral Stenosis

Mitral stenotic jets are characterized by a bright burst of color from the mitral valve orifice in very early diastole. An instant later, a central core of aliasing is frequently seen that persists throughout the remainder of diastole. This appearance has often been referred to as the "flame-like" pattern of mitral stenosis and is present in many, but not all, patients with mitral stenosis.

The apical views are clearly the best for recording this characteristic appearance, as the interrogating beam is nearly parallel to flow and the best mean velocity estimates are possible.

A typical mitral stenotic jet from the apical two-chamber view is shown in **Figure 4.37**. Note that a central core of aliasing is less evident in this jet. Note also that a small jet of aortic insufficiency is readily separated from the stenotic mitral valve flow.

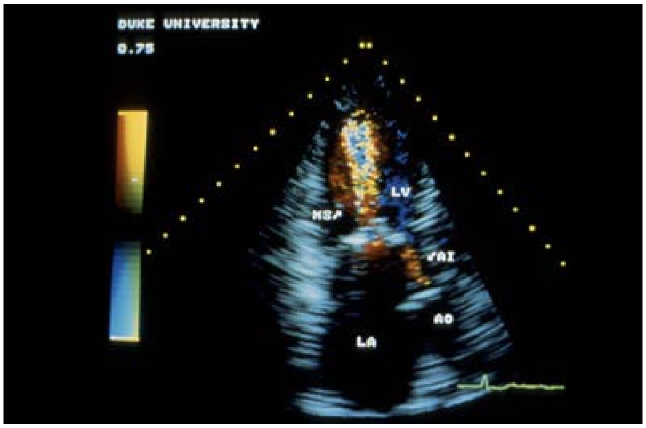

Figure 4. 37 Apical two-chamber view of a small degree of aortic insufficiency readily distinguished from that of mitral stenosis. A variance map was used.

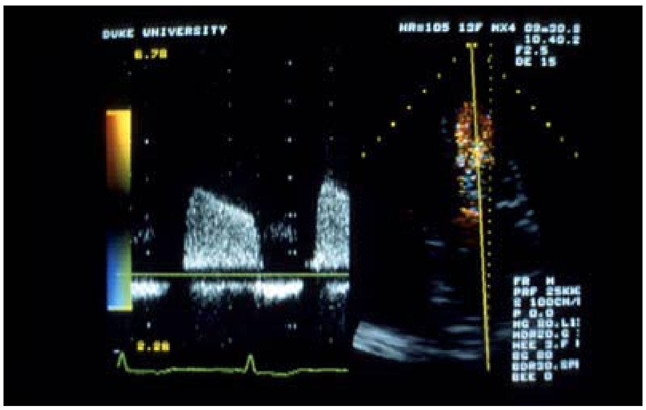

Figure 4. 38 More severe mitral stenosis is depicted on the spectral recording on the left. A variance map was used. For details, see text.

Figure 4. 39 Parasternal short-axis view of flow through a fully open aortic valve as it fills the aortic orifice. A variance map was used.

When a color imaging system contains CW Doppler capabilities, identification of the direction of the stenotic jet is very helpful and allows for reasonably precise parallel orientation of a CW beam with the stenotic jet. This provides a means for operator interaction between the beam and the jet to assure proper recording of peak velocities for gradient quantification.

There is a demonstration in **Figure 4.38** of the combined use of color flow and CW Doppler for detection of severe stenosis where the peak transmitral valve gradient approaches 3 m/s. The pressure half-time is also markedly delayed in this patient. When using systems equipped with CW capabilities, the color flow image is automatically frozen when switching into the conventional mode.

Aortic Stenosis

In normal individuals, flow is usually seen to fill the entirety of the left ventricular outflow tract. In the short-axis view of the aorta, normal flow can be seen filling the aortic valve orifice in some patients. **Figure 4.39** demonstrates the appearance of normal aortic outflow in a variance map. Little aliasing is seen in this view since the maximum scan depth is rather shallow. In addition, the dull hues of red indicate that relatively low mean velocities were calculated in this situation due to the rather perpendicular orientation of the interrogating beam with the aorta.

