Use of Doppler Techniques (Continuous-Wave, Pulsed-Wave, and Color Flow Imaging) in the Noninvasive Hemodynamic Assessment of Congenital Heart Disease

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Doppler echocardiography is a relatively new technique that has become an integral part of the cardiovascular ultrasound examination. The hemodynamic information provided by the Doppler technique is complementary to the tomographic anatomy depicted by the two-dimensional examination and, in some patients, may obviate the need for cardiac catheterization. In this article, we focus on the role of Doppler echocardiography in the noninvasive diagnosis of congenital cardiac abnormalities.

PRINCIPLES OF DOPPLER ULTRASOUND

The Doppler shift is an apparent change in sound frequency that results from the reflection of ultrasound from a moving target. In Doppler echocardiography, an ultrasound beam of known initial frequency is reflected from moving targets (primarily red blood cells) in the heart. Doppler signals are shifted proportional to the direction of blood flow (increased frequency signifies movement toward the transducer, and decreased frequency denotes movement away from it) and the velocity of flow (a large Doppler shift indicates increased velocity). After the information is processed, it is displayed to demonstrate direction, magnitude, velocity, and uniformity of velocity vectors (turbulent versus laminar), findings that assist in distinguishing normal from abnormal flow. Signal strength, which is proportional to the number of moving red blood cells, is represented in shades of gray on the spectral display (the darker the shade, the greater the number of targets).

Continuous-Wave Doppler.—With continuous-wave Doppler ultrasound, the emitting and receiving crystals function continuously and display information representative of all moving targets in the ultrasound beam. The continuous mode has no limitation of recordable velocities and therefore allows accurate measurement of high velocities. The signal, however, is not gated (it receives all underlying velocities); thus, spatial localization of the abnormal velocities is lacking.

Pulsed-Wave Doppler.—Pulsed-wave Doppler echocardiography uses short bursts of ultrasound with a process called range gating to facilitate signal analysis from a small area at a specified depth from the transducer. This sampling area (sample volume) can be moved or repositioned along the path of the ultrasound beam for examination of the spatial extent of the Doppler signals in relationship to the two-dimensional image (Doppler mapping). Because the pulsed-wave Doppler technique sends and receives ultrasound intermittently, however, accurate recording of high-velocity signals is more difficult than with

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continuous-wave studies (because of aliasing). Thus, pulsed-wave Doppler has signal aliasing at high frequencies but has depth acuity, whereas continuous-wave Doppler has no signal aliasing but does have depth ambiguity. Hence, these two Doppler modes are complementary, and when they are used together, each can supply the information missing from the other technique.

Doppler information is presented both as an audio signal and in a video and hard-copy format. The audio signal is crucial for “fine tuning” to give the best spectral profile. The video and hard copy are useful storage formats; video recording with sound allows retention of the audio signal.

**Color Flow Imaging.**—Two-dimensional color Doppler echocardiography (color flow imaging) is a two-dimensional display of intracardiac flow velocities. Because color flow imaging is a pulsed-wave Doppler technique, it has all the advantages (depth acuity) and disadvantages (inability to quantitate high velocities) of that mode. Each pixel in the two-dimensional image acts as a small pulsed Doppler sample volume and displays the movement of blood as a colored dot within the two-dimensional image. In a commonly used format, blood moving toward the transducer is represented as warm colors (shades of red), and blood moving away from the transducer is depicted as cold colors (shades of blue). Turbulent (nonlaminar) blood flow is represented by the addition of green hues to the other colors (a mosaic pattern). Aliased velocities shift the color from red to blue or vice versa (color reversal). A mosaic pattern and color reversal often coexist because high velocities are usually associated with turbulent flow.

**APPROACH TO THE PATIENT WITH CONGENITAL HEART DISEASE**

Doppler examination of the patient with congenital heart disease may be performed either during or immediately after two-dimensional echocardiographic examination. First, the patient must be relaxed; in the case of restless infants and young children, mild sedation may be helpful. In our laboratory, we use chloral hydrate, 75 to 100 mg/kg. A standard two-dimensional examination with use of a high-frequency (5.0- to 7.5-MHz) transducer is performed from all acoustic “windows”—including subcostal and suprasternal. Next, pulsed-wave Doppler examination in conjunction with simultaneous two-dimensional imaging and repositioning of the Doppler sample volume allows characterization of areas of normal and abnormal blood flow within the cardiac chambers and vessels. If an abnormal high-velocity signal is encountered, continuous-wave Doppler is used to quantitate instantaneous velocities, which can be used to calculate gradient, pressure, or flow. Color flow imaging is useful for clarifying the spatial extent of regurgitant and shunt lesions. Occasionally, Doppler examination may disclose abnormal flow velocities in the absence of an obvious abnormality on two-dimensional echocardiography—for example, a small muscular ventricular septal defect, small atrial septal defect, or mild atriopulmonary or atrioventricular valve regurgitation.

