



Quantification of Valvular Aortic Stenosis

Karen K. Stout, MD, Catherine M. Otto, MD, Division of Cardiology, Department of Medicine, University of Washington, Seattle, Washington

Valvular aortic stenosis is common in the elderly with mild valve thickening affecting 25% of adults over age 65 years and stenosis affecting between 1–3% of elderly adults. Accurate diagnosis and quantitation of disease severity are important as valve replacement is needed when severe symptomatic obstruction is present. However, the symptoms of aortic stenosis are non-specific. Most patients present with decreased exercise tolerance or exertional dyspnea, while even the classical symptoms of angina, syncope and heart failure have many other possible causes, particularly in the elderly. This clinical problem is confounded by the high prevalence of systolic murmurs in the elderly. While most of these murmurs are due to aortic sclerosis or a flow murmur, some are due to severe aortic stenosis.

Physical Examination

Unfortunately, physical examination is not reliable for evaluating aortic stenosis severity, except at the extremes of the disease spectrum. Physical examination findings that are specific for severe aortic stenosis include a systolic thrill at the right upper sternal border with a 4/6 systolic crescendo-decrescendo murmur, a single S2 and a slow and diminished carotid upstroke (*pulsus parvus et tardus*). Conversely, severe aortic stenosis reliably can be excluded when there is no systolic murmur or when a normal physiologic split S2 is clearly appreciated.

However, most patients with suspected aortic stenosis have a grade 2/6 to 3/6 murmur and it may be difficult to be certain if S2 is split. These patients may have no obstruction to flow across the valve or may have severe obstruction. Further, in the elderly, the carotid upstroke may be normal due to superimposed hypertension and atherosclerosis, even when severe stenosis is present. It also can be difficult to distinguish mitral regurgitation from aortic stenosis as the aortic stenosis murmur radiates to the apex (instead of the carotids) in some patients. Thus, in most adults with suspected aortic stenosis, echocardiography is necessary to verify the diagnosis and accurately quantify the severity of valve obstruction.

Echocardiography

Echocardiography has become the clinical standard for evaluating the severity of aortic stenosis. Echocardiography

allows noninvasive assessment of stenosis severity, the underlying valve morphology and the cardiac response to the outflow obstruction, including left ventricular hypertrophy, pulmonary hypertension and mitral regurgitation.

Aortic Jet Velocity

The velocity (v) of blood across the stenotic aortic valve is directly related to the pressure difference (ΔP) between the left ventricle and aorta as described by the Bernoulli equation. A simplified version of the equation that ignores viscous losses and acceleration results in $\Delta P = 4v^2$. This simplified Bernoulli equation has proven remarkably accurate when compared with simultaneous pressure measurements. When comparing invasive and Doppler measures of transaortic pressure gradient, it is important to remember that the difference between peak left ventricular and peak aortic pressure (often called the peak to peak gradient at catheterization) does not equal the maximum instantaneous ventricular to aortic gradient as reflected in the maximum aortic jet velocity. Mean gradients, measured by averaging the instantaneous catheter or Doppler gradient over the systolic ejection period, correspond more closely with each other.

A simplified approach to calculation of the mean transaortic gradient is derived from the empiric observation that there is a close linear correlation between maximum and mean gradients for native aortic valve stenosis. Thus, mean pressure gradient (ΔP) can be estimated as: Mean $\Delta P = 2.4 (V_{\max})^2$ eliminating the need to trace the Doppler velocity curve.

The clinical value of Doppler velocity data depends on recording the data correctly. Recording the aortic stenosis jet is one of the most technically demanding aspects of an echocardiographic study. Since velocity is calculated from the Doppler frequency shift, the ultrasound beam must be aligned parallel to flow for accurate velocity recordings. However, the jet of blood through the stenotic valve has an unpredictable direction that cannot be visualized. Thus, examination from several ultrasound windows with careful patient positioning and transducer angulation is necessary. The velocity of the aortic stenosis jet (V_{AS-JET}) then is defined as the highest continuous wave Doppler signal obtained from any window (Figure 1). Thus, the most common error on a Doppler study is underestimation of stenosis severity due to a non-parallel intercept angle. Overestimation of stenosis severity is much less common but can occur if another signal such as mitral regurgitation is mistaken for the aortic jet. Each echocardiography laboratory needs to ensure adequate sonographer training and patient examination time for obtaining accurate data.

