Doppler Echocardiography
Use of a Graphical Display System

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SUMMARY Pulsed Doppler echocardiography (PDE) is a technique for evaluating blood flow characteristics at specific locations within the heart and great vessels. Because this method assesses blood flow rather than cardiac structures, PDE complements the findings of M-mode echocardiography. A new on-line graphical method for displaying pulsed Doppler information provides 1) a printed, permanent record of flow information, 2) precise timing of blood flow events, and 3) information on the direction of flow in the heart and great vessels.

CARDIAC ULTRASOUND has greatly enhanced our ability to define structural disorders in the heart and great vessels. While certain cardiac diseases lend themselves to firm diagnosis by M-mode echocardiography, many valvular and congenital disorders result in normal or nonspecific echocardiographic findings. In these disorders structural abnormalities clearly exist which cannot be evaluated with present echocardiographic techniques. A range-gated pulsed Doppler device has therefore been developed which can identify blood flow patterns at well-defined intracardiac locations.

The use of the pulsed Doppler device for the evaluation of murmurs has been previously described using an audible signal as the primary output for interpretation. This system, however, has recently been further improved by the introduction of a graphical recording method which increases ease of interpretation, provides a printed record of pulsed Doppler findings, and allows for more precise timing of blood flow events. It is the purpose of this paper to illustrate the applications of this graphic technique in identifying valvular abnormalities and septal defects.

Methods

In accordance with the Doppler theory, the frequencies of sound reflected from an object will be altered if that object is moving. This alteration is known as Doppler shift. Blood will reflect high frequency sound because it contains particulate matter — namely the blood cells. The pulsed Doppler device uses repetitive bursts, or pulses, of sound in the megahertz range, much like traditional M-mode echocardiographic systems. While most ultrasonic waves are reflected from the various cardiac structures, a small amount is backscattered by the blood cells within the chambers themselves. These waves can be analyzed using a special Doppler shift detector system. If an ultrasonic beam is directed at a nonturbulent moving blood sample, the reflected sound waves will be of fairly uniform Doppler shift. By contrast sound waves reflected from a turbulent blood sample will show wide fluctuations in Doppler shift.

The pulsed Doppler functions by detecting the Doppler shift from moving blood within the heart or great vessels and provides an output by which blood flow characteristics can be recognized. The primary advantage of the pulsed, as opposed to the continuous wave Doppler is that blood flow velocity may be evaluated from discrete intracardiac positions. This flow velocity is detected in a teardrop-shaped region called the sample volume which may be chosen from any depth from between 2 and 15 centimeters along the ultrasonic beam through the use of a movable range-gating system. The sample volume measures approximately 2 mm in diameter and 4 mm in length.

The device employs a 3 MHz piezoelectric transducer with a ½ inch diameter crystal focused at 5 cm. The transmitter circuit emits 1 msec ultrasonic bursts at a pulse repetition frequency that may be varied between 3,500 and 10,000 bursts per second depending on the depth of penetration desired. The returned signal is divided such that one portion is used to create a traditional A-mode display for orientation; however the quality of this A-mode Doppler display is not yet comparable to conventional devices due to inherent resolution limitations. The other portion of the returned signal is used for Doppler flow velocity information. The magnitude and direction of the Doppler shift is determined in a special phase detector circuit where the returned frequency is compared to the transmitted frequency. Positioning the transducer in a manner similar to that used in traditional echocardiography and using the A-mode display for orientation, the sample volume is placed at well defined intracardiac locations simply by adjusting the range gate knob (fig. 1).

There are two types of output available from a pulsed Doppler device. The first provides an audible signal in the range of 400 Hz to 5 kHz which corresponds to the spectrum of Doppler shifts produced by normal or disturbed blood flow. The interpretation is based on evaluating the tonal quality of the signal. Smooth blood flow characteristically has a narrow bandwidth pattern which produces a tonal “musical-like” sound whereas disturbed or turbulent flow has a wide bandwidth pattern which produces a harsh, scratchy sound. This method has been described in detail in previous publications.

