RECENT ADVANCES in ultrasound instrumentation have yielded noninvasive techniques combining high-resolution two-dimensional echocardiographic imaging with quantitative pulsed or continuous-wave Doppler techniques. The combination has added to the descriptive capabilities of two-dimensional echocardiography a variety of new clinical ultrasound applications related to defining blood flow patterns in the heart. Examples of qualitative applications of Doppler might be detection of mixed valvular insufficiency, such as tricuspid regurgitation in a patient with predominant mitral valve disease, or detection of a "silent" ductus arteriosus in a critically ill premature infant.

Among the quantitative applications of Doppler techniques that have assumed substantial importance in the evaluation of valvular heart disease are methods using the maximal velocity of flow across a stenotic valve to estimate transvalvular gradients. Difficulties in the clinical application of the velocity-gradient method rest in ensuring that the highest velocity area of the jet has been interrogated in a direction parallel to flow. Controversy still exists as to whether simultaneous imaging should be used to achieve the spatial orientation necessary for determining the angle of interrogation relative to flow or whether nonimaging methods should be used to orient the direction of Doppler interrogation based exclusively on the audio signal, assuming the cleanest sounds and highest recorded velocity correspond to the direction of flow.

Other methods have also been described that attempt to quantitate valvular insufficiency by moving a single pulsed Doppler sample volume around within the cavity receiving the regurgitant flow to describe the spatial distribution of the regurgitant jet as an estimate of the severity of valvular regurgitation.

Another application of Doppler echocardiography that has been widely reported in the literature, but still not widely practiced clinically, combines the calculated mean velocity of flow as a function of time and the area of flow (usually estimated from an anatomic measurement on echocardiography, such as a valve anulus or vessel diameter) to estimate volume flow in milliliters per minute. The number of different methods described for volume flow calculation by Doppler differ not in the Doppler velocity component but in the method for estimating the area of flow (i.e., whether to use vessel diameters, aortic sinus of Valsalva diameter, separation of the aortic valve cusps, mitral valve orifice, or mitral valve anulus size as in the reference cited).

It appears, therefore, that what is most difficult to achieve in Doppler echocardiography at present and most controversial in all of the above applications of the Doppler method is the spatial orientation of flow related to defining the location and distribution of the areas where normal or abnormal flows (e.g., regurgitant or stenotic jets) occur. Consequently, it would appear that the recent introduction of instrumentation capable of providing real-time, noninvasive Doppler mapping of flow potentially represents a major advance in the capabilities of Doppler echocardiography.

Real-time Doppler flow mapping systems are based on earlier work with multigated Doppler methods and therefore use a pulsed Doppler method to establish a number of individual depth gates along any particular line of sight within the sector image and to interrogate that line of sight for echo information and then for Doppler information before steering to the next line of sight. A number of gates along each line of sight are built and flow information is assembled from a number of lines of sight within the sector to establish a two-
A three-dimensional matrix of flow referable to the spatial orientation within the two-dimensional image. The available pulse repetition frequency at any depth is therefore shared between imaging and Doppler interrogation. As an example, one available system performs 90 degree anatomic sector scanning and is often used to interrogate velocities within a 52 degree flow imaging sector. The quantitative solution of the Doppler velocities present within any particular spatial location are determined separately and rapidly by digital electronic processing most often achieved by using an autocorrelator, which estimates velocities and passes them to a digital scan converter where they are read out into a color converter for display. Since there are limitations as to how rapidly these computations can be performed, the highest pulse repetition frequency available in this system at which flow can be calculated is 8 KHz, which is a lower Nyquist limit than for most single-gate pulsed Doppler systems. Although a variety of methods potentially exist for display in flow imaging, it has been convenient to display velocity encoding in any one particular location by colors superimposed on the real-time image. In several systems flows toward the transducer have been coded in increasing brightnesses of red to yellow and flows away from the transducer in increasing brightnesses of blue (figure 1); flows with unusual spectral broadening, representing turbulent or abnormal flow, have been shown in green.

Although limitations appear to be present in early versions of these systems, mostly related to velocity aliasing even at physiologic velocities, to signal-to-noise problems for signals obtained from deep structures, and to their basic Doppler spatial resolution, the controversies and difficulties in Doppler methods cited above are not so different from some of the questions that arose over M mode echocardiography related to the understanding of specific M mode echo patterns of chordal or valve motion in terms of cardiac function and anatomy. In fact, the early two-dimensional systems were believed to have signal-to-noise problems and were thought to be lower in resolution than M mode. Since standardization and ease of acquisition of M mode tracings and a greater understanding of M mode patterns have obviously been achieved from the spatial orientation gained with the mating of M mode and two-dimensional echocardiography, it can be expected that a greater understanding of the meaning of