A complete Doppler examination should include the following: a pulsed-wave examination and color flow imaging of all valves for regurgitation; pulsed-wave, continuous-wave, and color flow imaging examinations of valves and septa for abnormal antegrade flow signals (an indication of stenosis or shunt, respectively); and pulsed-wave, continuous-wave, and color flow imaging examinations of the great vessels and branches for localized stenotic lesions or abnormal communications.

**CONGENITAL CARDIAC LESIONS**

Congenital malformations often involve a combination of shunt lesions, valvular stenoses, and valvular regurgitation. Rather than considering each lesion complex, such as tetralogy of Fallot, we will focus on their individual components. Our comments will be limited primarily to Doppler examination and will not include the two-dimensional echocardiographic features.

**Shunt Lesions.**—Doppler echocardiography can be used to detect intracardiac shunts, to quantitate the decrease in pressure across the defect (that is, an indirect assessment of the size of the defect and the resultant pressures), and to measure left-to-right shunts semiquantitatively.

**Atrial Septal Defect.**—Atrial septal defect is a relatively common congenital lesion that lends itself well to Doppler echocardiographic diagnosis. Because flow velocities across this defect are relatively low, spatial localization with pulsed-wave Doppler and color flow imaging are the examination techniques of choice. With the pulsed-wave Doppler sample volume in the right atrium adjacent to the suspected defect, a characteristic audio and spectral flow velocity profile of
the left-to-right shunt is obtained. The spectral display consists of turbulent flow that commences in late ventricular systole, reaches its peak in early diastole, declines in mid-diastole, and is accentuated after atrial systole (Fig. 1).

The percentage left-to-right shunt has been approximated by estimating the ratio of pulmonary flow to systemic flow with use of Doppler techniques. The product of the Doppler-derived mean velocity of the outflow tract and the echocardiographically measured area of the outflow tract equals the flow; a comparison of flows in the right and left ventricular outflow tracts will yield the ratio of pulmonary to systemic flow. Although Doppler examination has been used to estimate the percentage shunt by determining these relative flows within the heart, appreciable atrioventricular or semilunar valve regurgitation can reduce the accuracy of this method. In addition, an error in determining the dimension of the outflow tract is a potential problem.

Color flow imaging displays a real-time two-dimensional color map of the abnormal flow velocities. The left-to-right shunt flow is visualized as an orange-red pattern, commencing at the left atrial side of the defect and passing through the defect and into the right atrium (Fig. 2 and 3). The area occupied by this jet roughly corresponds to the magnitude of the left-to-right shunt.

**Ventricular Septal Defect.**—In ventricular septal defect, the size of the defect determines the choice of Doppler examination. Small defects, often difficult to image directly, generate the highest velocity flow (proportional to the pressure gradient between the two ventricular chambers). Image-directed pulsed-wave Doppler is useful in localizing the site of ventricular septal defect by detecting a high-pitched audio signal and a turbulent as well as aliased flow velocity spectral display. Continuous-wave Doppler can detect and also measure peak systolic velocities across the defect (Fig. 4). Concomitant two-dimensional imaging is helpful for orientation of the continuous-wave beam. In addition, by means of continuous-wave Doppler, a diastolic component of the left-to-right shunt can frequently be recorded, consisting of velocities that range from 1.0 to 1.5 m/s (Fig. 5). This phenomenon is usually present in small to moderate-sized ventricular septal defects.

The modified Bernoulli relationship (pressure gradient = 4V², in which V is the maximal velocity) is used to calculate the transventricular pressure difference. By subtracting the Doppler-derived
Fig. 2. Secundum atrial septal defect, as depicted on color flow Doppler imaging. *Left*, Modified apical four-chamber image, showing large atrial septal defect (asd). *Right*, Left-to-right shunt flow, manifested as abnormal (orange) flow velocities that begin at site of defect (arrowheads) and fill most of right atrium. For explanation of abbreviations, see legend for Figure 1.

Fig. 3. Primum atrial septal defect. *Left*, Two-dimensional image, showing inferior atrial septal defect (asd) of partial atroventricular canal type. *Middle*, Color flow Doppler image, showing left-to-right atrial flow velocities originating in left atrium and extending across septal defect into right atrium and through tricuspid valve into right ventricle during diastole. *Right*, Simultaneous color flow mapping (top) and pulsed-wave Doppler (bottom) spectral profile. Sample volume is positioned along right side of septal defect just above tricuspid valve. In diastole, shunt flow is depicted in red and as an anteriorly directed spectral profile. In systole, a posteriorly directed signal (blue color) represents tricuspid regurgitation; this signal causes aliasing on pulsed-wave spectral analysis. For explanation of abbreviations, see legend for Figure 1.
transventricular gradient from the systolic blood pressure, right ventricular systolic pressure can be estimated in the absence of left ventricular outflow obstruction.

In large ventricular septal defects, the equalization of pressure in the ventricles results in low transventricular velocities. These large defects are easily imaged by two-dimensional echocardiography; continuous-wave and pulsed-wave Doppler examinations add little diagnostic information. Color flow imaging may be used to localize small defects (Fig. 6) and to assess the direction of the shunt flow. The determination of the spatial vector of the jet may aid in the accurate alignment of the continuous-wave beam for recording the highest velocities. In large defects, color flow Doppler imaging will show a triphasic direction of low-velocity shunt flow.