Unlike mitral stenosis, the forward jet of aortic stenosis into the aortic root is rarely well delineated using color flow methods. In this disorder, turbulence is seen to fill almost the whole of the aortic root and to possess little directional information. When imaged, these jets frequently have marked variance in

Figure 4. 40 Parasternal long-axis jet of aortic stenosis. Marked turbulence is seen where these jets can be detected that originate at the aortic valve level (arrow), and fills almost the entirety of the aortic root. A variance map was used.

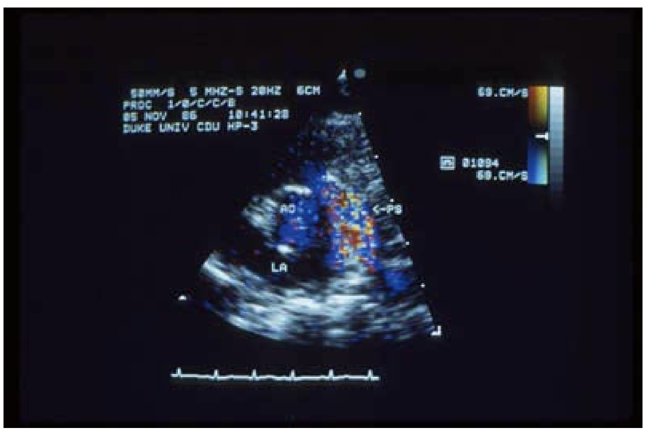

Figure 4. 41 Short-axis view at the level of the aortic root, demonstrating turbulent flow in the main pulmonary artery due to pulmonic stenosis. A variance map was used.

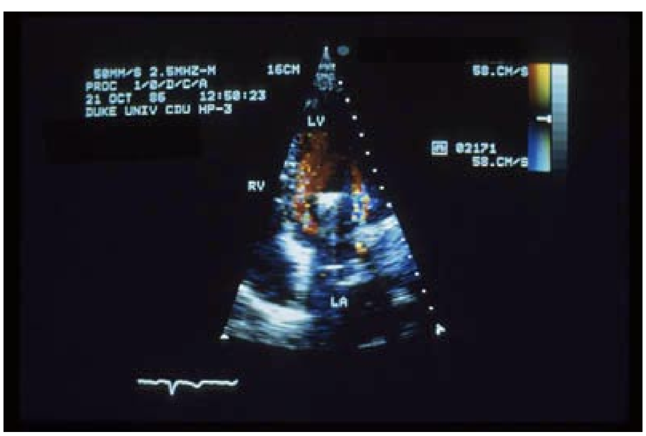

Figure 4. 42 Apical four-chamber view of normal diastolic flow through a Starr-Edwards mitral prosthesis. Note that the flow on either side of the ball is symmetric. A variance map was used; spatial filters are off.

the final display, as is seen in **Figure 4.40**. The turbulence begins at the orifice *(arrow)* and generally fills the entire root. Note that a discrete jet is not visualized.

Tricuspid and Pulmonic Stenosis

Tricuspid stenosis results in a color flow imaging study very similar to that of mitral stenosis except that the abnormal flow is seen to emerge from the tethered tricuspid valve leaflets. Stenosis of the pulmonary valves usually results in a very diffuse jet like that of aortic stenosis. It is, however, more readily detected than that of aortic stenosis. Most degrees of pulmonary stenosis fill the proximal pulmonary artery with a large mosaic, resulting from both aliasing and turbulence.

The pulmonary artery is best investigated using the short-axis approach. **Figure 4.41** shows marked turbulence and aliasing within the pulmonary artery from pulmonic stenosis. Here, abnormal flow is seen up to the bifurcation of the main pulmonary artery.

FLOW IMAGE STUDIES OF PROSTHETIC VALVES

Imaging of flow through prosthetic valve is possible and may be of great help in assessing the proper working status.

Since color flow imaging is so successful in detecting insufficiency from native valves, it might be simply assumed that it is as useful for assessment of prosthetic valve dysfunction. The masking effect described in *Unit 2* is also seen with color flow imaging, and the same cautions should be exercised when performing color flow interpretations as with the conventional approaches.

