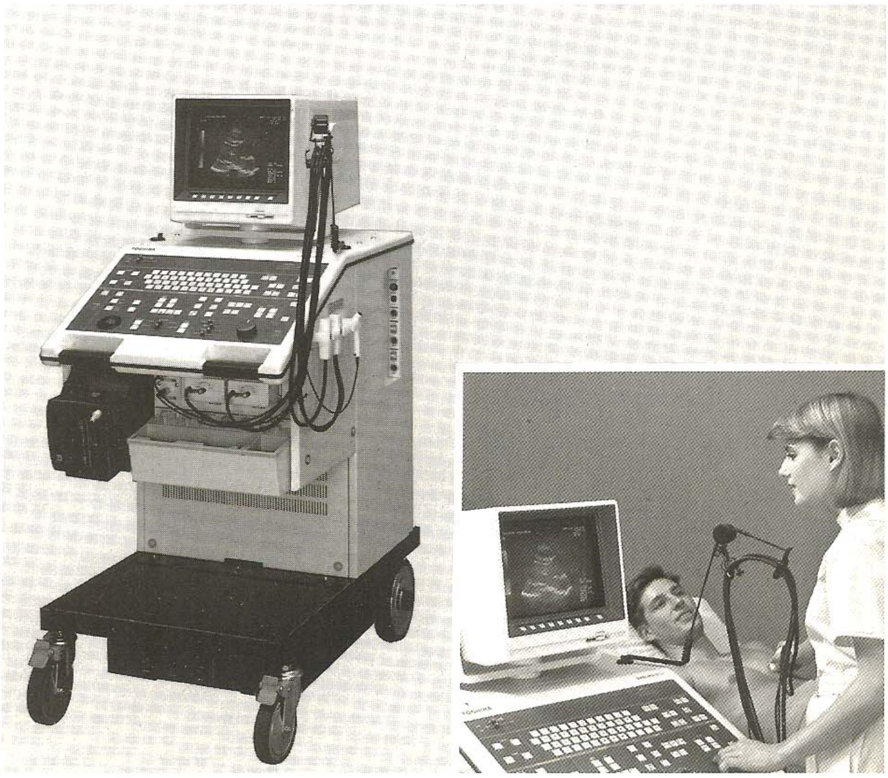
TOSHIBA
NEW PRODUCT

PHASED ARRAY SECTOR SCANNER WITH COLOR BLOOD FLOW IMAGING SYSTEM, MODEL SSH-65A

The SSH-65A Phased Array Sector Scanner provides two-dimensional cardiac blood flow data in color. In addition to conventional morphological diagnosis by means of B-mode cross-sectional imaging, it provides color data displays for blood flow direction, velocity and dispersion in real time. Therefore, it allows the quick and accurate diagnosis of regurgitation peculiar to valvular diseases, jet flow due to stenosis, shunt flow, and other anomalous blood flow phenomena.

Its continuous and pulsed-wave Doppler functions make for accurate measurement of both high-speed blood flow and velocity changes over time.

The SSH-65A, by providing information on both morphology and hemodynamics, widens the range of applications for ultrasound examinations of circulatory organs.



Major features of the system are:

- **Color Blood Flow Display**
  In addition to the B-mode cross-sectional imaging, the two-dimensional blood flow information can be displayed in color, enabling easy diagnosis of regurgitation, shunt flow, etc. The SSH-65A's clear and distinct color displays are highly effective for explaining diseases and presenting data at conferences.
- **Real-Time Display of Blood Flow**
  The two-dimensional, real-time blood flow display permits observation and recording of a wide range of blood flow movements at one time.
- **Pulsed-Wave Doppler and Continuous-Wave Doppler**
  The SSH-65A incorporates pulsed and continuous-wave Doppler functions, making it possible to measure the absolute velocity as well as changes in velocity over time. The blood flow spectrum also allows for the measurement of velocity slopes (accelarations) and calculations of pressure gradients, blood flow volumes, and more.
- **Velocity and Power Display Modes**
  In addition to the velocity display mode which indicates blood flow direction, mean velocity and dispersion, the power display mode indicates the intensity of reflected echoes and the blood flow direction, making it easy to monitor low-speed blood flow as well as reducing the angle dependency between the blood flow and the ultrasonic beam.
- **Zero-Shift Function of Color Display**
  The zero-shift function makes it possible to display up to double the maximum measured unidirectional flow velocity on the color display. Color reversal (aliasing), common when using the Doppler method to measure high-speed blood flow, can be relieved.
- **Comprehensive Functions for Effective Cardiac Examinations**
  As a single unit, the SSH-65A can carry out accurate and extensive cardiac examinations owing to its dual image display, dual phase cardiac synchronization freeze, physiological waveforms display, distance and area measurements, and calculations related to cardiac functions.

Clinical Experience with the Toshiba SSH-65A Color Doppler Flow Imaging Apparatus

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Cardiac ultrasound has profoundly changed the practice of cardiology. The diagnostic superiority of the method results from its capacity to differentiate cardiac structures from blood-filled cavities without the use of contrast materials. As a result, it is a highly effective method for the study of cardiac anatomy and function as well as changes of hypertrophy and cavity dilatation.[1] However, no direct information on blood flow is obtained and the hemodynamic consequences of both structural and functional abnormalities cannot be directly assessed. This is most apparent for lesions such as valvular insufficiency and intracardiac shunts, which cannot always be diagnosed confidently by echocardiography alone.

With the introduction of quantitative pulsed and later continuous wave Doppler echocardiography, the study of velocity and other characteristics of intracardiac blood flow became possible.[2] Information on blood flow is obtained from a selected area or along a one-dimensional path of the ultrasound beam. When Doppler systems are integrated within the ultrasound imaging system, cross-sectional views and thus anatomical landmarks are used as background orientation for Doppler interrogation. Some systems use the audio signal for orienting the Doppler examination. Obviously, these approaches require extensive experience and operator skill. The major problem is that blood flow abnormalities are often confined to relatively small areas and require a time-consuming examination of multiple cross-sectional views using multiple sample volume positions and beam directions within each of these cross-sections. Interrelated data on structure, function, and blood flow are obtained sequentially which often makes interpretation difficult. Not the least of all problems is that spectral outputs of Doppler determined velocities are difficult to comprehend certainly by the non-expert.

Color-coded Doppler flow imaging overcomes most of these limitations. It allows real-time visualization of both spatially correlated intracardiac blood flow velocities and dispersion and superimposes them on cross-sectional images using color-coded flow schemes.

Basic Concepts

Color-coded Doppler flow imaging systems are based on the moving target indicator (MTI), originally developed for radar systems and autocorrelation techniques.[3–5] Contrary to the cross-sectional imaging systems, where the echo amplitudes along a line of the sector are assembled and displayed, phased array flow mapping systems sample the velocities of echoes along the line of sight. The MTI principle thus implies that no velocity information can be obtained from one transmit-receive cycle only. Therefore, the same line of the sector has to be addressed a number of times. This limits the highest velocities which can be measured, and/or decreases the segment size of the sector image displayed with blood flow information.