Despite these potential limitations, maximum aortic jet velocity alone has been shown in several studies to be highly predictive of clinical outcome. Since a given maximum aortic velocity consistently corresponds to a given mean pressure gradient, little additional value is added by

reporting calculated pressure gradients rather than the directly measured maximum aortic velocity alone.

Aortic Valve Area

The velocity (and pressure gradient) across the stenotic valve depends on volume flow rate as well as valve area. When transaortic volume flow rate is increased (e.g., aortic regurgitation) or decreased (e.g., left ventricular systolic dysfunction), additional calculations may help guide therapeutic decisions.

Echocardiography allows calculation of the aortic valve area (AVA) using the continuity equation based on the concept that the stroke volumes proximal to and in the stenotic orifice are equal: $AVA = (V_{LVOT} \times CSA_{LVOT}) / V_{AS-JET}$. Where the cross-sectional area of the left ventricular outflow tract (CSA_{LVOT}) is calculated as: $CSA_{LVOT} = \pi(D/2)^2$.

The diameter (D) of the left ventricular outflow tract is measured in a parasternal long-axis view immediately adjacent to the aortic valve to optimize the axial resolution of the image. Left ventricular outflow tract velocity (V_{LVOT}) is measured from an apical view to provide a parallel orientation with flow. Measuring diameter adjacent to the valve and identifying an aortic valve closure signal on the Doppler tracing ensures that flow and diameter are measured at the same anatomic location. Any discrepancy in the spatial location of these measurements can result in over or underestimation of volume flow (Figure 1).

It is important to understand that the invasive Gorlin formula and the noninvasive continuity equation, although both estimates of aortic valve area, are measuring different parameters. The Gorlin equation is a measure of the anatomic orifice area, whereas the continuity equation is a measure of physiologic flow area of the vena contracta. As such, these equations would not be expected to yield identical results, but both provide reproducible, reliable data that can predict clinical outcome and guide patient management.

Other Measures of Stenosis Severity

The normal area of the aortic valve, obviously, is related to body size; for example, being smaller in children than adults. One approach to indexing the valve area to body size is to divide valve area by body surface area. Another approach is to delete the outflow tract cross-sectional area from the continuity equation, leaving the ratio of outflow tract velocity to aortic jet velocity. This velocity ratio is effectively indexed for body size as the area of the outflow tract is the expected normal valve area for that individual. Thus, a ratio close to 1 is normal, a ratio of 0.5 indicates a valve area half normal size, and a ratio of 0.25 is consistent with severe stenosis (i.e., a valve area one quarter normal size). Some clinicians look at the “step up” in velocity across the valve which is the inverse of the velocity ratio.