Color Flow Examination of Prosthetic Valves

Color flow imaging provides a means for

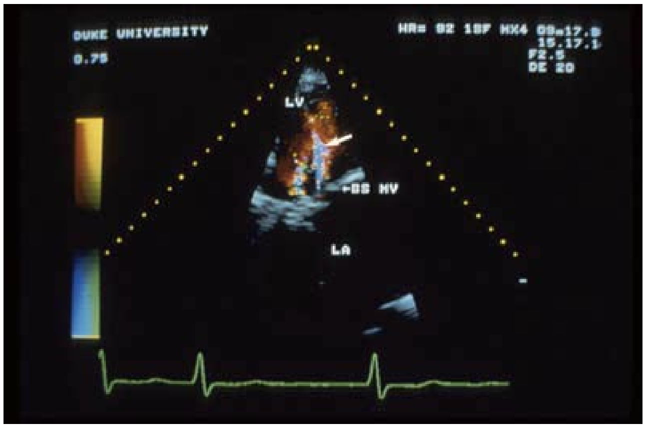

Figure 4. 43 Apical four-chamber view of normal diastolic flow from a Bjork-Shiley mitral prosthesis. Note that these two jets are not symmetric. The smaller one comes from the lesser orifice, while the larger of the jets (arrow) emerges through the greater orifice. A variance map was used.

easy spatial identification of flows through prosthetic valves if the proper transducer orientations and limitations are kept in mind. **Figure 4.42** demonstrates an apical four-chamber view of forward diastolic flow through a Starr-Edwards valve in the mitral position. Jets are seen to emerge on both sides of the ball and enter the left ventricle. The jets are symmetric in size and shape when there is orientation of the interrogating beam directly through the center of the flow plane.

An image of normal diastolic flow through a Bjork-Shiley prosthetic valve as imaged from the apical four-chamber view is shown in **Figure 4.43**. Note carefully that forward flow can be seen through both the major and minor orifices of the valve when the prosthesis is functioning normally. As seen in this example, the area of flow through the major orifice is two or more times larger than the area of flow through the minor orifice. Since the Bjork-Shiley valve is a tilting disc, forward flow should always be imaged through both. When it is not, thrombus or other material may be occluding either orifice. Note that this valve has a lesser orifice and a greater orifice so that normal forward flow will never be symmetric.

Figure 4. 44 Left parasternal long-axis view in systole showing abnormal flow posterior to the valve ring into the left atrium,. This is compatible with a periprosthetic leak. Arrows indicate the location of the prosthetic valve ring. A variance map was used.

Forward flow through a bioprosthesis usually fills the whole of the valve orifice under normal conditions. Occasionally, a perivalvular leak may be visualized, as is seen in the patient in **Figure 4.44**. A small mitral regurgitant jet is visible posterior to the ring of a porcine prosthesis (*arrows*) in systole.

COLOR FLOW IMAGING OF COMMON CONGENITAL DISORDERS

Color flow Doppler echocardiography also has an extremely useful role in the assessment of congenital abnormalities. By superimposing flow data on the two-dimensional echocardiogram, recognition of abnormal flows is easy in many disorders. When examining small infants, there is frequently little time to perform a complete conventional PW Doppler examination. When complex anatomy is encountered, use of blind conventional CW Doppler is often complicated by the absence of usual flow landmarks that assure the user of beam location.

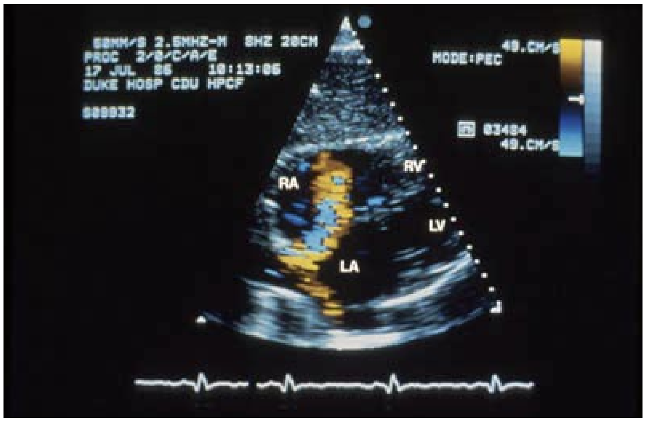

Figure 4. 45 Subcostal view of interatrial shunting. Flow is seen to emerge from a pulmonary vein and cross the interatrial septum into the right atrium. An enhanced map was used, spatial filters are on.