Although the technique found its origin in multigated Doppler systems[6,7] where serial processing of blood flow information is performed at a number of discrete positions along the line of sight, the MTI blood flow velocity information is continuous, and the discrete steps (pixels) on the output screen of an MTI Doppler flow imaging system result from the speed with which analog signals are digitized in the scan converter. Japanese investigators pioneered most of the research and development for the production of commercially available color-coded Doppler flow imaging systems.[4,5] Independently, Bommer in the United States has designed a prototype instrument, but clinical evaluation thusfar has been limited.[8]

In the Toshiba SSH-65A apparatus, flow towards the transducer is coded as red, and blue designates flow away from the transducer. In American prototype instruments, flow coming towards the transducer is coded in blue, and flow going away from the transducer in red. (In astronomy where color shifts were recognized by Christian Doppler, the color of a star moving away is shifted to red.) The velocity is coded proportional to the brightness of each color. Additional parameters such as the power or amplitude intensity of the returning signals can also be displayed in one of these colors and allow blood flow velocities as low as 3 cm. s^{-1} to be encoded in color. Clinical evaluation of this feature is presently in progress.[9] Variance or turbulence is calculated and coded as the amount of green and yellow mixed with red or blue resulting in a mosaic pattern of colors. The color-coded blood flow data sampled at any sound beam pathway within a cardiac cross-section can also be superimposed on M-mode echocardiograms. In a given area, at different phases in the cardiac cycle, this provides a higher temporal resolution and a wider range of velocities displayed in color, and thus provides the capability of an accurate analysis of timing and direction of blood flow. Conventional pulsed and continuous wave Doppler spectral outputs can be selected from user designated positions within the cross-sections for accurate measurements of high velocities. Thus, color-coded Doppler flow imaging permits a comprehensive study of the direction, velocity, uniformity and timing of intracardiac blood flow simultaneously with an analysis of cardiac structures and function.

Aliasing which limits the maximum velocity which can be measured with pulsed Doppler systems also occurs in the color-coded Doppler flow imaging systems for the same physical reasons as in conventional pulsed Doppler systems. Aliasing indicates the ambiguous display of flow velocities which have exceeded the Nyquist limit as going in the opposite direction (the Nyquist limit is due to a sampling phenomenon which limits the maximum frequency or velocity shift measurement to one half of the frequency at which the pulsed wave transducer transmits pulses). Thus velocities exceeding the Nyquist limit for a given pulse repetition frequency are encoded with the reversed color which gives an artifactual impression of flow reversal on the display. The aliasing phenomenon gives a (multi-) layered appearance to high-velocity jets with the highest velocities in the middle. In practice the aliasing phenomenon is very helpful as it indicates the maximum velocities in a jet and their accurate direction. The integration of continuous wave Doppler capabilities permits the guided interrogation of these high velocity jets with optimal alignment of the jet flow and sound beam or allows the accurate determination of the angle between the two.[10,11]

The frame rate of presently available color Doppler flow imaging systems is always lower than that of two-dimensional echocardiographic imaging systems alone at similar depths of imaging as there is an inherent trade-off between the number of successive pulses, the line density per sector and the depth.

Clinical Application

Color-coded Doppler flow imaging provides an important way to study the physiology and pathophysiology of intracardiac blood flow.[12-14] Many cardiac conditions will be more easily diagnosed with the dynamic color Doppler flow maps.[15] The spatially-oriented blood flow information allows the rapid screening for abnormal blood flow patterns. This offers advantages for the diagnosis of multi-valvular heart disease where the clinical differentiation may be difficult and conventional pulsed Doppler findings confusing. The method is further helpful in the grading of the severity of each lesion independently. Examples are tricuspid regurgitation in the presence of left-sided valve disease (Fig. 1) and mixed mitral stenosis and aortic insufficiency (Fig. 2). In conditions where two jetflows overlap each

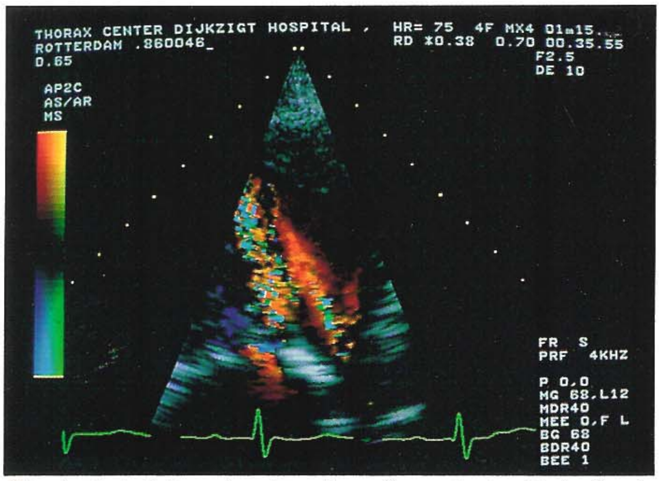

Fig. 1. Apical four-chamber view of a patient with both mitral stenosis and aortic regurgitation. The color-coded Doppler flow map which was obtained in mid-diastole shows the separate jets within the left ventricle. The mosaic of colors indicates turbulence and several color inversions have occurred in the high-velocity jet of aortic regurgitation. Measuring the velocity of the jet would require sampling by continuous wave Doppler.

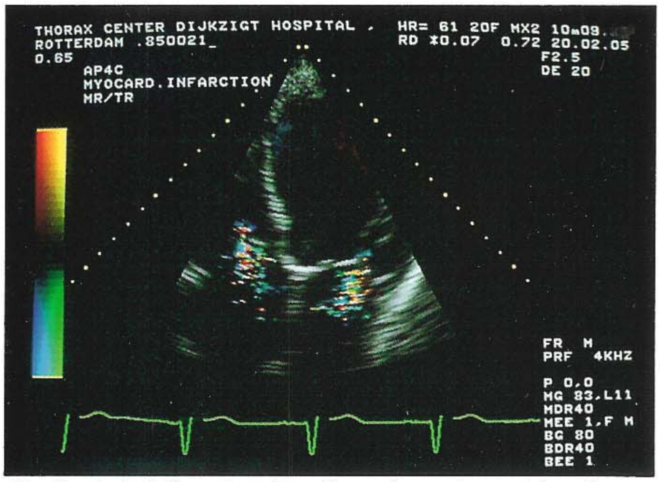

Fig. 2. Apical four-chamber view of a patient with ischemic cardiomyopathy. The jets of mosaic colors recorded during systole posterior to the atrioventricular valves indicate mitral and tricuspid regurgitation.