The second type of output available is an on-line graphical display of the Doppler shift frequencies which is printed on a (Honeywell #1856) strip chart recorder. A circuit has been built into the pulsed Doppler detector for performing analysis of flow and creating a display pattern. This circuit creates what is called a time interval histogram (TIH) (fig. 2), which is a dot pattern by which flow velocity characteris-
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FIGURE 1. The sample volume is a teardrop-shaped region which may be selected from anywhere along the ultrasonic beam axis, by adjusting the depth gate. An A-mode display is used for orientation.

dicated can be easily identified. The pattern is derived by measuring the time between successive zero crossings of the audible signal waveform. A zero crossing is defined as the instant in time when the Doppler shift signal passes through its zero intensity level (fig. 2). A dot is printed on the strip chart paper for each zero crossing event such that the distance of a particular dot above or below the zero flow velocity baseline is directly proportional to the Doppler shift frequency. For example, if the Doppler shift frequency is relatively low, a dot will be printed near the zero velocity baseline. However, if the Doppler shift frequency is relatively high, a dot will be printed proportionately farther away from the baseline. Any dot printed above the baseline (positive) represents relative blood velocity toward the transducer and conversely any dot printed below the baseline (negative) represents flow velocity away from the transducer. A dot pattern is thus produced which shows the Doppler shift spectrum, and this pattern is used to identify blood flow characteristics within the sample volume. When laminar flow exists, blood cells within the sample volume have fairly uniform direction and velocity. Therefore backscattered sound waves will have a fairly uniform Doppler shift. The time interval histogram produced by this flow has a narrowly clustered dot pattern (narrow band pattern) (fig. 3A). When “disturbed” flow exists, the blood cells have varied direction and velocity which produce a time interval histogram with a widely dispersed dot pattern (wide band pattern) (fig. 3B).

Strip chart records contain simultaneous recordings of 1) the M-mode display of the received Doppler signal (in the form of a traditional M-mode echo display) with a superimposed line indicating the location of the sample volume at any particular time, 2) the time interval histogram of the Doppler signal (also called a spectral display), and 3) a standard electrocardiogram. It is also possible to record an analog waveform of flow which corresponds to the mean value of the Doppler frequency shift; this can be shown as a separate channel on the recording but has proved of limited value and has been deleted from most later recordings.

Patients for the study were selected from the routine referrals to our ultrasound laboratory for clinical evaluation. Most, but not all, with abnormal findings have had documentation of their pathology by cardiac catheterization and angiography. Each patient seen in our ultrasound laboratory routinely undergoes systematic cardiac ultrasonic examination, beginning with a complete M-mode echocardiographic assessment. Following this a pulsed Doppler examination is performed. Beginning from the suprasternal notch, sampling is obtained from the proximal aorta and the right pulmonary artery. The transducer is then placed on the precordium and sampling performed on the inflow and outflow side of each valve and within each valve orifice itself to determine whether forward flow across the respective valve has a laminar or turbulent pattern, and whether regurgitant flow exists. When a septal defect is suspected, sampling is performed along the septum on the outflow side of the suspected defect, following which attempts are made to pass the sample volume directly through the defect.
There are inherent technical limitations in the zero crossing detection system of the graphical display which make it slightly less sensitive and less immune to extraneous noise interference than the audible detection system. Therefore representative recordings of Doppler abnormalities are obtained both on magnetic tape and the graphical display system.

Results

General

Normal and Turbulent Flow

Blood flow within a vessel or chamber is usually laminar and produces a time interval histogram with a narrowly clustered dot pattern (fig. 3A). Turbulent or disturbed flow, by contrast, produces a time interval histogram with a widely dispersed dot pattern (fig. 3B). With disturbed blood flow the presence of dots which are widely dispersed both above and below the zero line illustrate the marked variation in blood cell direction and velocity within the sample, with some cells moving toward and others away from the transducer.