Figure 4. 46 Subcostal view of the large interatrial septal defect in a child. The central core of aliasing is seen through the atrial septal defect. A turbulence map was used.

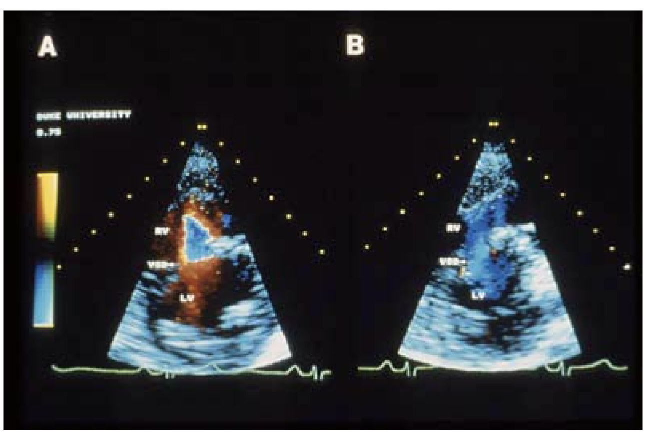

Figure 4. 47 Left parasternal short-axis view of the left ventricle is seen in panel A where the left-to-right component of flow is shown through a very large ventricular septal defect. In panel B, right-to-left component of flow is visualized. A turbulence map was used.

Atrial Septal Defect

In infants and small children, atrial septal defects are often directly visualized using two-dimensional echocardiography. In adults, the situation is somewhat different, as difficulties with image quality and other factors limit detection of the actual defect. **Figure 4.45** demonstrates flow from a pulmonary vein directly across an atrial septal defect from the subcostal view in a 32 year-old woman in whom there was little indication of the presence of such a defect on the two-dimensional image alone.

Color flow imaging helps greatly in identifying patients with interatrial shunting. The subcostal views are clearly the best for this purpose as the interatrial septum is oriented perpendicular to the sound beam and readily visualized, while any abnormal flow through the septum is parallel to the beam and toward the transducer.

In **Figure 4.46**, flow can be seen from the left atrium to the right atrium through a large atrial septal defect in a child. In fact, the anatomic limits of the defect may be more clearly defined by the image of the flow in relationship to the anatomic target information.

Ventricular Septal Defect

Most clinically significant ventricular septal defects in infants are readily imaged with two-dimensional echocardiography. In adults, it is rare to find a totally unsuspected ventricular septal defect that is large. In **Figure 4.47**, there is a very large ventricular septal defect in a 30 year-old woman with Eisenmenger physiology (marked elevation of pulmonary pressures in excess of systemic) from the left parasternal short-axis view of the left ventricle. Systolic flow from left to right is seen as a bright burst of red with a central core of aliasing **(Fig. 4.47, panel A)**. The diastolic image from the same patient shows the right-to-left component in blue **(panel B)**.

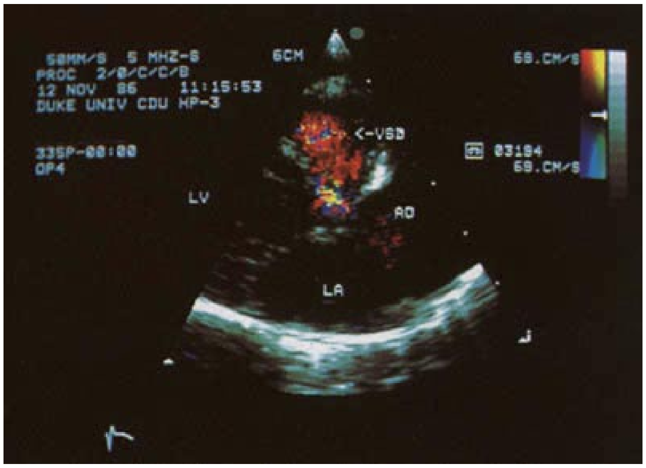

Figure 4. 48 Parasternal long-axis view of the left ventricle demonstrating left-to-right shunting from a subaortic ventricular septal defect. A variance map was used.