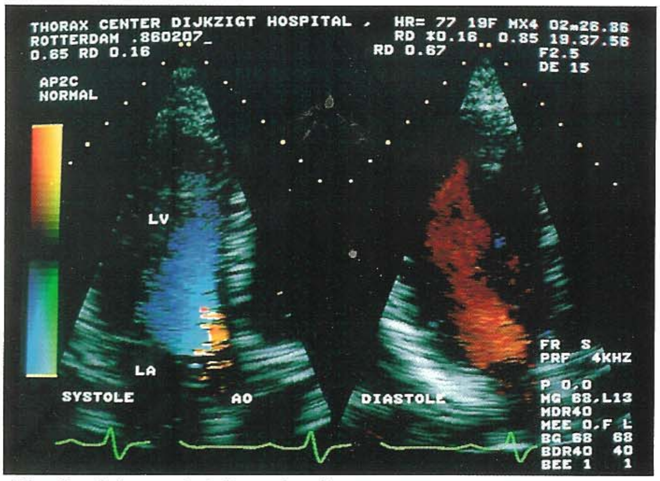

Fig. 3. Color-coded Doppler flow mapping of a normal heart. Apical long axis views during systole (at left) and during diastole (at right) are shown. During systole flow is away from the transducer and encoded in blue. Note the increasing brightness indicating an increasing velocity in the left ventricular outflow tract until the color changes into red/yellow as a result of the aliasing phenomenon when the velocity exceeds the Nyquist limit. Left ventricular inflow is encoded in red. Note the higher velocity in the outflow area of the anterior mitral valve leaflet (AO=aorta; LA=left atrium; LV= left ventricle).

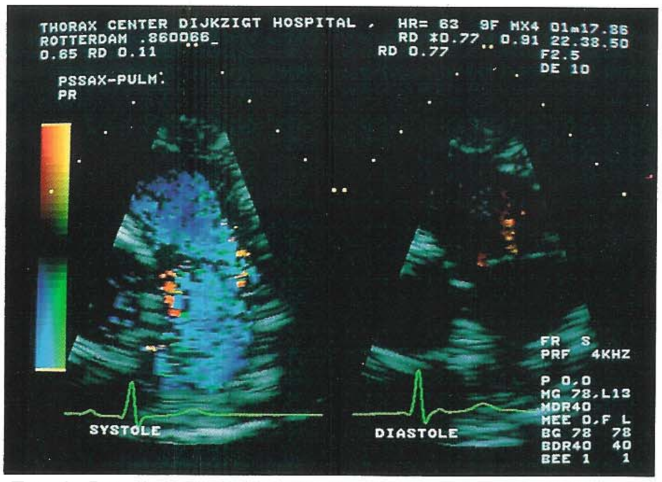

Fig. 4. Parasternal short axis views with color-coded Doppler flow maps of the right ventricular outflow tract and main pulmonary artery in systole (left panel) and diastole (right panel). The blue color indicates flow away from the transducer and completely fills the outflow tract and main pulmonary artery during systole. Small areas of turbulence are seen around the pulmonary valve cusps. In diastole a small jet emanating from the center of the pulmonic valve is seen indicating insignifcant pulmonary regurgitation often seen in normals.

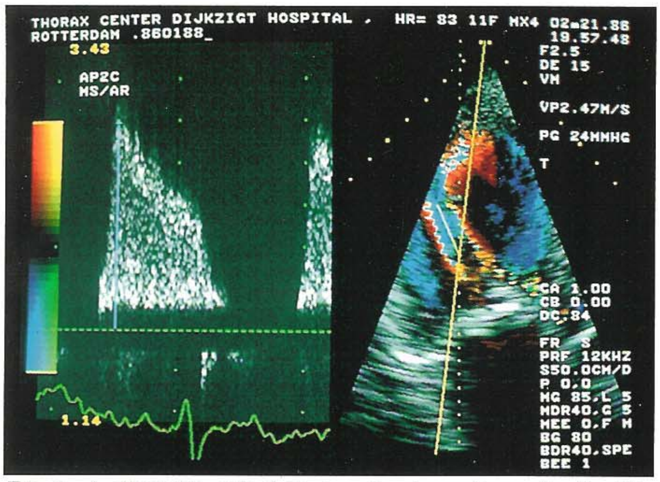

Fig. 5. A diastolic apical long axis view of a patient with mitral stenosis is shown to the right. The stenotic jet is visualized and bends off towards the apex as it hits the left ventricular wall. Central aliasing of high velocities in the middle of the stenotic jet which are encoded in blue create a "flame-shaped" appearance of the jet. Continuous wave Doppler sampling is performed along a sound beam indicated on the flow map and the spectral velocity output is shown to the left. The angle between the jet flow and sound beam can be adjusted on the flow map allowing an accurate calculation of blood flow velocity. As an example the velocity has been measured in early diastole (indicated by the cursor on the spectral velocity output) and automatically calculated by machine software. The peak velocity (VP) in this beat is 2.47 m.s.$^{-1}$ representing a pressure difference of 24 mmHg at that particular moment in diastole. Note also the small jet in the left ventricular outflow tract indicating aortic regurgitation.

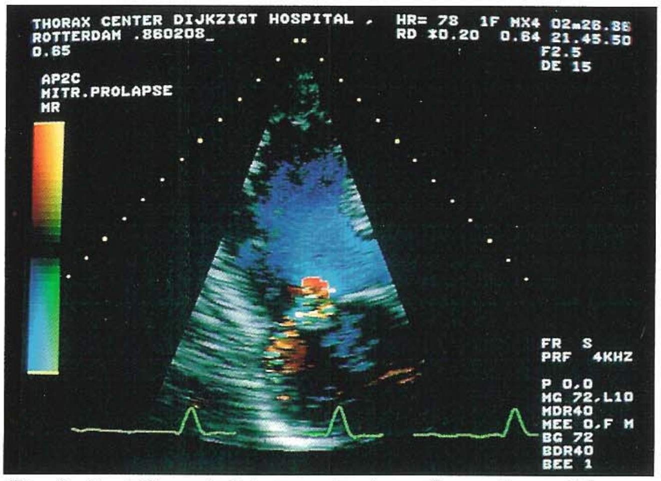

Fig. 6. Systolic apical long axis view of a patient with prolapse of the anterior mitral valve leaflet. The regurgitant jet is eccentric and is directed towards the lateral left atrial wall. Note the mosaic pattern which indicates the turbulence and the increasing blood velocity proximal to the defect within the left ventricular cavity. Note that conventional blind Doppler interrogation may result in recording the velocity within the ventricle and the presence of the eccentric jet may have been missed.

other, one lesion may be overestimated or the second may be missed. Furthermore, eccentrically-directed jets which are difficult to assess with conventional pulsed Doppler are now directly appreciated.

In addition to the structural abnormalities, complicated but specific flow disturbances most often characterize congenital heart diseases. Color-coded Doppler flow imaging allows a comprehensive diagnosis in most patients.[16-18] In general, more complex lesions have more lesion-specific blood flow patterns which will be more readily detected.