**Patent Ductus Arteriosus.**—In uncomplicated patent ductus arteriosus, Doppler-detectable continuous turbulent flow is present in the main pulmonary artery, and a pulsed-wave or continuous-wave Doppler examination is suitable for detection of this disturbance. Color flow Doppler imaging may be used to localize small defects (Fig. 6) and to assess the direction of the shunt flow. The determination of the spatial vector of the jet may aid in the accurate alignment of the continuous-wave beam for recording the highest velocities. In large defects, color flow Doppler imaging will show a triphasic direction of low-velocity shunt flow.

**Stenotic Lesions. Left Ventricular Inflow Obstruction.**—Parachute deformity of the mitral apparatus is one type of congenital left ventricular inflow obstruction; less common abnormalities are supravalvular mitral ring, double-orifice mitral valve (Fig. 9), and cor triatriatum. The apical transducer location provides the best orientation relative to the usual vector of transmitral flow, and continuous-wave Doppler study yields unambiguous determinations of the spectral pattern and accurate measurement of velocity. In addition, pulsed-wave Doppler may facilitate spatial localization of peak velocities (that is, the site of the obstruction)—valvular, supravalvular (as in the case of mitral ring), or subvalvular chordal apparatus. At the site of maximal obstruction, the Doppler velocities will be the highest. Besides determining the instantaneous velocity and the site of obstruction, one may calculate the mean transmitral gradient and the diastolic pressure...
half-time. Continuous-wave Doppler is best for these determinations because the highest velocities are most easily determined by this mode, and time-consuming scanning with the sample volume above, through, and below the mitral orifice is unnecessary.

The mean gradient can be calculated by measuring the peak transmitral velocities at intervals, applying the modified Bernoulli equation (gradient = $4V^2$), and reconstructing a curve of instantaneous gradient versus time. (The area under this curve divided by the diastolic filling time is the mean gradient.) Although this calculation can be done by hand, a microcomputer can facilitate this process; most of the currently available Doppler instruments have software for this calculation.

The diastolic pressure half-time is the time (in milliseconds) needed for the instantaneous transmitral gradient to decrease to half its initial highest level. This measurement of mitral obstruction has been validated in the catheterization laboratory and is relatively independent of heart rate. Because the Doppler spectral display represents velocity rather than pressure, a correction factor of $\sqrt{2}$ is necessary. Figure 10 shows the technique of half-time determination; the initial maximal transmitral velocity ($V$) is measured, and the time necessary for $V$ to decrease to $V/\sqrt{2}$ is the diastolic half-time. Normal values are less than 60 ms. The effective mitral valve area can be approximated by the formula $MVA = 220 \text{ ms/diastolic half-time}$.

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**Fig. 5.** Ventricular septal defect, as depicted on color flow Doppler imaging. **Top Left,** Parasternal long-axis view, showing left-to-right shunt through small paramembranous ventricular septal defect. Predominantly orange jet indicates flow toward transducer. Central blue area represents color aliasing. **Top Right,** Parasternal short-axis view, showing spatial extent of orange jet of left-to-right shunt flow into right ventricle. **Bottom,** Continuous-wave Doppler spectral profile, showing peak systolic velocity of 4.4 m/s corresponding to transventricular pressure decrease of 77 mm Hg. Note also the diastolic left-to-right shunt velocity profile (1 m/s). Ao = aorta; RVO = right ventricular outflow tract. For explanation of other abbreviations, see legend for Figure 1.

**Fig. 6.** Ventricular septal defect. **Top Left,** Parasternal long-axis view of small paramembranous ventricular septal defect (not well delineated in this stop-frame image). **Top Middle,** Color flow Doppler image during systole. Mosaic jet directed from left ventricle to right ventricular outflow tract originates from area of defect (arrow). **Top Right,** Shunt flow continues during diastole, but lower velocity flow shows homogeneous red jet without aliasing. **Bottom,** Continuous-wave Doppler spectral profile. During systole, maximal velocity profile of 4.5 m/s corresponds to decrease of 81 mm Hg in transventricular pressure. During diastole, shunt flow continues with velocity of 0.9 m/s. Ao = aorta. For explanation of other abbreviations, see legend for Figure 1.
Fig. 7. Patent ductus arteriosus. A, High parasternal long-axis image of aorta and pulmonary artery. Sample volume of pulsed-Doppler instrument is positioned in area of ductus (arrowheads). B, Pulsed-wave spectral display, showing turbulent diastolic and systolic flow. Flow velocities are directed anteriorly from aorta to pulmonary artery, as shown by their representation above baseline. Velocities are highest in systole, where slight aliasing is evident on bottom portion of tracing. C, Continuous-wave Doppler profile of another patient with patent ductus arteriosus. Continuous flow velocities, anteriorly directed, are recorded from a transducer location similar to that described above. Highest velocities occur in systole. Calibration markers (cal) are at 2 m/s. Maximal velocities are slightly less than 4 m/s. A = anterior; Asc = ascending aorta; Des = descending thoracic aorta; LPA = left pulmonary artery; MPA = main pulmonary artery; P = posterior. For explanation of other abbreviations, see legend for Figure 1.