Of course, most such defects are small and difficult to image directly. Despite the ready detection of larger defects in children, these smaller defects are nearly impossible to image using two-dimensional echocardiography in adults. Conventional PW Doppler is very reliable for detection of these abnormal flows, but the process is long and arduous as it involves complex mapping of all portions of the interventricular septum.

With color flow imaging, however, these defects are easily seen. **Figure 4.48** shows the typical appearance of an abnormal jet in a patient with a small ventricular septal defect in the subaortic area.

ROLE OF THE VARIOUS DOPPLER METHODS

The Role of Conventional Pulsed Doppler

Conventional PW Doppler is able to locate abnormal flows in space precisely, but suffers because true velocity recordings are not possible due to aliasing. Using spectral displays, the timing of onset of a jet may be accurately recorded but accurate recording of peak velocities is impossible in most abnormal jets since these velocities are invariably high and aliasing results. As a consequence, PW Doppler is commonly used to detect the location of turbulent jets but the examination is laborious and excessively long as it requires tedious mapping to identify the location and size of an abnormal jet.

Conventional PW Doppler does have a unique role for the location of abnormal flow or the timing of flow events. The spectral velocity tracing is mandatory for calculation of flow velocity integrals if cardiac output or other measurements are made.

The Role of Conventional Continuous Wave Doppler

Conventional CW Doppler is able to record very high velocities, but suffers because it is not possible to exactly locate the jet in space. This method is ideal for precisely quantifying transvalvular gradients or other quantitative manipulations based on peak velocity determinations. Along with high PRF, it is the only Doppler method where such high peak velocities can be readily detected. Most users would indicate that mastery of the technique is difficult and time-consuming.

The Role of Color Flow Imaging

Color flow imaging is based on PW Doppler principles and, like conventional PW Doppler methods, cannot accurately record high velocity information. Its unique advantage over conventional PW Doppler is that it displays the flow, normal and abnormal, directly onto the echocardiographic image. For those familiar with two-dimensional echo approaches, the PW Doppler examination may be quickly conducted using color flow. When compared with the conventional PW Doppler approach, the tedious mapping techniques necessary with the earlier technique are avoided.

Because there is no special display, however, precise timing of events is not possible. Timing information is further complicated by the fact that it takes so long to create the two-dimensional color flow display. In addition, aliasing occurs at least as frequently as with conventional PW Doppler, and peak velocities cannot be detected or identified in disease states.

The Combined Roles of Doppler Methods

Given these facts, it appears that Doppler color imaging has an important role with the conventional approaches. Color flow methods are approximately quantitative concerning the size and direction of the abnormal jets. More precise quantitative work, such as derivations of measurements form peak velocity information, remains within the province of CW Doppler.

There is no question that the basics of color flow mapping may be learned reasonable quickly by experienced users of two-dimensional echocardiography. PW Doppler requires a longer learning time. CW Doppler requires the longest time in order to gain the experience to perform a proper examination.

The examination time required for a color flow study is relatively short in comparison with the other methods. Simply switching color on and off as the two-dimensional examination is performed can reveal useful information in a short period of time. In routine clinical practice, color flow replaces conventional PW Doppler echocardiography in most, but not all, cases. Despite its increased cost, its ease of use and relatively rapid technical mastery has resulted in considerable savings of time and patient cost. While we feel that a complete Doppler examination of the heart requires all Doppler methods, the introduction of color flow has placed the conventional approaches into specific perspectives, now much more readily understood even by beginners in the use of Doppler techniques.

Further Reading
Those interested in learning further about Doppler echocardiography are recommended to read *Basic Doppler Echocardiography* edited by Joseph Kisslo, David Adams and Daniel B. Mark and *Doppler Color Flow Imaging* edited by Joseph Kisslo, David Adams, and Robert N. Belkin (both are published worldwide by Churchill Livingstone). These books have been the inspiration for this teaching program.

Figure Legends

Figure 4. 1 Systolic parasternal long-axis color flow image of mitral regurgitation. The mitral regurgitation jet comprises a mosaic of varying colors. A variance map is used. Note the direction of flow indicated by the color bar on the right (Abbreviations, page 39).