1. Normal Intracardiac Blood Flow

Intracardiac blood flow patterns are best studied in the apical long axis (Fig. 3) and four chamber views. Ejection flow during systole is encoded in blue and seen over the major part of the outflow tract. The intensity of the blue color increases towards the aortic valve indicating an increasing velocity. Aliasing often occurs in the subaortic area. Blood flow is unidirectional and laminar. In diastole, mitral inflow is displayed in red extending from the mitral orifice into the left ventricular inflow tract. Some turbulence may occur at the outlet of the mitral valve around the edges of both leaflets. An early diastolic inflow wave can be distinguished from a late diastolic post-atrial contraction filling wave in most normal subjects. In the apical area, blood flow is rarely visualized because its flow velocity there is below the threshold for color encoding. The power mode display may demonstrate the flow pattern in this area. Tricuspid inflow is similar to mitral inflow, but the colors are less pronounced because of the lower velocities producing lower amplituded Doppler coding. The right ventricular outflow tract and pulmonary artery most often demonstrate a uniform blue color and small areas of turbulence are seen around the pulmonary valve cusps (Fig. 4). Blood flow in the left atrium is usually not well visualized due to low velocities and distance. Normal right atrial flow has specifically been studied by Miyatake et al.[19] They found that the main blood flow towards the tricuspid valve was superiorly oriented and along the interatrial septum.

2. Mitral Stenosis

The stenotic flow jet in patients with mitral stenosis is generally best detected in the apical long axis and four chamber views (Fig. 1). The jet has a "flame-shaped" appearance with central aliasing and a yellow peripheral zone resulting from turbulence. The valve orifice which is usually not apparent from the two-dimensional imaging is now visualized. Our experience indicates that the direction of the jet cannot be predicted from two-dimensional images. Direct visualization of the jet allows the guided interrogation with continuous wave Doppler parallel to flow (Fig. 5). Such application enhances the accuracy of peak velocity determination for the assessment of the severity of mitral stenosis.[10, 11] Thickened and calcified mitral valves reflect most of the ultrasound energy which hampers visualization of regurgitant lesions (posterior to the valve) when mild to moderate.

3. Mitral Regurgitation

Using conventional Doppler systems, regurgitant lesions are diagnosed by demonstrating systolic (atrioventricular)

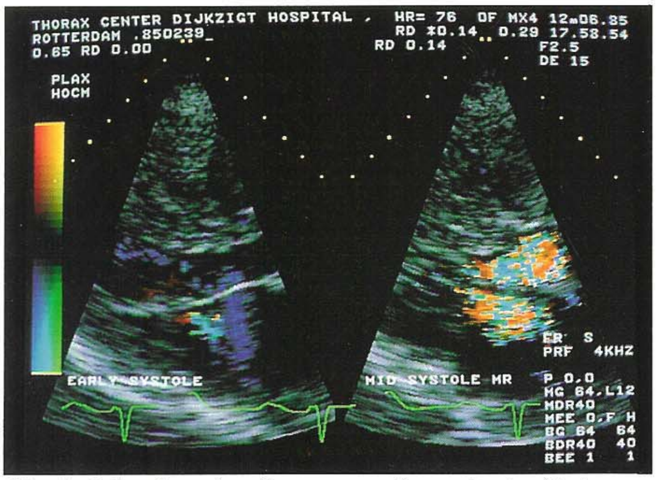

Fig. 7. Color Doppler flow maps of a patient with hypertrophic cardiomyopathy (HOCM). The left panel is recorded in early diastole and shows a small regurgitant jet posterior to the mitral valve which is in a normal closed position. In mid-systole (at right) the mitral valve demonstrates systolic anterior motion causing outflow tract obstruction. The narrowing and turbulent jet are clearly appreciated. Note the increased jet of mitral regurgitation in the left atrium.

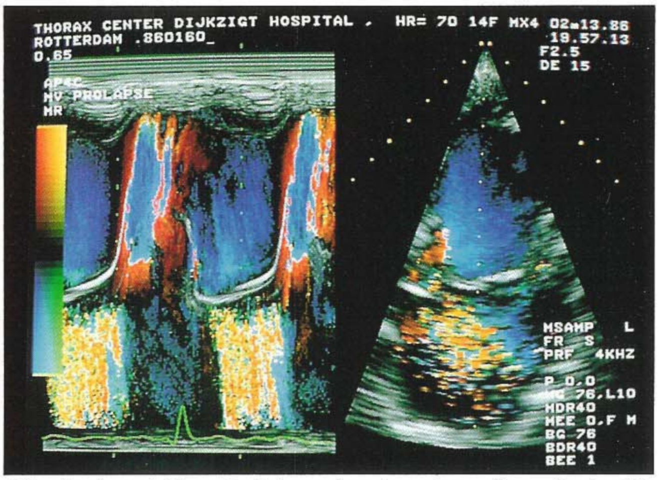

Fig. 8. A systolic apical four chamber view of a patient with mitral valve prolapse and severe mitral regurgitation. Note the wide area and extent of turbulent flow in the left atrium confirming severe mitral regurgitation. A single Doppler line is selected and indicated on the flow map. The blood flow velocity and its dispersion at each point along this interrogating Doppler beam axis is displayed in color and superimposed on the M-mode echocardiogram (at left). In addition to a better temporal resolution for studying time relationships, a wider range of velocities is now displayed, particularly in the low velocity range. During diastole, there is an increased velocity due to larger volume flow resulting in color reversal (aliasing).

or diastolic (semilunar) retrograde flow adjacent to the valve. In the case of mitral regurgitation the retrograde jets will be adjacent to the mitral orifice going to the left atrial cavity. "Mapping techniques" where a range-gated sample volume is moved around the receiving cavity (in this case the left atrial cavity) have been proposed to assess the severity of the regurgitation by measuring the breadth and length of the jet. This approach is a blind technique and therefore cumbersome and time consuming. Moreover, regurgitant jets may be eccentric especially in mitral valve prolapse (Fig. 6) or leaking prosthetic valve and part of the jet is easily missed. The sample volume may also overlap in a contiguous chamber and detect potentially misleading flows such as in the aorta when one searches for an eccentric regurgitant jet in the left atrium.

With the new color-coded Doppler it is possible to visualize a regurgitant jet that is in a direction opposite to what is expected at a given point in the cardiac cycle.[20] Because of the high velocity both aliasing and turbulence occur which results in a mosaic of colors (mixture of blue and yellow). The method greatly facilitates the diagnosis and may help to semi-quantitatively grade the severity of valvular insufficiency[21,22] (Figs. 2, 7 and 8).