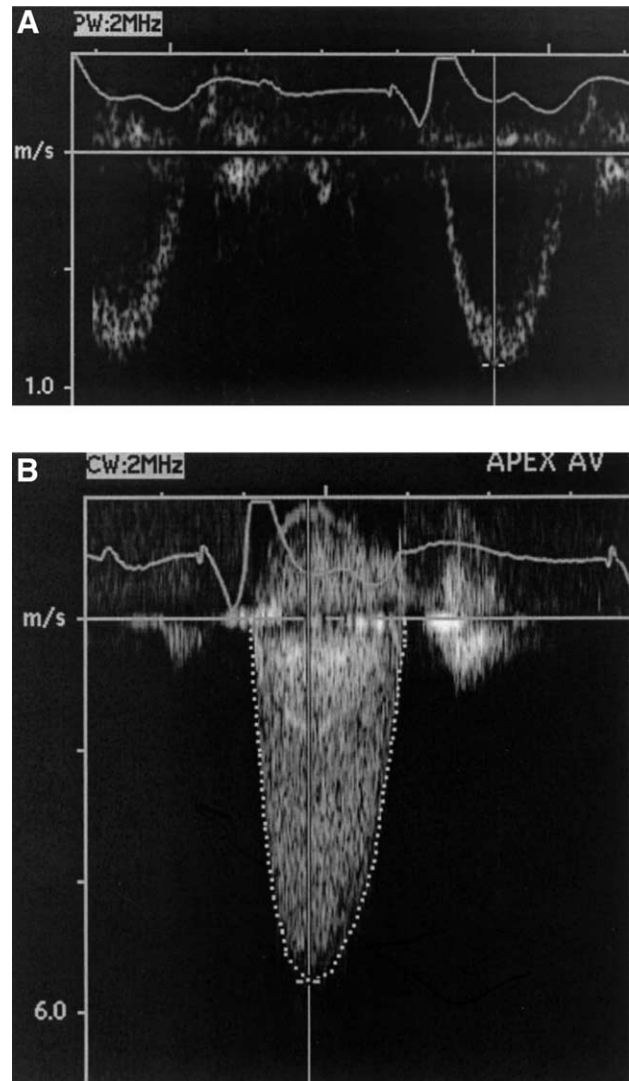


Figure 1. Doppler data needed for evaluation of aortic stenosis severity. (A) The left ventricular outflow tract velocity (LVOT) is recorded with pulsed Doppler from an apical approach with the sample volume positioned immediately proximal to the aortic valve. Note the smooth envelope of flow with a narrow band of frequencies at any time point and a clearly defined peak velocity of 0.9 m/s. (B) The aortic jet velocity is recorded with continuous wave Doppler from whichever window yields the highest velocity signal (in this case, an apical view). The maximum velocity of 5.6 m/s corresponds to maximum pressure gradient of 125 mm Hg and a mean gradient of 75 mm Hg. The LVOT to aortic velocity ratio is 0.16 and aortic valve area (measured LVOT diameter of 2.4 cm) is 0.7 cm².

Other measures of aortic stenosis severity include 2D planimetry of the orifice area on transesophageal imaging, valve resistance, stroke work loss and various ratios of jet velocity or pressure gradient to measures of left ventricular systolic function. None of these approaches has gained wide clinical acceptance. Although 2D planimetry of valve area on short axis images occasionally is helpful, caution is needed due to shadowing and reverberations from the calcified leaflets and errors due to non-planar aortic valve anatomy. However, planimetry on transesophageal echocardiography may be helpful when valve stenosis is first

recognized in the operating room at the time of coronary bypass surgery. Standard measures of aortic stenosis severity are difficult to obtain from the transesophageal approach as a parallel intercept angle with the aortic jet and outflow tract rarely is possible.

Low-Output Aortic Stenosis

Some patients may present with markedly decreased left ventricular function and restricted leaflet opening on echocardiography suggestive of aortic stenosis. Confusion regarding the significance of the stenosis and thus the appropriate management arises for several reasons. First, when ventricular outflow tract velocity is decreased, aortic velocity is similarly decreased, yielding a seemingly low gradient across a significantly stenosed valve. Alternatively, decreased cardiac output may be insufficient to adequately open the valve, giving the appearance of significant stenosis when in fact the leaflets are pliable, and will open more fully if cardiac output is increased. The continuity equation correctly indicates a small valve area, however, valve area is small due to inadequate opening force rather than due to stiff valve leaflets.

In patients with depressed left ventricular function due to aortic stenosis, valve replacement has substantial benefit. In contrast, valve replacement is unlikely to be beneficial in patients with other causes of left ventricular dysfunction and only mild or moderate coincident aortic stenosis. Several means of determining if decreased left ventricular function is due to aortic stenosis have been proposed.

Dobutamine stress echocardiography can provide insight into the mobility of the aortic leaflets. By the described relationships between flow, pressure gradient and aortic valve area, one would expect that a relatively fixed obstruction due to aortic stenosis would result in an increased pressure gradient with increased cardiac output. Conversely, a more pliable valve would be expected to open further with increased force applied to the valve leaflets. In this case, dobutamine mediated increases in cardiac output results in a smaller increase in pressure gradient.