Both the mean gradient and the diastolic pressure half-time are useful for estimating the severity of left ventricular inflow obstruction. The interpretation of gradient measurements is limited without an estimation of transmitral flow. In patients with associated volume overload of the left side of the heart (ventricular septal defect, patent ductus arteriosus), transmitral velocities and the mean gradient will often be increased, but the diastolic pressure half-time will not be substantially changed. In contrast, a modest elevation of the mean mitral gradient in the presence of low transmitral flow may alone cause an underestimation of the severity of valvular obstruction; again, determination of the diastolic pressure half-time may more accurately reflect the severity in these cases.

Color flow imaging in congenital mitral stenosis is similar to that in the acquired form. The jet of increased inflow velocities originates at the site of the obstruction and is directed into the left ventricle (Fig. 11). Usually, the velocity signal is oriented toward the left ventricular apex; occasionally, orientation may be toward the septum or the
Fig. 8. Patent ductus arteriosus, as depicted on color flow Doppler imaging. Top, Short-axis image of pulmonary artery and its branches (left and right pulmonary arteries [lpa and rpa, respectively]). Bottom Left, Patent ductus arteriosus, shown in diastolic frame. Orange pattern (arrowheads) originates from main pulmonary artery close to bifurcation. Orange color indicates velocities directed anteriorly, occurring as result of shunt flow from the ductus. Bottom Right, Normal color flow examination, shown in systolic frame. Homogeneous antegrade low-velocity flow is represented in blue, directed posteriorly (away from Doppler transducer). \( AO = \) aorta; \( PV = \) pulmonic valve. For explanation of other abbreviations, see legends for Figures 1 and 7.

Fig. 9. Double-orifice mitral valve. Left, Apical two-chamber echocardiographic view, showing left ventricle (\( LV \)), mitral valve (\( MV \)), aortic valve (\( AV \)), and left atrium (\( LA \)). Right, Corresponding color flow Doppler image. Left ventricular inflow (\( l \)), as manifested by orange pattern, clearly originates from two separate areas of mitral valve. At operation, presence of double-orifice mitral valve was confirmed.

posterior wall. In the center of the signal, color reversal due to aliasing is usually evident. In double-orifice mitral valve, color flow Doppler imaging shows two discrete areas of left ventricular inflow signal, each corresponding to a single orifice (Fig. 9).

Left Ventricular Outflow Obstruction.—Congenital valvular aortic stenosis, due to a bicuspid or unicuspid aortic valve, is probably the most common cause of congenital left ventricular outflow obstruction (Fig. 12 and 13). Other lesions that produce left ventricular outflow obstruction include discrete subaortic stenosis (Fig. 14 and 15), hypertrophic obstructive cardiomyopathy (Fig. 16), supravalvular aortic stenosis, and, indirectly, coarctation of the aorta. These lesions can be accurately distinguished on the basis of their two-dimensional echocardiographic features; however, pulsed-wave Doppler study will contribute to spatial localization of high velocities and thus further confirm the site of obstruction. For example, in hypertrophic obstructive cardiomyopathy, gradients may occur at midventricular, chordal, or mitral leaflet levels, and frequently associated mitral regurgitation can also be detected. Color flow examination facilitates visualization of the high-velocity (mosaic) jet and may assist in alignment of the continuous-wave Doppler beam for accurate assessment of peak velocities. Color reversal and variance denote the site of peak velocities, whether they occur in the left ventricular outflow tract or the aortic valvular or supravalvular region.

With application of the modified Bernoulli equation to the continuous-wave Doppler profile of aortic velocity, the mean and the peak instantaneous gradients can be calculated. These findings, in combination with the two-dimensional results, will provide a reliable estimation of gradient in most cases.\(^{20}\) In the foregoing process, however, several important factors deserve specific comment. First, the maximal transstenotic velocity must be used. Determining this value necessitates Doppler examination from multiple transducer locations—apical, suprasternal, supraclavicular, subcostal, and right parasternal—and selection of the highest velocity that is representative of the actual degree of obstruction. Second, one must remember that the Doppler velocity profile represents the maximal \textit{instantaneous} gradient.\(^{21}\) The maximal instantaneous gradient is usually (often substantially) different from the peak-to-
peak gradient, as measured by left ventricular-ascending aortic pullback at cardiac catheterization. Third, as mentioned in the previous section on mitral obstruction, transstenotic gradients are greatly affected by the transvalvular flow rate, and some estimation of aortic flow is necessary for determination of valve area. Although correlation of the continuous-wave Doppler findings with the catheter-determined transstenotic gradients has been excellent, further investigation of noninvasive measurement of valve area is necessary. The preliminary work in this area seems promising.22,23

Aortic coarctation is sufficiently different from the aforementioned lesions to merit special comment. In infants and adolescents, the coarcted segment can be directly imaged in most cases; however, two-dimensional imaging is less effective in older children and adults. With use of the suprasternal transducer position, continuous-wave or pulsed-wave Doppler alone can be used to follow the course of the descending thoracic aorta in cases of suspected coarctation, and an abnormal velocity profile can be found in most cases.24,25 The peak systolic velocity can be used to estimate the maximal gradient across the coarcted segment.26 The presence of a persistent signal (increased velocities) during diastole is further evidence of major (that is, diastolic) obstruction (Fig. 17).