A good agreement between the planimetered surface area of the regurgitant jet and the cine-angiographic assessment of severity of mitral incompetence has been reported by Omoto et al.,[20] Kitabatake et al.,[21] and Miyatake et al.,[22] while others have found a poor correlation.[23] Apart from experience in using the technique there are several reasons to explain this discrepancy. First of all, there are fundamental differences between the topographic display of the velocities of a regurgitant jet by Doppler and its densitographic display by angiocardiography after the injection of a radioopaque contrast medium. Second, there are several determinants of the length and area of a regurgitant jet. They are not only related to the size of the defect but also to the magnitude of the pressure drop across the valve. The compliance of the receiving chamber is another factor which influences both the magnitude of the jet and its time course (Fig. 9). An important yet unknown factor in a given patient is the irregular shape of the defect which causes turbulence. Turbulence leads to a loss of kinetic energy and as a result the length/area of the jet will decrease while its volume is less influenced.

Small regurgitant jets may not be detected behind thickened/calcific mitral valves because of poor sound penetration across the diseased valve (Fig. 10). Transesophageal color Doppler echocardiography may prove to have superior sensitivity for the demonstration of such small jets.

There are also technical factors which may affect the color coding of a regurgitant jet. The signal-to-noise ratio by influencing gain settings have an effect on the display of the surface area of a jet and so do the MTI filter characteristics which separate blood flow velocity shifts from velocity shifts introduced by anatomical structures and/or reverberations (clutter). The higher the order of the filter, the more effectively "non-flow" information is suppressed and the less is the effect of the gain settings.

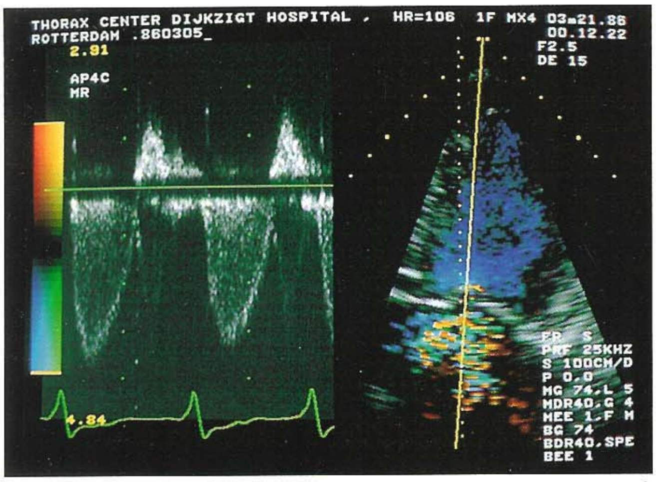

Fig. 9. Color and continuous wave Doppler study of mitral regurgitation. Two turbulent jets are seen posterior to the mitral valve arising from the same central defect (at right). The continuous wave Doppler trace at left shows a waveform consistent with severe mitral regurgitation. Indeed, when the regurgitant volume is large, pressure in the left ventricle rapidly decreases while the pressure in the left atrium increases (high V-wave). Thus, the pressure differences rapidly decrease during systole resulting in a rapidly decreasing blood flow velocity.

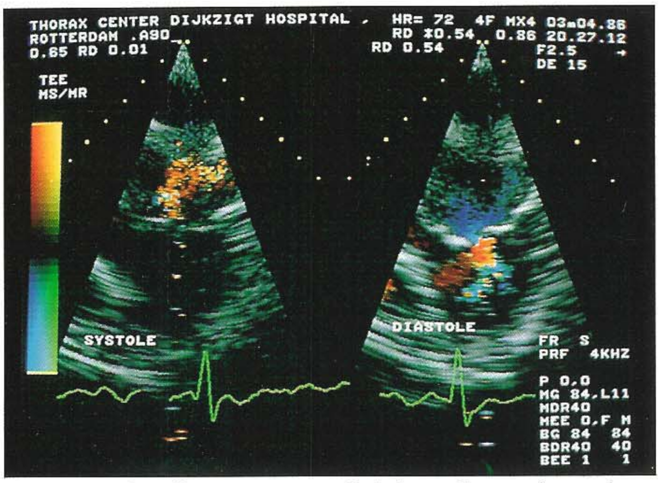

Fig. 10. Color flow maps recorded from the esophagus in a patient with mitral stenosis. During the precordial study a regurgitant jet could not be demonstrated. The transesophageal (TEE) study clearly showed a small turbulent jet of mitral regurgitation (at left). The right frame is recorded during diastole and shows the jet of mitral stenosis in the left ventricle.

Thus despite great and widespread enthusiasm, quantification of regurgitant lesions can only be semi-quantitative at best and close agreement with angiocardiography would not be expected.

4. Aortic Stenosis

Our experiences with color Doppler flow imaging in patients with aortic stenosis so far have been disappointing because the stenotic jet is rarely seen in adult patients in the apical views. This may result from the distance at which the Doppler signals are sampled, resulting in a low sensitivity, and from the fact that the aortic valves are frequently calcified, resulting in poor sound penetration across the diseased valve. In some patients the jet may be visualized from the right sternal border and appear as a broad mosaic of colors (Fig. 11). Unlike in mitral stenosis the direction of the maximum velocities is ill-defined. In young patients with con-

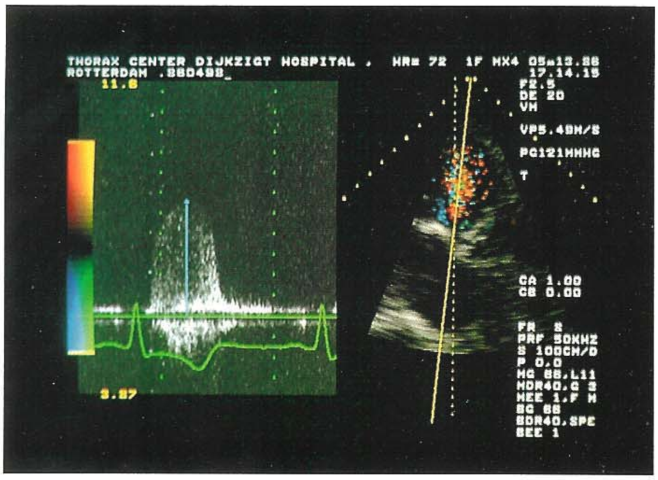

Fig. 11. Color Doppler flow map of the aortic root recorded from the right parasternal border (RPS) of a patient with aortic stenosis. The stenotic jet could not be visualized from the left parasternal or apical views. Note the jet of mosaic colors indicating turbulence. Peak velocity measured from the continuous wave Doppler trace (at left) is 5.49 m.s.$^{-1}$ corresponding to a peak pressure difference of 121 mmHg across the stenotic aortic valve, indicating severe aortic stenosis.