With careful monitoring, dobutamine is infused beginning at 5 mcg/kg/min, and then increasing by 5 mcg/kg/min every 3 minutes to a maximum dose of 10 or 20 mcg/kg/min. At each stage, left ventricular outflow tract diameter and flow, aortic stenosis jet velocity and 2D echocardiographic ejection fraction are measured and valve area is calculated. If the valve leaflets are flexible, an increase in transaortic volume flow rate will result in an increase in valve area by at least 0.2 cm². A fixed valve area despite an increase in flow rate suggests severe stenosis. Interpretation is problematic if flow rate does not increase; either severe stenosis is present or the left ventricular myocardium is unresponsive to dobutamine.

While experienced centers find dobutamine stress evaluation of aortic stenosis severity helpful in selected cases, caution is needed. The expected changes in valve area are

similar to the measurement variability of this method. Infusion of dobutamine can cause arrhythmias or hypotension so that careful monitoring is needed and the test should be stopped promptly if complications occur. Most importantly, there is little outcome data to support clinical decision making on the basis the change in valve area with dobutamine stress. Since valve replacement is life saving when severe stenosis is present, the decision to defer valve surgery should be made only after thoughtful consideration.

An often overlooked simple approach to evaluation of stenosis severity in the patient with left ventricular dysfunction is to look at valve anatomy. The patient with a heavily calcified valve is likely to benefit from valve replacement, whereas surgery is not helpful when leaflets are thin with reduced opening due to low cardiac output. Valve calcification can be assessed by transthoracic or transesophageal echocardiographies, by fluoroscopy or by direct inspection at the time of surgery. Electron beam computer tomography (EBCT) also may be helpful in evaluation of valve calcification, although further evaluation of this approach is needed.

Correlation Between Symptoms and Stenosis Severity

Aortic stenosis can be categorized based on valve area (severe <1.0 cm², moderate 1.0–1.5 cm², and mild >1.5 cm²) or jet velocity (severe >4.0 m/s, moderate 2.5–4.0 m/s and mild <2.5 m/s) based on concepts of fluid dynamics and on clinical outcome data. However, there is substantial overlap between hemodynamic severity and symptoms, such that the exact jet velocity or valve area at which symptoms occur varies from patient to patient. This is observed with both aortic jet velocities and aortic valve areas where symptoms can be seen in a patient with a velocity of 3.4 m/s while a patient with a velocity of 5.0 m/s remains asymptomatic. Similarly, a patient with a valve area of 1.1 cm² may be symptomatic while another patient with a valve area of 0.7 cm² is asymptomatic.

Currently, timing of intervention is based on symptom onset, rather than stenosis severity per se, as clinical outcome without valve replacement in symptomatic patients is very poor. In contrast, asymptomatic patients, regardless of stenosis severity, have clinical outcomes similar to age-matched normal with a risk of sudden death <1% per year (lower than the risk of valve replacement).

In the patient with definite symptoms and a heavily calcified immobile valve, measures of stenosis severity simply confirm the need for valve replacement. In the patient with symptoms that might be due to aortic stenosis but a normal valve on echocardiography, it is evident that valve replacement would not be beneficial.

Given the overlap in disease severity between symptomatic and asymptomatic patients, precise quantitation of stenosis severity is most important in two situations: 1) following disease progression in asymptomatic patients so