Valvular Stenosis and Regurgitation

Within and on the outflow side of a stenotic valvular orifice a jet of disturbed flow exists which produces a broad band pattern on Doppler examination. Valvular regurgitant lesions produce a broad band Doppler pattern, which is detected on the inflow side of the valve being examined.

Septal Defects

Much like valvular abnormalities, these lesions are detected by the turbulence which they produce. Large gradients, as seen for example in small ventricular septal defects, cause severe turbulence and produce markedly broad band patterns on Doppler examination. By contrast small gradient defects, as seen in atrial septal defects and large ventricular septal defects, cause less severe turbulence and produce mildly broad band patterns on Doppler examination.

Aortic Valve Flow

With the transducer positioned over the precordium, the systolic flow in or just above the aortic valve is normally laminar or slightly disturbed (fig. 4A). In diastole no flow is appreciated. As a valve leaflet traverses the sample volume this produces a fine mark on the recording which has been arbitrarily labeled a valve click because of its audible Doppler characteristics. Clicks during opening and closure of the aortic leaflets are usually recorded when the sample volume is placed within the valve orifice. Flow in the left ventricular outflow tract is essentially identical to that in the
proximal aorta except that valve clicks are not detected.

In aortic stenosis a jet of systolic turbulence is detected within and above the aortic valve and is represented by a broad band Doppler pattern (fig. 4B). In diastole a narrow band dot pattern is recorded at or near the zero flow baseline because no flow is present and the Doppler shift is therefore zero.

In aortic insufficiency a regurgitant jet may be detected during diastole within the valve orifice, in the left ventricular outflow tract, and frequently well down into the left ventricular chamber (fig. 5A). When searching for this lesion in the presence of mitral stenosis, diastolic turbulence must be documented within the aortic valve or high left ventricular outflow tract to make a firm diagnosis of coexisting aortic insufficiency. If attempts are made to follow the disturbed flow into each valve orifice, mitral stenosis and aortic insufficiency can be easily differentiated from one another.

With idiopathic hypertrophic subaortic stenosis or subaortic rings, a broad band systolic pattern is detected within the left ventricular outflow tract in most patients (fig. 5B). In some of these patients disturbed flow may also be detected to a lesser extent above the aortic valve.

**Mitral Valve Flow**

If the sample volume is placed in the left ventricular inflow region, nonturbulent, anteriorly directed flow is found to commence with opening of the mitral valve (fig. 6A). This flow diminishes but is sustained until late diastole when a small flow wave occurs with atrial contraction. The mitral valve then closes and flow recorded from this position ceases. In some patients the early and late diastolic flow waves are separated in mid-diastole by what appears to be a period of virtually no detectable flow by Doppler. In mitral stenosis a broad band diastolic pattern is found within the mitral valve orifice, in the left ventricular inflow region, and frequently just posterior to the mitral valve in the left atrial outflow region (fig. 6B). Normal flow patterns in the left atrial outflow region are quite similar to those detected in the left ventricular inflow (fig. 7A). Mitral regurgitation is represented by a broad band pattern detected in the left ventricular inflow (fig. 7B).
atrial outflow region during systole (fig. 7B). This turbulence is frequently confined to the latter half of systole in the presence of mitral valve prolapse.

Tricuspid Valve Flow

In both the normal and pathologic state, flow proximal and distal to this valve is quite similar to that detected at the mitral valve with the Doppler detector (fig. 8A, 8B).

Pulmonic Valve Flow

The normal right ventricular outflow tract has a rather characteristic narrow band, negatively deflected pattern in systole since flow is directed posteriorly, away from the transducer. No significant flow occurs in diastole (fig. 9A). A similar pattern occurs in the proximal pulmonary artery; however mild systolic turbulence may be detected in the absence of a pathologic pulmonic valve. In pulmonic stenosis a broad band pattern is detected during systole in the proximal pulmonary artery. Pulmonic regurgitation produces a broad band pattern in the right ventricular outflow tract during diastole (fig. 9B).

