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Editorial Comment

Aortic Stenosis: Most Cases No Longer Require Invasive Hemodynamic Study*

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The assessment of patients with aortic stenosis has frequently included hemodynamic data obtained by way of catheterization. In difficult cases, either atrial septal or left ventricular puncture has been used to obtain left ventricular pressure. In this issue of the Journal, Otto et al. (1) have highlighted the Doppler echocardiographic assessment of aortic stenosis. Utilization of the Doppler techniques that they describe has matured in many noninvasive laboratories around the world. With this maturation it is no longer necessary to subject most patients with aortic stenosis to invasive measurements of left ventricular and aortic pressures.

Validation of the modified Bernoulli equation. Pressure gradients are determined with a Doppler transducer by measuring the maximal velocity (V_{max}) of red blood cells in the jet just beyond the stenosis. This maximal velocity is then inserted into the modified Bernoulli equation, which was introduced into clinical cardiology by Holen et al. (2) and Hatle et al. (3) to determine the pressure (P) gradient between the left ventricle (LV) and the aorta:

$$\text{Pressure gradient} = P_{LV} - P_{aorta} = 4\ V^2_{max}. \qquad [1]$$

This formula has been thoroughly validated for the assessment of aortic stenosis using an open-chested dog model (4), with use of Doppler measurements obtained simultaneously with invasive pressure measurements (5), and with numerous nonsimultaneous studies correlating Doppler and invasive hemodynamics (6–9).

Substituting the maximal velocity into the simplified Bernoulli equation yields the maximal instantaneous gradient across the aortic valve. This is the maximal difference between left ventricular and aortic pressures that occurs during the ejection period (9). Because the peak of aortic pressure occurs *after* the peak of left ventricular pressure, the maximal instantaneous gradient is *not* the same as the peak to peak gradient, which is used in many invasive laboratories. Although the peak to peak gradient is convenient, it is a contrived variable. It never occurs in real time, and therefore it cannot be calculated from the Doppler velocity spectrum.

The best estimate of the degree of obstruction obtained with pressure data alone is given by the *mean* systolic gradient. This variable is easily obtained in the noninvasive laboratory. Once the maximal aortic velocity spectrum is determined, current instruments allow on-line calculation of the mean gradient. Accuracy of the Doppler-derived mean aortic gradient has been well validated (5,9).

Noninvasive aortic valve area. It is well known that the aortic gradient only partially characterizes the degree of aortic stenosis. A high output state, for example, in an anemic patient, can result in a large gradient even when aortic stenosis is mild. Conversely, a low output state, as in "end-stage" aortic stenosis, can result in a relatively low pressure gradient even though the degree of stenosis is critical. The value of routinely calculating aortic valve area when assessing and following up patients with aortic stenosis is underscored by the experience described by Otto et al. (1) in their current article. Of the 42 patients with aortic stenosis that they followed up serially, 10 (24%) showed either no change in maximal aortic gradient or a decrease in gradient between two of the follow-up studies. Aortic valve area data were available for 9 of these 10 patients, and 5 of the 9 showed a *decrease* in aortic valve area. Therefore, the condition of ≥12% of their patients would have been erroneously categorized as being unchanged (or even improved) at follow-up had aortic valve areas not been calculated.

Aortic valve area is derived from two-dimensional and Doppler echocardiography by the simplified continuity equation:

$$\text{Aortic valve area} = \text{area}_{LVOT} \times \left(\frac{V_{LVOT}}{V_{max}}\right), \qquad [2]$$

where LVOT = left ventricular outflow tract and V = flow velocity. By assuming circular geometry, the area of the LVOT is calculated from a measurement of its diameter (d_{LVOT}), and equation 2 is then converted to the form we use on a daily basis:

$$\text{Aortic valve area} = 0.785\ (d_{LVOT})^2\left(\frac{V_{LVOT}}{V_{max}}\right). \qquad [3]$$

In the catheterization laboratory, the aortic valve area is usually calculated from the Gorlin equation (10). Otto and her colleagues (11) at the University of Washington were instrumental in validating Doppler-derived aortic valve area

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Table 1. Doppler-Derived Versus Catheterization-Derived Aortic Valve Area

Author	Number of Patients	r
Skjaerpe et al. (12)	30	0.89
Otto et al. (11)	48	0.86
Zoghbi et al. (13)	39	0.95
Tierstein et al. (14)	30	0.88
Oh et al. (15)	100	0.83

against the Gorlin method obtained invasively. As detailed in Table 1, the Doppler echocardiographic method has now been validated by multiple centers (11-15).

Reproducibility of Doppler aortic valve area. The echocardiographer must undergo a training period before becoming expert in obtaining noninvasive hemodynamic measurements for patients with aortic stenosis. A practical demonstration is available (16). The systolic diameter of the left ventricular outflow tract must be precisely measured from the parasternal examination. The left ventricular outflow tract flow velocity is measured from the apical long-axis orientation discounting prestenotic acceleration, which occurs in the dome of the valve (12). Finally, the maximal aortic velocity can be confidently obtained only when the aortic valve is interrogated from multiple transducer locations (9).

In the first part of their study, Otto et al. (1) analyzed the interobserver variability in *obtaining* the left ventricular outflow tract velocity (V_{LVOT}) and the maximal aortic velocity (V_{max}). The mean coefficient of variation for these variables when recorded by two separate, experienced sonographers, was 4.6% and 3.2%, respectively. Demonstration of this excellent degree of reproducibility is a necessary precursor to using this Doppler echocardiographic method to follow up patients with aortic stenosis. The third measurement used in the valve area calculation, the left ventricular outflow tract diameter, was not examined for reproducibility—presumably because it usually changes very little on serial follow-up—as was the case with their second group of patients (1).

Serial follow-up of patients with aortic stenosis. One of the most exciting applications of Doppler echocardiography lies in refining our understanding of the natural history of the various stenotic and regurgitant lesions. Particularly for the stenotic lesions, precise hemodynamic characterization can now be accomplished serially with a frequency that was not justifiable when only invasive measurements were available. A serial assessment of patients with aortic stenosis obtained with use of V_{max} has been recently presented (17). Otto et al. (1) have now provided serial assessment utilizing peak gradient, mean gradient and aortic valve area.

In this current series, patients who became symptomatic during the study showed a more rapid rate of disease progression than did those who remained asymptomatic. Even though the rate of progression could not be predicted from variables obtained at the initial study, this series suggests that a slope of progression can be determined for individual patients with use of serial studies. This slope could then be utilized to estimate when the patient will require valve surgery. This would have many practical applications, such as determining which patients with mild or moderate aortic stenosis who require coronary bypass grafting should have concomitant valve surgery. Finally, as the authors suggest, larger series with a longer follow-up time and with more patients with mild stenosis are likely to reveal factors that influence the rate of disease progression, such as valve architecture and degree of associated regurgitation.

Ultrasound technology is currently so precise that by making one measurement of distance and two velocity measurements we can accurately calculate a variable as complex as aortic valve area. Armed with this technology, we no longer need to subject the majority of patients with aortic stenosis to invasive measurement of hemodynamics. To be certain, some of these patients will require coronary angiography before valve replacement, but the severity of aortic stenosis, associated valve lesions, and left ventricular function can all be fully assessed by two-dimensional and Doppler echocardiography. Invasive laboratories have become busier with *therapeutic* procedures. They can now be relieved of many *diagnostic* procedures that can be perfomed in the echocardiographic/hemodynamic laboratory.

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