Figure 4. 2 Three color bars from a color flow system. When there is no flow, black is displayed (center) in the standard bar (left), flow toward the transducer at the top is in red, flow away in blue. Progressively faster velocities are displayed in brighter shades of red or blue. The center bar is in an enhanced map, and the right bar in a variance map (explained later in the text).

Figure 4. 3 In a color flow-imaging device, the returning echo data are processed through two channels that ultimately combine the image with the color flow data in the final display.

Figure 4. 4 Color flow Doppler systems use PW Doppler principles in a multigate, rather than range-gate format. For details, see text.

Figure 4. 5 Color flow imaging systems collect the phase shift information at each of the multiple gates and then process the information with color presented in the final display.

Figure 4. 6 Hundreds of gates are present along each line throughout the color flow image. In gates where there is target information, no color is displayed (open gate at lower left),

Figure 4. 7 If color was mapped on a conventional spectral recording, only one color could be placed in each bin. Progressively increasing velocities towards the transducer would be displayed in brighter hues of red while flow away would be displayed in blue.

Figure 4. 8 Schematic representation of spectral recording showing the differences between peak and mean velocities. In the case of normal laminar flow, peak and mean velocities may be very close. For turbulent flow, there may be a significant difference between peak and mean velocity.

Figure 4. 9 Pulse nomenclature used in the development of color flow images. The number of pulse trains determines the size of the pulse packet. The larger the packet, the better the estimation of mean low velocity.

Figure 4. 10 Parasternal long-axis views of an aortic regurgitant jet showing the effect of packet size changes. Panel A was acquired with large packet size, panel B with medium packet size, and panel C with small packet size. Large packet sizes have the best estimates of mean flow but come at the expense of frame rate. Spatial filtering is used with variance maps.

Figure 4. 11 A simple diagram showing the operation of a color flow processor where data from three pulse trains are used to estimate velocity, and one mean estimate is finally displayed in the gate.

Figure 4. 12 At the far ranges gates are separated due to divergence of the radial scan lines. Data from adjacent gates are averaged to smooth the image.

Figure 4. 13 If the color flow data were displayed in a spectral format, aliased flow towards the transducer would be cut off at the top and the aliased flow into the opposite channel would be reversed in color.

Figure 4. 14 Using a color wheel, baseline, or zero, flow is displayed in black. High mean velocity data are aliased between brighter hues of red and blue and may be easily recognized in the final display.

Figure 4. 15 Modified apical four-chamber view of flow through an atrial septal defect and into the tricuspid orifice in diastole. The bright yellow flow aliases into bright blue within the central core of the flow jet (arrow). This is an enhanced map.

Figure 4. 16 In laminar flow there is little variation (variance) of velocities on either side of the mean velocity. In turbulent flow, when many different velocities are present, there is great variance.

Figure 4. 17 Apical four-chamber diastolic view of aortic insufficiency demonstrating two different maps. The image is identical except for the map changes. Panel A shows a conventional red/blue map. Panel B shows a velocity/variance map where the regurgitant jet is readily identified.

Figure 4. 18 When variance is detected, hues of green may be added to the red and blue flows, resulting in shades of yellow, white, and blue-green (cyan).

Figure 4. 19 Parasternal long-axis view of two-dimensional echocardiogram (panel A). The color is switched on (panel B) revealing the mitral regurgitant jet. A variance map is used.

Figure 4. 20 Parasternal long-axis images of mitral insufficiency demonstrating the effect of color gain on the area of a regurgitant jet.

Figure 4. 21 Parasternal short-axis view showing the left anterior descending coronary artery. The flow within the vessel is obscured by the surround tissue artifact in the panel A. The panel B shows good separation between flow and vessel wall.

Figure 4. 22 Left parasternal long-axis view of blood emerging from a pulmonary vein (arrow) and filling the mitral valve orifice. An enhanced map was used.

Figure 4. 23 Parasternal long-axis view of mitral regurgitation directed toward the posterior left atrial wall. A turbulence map was used.

Figure 4. 24 Left parasternal long-axis view showing a more severe degree of mitral regurgitation than seen in the previous figure. A variance map was used.

Figure 4. 25 Subcostal view of severe mitral regurgitation. A variance map was used; spatial filters are off.

Figure 4. 26 Parasternal long-axis views of a mitral regurgitant jet in a patient with a diffuse cardiomyopathy. A variance map was used.