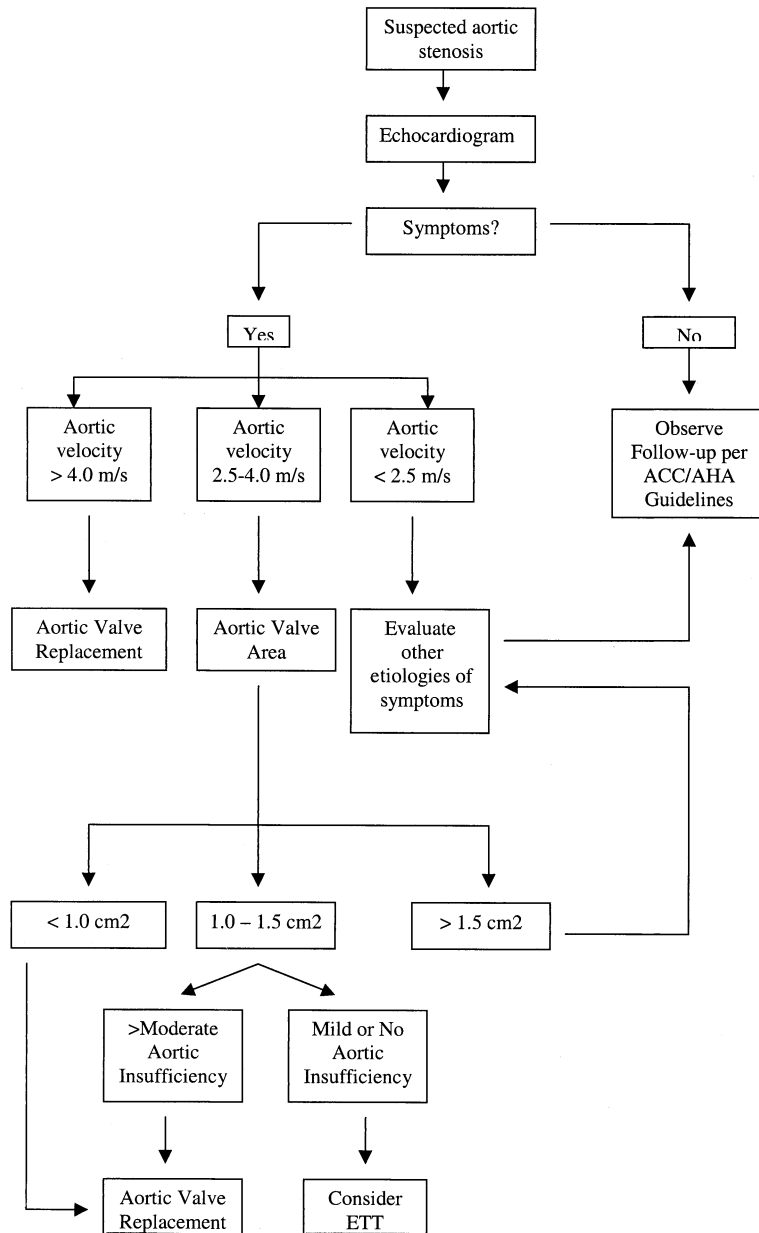


Figure 2. Flow diagram outlining our clinical approach to adults with suspected valvular aortic stenosis. This approach serves as a starting point for clinical decision making with decisions in individual patients influenced by other factors such as surgical risk, comorbid conditions and patient preference.

that valve surgery can be performed promptly once symptoms occur and 2) determining whether symptoms are due to aortic stenosis or other causes. For example, in a patient who presents with symptoms and an aortic velocity suggestive of moderate stenosis, calculation of valve area is essential (Figure 2). A small valve area suggests surgery is indicated, while a large valve area prompts evaluation for other causes of the symptoms.

Exercise Testing in Aortic Stenosis

Exercise testing is of little value for evaluation of coexisting coronary artery disease in adults with aortic stenosis because ECG changes are nonspecific. Significant ST-segment

depression seen in 80% of adults with asymptomatic aortic stenosis and does not correlate with the presence or absence of coronary artery disease.

In patients with severe symptomatic aortic stenosis, exercise testing is high risk and should not be performed. However, exercise testing may be performed cautiously in patients who are poor historians, in whom subtle symptoms are suspected or when it is unclear if the degree of aortic stenosis explains the patient's symptoms. The parameters of interest are exercise tolerance and the blood pressure response to exercise. A rise in systolic blood pressure <10 mm Hg indicates early symptoms. The test should be stopped promptly if blood pressure fails to rise and valve

replacement surgery considered. A normal blood pressure response to exercise would imply the observed stenosis is not hemodynamically significant at that point in time.