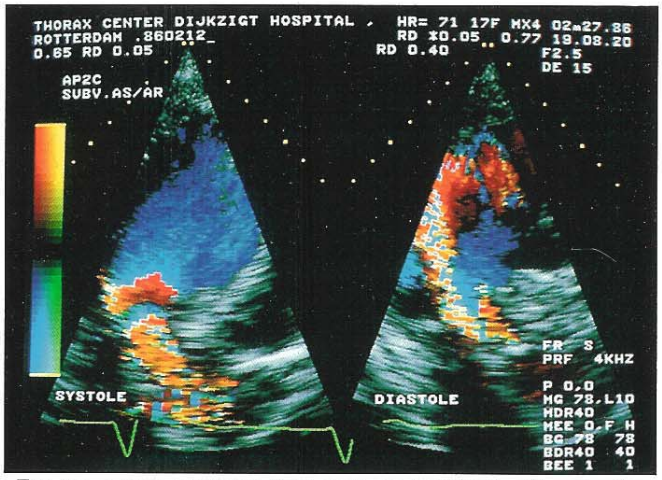

Fig. 12. Color Doppler flow map of a patient with subvalvular aortic stenosis. During systole (left panel) the level of the discrete membranous obstruction in the outflow tracts is seen with the jet of mosaic colors indicating turbulence behind it. Note the increasing velocity proximal to the obstruction resulting in aliasing. During diastole (right panel) the high velocity jet of aortic regurgitation strikes the anterior mitral leaflet and then reaches the apex.

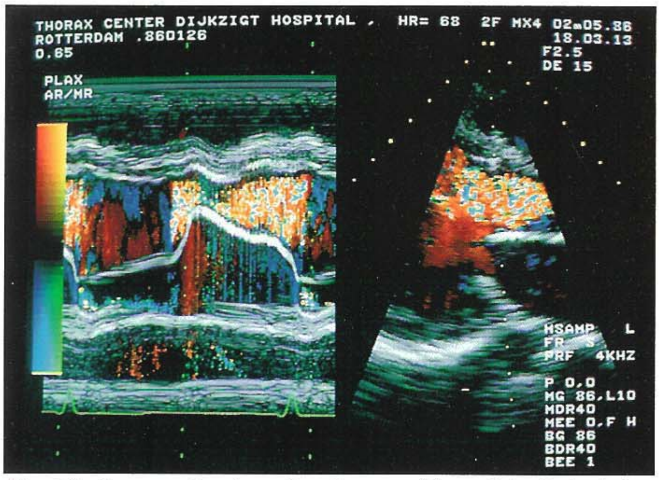

Fig. 13. Long axis view showing a wide and turbulent jet that fills the left ventricular outflow tract during diastole indicating severe aortic regurgitation (at right). The color Doppler signals obtained along a sound beam axis and superimposed on the M-mode echocardiogram demonstrates the exact timing of the regurgitant flow in the cardiac cycle.

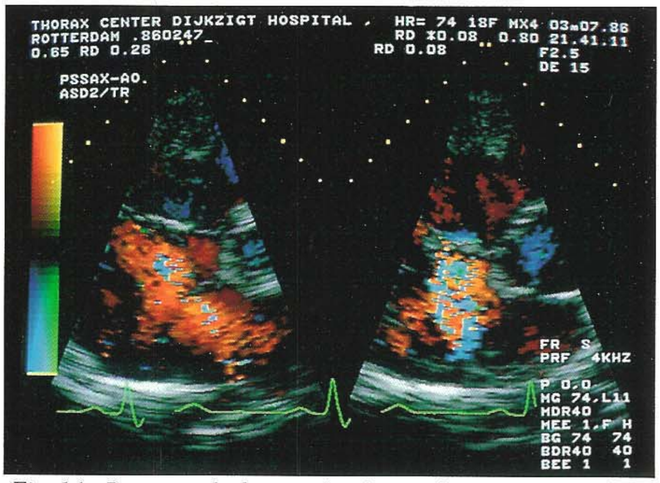

Fig. 14. Parasternal short axis views of a patient with an atrial septal defect of the secundum type. The systolic frame shown at right demonstrates severe tricuspid regurgitation indicated by the wide area of mosaic colors in the right atrium. Left-to-right shunting blood flow is visualized on the diastolic frame (at left).

genital aortic stenosis or subvalvular membraneous aortic stenosis the jets are often seen well (Fig. 12). This has been our experience in pulmonic valve stenosis as well.

5. Aortic Regurgitation

In this condition the regurgitant flow is seen as a reddish-yellow spurt backwards from the aortic orifice into the left ventricular outflow tract during diastole.[14,20] It is best seen in the apical long axis (Figs. 1, 5 and 12) and parasternal long axis views (Fig. 13). The direction of the jet varies from either being in the central zone of left ventricular outflow tract, along the interventricular septum or along the anterior mitral leaflet. Unlike with pulsed Doppler echocardiography, the regurgitant jet is easily differentiated from a coexisting jet of mitral stenosis (Fig. 1). Although it has been shown in animals with experimentally-produced aortic insufficiency that the spatial distribution and the length of the jet into the left ventricle of the regurgitant jet was quantitatively related to the regurgitant fraction,[24] the same limitations as discussed with mitral regurgitation are present. The length of the jet is highly dependent on the imposed systemic afterload and therefore unreliable to quantitate the severity of aortic regurgitation. Some investigators have suggested that the width of the jet is a more accurate reflection of the severity of the regurgitation than the jet length.[25] This needs further clinical confirmation, however.

6. Tricuspid Regurgitation

The parasternal short axis view will show the regurgitant jet from the tricuspid orifice into the right atrial cavity during systole which is usually seen as a mosaic pattern in blue and yellow[13,14] (Figs. 2 and 14). In addition to the reasons already given in explaining the discrepancy in assessment of left-sided valvular regurgitation, there are some specific problems related to the tricuspid valve. The examiner must be cautious to exclude other sources of systolic right atrial flow, including normal systemic venous return, coronary sinus drainage and sometimes an atrial septal defect. As the valve plane may move considerably during the cardiac cycle the angle of interrogation will change from one area to another within the jet. As a result, the lower velocities at the perimeter of the regurgitant jet and more particularly at its tail may fall below the threshold for color-coding. This will result in an underestimation of the degree of insufficiency. Future instruments should incorporate an automatic angle correction before color coding. It is not uncommon to see trivial regurgitation in otherwise normal individuals, and this should not be considered pathologic. Significant tricuspid regurgitation is often a marker of pulmonary hypertension and allows the estimation of right ventricular and pulmonary arterial systolic pressure from the peak velocity across the valve (Fig. 15).

7. Pulmonary Regurgitation

The regurgitant flow in patients with this condition is seen as a jet that runs from the center of the pulmonary orifice backwards into the right ventricular outflow tract during diastole. It is best visualized with the parasternal aortic short axis view. Pulmonary regurgitation is common in pulmonary hypertension. However, mild pulmonary regurgitation is seen in healthy subjects and has no clinical significance in the absence of other abnormalities and when volocities are low (Fig. 4).