An uncommon cause of outflow obstruction occurs in patients with a single ventricle and a restrictive ventricular septal defect that communicates with an outflow chamber (bulboventricular foramen) (Fig. 18 and 19). Anatomic localization and quantitation of obstruction are possible with combined two-dimensional pulsed-wave and continuous-wave Doppler examinations. Knowledge of this problem is particularly important before surgical correction is undertaken.
Fig. 12. Congenital valvular aortic stenosis. Top Left, Long-axis echocardiographic view, showing thickened and immobile aortic valve (AV) cusps (arrowheads). Top Right, Short-axis echocardiographic view, showing similar findings. Bottom Left, Simultaneous continuous-wave Doppler examination and catheterization in a patient with valvular aortic stenosis. From the suprasternal transducer position, antegrade aortic velocity is directed toward the transducer. Peak velocity of 3.8 m/s predicts a maximal instantaneous gradient of 57 mm Hg. Simultaneous catheterization of left ventricle and ascending aorta shows maximal instantaneous gradient of 58 mm Hg. Note difference in measurement of maximal gradient (max) and peak-to-peak gradient (p-p), as discussed in text. Bottom Right, Similar studies in another patient with valvular aortic stenosis. Examination is from right parasternal region. Again, flow is toward transducer, and maximal velocity of 3.8 m/s predicts a maximal gradient of 57 mm Hg, as in prior case. Simultaneous catheterization of left ventricle and aorta demonstrates maximal instantaneous gradient of 52 mm Hg. Note large discrepancy between maximal instantaneous gradient and peak-to-peak gradient (37 mm Hg) in this case. These cases illustrate that similar Doppler velocities and maximal instantaneous gradients may be present in patients who will be found to have substantially different peak-to-peak gradients at catheterization. RVO = right ventricular outflow tract. For explanation of other abbreviations, see legends for Figures 1 and 7.
**Right Ventricular Outflow Obstruction.**—
The most common cause of right ventricular outflow obstruction is valvular pulmonary stenosis (Fig. 20 and 21). Subvalvular, supravalvular, or peripheral stenoses may also be present. The use of pulsed-wave Doppler for localization of the obstruction and continuous-wave Doppler for measurement of the gradient is similar to the approach in obstructive lesions of the left side of the heart. Again, the use of multiple transducer locations—left parasternal, subcostal, and suprasternal—for selection of the highest velocities is necessary for accurate results. Color flow imaging shows a mosaic pattern, beginning at the area of obstruction and extending distally. With subpulmonic obstruction, the mosaic pattern will begin proximal to the pulmonary leaflets. Often, subpulmonic and pulmonic obstruction coexist; a mosaic pattern will appear distal to both areas of obstruction.

**Regurgitant Lesions.**—Atrioventricular and semilunar valve regurgitation are important features of many congenital malformations. Pulsed-wave Doppler is useful for determining the site and the spatial extent of the regurgitant signal and continuous-wave Doppler can provide valuable information on the pressure gradients.

**Atrioventricular Valve Regurgitation.**—The apical transducer position is the best approach for evaluation of atrioventricular valve regurgitation. By positioning the pulsed-wave Doppler sample volume in the atrium at various distances from the valve, the atrium can be “mapped” for the presence of an abnormal sys-

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**Fig. 13. Valvular aortic stenosis.** **Top Left,** Suprasternal long-axis echocardiographic view of ascending aorta (ASC AO). **Top Right,** Color flow Doppler image from same orientation. Anteriorly directed jet of flow is represented as yellow area in ascending aorta. Color variance also present in this region indicates turbulence and increased velocities. **Bottom,** Continuous-wave Doppler examination from location of ascending aorta. Peak velocity of 4.3 m/s corresponds to peak instantaneous gradient of 74 mm Hg. RPA = right pulmonary artery. For explanation of other abbreviations, see legends for Figures 1 and 7.