Summary

The symptoms and signs of aortic stenosis are common in elderly adults and the physical examination is unreliable for excluding severe stenosis or for estimating stenosis severity. Echocardiography is the optimal method for evaluation of valve anatomy and stenosis severity. Standard measures of stenosis severity are aortic jet velocity and valve area. Doppler velocity data can be used to estimate pressure gradients, for physicians unfamiliar with jet velocity information. Another simple approach is the velocity ratio or "step-up" across the valve.

In patients with aortic stenosis and left ventricular dysfunction, the change in valve area with changes in volume flow rate may be useful. Simply evaluating the extent of valve calcification also is helpful in this situation. Exercise testing is risky in symptomatic patients, but the blood pressure response to exercise can be used to assess the relationship between symptoms and stenosis severity in equivocal cases.

When echocardiographic data are suboptimal or when there is a discrepancy between clinical assessment and Doppler data, invasive measurement of pressure gradients and calculation of valve area may be considered.

Questions and Answers

1. A 60-year-old man is referred for symptoms of exertional fatigue and chest discomfort. A III/VI harsh systolic murmur is heard on exam and an echocardiogram is ordered that shows an aortic velocity of 3.2 m/s. What are the maximal and mean pressure gradients?

Using the equations for calculating maximal and mean pressure gradient based upon a maximal aortic velocity: $\Delta P = 4v^2 = 4(3.2)^2 = 41$ mm Hg; Mean $\Delta P = 2.4 (V_{MAX})^2 = 2.4(3.2)^2 = 25$ mm Hg.

2. His risk factors for coronary disease include only his age and gender, and his medical history is otherwise unremarkable. His echocardiogram demonstrates normal left ventricular size and function, without significant aortic or mitral regurgitation or pulmonary hypertension. His LVOT velocity is 1.2 m/s and his LVOT diameter is 2.4 cm. How can you determine

whether he would benefit from an aortic valve replacement?

This patient has moderate aortic stenosis and indeterminate symptoms. The first step is to calculate his aortic valve area. Given the continuity equation and $CSA = \pi r^2$: $AVA = (V_{LVOT} \times CSA_{LVOT}) / V_{AS-JET} = (1.2 \text{ m/s} \times 4.5 \text{ cm}^2) / 3.2 \text{ m/s} = 1.7 \text{ cm}^2$. Since this patient's valve area is greater than 1.5 cm², it is unlikely his aortic stenosis accounts for his symptoms. Other causes of exertional chest discomfort, such as coronary artery disease, should be evaluated.

3. A 72-year-old man is admitted with heart failure. Echocardiography shows a calcified aortic valve, a dilated left ventricle and an ejection fraction of 30%. The LVOT velocity is 0.6 m/s and aortic velocity is 3.2 m/s and the LVOT diameter is 2.5 cm. What is the aortic valve area? Again, given the continuity equation and $CSA = \pi r^2$: $AVA = (V_{LVOT} \times CSA_{LVOT}) / V_{AS-JET} = (0.6 \text{ m/s} \times 4.9 \text{ cm}^2) / 3.2 \text{ m/s} = 0.9 \text{ cm}^2$
4. How can you determine if this patient would benefit from an aortic valve replacement?

Valuable information regarding the significance of the increased aortic velocity is obtained by looking at the valve itself. In this circumstance, the valve is described as calcified and therefore is likely stenotic. It may be helpful to review the transthoracic images and consider transesophageal imaging or fluoroscopy to further define the extent of valve calcification. Another approach is to consider a dobutamine stress echocardiogram to evaluate the change in valve area with changes in volume flow rate. This patient underwent dobutamine stress echocardiography and the LVOT velocity was 0.8 m/s and the aortic velocity was 4.5 m/s at peak dose (20 mcg/kg/min). This yields a valve area of 0.9 cm². The failure of valve area to increase with an increase in transaortic volume flow rate suggests a rigid valve, consistent with significant aortic stenosis. Although definitive outcome studies are lacking, some clinicians consider that these results indicate he would benefit from aortic valve replacement. Prior to surgery a coronary angiogram needs to be performed to assess for the presence of concurrent coronary artery disease that could require bypass grafting.

Address correspondence and reprint requests to Catherine M. Otto, MD, Division of Cardiology, Box 356422, University of Washington, Seattle, WA 98195-6422.