8. Atrial Septal Defect

Patients with atrial septal defect can

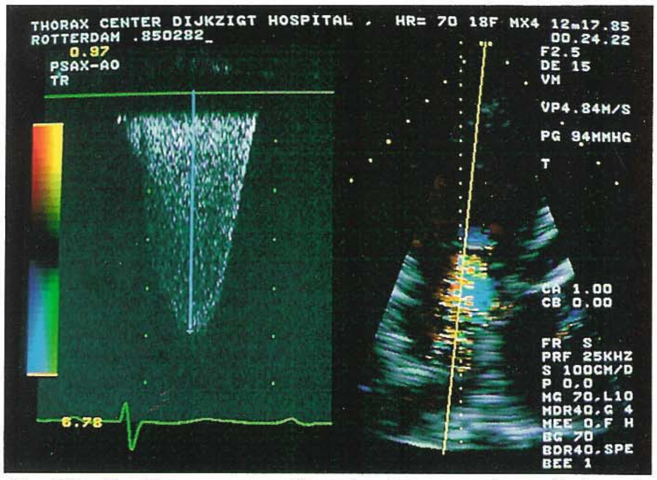

Fig. 15. Continuous-wave Doppler interrogation of the tricuspid regurgitant jet is performed along the sound beam axis shown on the color Doppler flow map at right. Peak systolic velocity (VP) is 4.84 m.s.$^{-1}$ corresponding to a peak systolic pressure difference (PG) of 94 mmHg between the right ventricle and right atrium. Adding clinically estimated central venous pressure provides an estimated right ventricular systolic pressure of approx. 105 mmHg, indicating severe pulmonary hypertension.

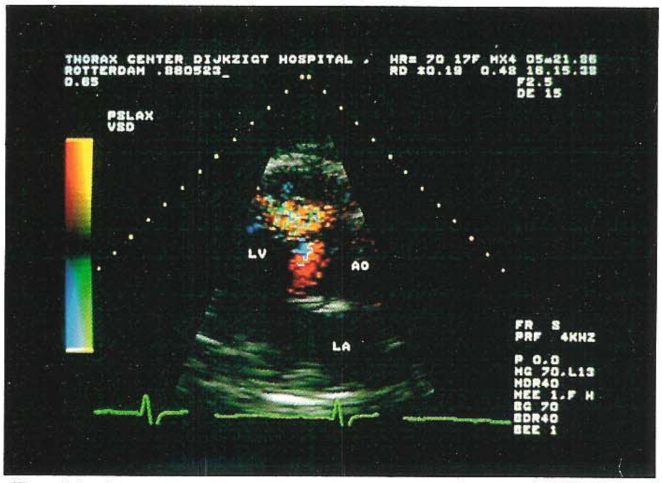

Fig. 16. Long axis view and a left-to-right shunt through a high ventricular septal defect which was unexpectedly visualized in a 64-year-old woman with a systolic murmur.

be diagnosed with color-coded Doppler using either the parasternal short axis view (Fig. 14) or the subcostal approach. Reddish-yellow Doppler signals will be seen spreading from the left atrial cavity near the defect towards the tricuspid orifice through the defect, indicating a left-to-right shunt, and is mainly observed in late systole.[26] The advantage of color Doppler imaging is the localization of atypically-located atrial septal defects, such as in the sinus venosus position, and the diagnosis of multiple atrial septal defects.[27]

9. Ventricular Septal Defect

Immediate visualization of jets which are difficult to find with conventional Doppler techniques as well as their localization is a major advantage of the technique. The direction of flow is of clinical importance and is better detected by color-coded Doppler flow imaging than conventional Doppler techniques.[28, 29] This results from the fact that with pulsed Doppler, flow velocity is measured at a fixed point in the heart and the sample volume may be on different sides of the defect as a result of cardiac motion. With color-coded Doppler flow imaging the flow information is displayed upon structure and directional information is therefore more accurate. This has advantages for defining the relationship of the flow orifices in ventricular septal defects which appear to be covered by aneurysms and in patients with complicated lesions where bidirectional flow is present. In patients with simple ventricular septal defects, additional or multiple ventricular septal defects, especially in the muscular septum (Swiss-cheese type septum), may exceptionally be present and these are readily diagnosed. Unlike large defects where velocities are low and flow is laminar, smaller defects cause turbulent jets with high velocities (Fig. 16). The technique provides an easy serially applicable technique for detecting residual leaks around ventricular septal patches.

10. Prosthetic Valves

Prosthetic valves have characteristic flow patterns, and their changes may be helpful in the diagnosis of valve dysfunction[30] (Fig. 17). Anterograde transprosthetic flow is readily seen and used to guide a continuous wave Doppler cursor through the maximal velocity allowing an accurate postoperative baseline measurement of pressure drop across the prosthesis. The color-coded Doppler flow imaging also gives more information regarding malfunction of prosthetic valves. It is possible to differentiate between central and paravalvular insufficiency (Fig. 18), and since the flow patterns of prosthetic valve insufficiency are often eccentric, they are readily diagnosed, although interpretation requires substantial experience and theoretical background. In mechanical prosthetic valves there are many artifacts produced by the prosthesis, which may be confused with regurgitant jets whose detection may be hampered by the dense shadowing distal to the valve. Transesophageal color Doppler flow imaging is extremely helpful in patients where regurgitation of a mitral prosthesis is suspected (Fig. 19). In patients with a Hancock mitral prosthesis investigators of the Stanford group have noted a deviation of flow towards the septum reversing the direction of normal intraventricular flow. This pattern is also observed in patients with Björk-Shiley mitral prostheses positioned in the orifice in such a way that the main flow is directed towards the septum. Such an abnormal filling pattern of the left ventricle may

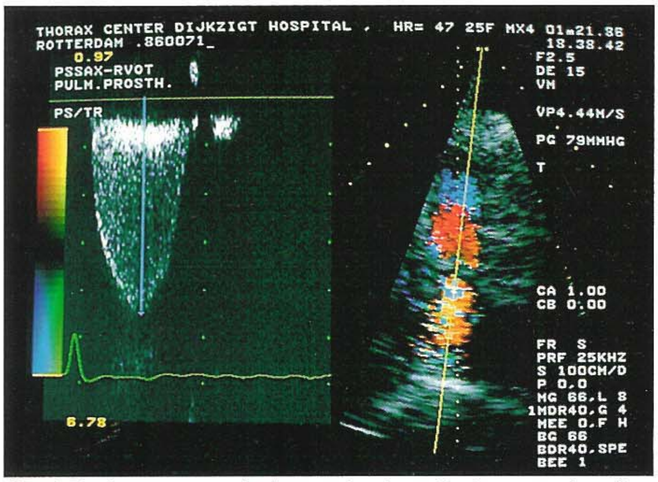

Fig. 17. A parasternal short-axis view during systole of a patient with a stenotic pulmonary Hancock prosthesis. The level of the stenotic valve is seen on the color flow map to the right. Note the increasing velocity proximal to the valve and the mosaic of colors behind it indicating a turbulent jet. The spectral output on the left was obtained by continuous wave Doppler sampling along the sound beam axis indicated on the flow map. From this recording a peak systolic velocity of 4.44 m.s.$^{-1}$ was calculated corresponding to a peak pressure difference across the stenotic valve of 79 mmHg.