**Fig. 14. Subaortic stenosis.** **Top Left,** Parasternal long-axis echocardiographic image of patient with subaortic membrane (arrowheads). **Top Right,** Apical color flow Doppler image, showing left ventricle, left ventricular outflow tract, aortic valve (AV), and subaortic membrane (arrowheads). Normally, this area would contain blue signals as an indication of homogeneous, relatively low-velocity flow in left ventricular outflow tract. In this case, color reversal and variance occur because of increased velocities and turbulence, which produce yellow and green signals. **Bottom,** Continuous-wave Doppler examination through outflow tract shows peak velocity of 5 m/s, indicating peak instantaneous gradient of 125 mm Hg across membrane. For explanation of abbreviations, see legends for Figures 1 and 7.
Fig. 15. Subaortic obstruction, as shown on simultaneous Doppler and catheterization studies. Continuous-wave Doppler examination from apical position shows velocity profile of 2.8 to 3.1 m/s (displayed below baseline), recorded from ventricular outflow tract. Simultaneous dual-catheter study, with pullback of one catheter from left ventricular base to aorta and other catheter remaining in left ventricular apex, demonstrates subaortic location of gradient. Maximal instantaneous velocities (max) measured at catheterization (shown in parentheses above baseline) correspond to those derived from Doppler measurements (shown in parentheses below baseline).

Fig. 16. Muscular subaortic stenosis. Left, Echocardiogram, showing muscular thickening of ventricular septum (VS) that has narrowed the left ventricular outflow tract (double-headed arrow). Posterior wall (PW) is also hypertrophied. Aortic valve leaflets (arrowheads) are thickened. Right, Continuous-wave Doppler examination from apical transducer location demonstrates peak systolic velocity of 4.5 m/s, which corresponds to peak instantaneous gradient of 81 mm Hg. Outflow tract velocity is displayed below baseline. Diastolic velocity, displayed above baseline, indicates aortic insufficiency. Ao = aorta. For explanation of other abbreviations, see legend for Figure 1.
Fig. 17. Coarctation of the aorta. **Top Left,** Suprasternal long-axis echocardiographic image of aortic arch (Arch) and descending thoracic aorta (Des). Two sample volumes (SV) were used—position 1 above coarcted segment and position 2 below area of coarctation (arrow). **Top Right,** Pulsed-wave Doppler spectral profile of coarctation of aorta. Above area of coarctation (SV1), relatively normal antegrade flow signals are present. Presence of signal above and below baseline indicates large angle difference between direction of flow and axis of Doppler ultrasound beam. Below area of coarctation (SV2), velocities are considerably increased and aliasing is present because of coarctation. Peak velocity cannot be calculated because of aliasing. **Bottom,** Continuous-wave Doppler spectral profile from similar suprasternal examining positions. Peak velocity of 3.6 m/s indicates a decrease in pressure of approximately 52 mm Hg across coarcted segment. Note long duration of signal that extends through diastole, indicating persistent gradient even in late diastole. This finding is commonly associated with severe coarctation. RPA = right pulmonary artery. For explanation of other abbreviations, see legends for Figures 1 and 7.

pulmonary artery peak pressure. This method seems more accurate than other techniques for estimating pulmonary artery pressure. Sequential Doppler-derived pulmonary pressures may be used for such purposes as clinical follow-up and determination of the response to drug intervention.

**Semilunar Valve Regurgitation.**—Semilunar valve regurgitation is likewise best approached from the apical transducer location for the aortic valve and from the left parasternal or subcostal position (or both) for pulmonary valve regurgitation. The transducer location must be modified in patients with malposition of the great arteries. Semilunar valve regurgitation may be “mapped” by pulsed-wave Doppler or color flow imaging, as described in the previous section on atrioventricular valves. The slope of the aortic regurgitant peak velocities on continuous-wave Doppler examination has been related to the severity and the acuteness of aortic insufficiency. A rapid decline in peak velocities indicates a reduction in the difference in pressure between the aorta and the left ventricle as the left ventricular end-diastolic pressure increases, and this finding suggests severe regurgitation.

**POSTOPERATIVE CONGENITAL HEART DISEASE**
Prolonged survival is now common in patients with many types of complex congenital heart disease, primarily because of continuing advances in cardiac surgical procedures. Such postoperative patients represent an increasing proportion
of both pediatric and adult patients encountered by cardiologists. Cardiac catheterization has been necessary in patients in whom abnormal pressure gradients, residual shunting, or valvular insufficiency was suspected. Doppler echocardiography will provide such information in many of these patients and will often either eliminate the need for catheterization or facilitate selection of those cases in which further invasive studies are necessary.

**Valvular Disease.**—In the postoperative patient, valvular disease may include residual stenosis, inadequate repair of regurgitation, or malfunction of a prosthetic valve. Repaired native valves should be examined for stenosis and regurgitation, as previously described in detail for the preoperative patient. In comparison with native valves, prosthetic valves usually have higher antegrade flow velocities, inasmuch as they are all inherently mildly stenotic. The limits of normal antegrade velocity have not been fully established for various types of prosthetic valves and in particular for the small valves used in pediatric patients. All mechanical prostheses have a minimal degree of regurgitation and will often generate a regurgitant signal. If the signal is localized...
to the immediate vicinity of the prosthesis on pulsed-wave Doppler examination, this finding does not necessarily imply malfunction. Occasionally, similarly localized bioprosthetic regurgitation may be normal. During examination, "mapping" of the regurgitant chamber will help establish the extent of the regurgitation. In addition, Doppler examination of the margin of the sewing ring will help localize periprosthetic regurgitation. Although clearly abnormal, small periprosthetic leaks are probably more common than appreciated with auscultation, and determining their importance necessitates clinical correlation.