Atrial Septal Defect

When an atrial septal defect is suspected, the transducer may be directed in such a manner that the sample volume is passed from the left atrial chamber to the right atrial chamber while flow is being assessed (ASD maneuver). If this maneuver is performed several times with the range-gate set at slightly different distances, a sample can usually be obtained from directly within, and on the outflow side of the atrial septal defect. Intra-atrial shunting generally produces a turbulent pattern with the Doppler detector, but the timing has been variable. Recent intracardiac Doppler studies performed elsewhere suggest that shunting generally occurs at three separate points during each cycle: during 1) late systole, 2) early diastole, and 3) late diastole corresponding to atrial contraction. While we have frequently observed a similar timing pattern with the Doppler detector, in two

![Diagram of ventricular flows](image-url)
patients shunting was observed to begin in late diastole and extend through early systole (fig. 10). Johnson et al. have shown that atrial septal defects with left-to-right shunt can be detected with the pulsed Doppler device in two-thirds of patients.12

Ventricular Septal Defects

Membranous ventricular septal defects are characterized by the presence of a broad band systolic jet in the right ventricular outflow tract (fig. 11). This turbulent jet can frequently be followed through the interventricular septal defect itself. The localization of systolic turbulence to the right ventricular outflow tract and through a portion of the interventricular septum differentiates this lesion from infundibular pulmonic stenosis. In the latter the systolic turbulence is confined to the right ventricular outflow tract.

In the muscular form of ventricular septal defect, a systolic jet exists in the body of the right ventricle. For reasons that are not entirely clear, the jet is frequently difficult to identify and can only occasionally be followed through the septal defect itself.

Discussion

The range-gated pulsed Doppler instrument can greatly extend the amount of useful information obtained in a cardiac ultrasound examination. Because it deals with cardiac blood flow rather than cardiac structure, this device tends to complement information obtained from M-mode echocardiography. The information generated is of four basic types.

Identification of the origin of murmurs. By sampling at precise intracardiac locations, the pulsed Doppler device can reliably identify the location and timing of turbulent blood flow events. The timing corresponds to that heard with the stethoscope or recorded on phonocardiogram. From this Doppler information the abnormality causing a particular murmur may be directly inferred. This is especially useful in those lesions such as mitral regurgitation, tricuspid regurgitation, pulmonic regurgitation, and ventricular septal defects which produce either minimal or nonspecific abnormalities by traditional M-mode echocardiography. For example, the development of a new systolic murmur heard
from the left lower sternal border to the apex in a patient several days after an acute myocardial infarction could represent an acquired ventricular septal defect or mitral regurgitation from severe papillary muscle dysfunction. Traditional M-mode echocardiography would not distinguish between these two entities. However by localizing the site of the flow disturbance, the pulsed Doppler detector can be used to provide a firm diagnosis. Similarly, pulmonic can be separated from aortic regurgitation, aortic stenosis from subvalvular obstructive disease, and mitral from tricuspid regurgitation. In light of recent reports of normal posterior leaflet motion in some cases of mitral stenosis, the Doppler detector should prove a useful adjunct in deciding whether this disease is present or not.

The obtaining of information not recognized on physical examination. Loud murmurs on auscultation may sometimes obliterate the presence of other softer but potentially significant murmurs. For example, mitral or tricuspid regurgitation might be overlooked in the face of a harsh aortic flow murmur, but the presence of multiple areas of disturbed flow can be easily recognized on pulsed Doppler examination.

As another example, the diagnosis of an atrial septal defect can sometimes be difficult to make with confidence using our usual clinical modalities. Paradoxical septal motion seen on echocardiogram is neither specific, nor a constant feature, and provides only indirect support for the diagnosis. While the flow across an ASD is almost always inaudible by auscultation, it can usually be detected on Doppler examination.