Figure 4. 27 Panel A shows a left parasternal long-axis view of a patient with a very narrow jet of aortic insufficiency. Panel B shows the limits of the jet in short axis.

Figure 4. 28 Left parasternal long-axis view of aortic insufficiency filling the entirety of the left ventricular outflow tract in diastole. A variance map was used.

Figure 4. 29 Parasternal long-axis view of a narrow aortic regurgitant jet directed at the anterior mitral valve leaflet. This jet seems to bounce off the leaflet toward the left.

Figure 4. 30 Parasternal long-axis view of severe aortic insufficiency following the posterior portion of the interventricular septum. A variance map was used. This is the same patient as shown in the next figure.

Figure 4. 31 The severe aortic regurgitation is seen on the right. The simultaneous M-mode color recording (left) shows premature closure of the mitral valve apparatus and the onset of mitral regurgitation in mid-to-late diastole. A variance map was used.

Figure 4. 32 Left parasternal short-axis view of the aortic root and right atrium. Low velocity flow can be seen to emerge from the inferior vena cava and move through the right atrium and tricuspid valve into the right ventricle. An enhanced map was used.

Figure 4. 33 Apical four-chamber view of both tricuspid and mitral regurgitations. The tricuspid regurgitant jet is directed toward the interatrial septum. A variance map was used; spatial filters are off.

Figure 4. 34 Long-axis view of the inferior vena cava during systole where tricuspid regurgitant flow is shown in red. Note the regurgitant flow into the hepatic vein. A variance map was used; spatial filters are on.

Figure 4. 35 Parasternal short-axis views of the aortic root showing the pulmonary outflow tract. Panel A shows flow in very early systole as it fills the proximal pulmonary artery to the bifurcation. Panel B shows flow an instant later when marked aliasing normally occurs. Variance maps were used.

Figure 4. 36 A flame-like appearance of pulmonic insufficiency is seen in the left parasternal short-axis view. A turbulence map was used.

Figure 4. 37 Apical two-chamber view of a small degree of aortic insufficiency readily distinguished from that of mitral stenosis. A variance map was used.

Figure 4. 38 More severe mitral stenosis is depicted on the spectral recording on the left. A variance map was used. For details, see text.

Figure 4. 39 Parasternal short-axis view of flow through a fully open aortic valve as it fills the aortic orifice. A variance map was used.

Figure 4. 40 Parasternal long-axis jet of aortic stenosis. Marked turbulence is seen where these jets can be detected that originate at the aortic valve level (arrow), and fills almost the entirety of the aortic root. A variance map was used.

Figure 4. 41 Short-axis view at the level of the aortic root, demonstrating turbulent flow in the main pulmonary artery due to pulmonic stenosis. A variance map was used.

Figure 4. 42 Apical four-chamber view of normal diastolic flow through a Starr-Edwards mitral prosthesis. Note that the flow on either side of the ball is symmetric. A variance map was used; spatial filters are off.

Figure 4. 43 Apical four-chamber view of normal diastolic flow from a Bjork-Shiley mitral prosthesis. Note that these two jets are not symmetric. The smaller one comes from the lesser orifice, while the larger of the jets (arrow) emerges through the greater orifice. A variance map was used.

Figure 4. 44 Left parasternal long-axis view in systole showing abnormal flow posterior to the valve ring into the left atrium,. This is compatible with a periprosthetic leak. Arrows indicate the location of the prosthetic valve ring. A variance map was used.

Figure 4. 45 Subcostal view of interatrial shunting. Flow is seen to emerge from a pulmonary vein and cross the interatrial septum into the right atrium. An enhanced map was used, spatial filters are on.

Figure 4. 46 Subcostal view of the large interatrial septal defect in a child. The central core of aliasing is seen through the atrial septal defect. A turbulence map was used.

Figure 4. 47 Left parasternal short-axis view of the left ventricle is seen in panel A where the left-to-right component of flow is shown through a very large ventricular septal defect. In panel B, right-to-left component of flow is visualized. A turbulence map was used.

Figure 4. 48 Parasternal long-axis view of the left ventricle demonstrating left-to-right shunting from a subaortic ventricular septal defect. A variance map was used.