**FIGURE 1.** Stop-frame from a real-time color-coded Doppler flow mapping examination shows regurgitant flow in systole across the center of the tricuspid valve. In this system, flow away from the transducer is shown as increasing intensities of blue and flow toward the transducer as increasing intensities of red. The area of tricuspid regurgitation is shown in blue. The mixtures of colors within the jet suggests turbulence, as do the green hues superimposed on the regurgitant flow area. RV = right ventricle; RA = right atrium; TI = tricuspid insufficiency.
Doppler flow waveforms and greater ease in the standardization of their acquisition at known angles of incidence from known locations of the heart will be achieved by the mating of single-gate or continuous-wave Doppler interrogation with the two-dimensional flow mapping that has been achieved in these new systems. It is also important to point out that M mode was not made obsolete by two-dimensional echocardiography and that both single gate pulsed Doppler interrogation and continuous Doppler-derived spectral velocity waveforms displayed to show velocity as a function of time will not be obviated by this new technology. Like two-dimensional compared with M mode echocardiography, however, there are specific applications of two-dimensional Doppler flow mapping that will be the direct results of the spatial display of information and will not be available from waveform Doppler alone.

The real-time display of these devices is obviously dynamic. However, it would be judicious to point out that even though the Doppler-derived information looks easier to understand in this format, a large amount of information is being displayed at any instant in time and a substantial learning curve is still required in the performance and understanding of this type of examination.

A variety of applications have already been suggested for Doppler flow mapping as potentially important new additions to Doppler capabilities. Qualitatively, flow mapping allows a rapid orientation to the presence and position of small atrial and ventricular septal defects. Of substantial importance is the potential spatial orientation the technique provides for identification of small (figure 2) or even multiple septal defects. The rapid identification of valvular insufficiency has been reported on by Miyatake et al. and Yock et al., although there are some apparent signal-to-noise problems in color-coded Doppler flow data at the depths often necessary for the detection of mitral insufficiency. Of substantial interest in the evaluation of valvular insufficiency is preliminary evidence that flow mapping provides a semiquantitative approach to the determination of the severity of the valvular insufficiency. Spatial distribution of the regurgitant jet in the left ventricle in dogs with experimentally produced aortic insufficiency was quantitatively related to regurgitant fraction in a recent study from our laboratory. The real-time display of the aortic regurgitant jet seems to greatly facilitate this application of Doppler techniques.

Experience in Japan and in the United States also suggests that even though these systems are limited in pulse repetition frequency, they can provide a unique image of high-velocity jet lesions; the aliasing that occurs in the display presents color inversions that give a layered appearance to high-velocity flows almost like a candle flame, with the highest velocity shown in the center and layers of blue, red, blue, and red representing the individual velocities, which, having reached the Nyquist limit determined by one-half the pulse repetition frequency, “wrap around” to the reverse color. This layered appearance is illustrated in figure 3 and shows not only the spatial orientation of jets and the area of highest velocity but also the angular orientation of jets from the stenotic lesions. This allows one to perform guided continuous Doppler interrogation

![Figure 2](image.png)

**FIGURE 2.** Short-axis view in the upper panel shows a barely imaged, small muscular ventricular septal defect (almost too small to be imaged [arrow]) at the level of the papillary muscles. In the lower panel, flow toward the transducer coming through the ventricular defect delineates the area of the left-to-right shunt. VSD = ventricular septal defect.
FIGURE 3. Apical view from a patient with mitral stenosis shows flow across the stenotic valve. Since the flow is high in velocity and exceeds the Nyquist limit even though it is going toward the transducer, the area of highest velocity aliases into the color blue (i.e., it “wraps around”). The display therefore shows the area of highest velocity as well as the spatial orientation of the jet. LV = left ventricle; LA = left atrium; MS = mitral stenosis.

FIGURE 4. Short-axis view of the right ventricular inflow tract shows the area of diastolic tricuspid valve inflow in a patient with an atrial septal defect (ASD). The combination of the diameter of flow imaged in the area of the sample volume (dashed line) and the spectral waveforms in the lower righthand trace (calibration 20 cm/sec/division) can be used to calculate pulmonary blood flow noninvasively. RV = right ventricle; RA = right atrium; TV = tricuspid valve.
across the highest velocity area and to perform rational angle correction within the plane of imaging.

Finally, the controversy that still exists for Doppler volume flow calculations is whether they have indeed achieved “clinical” accuracy. The Doppler flow mapping systems provide an index of the “area of flow” by solving for flow within the image. Such a flow area may be especially useful in patients with low cardiac output. The area of the imaged flow, especially if from a region of the heart or a great artery identified as having a fairly flat flow profile when combined with selected single-gate spectral Doppler time-velocity waveforms, may provide a more accurate method for calculating volume flow (figure 4) without reliance on anatomic boundaries.

Conclusion. The new color flow mapping Doppler technologies provide a dynamic method for studying the spatial distribution of blood flow velocities in the heart, unlike any noninvasive or invasive technique previously available. The advent of these new instruments represents a substantial opportunity for advancing the applications of Doppler echocardiography and for furthering our understanding of the patterns of blood flow in the circulatory system in health and disease.

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