A substantial increase in antegrade flow velocities implies obstruction of a valvular prosthesis. Use of the modified Bernoulli equation to predict the instantaneous transprosthetic pressure gradient seems as accurate as when applied to native valves, but large numbers of patients have not been systematically studied to date. Further investigation will be necessary to establish definite Doppler criteria for normal and abnormal function of prosthetic valves.

**Residual Shunting.**—After repair of intracardiac communications, residual shunting may be present. The atrial and ventricular septa, includ-

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**Fig. 19.** Complex congenital heart disease, as depicted by simultaneous Doppler and dual-catheterization studies. Patient had double-inlet left ventricle, with aorta arising from outflow chamber; prior pulmonary artery banding had been done. **Left**, Continuous-wave Doppler examination from subcostal transducer position during catheterization. Catheters are in common ventricular chamber and pulmonary artery distal to band. Peak velocity of 5.2 m/s predicted gradient of 108 mm Hg on basis of modified Bernoulli equation. Maximal instantaneous gradient (max) was 121 mm Hg measured at catheterization, in comparison with 110 mm Hg peak-to-peak gradient (p-p). **Right**, Obstruction of bulboventricular foramen. Suprasternal examination of bulboventricular foramen. Suprasternal examination of subaortic stenosis showed anteriorly directed flow velocity of 3.7 m/s and a predicted peak instantaneous gradient (based on the modified Bernoulli equation) of 55 mm Hg. Dual catheterization of common ventricular chamber and ascending aorta shows maximal instantaneous gradient of 64 mm Hg. In this case, peak-to-peak and maximal instantaneous gradients are identical.
Fig. 20. Pulmonary stenosis. Left, Parasternal short-axis echocardiographic image, showing thickened pulmonary valve cusps (arrows and arrowheads). Real-time examination showed doming and restricted opening of valve. Right, Continuous-wave Doppler examination from parasternal transducer position. In this position, direction of flow through pulmonary valve is away from the transducer and represented as a spectral profile extending below baseline. Peak velocity of 3.2 m/s corresponds to peak instantaneous gradient of 41 mm Hg. Ao = aorta; PA = pulmonary artery; RVO = right ventricular outflow tract. For explanation of other abbreviations, see legends for Figures 1 and 7.

ing septal patches, should be examined as done preoperatively—with use of pulsed-wave Doppler for localization of the shunt and continuous-wave Doppler for measurement of high velocities and calculation of a decrease in pressure between chambers. In the early postoperative period, many patients with adequate repair may have evidence of small residual shunts; often, these will no longer be detected after repeated late examination. Of course, in patients who had closure of

Fig. 21. Severe pulmonary stenosis, as depicted on correlated Doppler and catheterization studies. Continuous-wave Doppler examination was performed with transducer in suprasternal position. Flow through pulmonary valve is toward the transducer, and flow velocities are represented above baseline. Peak velocity of 4.5 m/s indicates a peak instantaneous transvalvular gradient of 80 mm Hg. Simultaneous cardiac catheterization pullback record in this patient confirms these findings, with a peak pulmonary artery (PA) systolic pressure of 20 mm Hg and a peak right ventricular (RV) systolic pressure of 100 mm Hg.
Fig. 22. Pulmonary artery band. Left, Modified parasternal short-axis echocardiographic view in patient with dextrotransposition of great arteries. Aorta (Ao) is anterior to main pulmonary artery (MPA). A band constricts the main pulmonary artery (arrow and arrowheads). Right, Continuous-wave Doppler examination from subcostal position. Flow velocities directed below baseline indicate flow through banded segment, with a maximal velocity of 3.6 m/s corresponding to a peak instantaneous gradient of 52 mm Hg across band. Calibration markers (cal) are at 2 m/s. tv = tricuspid valve. For explanation of other abbreviations, see legends for Figures 1 and 7.

patent ductus arteriosus, no continuous pulmonary artery signal should be present postoperatively.

Palliative Procedures.—In patients with congenital heart disease, palliative procedures include pulmonary banding and procedures to increase pulmonary blood flow. The adequacy of banding can be accurately assessed by continuous-wave Doppler study (Fig. 19, 22, and 23), and Doppler-derived gradients correlate well with those found at catheterization. With knowledge of the right ventricular systolic pressure (derived from the continuous-wave tricuspid regurgitant signal), subtraction of the gradient across the band yields a noninvasive estimate of pulmonary artery systolic pressure. Occasionally, a pulmonary band may migrate distally and thereby produce asymmetric obstruction to flow in the right and left pulmonary arteries. Higher velocities or lower signal amplitude may be detected on continuous-wave examination of the more obstructed side. Color flow imaging shows a mosaic pattern at the site of the band, extending distally into the pulmonary artery.

