Doppler Echocardiography in Modern Cardiology*

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LVOT = left ventricular outflow tract; CSA = cross-sectional area; FW = pulsed wave; CW = continuous wave; CFM = color flow mapping

The recent introduction of Doppler-echocardiographic techniques into cardiac ultrasound examination has meant that cardiac function (in addition to the structural information previously available from two-dimensional echocardiography) can now be evaluated more thoroughly. Doppler-echocardiographic techniques currently enable the noninvasive measurement of pressure gradients across both native and prosthetic valves, across stenoses of great vessels, as well as the calculation of effective valve areas. In addition, these techniques allow for the estimation of the severity of regurgitant lesions, the detection of intracardiac shunts, the measurement of cardiac output, and of intra-cardiac pressures. The advent of color flow mapping technology has further enhanced these capabilities by allowing the super-imposition of color-encoded velocity information onto two-dimensional (2D) images, thus producing a real-time 2D “flow” velocity map.

Principles

The Doppler principle (first described by Christian Johann Doppler in 1842) allows the velocity of blood flow in the heart and great vessels to be calculated as the difference between the frequency of ultrasound transmitted from an external source (e.g., an ultrasound transducer) and that returning to the same source, following interaction with moving red blood cells. This “shift” in frequency between transmitted and returning ultrasound signals, which occurs following interaction with a moving target, is known as the “Doppler shift” and is related to the velocity of blood flow by the following equation:

\[ V = \frac{f_r C}{2 \lambda \cos \theta} \]  
(Equation 1)

where

- \( C \) = velocity of ultrasound in tissue
- \( f_r \) = difference in frequency between transmitted signal and returning signal
- \( \lambda \) = wavelength of incident ultrasound
- \( \theta \) = angle of incidence between Doppler beam and the plane of blood flow.

As \( f_r \) is known, \( f_0 \) can be directly measured by the Doppler flowmeter, \( C \) is a known constant and provided \( \theta \) is as close to 0 degrees as possible (as \( \cos 0 = 1 \)), the velocity of blood flow can be readily computed. In fact, if the angle of incidence, \( \theta \), is <20 degrees, the error in velocity calculation is acceptably small (6 percent), as the cosine of 20 degrees is 0.94 and \( \theta \) can be ignored.

Pressure Gradients

Knowing the difference between the velocities of blood flow in any two regions of the heart, the pressure gradient between those two regions (e.g., across a stenosis) can be calculated by applying the modified Bernoulli equation:

\[ \Delta P = 4V_2^2 - V_1^2 \]  
(Equation 2)

where

- \( \Delta P \) = pressure gradient across stenosis
- \( V_1 \) = velocity distal to lesion
- \( V_2 \) = velocity proximal to lesion
- \( V_{peak} \) = peak velocity distal to stenosis

This modification of the original Bernoulli equation omits effects due to viscous friction and flow acceleration, both of which are usually negligible in typical stenotic lesions. Also, \( V_1 \), the velocity proximal to the lesion, is usually <1 M/s in the human heart and thus becomes inconsequential in most calculations of gradient and can be omitted. However, in situations where \( V_1 \) is unusually elevated, (such as proximal to the aortic valve in aortic regurgitation), it may need to be included in Equation 2. It should be remembered that the Doppler gradient calculated in the above manner (as illustrated for aortic stenosis in Fig 1) is the instantaneous peak gradient. This is different from the peak-to-peak gradient usually measured at cardiac catheterization and these two parameters are not interchangeable. Nevertheless, it has been well demonstrated that the Doppler peak gradient correlates very closely to the simultaneous catheter-derived instantaneous peak gradient, as do the mean gradients obtained by the two techniques.5

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Valvular Stenoses

Doppler techniques can also be applied to calculate the effective area of the mitral and aortic valves. The mitral valve area can be derived by estimating the pressure half-time across the valve, which is the time period during which the diastolic pressure gradient falls to half of its maximum value. The mitral valve area is related to the pressure half-time by the following equation:

\[ MVA = \frac{220}{\text{pressure half-time (ms)}} \quad (Equation\ 3) \]

The mitral valve area derived in this manner has been shown to correlate closely with that calculated from the Gorlin formula at catheterization.1

The aortic valve area can be calculated by the use of the continuity equation: this states that, in a closed system, blood flow is constant. Thus, blood flow proximal to a stenotic valve is equal to that distal to the valve. The volume of blood flow (Q), which is also the cardiac output, is the product of the Doppler flow-velocity integral (FV1) and the cross-sectional area of the flow stream:

\[ Q = FV1 \times CSA \quad (Equation\ 4) \]

In practice, peak velocities (V) are easier to measure and can be substituted into the continuity equation without loss of accuracy. Thus, the continuity equation can be expressed as:

\[
\text{Flow proximal to aortic valve} = \text{Flow distal to aortic valve} \]

\[ \text{i.e., } FV1_{\text{aortic}} \times CSA_{\text{aortic}} = FV1_{\text{ventr}} \times CSA_{\text{ventr}} \]

or \[ V_{\text{aortic}} \times CSA_{\text{aortic}} = V_{\text{ventr}} \times CSA_{\text{ventr}} \]

where \( LVOT = \) left ventricular outflow tract and \( ao = \) aortic valve

\[ \text{i.e., } \frac{CSA_{\text{aortic}}}{V_{\text{aortic}}} = \frac{CSA_{\text{ventr}}}{V_{\text{ventr}}} \quad (Equation\ 5) \]