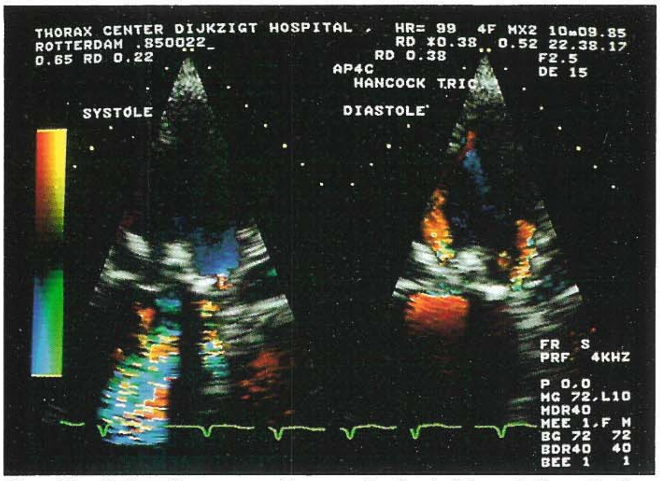

Fig. 18. Color flow maps in systole (at left) and diastole (at right) in a patient with a Hancock prosthesis in the tricuspid position. Two systolic regurgitant jets are seen in the right atrium indicating a central and paravalvular leak. Note the mosaic color pattern as a result of turbulence. During diastole, the inflow jet over the prosthesis is seen as well as an inflow jet via the paraprosthetic defect. Note the increasing velocity proximal to the central orifice in the right atrium encoded in red.

represent a significant loss of mechanical energy. Thus it appears that the study of flow dynamics will add to a better understanding of some clinical conditions in patients with valvular prostheses.

11. Volume Flow and Cardiac Output

The major limitation of volume flow and cardiac output lies in the accuracy of the measurement of cross-sectional flow area rather than the velocity measurement (mean temporal velocity times area of flow yields volume flow). Theoretically, the "area of flow" would be a more accurate measurement than the anatomical area and can be directly obtained from color flow images. Hoit et al.[31] reported good agreement between color Doppler derived areas of flow and calculated flow areas from cardiac output and conventional Doppler time velocity integrals in experimental animals. Valdez-Cruz et al.[32] found cardiac output measurements using color Doppler derived flow areas more accurate than when anatomically-derived areas of flow were used at low cardiac output states. One must realize, however, that the lower velocities at the boundaries of flow are not encoded for reasons discussed above. Furthermore, improvement in the resolution of flow imaging seems necessary in order to decrease measurement variability. Thus, further clinical validation and results from other centers are needed, and the application of volume flow measurements will become a major research goal.

Table 1. Clinical Uses and Research Areas for Color-Coded Doppler Flow Imaging

1. Physiology and pathophysiology of intracardiac blood flow (velocity, turbulence, flow profile ?, flow area ?).
2. Rapid detection and localization of single and multiple flow abnormalities.
3. Visualization of flow jets which are difficult to find with conventional Doppler modalities (multiple shunts).
4. Determination of the spatial orientation of flow jets permits for accurate angle correction and allows a more accurate quantitative velocity measurement by continuous or pulsed wave Doppler.
5. Visualization of transvalvular and intracavitary blood flow patterns in normal and dysfunctioning prosthetic valves.
6. Semi-quantitative grading of the severity of valvular insufficiency from extent and area of regurgitant jets.

12. Intracavitary Flow Abnormalities

Segmental wall motion abnormalities may produce intracavitary flow abnormalities (Fig. 20), while in dilated ventricles intracavitary flow is slow. The power spectrum display allows visualization of these slow flow patterns and may help us to understand why some patients after a myocardial infarction develop a laminated thrombus while others develop a pedunculated thrombus carrying a much higher risk for systemic embolization.[33]

13. Intraoperative Application

Intraoperative color-coded Doppler

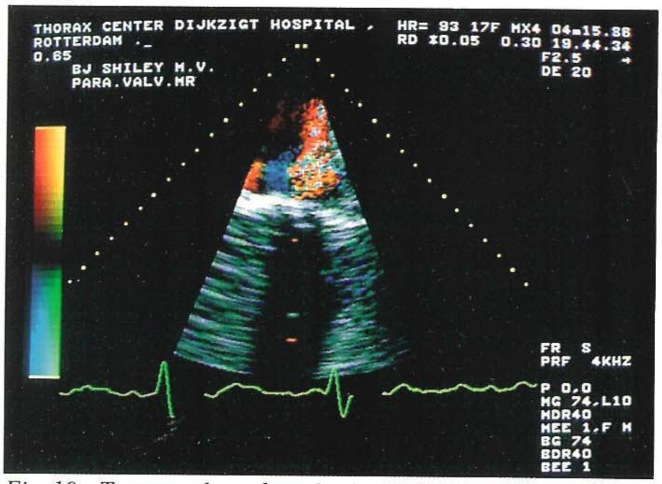

Fig. 19. Transesophageal study demonstrating a paravalvular leak which was not detected from the precordial approach in a patient with Björk-Shiley mitral valve prosthesis. Regurgitant jets are often difficult to visualize posterior to prosthetic valves.

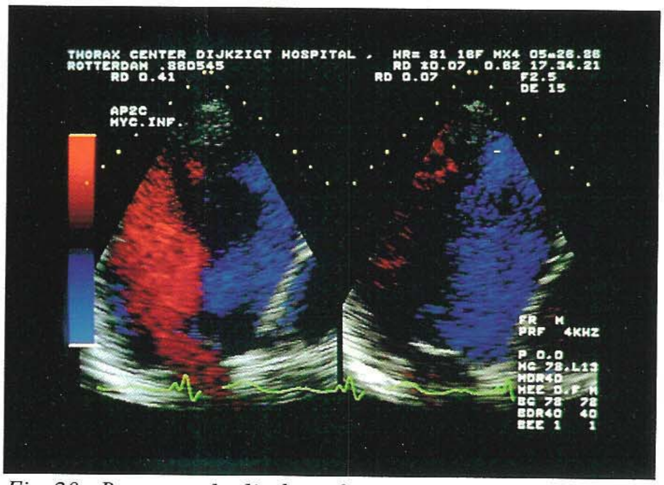

Fig. 20. Power-mode display of intracardiac blood flow in a patient with a dilated heart, aneurysm and low-output state as a result of a myocardial infarction. No flow was encoded in the mid-ventricular and apical region of the left ventricular cavity in the regular mode. In the power-mode, the inflow in early diastole is encoded in red from mitral valve to apex (left panel) and the outflow in systole is encoded in blue from apex to base (right panel).