Shunts to improve pulmonary blood flow may lend themselves to Doppler examination.\(^\text{36,37}\) The site of a Waterston or Potts anastomosis may be visualized with two-dimensional echocardiography, and the patency can be confirmed with

Fig. 23. Top Left, Parasternal short-axis echocardiographic image, showing pulmonary artery (PA) band (BAND). Top Right, Color flow Doppler study with flow away from transducer and normal antegrade velocities represented by blue jet. Increased velocities at level of band (arrowheads) produce color reversal (aliasing), shown as orange pattern, and mosaic colors due to high-velocity turbulent flow are noted further distally. Bottom, Continuous-wave Doppler spectral profile, showing peak velocities of 3.6 m/s corresponding to gradient of 52 mm Hg across band. For explanation of abbreviations, see legends for Figures 1, 4, 7, and 8.
pulsed-wave or continuous-wave Doppler techniques. These side-to-side connections produce a discrete stenosis that allows application of the modified Bernoulli equation for calculation of the pressure gradient. Subtracting the pressure decline from the systemic cuff pressure yields a close approximation of pulmonary artery systolic pressure. A nonimaging continuous-wave Doppler transducer is usually applied to multiple windows for optimal characterization of peak velocities. The maximal velocity can be underestimated if the angle between the Doppler beam and the maximal vector of shunt flow is too large.

In contrast, the decrease in pressure across a Blalock shunt or a tubular graft may be less accurate to measure with continuous-wave Doppler techniques. This shunt is long and narrow, and a single discrete area of decrease in pressure is not present; therefore, the modified Bernoulli equation may not strictly apply (Fig. 24). A low calculated gradient may be found in the presence of adequate flow and low pulmonary pressures.

Other Connections.—Conduits are commonly used to reestablish continuity between the right ventricle and the pulmonary artery. Obstruction of a conduit is a late complication, occurring in up to 20% of porcine heterografts by 33 months.38 Kinking at the anastomotic site, calcification of the prosthesis, and progressive neointimal peel formation may occur alone or in combination. Because of the retrosternal location of the conduit, complete two-dimensional echocardiographic imaging is often impossible. Doppler examination is useful for detecting and quantitating stenoses in a conduit.39,40 Generally, a nonimaging continuous-wave Doppler transducer is used in the parasternal, suprasternal, and subcostal locations to detect the spectral profile that corresponds to flow through the conduit and the high velocities that occur with stenosis of the conduit. Care must be taken to distinguish these signals from other high-velocity lesions, such as atrioventricular valve regurgitation or left-sided outflow obstruction. This distinction, which is seldom difficult, can be made on the basis of the orientation of the Doppler probe and the duration and spectral characteristics of the Doppler signal (Fig. 25).

Nonvalved venous connections, as used in the Fontan procedure and its modifications, are often utilized for repair in patients with defects such as univentricular heart and tricuspid atresia. Findings on Doppler assessment of flow profiles in the pulmonary artery have been related to the clinical outcome in these patients.41 Interatrial baffles, such as those used in the Mustard procedure, can redirect venous return in patients with complete transposition of the great arteries. Systemic venous obstruction has been a late problem often necessitating catheterization for diagnosis. The systemic and pulmonary venous connections can be visualized with two-dimensional echocardiography, and echocardiographically directed pulsed-wave Doppler studies can be used to examine areas of possible stenosis.42 In our experience with a limited number of cases, the presence of abnormal high-flow velocities has suggested ob-

Fig. 24. Patent Blalock shunt. Continuous-wave Doppler study with transducer in suprasternal position shows continuous flow with systolic accentuation. Maximal velocity of 2.8 m/s underestimates true gradient between subclavian and pulmonary arteries. See text for further discussion.
Fig. 25. Obstructed pulmonary artery conduit. In patient with complex congenital heart disease, surgical repair included placement of valved conduit between right ventricle (RV) and pulmonary artery (PA). Continuous-wave Doppler examination with transducer in parasternal position showed substantially increased velocities in the conduit, an indication of stenosis. Doppler velocities displayed below baseline during systole indicate flow through obstructed conduit. Velocities above baseline during diastole indicate insufficiency of conduit valve. Peak velocity of 4.8 m/s corresponds to peak instantaneous gradient of 92 mm Hg. At catheterization, a maximal instantaneous gradient (max) of 86 mm Hg was found. Peak-to-peak gradient (p-p) was slightly less (84 mm Hg) than at catheterization; thus, patients with this finding may be selected for subsequent cardiac catheterization.

CONCLUSION

Doppler echocardiography is a noninvasive procedure that uses ultrasound to measure intracardiac and intravascular flow velocities. These velocity measurements can be used to calculate intracardiac pressures in patients with stenotic, regurgitant, and shunt lesions. Complementary to two-dimensional echocardiography, Doppler examination provides spatial localization of abnormal flows and thus helps identify the site of intracardiac shunting; it also can be used to determine the extent of valvular insufficiency. With combined use of two-dimensional and Doppler echocardiography, comprehensive, noninvasive evaluation of many types of congenital heart disease has been facilitated. Consequently, in some patients, cardiac catheterization may be avoided; other patients can be identified for selective use of catheterization in a goal-directed study.

REFERENCES