Thus, knowing the peak velocity in the LVOT and across the aortic valve and computing the CSA of the LVOT from the outflow tract diameter (measured from two-dimensional images), assuming a circular orifice, the aortic valve area can be obtained. Although a number of assumptions are made in applying this equation, a high correlation has been found between the aortic valve area calculated by this method and that by the Gorlin formula at cardiac catheterization.8

Applications

Thus, the application of equations 2, 3 and 5 above allow the determination of transvalvular pressure gradients and valve areas, providing valuable information in a variety of clinical settings. One example of the value of using the aortic valve area in conjunction with the gradient estimation is in aortic stenosis of intermediate severity, especially in the setting of impaired left ventricular function: in these circumstances, the gradient alone may underestimate the true severity of stenosis, whereas the valve area (by equation 5 above) allows a more accurate assessment. Similarly, in the combination of mitral stenosis and regurgitation, the peak gradient across the valve may be accentuated by the increased forward flow accompanying the regurgitation, but calculation of the true mitral valve area (by equation 3 above) remains accurate.

Doppler-echocardiography applies these principles by a variety of techniques. A complete Doppler examination can utilize pulsed wave, continuous wave and color flow mapping approaches, each of which has specific advantages and limitations. The PW allows measurement of blood flow velocities at specific sites within the heart and great vessels, along with simultaneous imaging. In order to sample at a specific depth, the transmitted sound impulse must reach the area of interest and return to the transducer before the next sound impulse is emitted. However, because of the finite period of time taken by this process, the PW is unable to resolve velocities above a certain limit (called the Nyquist limit), which is a function of the depth of the area being interrogated and of the frequency of the transducer.

In contrast, CW Doppler allows ultrasound to be transmitted and received "continuously" and sampling
of velocities occurs all along the beam path. Thus, CW Doppler has the major advantage of being able to measure high velocities (such as those occurring frequently in valvular stenotic and regurgitant lesions), but has the limitation of the loss of spatial resolution.

Doppler color flow mapping uses the pulsed Doppler technique to record frequency or phase shifts in multiple locations and then superimposes color-encoded velocity information on real-time two-dimensional images, thus producing a real-time "flow map" simulating, to some extent, a noninvasive angiogram.

**Regurgitant Lesions**

Valvular regurgitation can be diagnosed with PW Doppler, by interrogating the area immediately behind the valve of interest and recording retrograde flow. Localization of regurgitant jets is often assisted by color flow mapping, which can guide the operator towards an eccentric or otherwise elusive jet, ie, "color-guided" Doppler sampling. In order to resolve the peak velocity of a regurgitant jet, CW is usually necessary and allows for the noninvasive estimation of intracardiac pressures by the use of the peak gradient represented by the jet (applying equation 2). For example, a peak velocity of 4 M/s in a jet of tricuspid regurgitation indicates a peak systolic pressure gradient across the tricuspid valve of 64 mm Hg. If the right atrial pressure is assumed to be 10 mm Hg, the right ventricular systolic pressure is equal to 74 mm Hg, which is then also indicative of a pulmonary artery systolic pressure of 74 mm Hg, assuming no pulmonic stenosis.6

Regurgitant lesions can be graded, semiquantitatively, by mapping the extent of the jet using PW or CFM, in the proximal chamber and such grading has been shown to be very similar to the semiquantitative angiographic criteria for grading regurgitation.7

In addition to native valvular disease, the above Doppler principles can be applied with validity to the assessment of prosthetic valves,8 intracardiac shunts,9 and the measurement of cardiac output.10

Thus, the addition of Doppler methodology to the cardiac ultrasound examination adds important functional information, not previously directly available from two-dimensional echocardiography. In a prospective study of 100 patients carried out in our laboratory, the addition of Doppler techniques, after the standard two-dimensional echocardiographic examination had been completed, added important additional diagnostic information in 63 percent of patients.11 On the basis of these results, we believe that Doppler techniques (including color flow mapping, if available) should be part of every cardiac ultrasound examination, especially where an evaluation of a stenotic/regurgitant lesion is requested, but also for a shunt, prosthetic valve, or an estimation of cardiac output or chamber pressure.

Doppler echocardiography now allows for accurate hemodynamic information (previously only available by catheterization) to be obtained noninvasively, in a manner which is readily repeatable over time and does not utilize ionizing radiation. This allows for improved patient management by the use of serial studies, with optimal planning of the timing of catheterization (if necessary), interventional procedures (such as percutaneous balloon valvuloplasty) or surgery. Increasingly, physicians will base important patient management decisions on the Doppler-echocardiographic study findings and thus obviate the (previously essential) need for cardiac catheterization.

**References**


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