Estimation of the quantitative significance of murmurs. This is an application that is just beginning to be explored. The Doppler detector alone has not proved useful thus far in quantitating the severity of stenotic valvular lesions. By contrast, it appears that regurgitant lesions are detected over an increasingly larger area and for a longer period of time as they become increasingly severe. For example insignificant mitral regurgitation may be detected during just a portion

**Figure 7.** Left atrial outflow region (LAOR). A) Normal. B) Mitral regurgitation. A moderately turbulent pattern (X) is detected in the LAOR during systole. While the patient did not undergo catheterization, this 21-year-old female had a strong family history of Marfan's disease and nonrheumatic mitral regurgitation. The patient had a loud mitral regurgitant murmur and diagnostic mitral valve prolapse on echocardiogram. e = early diastolic flow; a = late diastolic flow commencing with atrial contraction; VC = valve click.
of systole and the turbulence is localized to the inflow side of the mitral valve. However with severe mitral regurgitation turbulence is generally pansystolic and detected through much of the left atrium. This correlation awaits further validation studies by catheterization and angiography.

*Separation of innocent from pathologic flow murmurs.* The significance of systolic flow murmurs in young people is sometimes difficult to assess with the usual noninvasive methods. By Doppler examination innocent murmurs produce minimal or no turbulence, whereas pathologic flow murmurs tend to be quite turbulent. The reason for this is not entirely clear, as presumably some turbulence is being produced in the presence of functional murmurs. It may well be, however, that this turbulence is so mild that it is not detected by the pulsed Doppler device. This area of investigation also requires further evaluation and validation.

The use of a graphic display for the Doppler system has several advantages when compared to sole reliance upon an audible output. First, it provides a printed, permanent record which simultaneously shows 1) the M-mode display of the Doppler signal with a superimposed line indicating the locations of the sample volume at any particular time, 2) the Doppler spectral display (time interval histogram), and 3) the ECG. With the audible signal, storage must be done on electromagnetic tape, a somewhat cumbersome recording method which has made retrieval and transferring of information difficult.

Secondly, the graphic display improves ease of interpretation. A fair degree of expertise is necessary to interpret reliably the audible Doppler signal, and this becomes less critical with use of the graphic display.

Thirdly, a graphic display provides the opportunity to precisely time the onset and completion of turbulent blood flow events. This is useful in understanding flow characteristics in such disorders as atrial septal defects.

Finally, information generated from the phase shift detector system can now be applied to determine the direction of

**Figure 8.** Right atrial outflow. A) Normal. B) Tricuspid regurgitation (X). This patient had severe mitral stenosis at catheterization with mild functional tricuspid regurgitation. Exact quantitation of the tricuspid regurgitation was not performed.
Figure 9. Right ventricular outflow (RVOT). A) Normal. A characteristic, negatively deflected pattern is detected during systole because flow is posteriorly directed in the RVOT. B) Pulmonic regurgitation. A moderately turbulent, positively deflected pattern (X) is detected in the RVOT during diastole. PV = pulmonic valve.

Figure 10. Atrial septal defect. A scan is initiated with the sample volume in the left atrium. The transducer is then directed to the patient's right so that the sample volume passes through the defect into the right atrium. Abnormal flow is detected within and on the outflow side of the ASD. In this case the abnormal flow begins in late diastole and ends in mid-systole. Catheterization confirmed a left-to-right shunt in this patient at the atrial level with a pulmonic/systemic flow ratio of 2.2 to 1.
FIGURE 11. Ventricular septal defect (VSD). Marked turbulence (X) is found in the right ventricle during systole. A VSD with left-to-right shunt was documented in this nine-year-old female by left ventricular angiography and oxygen saturations. A pulmonic/systemic flow ratio of 1.8 to 1 (4 liter shunt) was found.
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